International Conference on

Ultrahigh Intensity Lasers

Goa
12- 17 October 2014
http://icuil2014.org/

Abstract Book

ICUIL 2014, Goa

The International Committee on Ultrahigh Intensity Lasers

ICUIL 2014 CONFERENCE

October 12-17, 2014

Goa, India

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ORGANIZED BY:

Tata Institute of Fundamental Research (TIFR), Mumbai
and
International Committee for Ultra-High Intensity Lasers

International Conference on Ultrahigh Intensity Lasers 2014

Welcome to the 6th International Conference on Ultrahigh Intensity Lasers at Goa! Here on the west coast of India, amidst scarlet sunsets on azure beaches, civilizations have met resulting in diversity of cultures and ideas. We hope this meeting fosters a similar confluence of ideas and brings together scientists from different walks of our interdisciplinary community. Apart from the traditional subjects of discussion, we will get to hear the latest developments in multinational efforts such as ELI, XCELS and IZEST, which are all reaching important stages in their evolution.

The scope of ICUIL 2014 includes, but is not limited to:

- **Ultra-intense laser design and performance**
  -OPCPA-Based
  -Nd Glass-Based
  -Ti: Sapphire-Based
- **Novel Technologies for Ultra-intense Lasers**
  -Grating and compressor modeling and fabrication
  -High damage threshold laser components
  -Temporal and spatial property/pulse control
  -Spatial, temporal and contrast characterization
- **Laser Acceleration**
- **Applications with extreme light**
- **Short-wavelength sources**
- **Attosecond science**
- **Plasma Optics**

Lead presentations will be used to introduce the session topics. The remaining presentations will highlight specific areas within the session topic. Poster presentations will allow extended discussion of the same topics. The conference will also feature a student poster competition.

As a first for ICUIL conferences, we are pleased to announce the award of Student Grants to encourage participation from young participants. We give five grants this year and the winners are:

Yasmina Azamoum	(*Laboratoire Lasers, Plasmas et Procédés Photoniques (LP3), Luminy, Marseille, France)*
Maimouna A Bocoum	(LOA, *Ecole Polytech, Paris*)
Sven Breitkopf	(Institute of Applied Physics, Friedrich-Schiller-Universitaet Jena)
Lu Li	(*LOA, Ecole Polytech, Paris*)
Arseniy Mironov	(National Research Nuclear University, Moscow)

Enjoy ICUIL 2014! Enjoy Goa!!

Catherine Le Blanc, Chang Hee Nam and Jake Bromage (TPC Chairs)

Chris Barty and G. Ravindra Kumar (Conference Chairs)

INVITED SPEAKERS:

BILL BROCKLESBY, UK
SAMUEL BUCOURT, FRANCE
TODD DITMIRE, USA
MIKE DOWNER, USA
TAE MOON JEONG, KOREA
I JONG KIM, KOREA
MASAKI KANDO, JAPAN
M. KRISHNAMURTHY, INDIA
WIM LEEMANS, USA
TOMAS MOCEK, CZECH REPUBLIC
PRASAD NAIK, INDIA
KAROLY OSVAY, HUNGARY
DIMITRIOS PAPADOPOULOS, FRANCE
BEDRICH RUS, CZECH REPUBLIC
WOLFGANG SANDNER, GERMANY
A.M. SERGEEV, RUSSIA
DANIEL URSESCU, ROMANIA
LENG YUXIN, CHINA

CONFERENENCE THEMES

ULTRA-INTENSE LASER DESIGN AND PERFORMANCE
PUMP LASERS FOR ULTRA-INTENSE LASERS
NOVEL TECHNOLOGIES FOR ULTRA-INTENSE LASERS
APPLICATIONS

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The Extreme Light Infrastructure ELI

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The Extreme Light Infrastructure ELI (www.eli-laser.eu) will be the world's first international user facility for the scientific laser community. It is part of the European ESFRI Roadmap for Pan-European Research Infrastructures of high priority.

ELI will be dedicated to the fundamental study of light-matter interaction in the laser intensity regime up to10^{23}W/cm^2, and beyond. ELI's laser technology is based on chirped pulse amplification of femto-second optical pulses in broadband solid state laser materials and (or) nonlinear crystals. Single-beam laser peak-power will exceed 10 Petawatt (10^{16} Watt). Diode pumping will allow for up to 10Hz operation at the multi-Petawatt level. Most of these specifications are at least one order of magnitude above today's peak values, with ELI's upcoming fourth pillar exceeding some of the specifications by yet another order of magnitude.

Besides studying fundamental effects of ultra-strong electro-magnetic forces (associated with such intensities) ELI will serve to investigate a new generation of compact secondary sources delivering particle and radiation beams of femto-second to atto-second duration at high energies. Technologies for conversion of laser into secondary radiation include non-linear frequency conversion in gases, plasmas and on surfaces, laser plasma acceleration of ions and electrons, eventually followed by x-ray generation in periodic magnetic devices, or through laser-driven effects in plasma or vacuum (betatron radiation, Compton backscattering etc.). The planned interaction areas will have about twenty photon and particle beamlines equipped with numerous state-of-the-art experimental stations for an efficient user facility mode of operation, enabling parallel use of the various primary and secondary sources. ELI will afford wide benefits to science, society and economics, ranging from basic science in physics, natural and life sciences to applications in medical and biomedical research, and in fast electronics and materials research.

Applications even include understanding of the aging of nuclear reactor materials and development of new methods of nuclear waste processing.

ELI is presently being constructed as a distributed research facility in the Czech Republic, Hungary and Romania. Hence, apart from being open to access by an international user community, ELI has a political mission and will be instrumental for establishing and sustaining new scientific communities in the host countries and their regional neighborhood. ELI employs, as the first of its kind, an innovative funding model that utilize European Regional Development Funds (ERDF) for construction, and an European Research Infrastructure

Consortium (ERIC) of participating countries for operation. Investment costs are presently estimated at about 850M€, not including ELI's yet to be decided fourth pillar. User operation is scheduled to commence in 2018.

Subexawatt Laser Project XCELS: Towards 10^{24}-10^{25} W/cm^2 Light Intensity

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Construction of the XCELS laser facility [1] will open up opportunities for studying absolutely new physical phenomena currently unattainable in any experimental laboratory worldwide. We will speak about the way present day optical technologies enable achieving subexawatt peak power and about the new critical experiments in physics that may be performed at this facility. The scope of these experiments includes, but is not restricted to, creating record bright directed gamma-ray sources, producing overdense electron-positron plasma and spatially structured avalanches of electromagnetic cascades, generating giant attosecond pulses with nearly Schwinger field amplitude, and probing the space-time structure of quantum vacuum.

With focused radiation, XCELS will achieve an important threshold value of light field peak intensity $I_{RD} \sim 10^{24}$ W/cm^2. Overcoming this threshold dramatically changes the ultrarelativistic dynamics of particles and plasma in a laser field, resulting in a radiation-dominant interaction, when electrons and positrons effectively convert energy from the optical to the gamma range and the dissipative component plays the dominant role in their motion in the laser field. This component is stipulated by the radiation friction force that becomes comparable with the ponderomotive force, and even exceeds it in some sections of the trajectory. The impact of this effect above the threshold I_{RD} is so strong that the particles are attracted to particular attractor trajectories [2,3]. With a further increase of intensity, there occurs a transition of the radiation trapping to an anomalous mode when the particles are attracted to the regions of maximum amplitude of the electric field [2]. This enables producing an energy converter to the gamma range with the efficiency approaching 100%. The particle motion along the trapped trajectories permits obtaining a narrow-beam photon source. Creation of such sources is an important part of the XCELS experimental program.

The flows of hard quanta of gamma-rays formed in the radiation-dominant mode provoke, at high-power laser radiation, generation of electron-positron pairs and chain reaction of developing electromagnetic cascade [4]. The arising avalanche is the mechanism of formation of overdense electron-positron plasma with particle concentration amounting to 10^{26} cm^{-3}. As a result of the radiation trapping of the arising particles the dense avalanche also becomes spatially structured – regions with giant bright gamma luminescence appear in it. Creation and investigation of this new state of matter – boiler with strongly interacting optical radiation, electron-positron plasma and gamma-rays will be the focus of the XCELS experimental program.

The subexawatt radiation of the XCELS facility will be used for further advance to the region of intensities $> 10^{25}$ W/cm^2. To achieve this goal we plan experiments on generating giant attosecond pulses on the surface of specially shaped solid targets [5,6]. Focusing of such targets in space permits forming moving brilliant foci with the size of the region of electromagnetic field ~ 10 nm. The electric field strength in such foci may exceed 10^{17} V/m and may approach the Schwinger field. Brilliant attosecond foci are an interesting experimental tool for probing the space-time structure of vacuum thanks to a possibility of its field ionization in the absence of electron-positron avalanche.

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Recent Progress on the Ultra-intense and Ultra-short Laser at SIOM

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The recent progress about the improvements of the femtosecond petawatt ultraintense and ultrashort Ti:sapphire laser facility are presented, which include the peak power improvement and temporal contrast enhancement. SIOM has developed the first Chinese petawatt (PW) femtosecond laser facility in 2007 using the chirped pulse amplification (CPA) scheme [1]. This laser system was recently upgraded to 2PW based on a 100-mm dia. Ti:sapphire amplifier and higher pump energy [2]. With a newly developed high-contrast broadband frontend, the pulse duration was compressed to ~26 fs, and the ASE contrast was promoted to $\sim 10^{11}$.

The suppression of transverse parasitic lasing (PL) is regarded as a serious technical bottleneck for larger aperture CPA amplifiers of 10 PW class. As an alternative approach, optical parametric chirped-pulse amplification (OPCPA) can support higher energy amplification without producing a photoluminescence effect. Lithium triborate (LBO) is an attractive nonlinear crystal that can support high efficiency and broadband OPCPA near 800 nm wavelength. A 10PW or higher peak power femtosecond laser system can be developed by combining the Ti:sapphire-based CPA chain and a LBO-based OPCPA booster amplifier. SIOM recently implemented a hybrid Ti:sapphire-CPA and LBO-OPCPA laser system [3], which can produce an amplified pulse energy of 28.68 J with a spectral bandwidth of 80 nm (FWHM). After pulse compression, the peak power of the laser system is 0.61 PW, and the pulse length is 33.8 fs.

Besides OPCPA, the splicing technology of Ti:sapphire crystals was being developed as a possible method for a high-energy chirped pulse amplifier laser system.

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HiLASE: Development of Fully Diode-Pumped, kW-class Pulsed Lasers for High-Tech Applications

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HiLASE (High average power pulsed LASErs, www.hilase.cz) is a new R&D Centre focused on strategic development of advanced diode-pumped solid state laser (DPSSL) technologies for real-world applications. Two key concepts are being explored within HiLASE: picosecond thin-disk laser amplifiers to reach kW average output power, and cryogenically cooled nanosecond multi-slab laser amplifiers to reach 100 J at 10 Hz output (Table 1). In Beamline B, by changing the pulse duration and the peak intensity of pump pulse at the repetition rate of 1 kHz, we obtained 45 mJ output with 19.3% O-O efficiency and nearly diffraction-limited beam from the Yb:YAG thin-disk regenerative amplifier [1]. In Beamline C, by efficient suppression of nonlinear phonon relaxation in Yb:YAG thin-disk, we generated average output power of 85 W at the repetiton rate of 100 kHz from a compact thin-disk regenerative amplifier. We have also designed and optimized parameters of multi-slab laser amplifier scalable to kJ regime [2-5]. The single-beam 100 J nanosecond laser system based on a gas-cooled cryogenic, diode-pumped Yb:YAG multi-slab architecture with wall-plug efficiency > 12% is now under construction at STFC-RAL (U.K.) and will be installed and commissioned in the HiLASE centre by September 2015. It will be the world's highest pulse energy, fully diode-pumped solid-state laser operating at 10 Hz. DPSSL systems deployed at the HiLASE facility shall be at disposal of external users since 2016 for testing and prototyping of various laser technologies, contract research and development, including laser induced damage testing (LIDT), extreme ultraviolet lithography (EUVL), laser shock peening (LSP), mid-IR generation, micro-nanostructuring, etc.

Laser system	**Thin-disk Beamline A**	**Thin-disk Beamline B**	**Thin-disk Beamline C**	**Cryogenic multi-slab**
Completed	Front-end	Regenerative amplifier with single thin-disk head	All, except of high power pump modules	10 J pre-amplifier
Under development	Regenerative amplifier	Add second thin-disk head into regenerative amplifier	Add high power pump modules	100 J power amplifier
Achieved energy @ repetition rate	1 μJ @ 1.75 kHz	45 mJ @ 1 kHz	0.8 mJ @ 100 kHz	10 J @ 10 Hz
Next milestone energy	150 mJ	100 mJ	2 mJ	50 J
Final energy	750 mJ	500 mJ	5 mJ	100 J
Operational	Q2 2015	Q2 2015	Q2 2015	Q3 2015

Table 1 Status of development HiLASE laser systems (April 2014).

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Ceramic Laser Technology, Today and Tomorrow

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We organize a Laser Ceramic Sympoisum every year. I report these recent progress reported in the LCS 2013 in Korea and discuss the future of high power solid state lasers which allow coherent beam combining. There are two fabrication methods on ceramic fabrication, a reative sintering method and a wet chemical method. Last 15 years, the optical quality of ceramic, which was made from nano-crystalline powder by means of wet chemical process has better than that of traditional reactive sintering one. The intense investigation and discussion in LCS meeting gave us a key to achieve the single crystal quality ceramics. Today these two methods can produce almost same quality, which means the quality and performance are better than single crystal. In LCS 2013 there are several important results for our future, for example, crystal fiber fabrication, solid state single crystal growth (SSCG), anti-reflection structure by nano-imprinting tech. and new scheme for thermal-lens-free cooling. SSCG is available for the single crystal growing from sintered ceramics by top seeding method. SSCG has a potential not only for cubic crystals but also anisotropic crystals like sapphire and apatite. We found the growing speed in SSCG is surprisingly higher than traditional growing theory. Some of these important results should be presented in this talk.

We have no doubt about new laser material and cooling design for the paradigm shift in power scaling. We need a large aperture amplifier for high power output. LLNL (Lawrence Livermore National Laboratory) developed 40x40 cm power amplifiers for NIF (National Ignition Facility) to achieve the ignition of laser fusion. Such type of scaling law is not so available any more because new frontier science request high peak & high average power all together. Coherent beam combining is a key to break the limit of aperture scaling scheme. So, we have made a big effort on a high power fiber laser array system. But, we still need an alternative idea for our future because the problem is not so easy to solve by only one laser technology.

A thermal-lens free solid state laser is possible, or not? This is a serious problem for laser technology today. Cooling efficiency of solid state lasers including a fiber laser is defined by the ratio of cooling surface to the active volume. We compare this ratio between a fiber laser ($\frac{V}{S}=\frac{\pi R^2 L}{2\pi RL}=\frac{D}{4}$) and a thin disk laser ($\frac{V}{S}=\frac{\pi R^2 L}{\pi R^2}=L$). Equivalent cooling condition is D=4L, where D is the fiber diameter and L is thickness of a thin disk laser. The cooling efficiency of a thin disk laser with 250 μm active volume is equivalent to the large mode area fiber laser with 85μm core and 1 mm outer diameter. When they are comparable, the combination of a fiber laser and a thin disk laser should be most promissing.

last two years, I proposed two concepts on the thermal-lens-free solid state laser in ICAN workshop. The first one is thermal-insulated end cooled solid state lasers (Fig.1), and the second one is the high speed rotary thin disk lasers for ultra-high efficiency cooling (Fig.2). The thermal-lens free concept of solid state lasers will be discussed in this presentation.

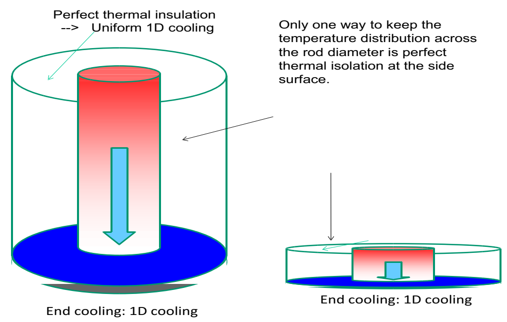

Fig. 1 Thermal isolation for axial cooling without lateral flow.

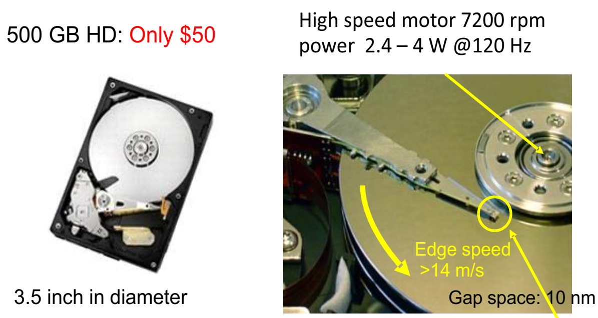

Fig. 2 High speed rotary thin disk laser in HD device.

Low Temperature Active Mirror Crystal vs Ceramic Yb:YAG Laser Amplifier Gain Comparison

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1. Introduction

The Lucia laser chain is a Diode-Pumped Solid-State Laser (DPSSL) with amplifier stages relying on Yb^{3+}:YAG active mirrors cooled from the High Reflectivity (HR) coated back surface. In order to double the current 14 J energy level achieved with a single water cooled room temperature power amplifier [1], a second amplifier need to be coupled. The first amplifier operates at room temperature (RT-amplifier), requires a pump intensity above 15 kW/cm² and is characterized by an electrical-to-optical efficiency $\eta_{e\text{-}o}$ equal to 2 to 3%. The second amplifier requires 3 times less pump light density and $\eta_{e\text{-}o}$ should reach 9%. To achieve such performances, the 60 mm 2 at% doped Yb^{3+}:YAG crystals of the RT-amplifier are replaced by 77 mm Cr^{4+}/Yb^{3+}:YAG cosintered ceramics in the low temperature amplifier (LT-amplifier). Operating temperature can be adjusted from 80 to 300 K thanks to an innovative and simple concept [2] based on a static low pressure helium cell in contact with the HR face of the disk. The LT-amplifier high flexibility in terms of temperature control allows absorption cross section measurements over a large temperature window. This prototype also permits a detailed exploration of the Yb^{3+}:YAG thermal behavior (section 2) under pumping condition varying from 6 to 660 W average power.

2. Gain medium internal temperature distribution

It is essential to make sure that the ceramic disk is as free as possible from internal thermal gradients. We have indeed observed [3] that such Yb:YAG disk is much more sensitive to internal constraints (from mechanical or thermal origin) when made of ceramic than its crystalline equivalent. The anamorphous nature of the ceramics makes it subject to much more important depolarization losses (due to birefringence) than a crystal.

The LT-amplifier pump source can deliver 1 to 2 ms 940 nm pulses from single shot to 10 Hz repetition rate. The pump delivery optical system allows a uniform distribution over a 6 cm² elliptical pump area of a maximum intensity of 5.5 kW/cm² (33 kW maximum peak power). We were therefore able to study the thermal behavior over two orders of magnitude of pump average power: from 6 to 660 W. The experiments were performed by inserting several thermal probes (PT100) inside a YAG disk and placing thermocouples in contact with its faces. A rather small (<5 K) axial thermal gradient was observed when filling the 400 µm thick helium cell with 750 mbar of helium and pumping at 5.5 kW/cm² intensity and 5 Hz.

3. Acknowledgements

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Pump Laser Design for a 10 Hz PW Class Laser System

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The next generation of ultra-high intensity laser facilities, such as ELI-Beamlines [1], require PW class lasers capable of operating at much higher pulse repetition rates than current flash-lamp pump technology will allow. Diode pumped solid state laser (DPSSL) technology overcomes the limitations of flash-lamps and offers the potential for efficient generation of high energy infrared ns pulses at 10's Hz repetition rates. After conversion into the green these are suitable for pumping PW laser systems, based on either Ti:sapphire or optical parametric chirped pulse amplifier (OPCPA) technology. The study of light-matter interactions and the successful development of lasers and support technology (targetry, diagnostics etc.), capable of operating under higher repetition rate conditions, will enable development of practical applications for PW laser technology. These include laser particle acceleration, active imaging and new medical therapies all of which are reliant on efficient laser generation of ions (protons etc.) or secondary radiation (x-rays, γ-rays etc.) at pulse repetition rates of at least 10 Hz.

To meet this challenge the DiPOLE project at the Central Laser Facility (CLF) is developing an efficient high pulse energy DPSSL architecture based on a cryogenic gas cooled, multi-slab ceramic Yb:YAG amplifier concept, capable of amplifying ns pulses to kJ pulse energies [2, 3]. Recently, a scaled-down prototype amplifier has met its design specification delivering 10 J pulses at 1030 nm and 10 Hz repetition rate with an optical-to-optical conversion efficiency of 21%. Second harmonic generation in LBO yielded 65% conversion efficiency into the green at 10 Hz. In addition, long term shot-to-shot energy stability of 0.5% rms at 7 J output was demonstrated during multiple extended runs, between 4 to 6 hours each totalling 48 hours, corresponding to almost 2 million shots. Following on from this success a larger scale laser, DiPOLE100, is under development at the CLF that will confirm the scalability of the cryo-cooled amplifier concept. This laser system is being built for the HiLASE project [4] in the Czech Republic and will deliver 100 J temporally-shaped ns pulses at 10 Hz with a fully integrated control system. A schematic diagram of the 100 J power amplifier from DiPOLE100 is shown in Figure 1.

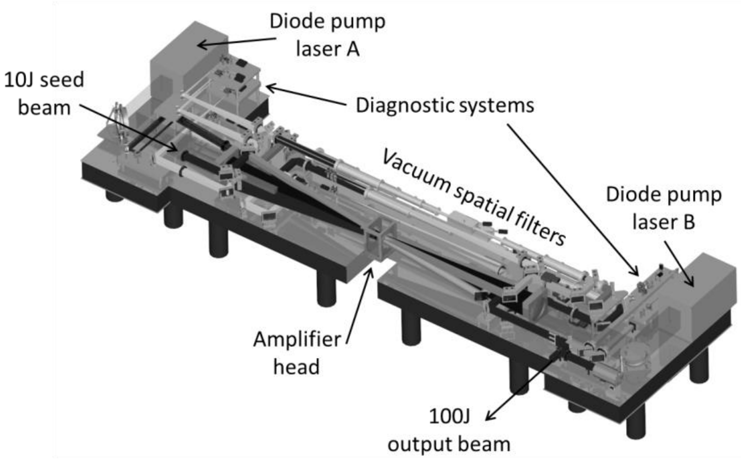

Fig. 1: Schematic of 100 J power amplifier from the DiPOLE100 system. The design is based on a 4-pass angularly multiplexed relay imaging extraction architecture. It includes active beam stabilisation and wave front control and supports a square high-order super-Gaussian beam of size 75 mm x 75 mm FWHM.

In this paper we will provide initial performance results from DiPOLE100, with particular emphasis on the active temporal and spatially-shaped front end, design details of the 100 J power amplifier and a progress update on the build of the system due for delivery in the second quarter of 2015. We will also briefly present plans for future high-energy DPSSL pump laser development within the CLF.

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Self-Phase Modulation Compensation in a Regenerative Amplifier Using Cascaded Second-Order Nonlinearities

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The amplification of short optical pulses is limited by the damage threshold of optical components and self-phase modulation (SPM). SPM leads to self-focusing and spectral broadening at intensities well below the damage threshold of optical components. Chirped-pulse amplification reduces the optical intensity during amplification, but is not simple to implement, particularly for picosecond pulses. We demonstrate that cascaded nonlinearities in a detuned nonlinear crystal [1] can alleviate SPM in a regenerative amplifier (RA). Intracavity compensation is efficient over a large range of operating conditions and allows for efficient amplification in a power amplifier (PA).

The operation of a Nd:YLF RA [2] seeded by a short optical pulse has been simulated. SPM leads to a spatially uniform spectral broadening and no significant modification of the wavefront because of the large number of round-trips that favor the linear cavity eigenmode. An intracavity component with a negative n_2 can compensate the broadening over a large range of operating conditions. The required per-pass nonlinear phase is much lower than 1 rad and can be obtained with cascaded nonlinearities. For a large detuning of a nonlinear crystal Δk (i.e., $\Delta kL \gg 1$), a spatiotemporal phase proportional to $n_2^{\text{eff}} = -4\pi d_{\text{eff}}^2 / c\varepsilon_0 \lambda n_{2\omega} n_\omega^2 \Delta k$ is induced on the fundamental pulse.

Significant SPM is experimentally observed without compensation in a Nd:YLF RA [Fig. 1(a)]. This broadening is detrimental to further amplification in a Nd:YLF PA because a fraction of the generated optical frequencies fall outside the gain bandwidth of that amplifier. Appropriate tuning of a 5-mm BBO crystal in the RA cavity leads to an output spectrum with a FWHM of 0.14 nm, which is consistent with the amplifier fluorescence spectrum. The intracavity nonlinear phase is varied by changing the RA pump-diode current [configurations (A), (B), and (C) in inset of Fig. 1(b) correspond to the same ejection time with low, optimal, and high current]. Without compensation, the PA gain decreases significantly when the intracavity nonlinear phase is increased. With compensation in the RA, a PA gain higher than 120 is maintained over all pumping conditions without retuning, leading to approximately twice the PA output energy. Simulation and experimental results at different energies and on a second regenerative amplifier will be presented.

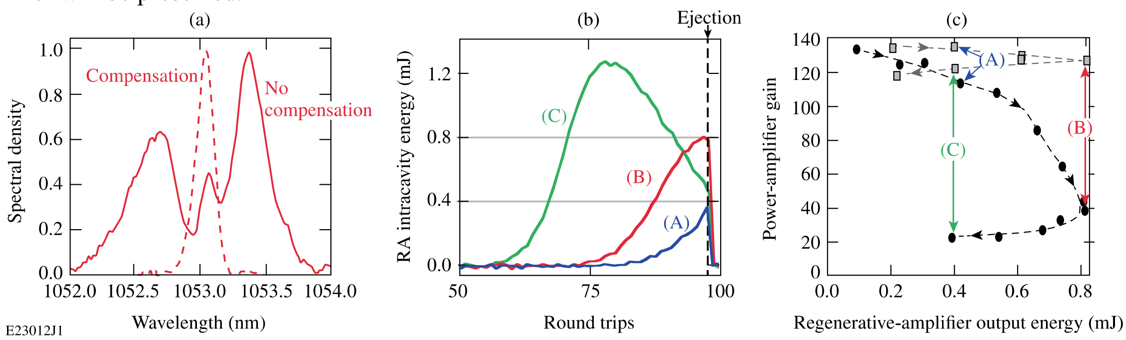

Fig. 1. (a) Optical spectra measured for an output energy of 0.8 mJ without (continuous line) and with (dashed line) SPM compensation. (b) Examples of buildup pulse trains where the vertical dashed line indicates ejection out of the cavity: (A), (B), and (C) correspond to regenerative-amplifier output energy of 0.4 mJ, 0.8 mJ, and 0.4 mJ, respectively. (c) Power-amplifier gain versus regenerative-amplifier output energy without (solid black circles) and with (solid gray squares) SPM compensation.

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Fundamental Research of High-Energy DPSSL for Pumping the Gekko-EXA OPCPA Preamplifier

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Large-aperture broadband OPCPA is a promising candidate to achieve an ultimate peak power approaching the exa-watt level. Gekko-EXA was conceptually designed based on OPCPA for sub-exa-watts peak power with few cycle pulse duration [1]. The design of Gekko-EXA includes two pump sources 100 J-class DPSSL and 10 kJ-class glass laser. Using the DPSSL-pumped OPCPA, ultra high peak power of peta-watts is obtained at 100 Hz after compression. Cryogenically-cooled Yb:YAG ceramics [2] are used as a laser material in the DPSSL system and large-aperture active-mirror is adopted as an amplifier scheme [3]. Those enable 100 Hz operation with 100 J pulse energy, corresponding to 70 J of the second harmonics as a pump source. After pulse compressor with a transmission grating pair, a pulse duration will be reduced to about 300 ps. As a fundamental development of the DPSSL system for pumping the preamplifier of Gekko-EXA, we are developing a 1 J-class cryogenically-cooled Yb:YAG laser.

Cryogenically-cooled ceramic Yb:YAG lasers attract great attention for their advantages in beam quality, scalability and efficiency. TRAM (Total-Reflection-Active-Mirror) architecture based on ceramic composite tech-nology [4] was proposed as an improvement of the thin-disk concept [5] for high-energy high-average power lasers. Multi-TRAM is an advanced varia-tion of the TRAM architecture for scaling to a higher pulse energy with a larger size of the beam [6]. In this paper, we report amplification of 10 ns pulses to pulse energy of 1 J at a repetition rate of 100 Hz by using a multi-TRAM.

The amplifier system consisted of cw fiber laser oscillator, electro-optic modulator, fiber amplifier, cryogenic TRAM regenerative amplifier and cryogenic multi-TRAM 4-pass amplifier, as illustrated in Fig.1. The system is designed to support pulse energy of more than 1 J with the repetition rate up to 100 Hz. The multi-TRAM is a monolithic composite ceramics which consists of a non-doped YAG trapezoidal prism and three Yb:YAG thin active layers. The multi-TRAM was pumped by two 2.5 kW fiber coupled diodes produced by Hamamatsu Photonics K.K. The maximum small signal single-pass gain of the multi-TRAM was measured to be ~12. At a total pump power of 4 kW and an input energy to the multi-TRAM amplifier of 10 mJ, an output energy of 1 J was obtained at 100 Hz.

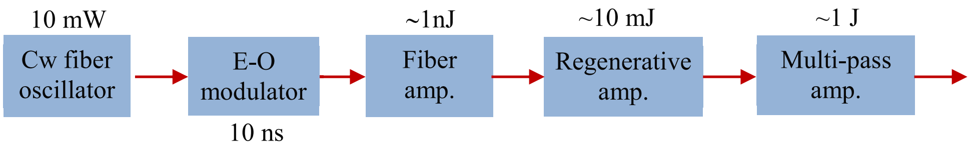

Fig.1 Schematic layout of the test system of Yb:YAG TRAM amplifier.

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Ultra-broadband Optical Parametric Amplification by Using Partially Deuterated KDP crystal for Gekko-EXA

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"Gekko-EXA" has been conceptually designed for ultra-high peak power generation of sub-EW.[1] Ultra-broadband amplification is a key technology for energy amplification of a few-cycle pulse. Optical parametric chirped-pulse amplification (OPCPA) is adopted in the advantages of high intensity contrast and broad spectral gain bandwidth. In the latest design, three types of pump sources of cryogenic Yb:YAG DPSSL (250J, 100 Hz)[2], split-disk laser (5 kJ, 0.01Hz)[3], and the LFEX laser (12 kJ, 0.0001Hz) [4] will be used at the corresponding OPCPA stages. The final output of 50 PW will be theoretically estimated at 10 fs pulse duration and 500 J pulse energy after compression. Some basic researches are going on against significant issues for the future development of the "Gekko-EXA" system.

An ultra-broad spectral gain width of ~500 nm around the center wavelength of 1 μm is required to realize enough high intensity contrast for plasma experiments. A partially deuterated KDP (p-DKDP) crystal is one of the promising crystals for such broadband OPA. Figure 1 shows our theoretical calculation of optical parametric gain by using Sellmeier equation in the reference [5] and [6], and more than 500nm of gain bandwidth has been shown. The Sellmeier equations have been estimated for KDP and DKDP by fitting to few observed refractive indices.[5, 6] For p-DKDP crystal with a deutration ratio between KDP and DKDP, theoretical estimation has been proposed by using Lorentz-Lorenz relation, but no experimentally observed data in near infrared has not been opened to our knowledge.

The refractive index of p-DKDP has been observed at different deuteration ratios, showing in fig. 2 for 70%. Small differences between the references and our experimental data are found out. Numerical spectral gain profiles are under calculating, based on our Sellmeier equation. In addition, OPCPA demonstration has been started with p-DKDP crystals.

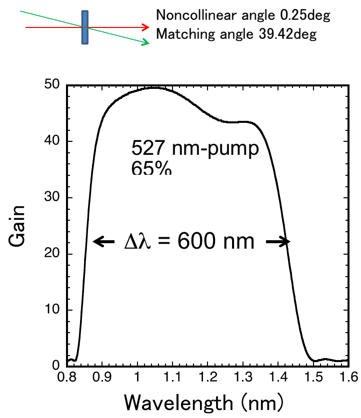

Fig. 1 OPA gain spectral profile with p-DKDP(65%).

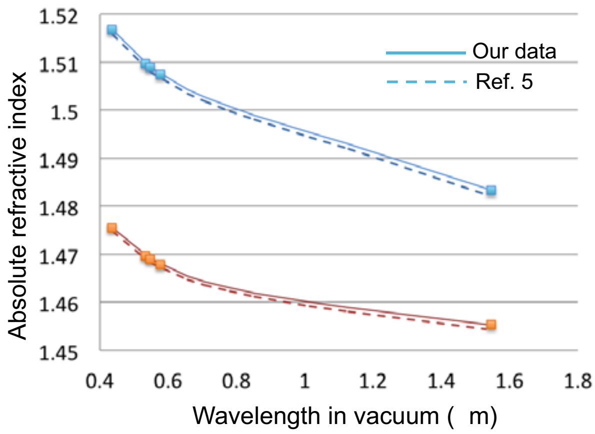

Fig. 2 Observed refractive indices of p-DKDP(70%).

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Ionization in Nano Plasma and Neutral Atom Acceleration

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Intense laser-produced-plasma is a complex amalgam of ions, electrons and atoms both in ground and excited states. They can be manipulated by suitable choice of parameters for compact and effective acceleration of ions [1] and electrons[2]. Since electrons respond instantly, appropriately tailored wake fields generate directed beam of even GeV electrons [3]. Directed acceleration of heaviour particles like ions is far more difficult. Since ion emission takes longer, the environment surrounding the laser plasma plays a crucial role [4]. Insofar the intense laser plasma studies have largely probed the ionisation in laser focus or non-location effects on ionisation. But with low energy electrons (~100 eV) electronic excitation can be as important ionisation. A careful choice of the experimental conditions can use this to generate a sheath of Rydberg excited systems surrounding the laser focus and use it to modifying the charge states of the ions and also the angular distribution of the atoms accelerated in the hot dense plasma. I present investigations to probe the microscopics of ionisation in a nano-cluster and how a dense ensemble of clusters can be used to form a Rydberg excited sheath [5] that can convert every ions to a neutral atom and pave for a compact neutral atom accelerator [6]. We show that ions can be reduced to even negative ions to form accelerated negative ions [5]. The charge transfer physics and the neutral atom emission can also be used to map the angular asymmetries in the Rydberg excited sheath which in turn affect the angular distribution of the energetic neutral atoms. We will present scheme of generating quasi-directional neutral atom emission from nano-cluster plasma.

In addition I will also give a overview of the recent advances made in intense laser plasma studies at the Tata Institute of Fundamental research and possible future plans.

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Radiation Pressure Acceleration of Protons with Femtosecond Petawatt Laser Pulses

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Laser particle acceleration has been explored to realize compact ultrashort proton/ion accelerators over last ten years [1, 2]. Energetic protons/ions have strong prospects for such applications as hadron therapy, radiography, isochoric heating of matter, inertial confinement fusion and nuclear/particle physics. Laser-driven proton/ion beams, compared to conventional accelerators, have outstanding features such as low emittance, small source size of a few µm, ultra-short duration of picoseconds and huge acceleration gradient of ~1 MeVµm^{-1}. Although laser-driven proton/ion acceleration has significant merits for unique applications, there exist numerous issues to overcome, such as attainable maximum energy, spectral and angular control, conversion efficiency, energy stability and repetition rate. Still the biggest challenge is the achievement of several hundred MeV protons suitable for hadron therapy.

We report proton/ion acceleration from ultrathin polymer targets by irradiating linearly polarized (LP), 30-fs, 1-PW Ti:sapphire laser at CoReLS. The laser intensity applied was from 5×10^{19} W/cm^2 to 3.3×10^{20} W/cm^2, and the target thinkness was from 10 nm to 100 nm. A maximum proton energy of 45 MeV was obtained when a 10-nm-thick target was irradiated by a laser intensity of 3.3×10^{20} W/cm^2 [3]. The transition of proton energy scaling from $I^{1/2}$ to I with respect to laser intensity I was observed as a consequence of the hybrid acceleration mechanism including target normal sheath acceleration, radiation pressure acceleration (RPA), and Coulomb explosion assisted-free expansion.

Recently we have succeeded in obtaining 80 MeV protons by applying circularly polarized (CP) laser pulses with an intensity of 6.1×10^{20} W/cm^2 to a 15-nm-thick polymer target. This result is one of the highest value obtained with a short pulse (30 fs) high-repetition rate (0.1 Hz) Ti:sapphire laser. The RPA of protons could be clearly confirmed from the optimal target thickness, quadratic energy scaling, laser polarization dependence, and 3D-PIC simulations. Our achievement of energetic protons via RPA mechanism indicates that laser energy transfer to particles can be controlled in the relativistic regime and that RPA can form a practical scheme for a laser-based proton accelerator in the 100-MeV range.

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Magnetic Electron Trapping Generates Efficient Quasi-Monoenergetic Ion Beam from Laser-Driven Plasmas

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Advanced ion accelerators based on laser-driven plasmas are potentially revolutionary because they are not only compact and affordable, but also deliver lower transverse emittance and higher current density relative to conventional accelerators. However, laser-driven ion beams still feature lower peak energy, wider energy spread, and lower efficiency than conventional accelerators, making them unsuitable for many applications. Several pioneering studies over the past decade have improved these beam parameters, mostly one at a time, and never all simultaneously [1]. Here we report a laser-driven aluminum 11+ ion beam where those beam parameters are enhanced simultaneously. Specifically the ion beam has an energy peak at 165 MeV with an energy spread as low as 7%, delivered with 5% conversion efficiency (i.e., the ion beam contains 4J of energy out of 80J incident laser energy on target). During the laser-plasma interaction, the plasma electrons are repeatedly driven forward by the incident laser and reflected backward by the self-generated plasma magnetic field that traps the electrons and makes them slower. Later, the trapped/slowed electrons are released forward with increased directionality when the magnetic field weakens as the laser exits the plasma that in turn shapes the laser-driven ion population into a quasi-monoenergetic ion bunch. The operative laser-plasma dynamics are strongly mediated by relativistic transparency (a relativistic plasma effect that causes dense, opaque plasma to become transparent, enabling efficient laser energy coupling into the plasma) [2], subsequent plasma channeling of the laser in the transparent plasma and self-generated magnetic field surrounding the channel [3,4]. The mechanism uncovered in our work may pave the route for next generation compact ion accelerators.

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Stabilizing Radiation Pressure Acceleration

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Acceleration of Background Gas Ions Induced by Coulomb Explosion of Clusters

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The laser-driven ion acceleration via the interaction of ultrashort, intense laser pulses with matter, known as laser-plasma acceleration, is featured by its high accelerating electric fields and short pulse length compared to conventional rf-accelerators. The recent advancements of novel laser-driven ion acceleration techniques now allow the maximum energy of ions up to several tens of MeV. In our recent studies, substantial enhancement of the accelerated ion energies up to 50 MeV/u has been demonstrated by utilizing a unique property of cluster medium, where submicron-size clusters are embedded in a background gas [1,2]. In such highly nonlinear interactions, we find that the acceleration mechanism consists of different processes such as, (a) acceleration of ions due to Coulomb explosion of individual clusters, (b) compression and acceleration of background gas ions due to the Coulomb explosion of clusters, (c) magnetic vortex generation and associated pinching near the rear surface [3], and (d) sheath acceleration at the interface between the medium and vacuum.

In this study, in order to understand the synergetic interplay between the Coulomb explosion of clusters and the background gas dynamics, we have conducted ion acceleration experiments using CO_2 clusters embedded in background H_2 gas [4] with the J-KAREN laser (1 J, 40 fs) at JAEA-KPSI [5]. In order to characterize the accelerated ions, we used a combination of a magnetic energy spectrometer (0.75 T) and CR-39 detectors covered by a 6 μm Al filter. By a careful analysis of etch pit positions on CR-39 and their structures including the etch pit growth behavior analysis with the multi-step etching technique [6], energy spectra for protons (from background gas) and carbon/oxygen ions (from clusters) are obtained separately for the first time. We found that the maximum energies of protons and carbon/oxygen ions are almost identical as ~2 MeV and ~2 MeV/u, respectively. Based on the experimental results, the acceleration mechanism of background gas ions induced by Coulomb explosion of clusters is discussed with the help from numerical simulations which employ a particle-in-cell (PIC) method including relaxation and ionization processes of plasma particles (EPIC3D) [7].

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Laser-Driven Proton Acceleration Studies using Structured Thin Foils

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The interaction of high-intensity ultra-short laser pulses with thin foils results in a compact ion acceleration. Such studies predominantly focus on lighter ions (predominantly protons) for applications in medical physics, high energy density science, laboratory astrophysics, nuclear physics, ion-driven fast ignition inertial confinement fusion, relativistic ion beam production and proton deflectometry [1,2]. A strong sheath electric field (TV/m) at the rear surface of the foil is created by the collective transport of a large number of hot electrons generated at the front surface of the foil by the action of the laser pulse. Ions, especially protons are accelerated in this sheath field in a ballistic way following the Target Normal Sheath Acceleration (TNSA) mechanism [3]. Typically a few percentage of the laser energy can be transferred to the ions [4]. To improve the ion acceleration efficiency either laser pulses of improved parameters are required or novel engineered targets needs to be used to couple more laser energy into the matter. It would be interesting to change the target parameters to enhance the light absorption. This path would in turn reduce the continuous requirement of improved peak laser intensity and higher repetition rate of laser systems. It would also allow development in material science and engineering for novel target design.

Nanoparticles or microparticles coating on a polished surface has been reported to couple more laser energy to the hot electrons by the local field enhancement [5, 6]. In spite of having higher laser energy coupling, the ion acceleration is reported to be suppressed with the nanoparticle (of 15 nm average diameter) coating [7]. To understand the effect of the structuring on the proton acceleration in more detail, particles of various sizes ranging from 10 nm to 2 μm are coated on the front side of a 2 μm thick Ta-foil. Sputtering technique has been employed to deposit particles in the range 10 nm to 300 nm. The thickness of the nanoparticulate coating would be about 100-300 nm, which is much larger than the skin depth of the laser used in the present experiment. Micron sized (~ 0.8 μm × ~ 2 μm) *E. coli* bacterial cells has been used as microparticles.

The proton acceleration is studied using a 800 nm, p-polarized Ti:sapphire laser at a laser intensity of 1.5×10^{19} W/cm^2 and a Thomson parabola ion spectrometer has been used to measure the proton energy spectra. Particles of smaller size (~ 10 nm) shows a suppressed ion acceleration features as compared to the plain foil and the microparticle coating provides a 1.5 times increment in the proton acceleration. On the other hand, the use of 100-200 nm particles exhibits almost 3 times increment in the highest proton cut-off energy. The proton acceleration following TNSA is found to be optimum for 100-200 nm sized particle coating.

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Ultrashort Pulse – High Intensity Laser Induced Hot Electron Generation and Transport in a Dielectric Slab

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The rapid advancement in the field of table-top ultrashort pulse, high intensity lasers, has enabled the generation of high density plasmas, using all types of targets. The high density plasma furnishes hot electrons and energetic ions, the transport dynamics of which are interesting from both physics and application points of view [1,2]. Since the electrons are much more mobile and intense, their interaction with the plasma and bulk matter yields various types of radiation viz., X-ray, Cherenkov, optical, THz and microwaves. These radiations carry the signature of the hot electron jets (0.1 – 2 MeV), and have often been used as a diagnostic to study their interaction dynamics [3,4].

In this work, an 800 nm laser with pulse width ~ 30 fs is focused onto a thick dielectric (BK7) slab with resultant peak intensity in the range of ~ 10^{18} – 10^{19} W/cm^2. The plasma dynamics and hot electron transport in the bulk transparent medium is investigated by rear-side imaging of the plasma emission and Cherenkov radiation respectively, by an ICCD camera. The novelty of the experiment lies in the achievement of a high laser pulse contrast ratio (LPCR = pedestal/peak) ~ 10^{-9}, which is 3 orders of magnitude better than previous experiment [3]. This discounts the possibility of a dense pre-plasma formation and subsequent reflection of the main pulse, thereby allowing better coupling of the laser to the target. This has been confirmed using pump-probe shadowgraphy.

The data is taken at laser energy of 150 mJ, focused on a 10 μm spot (intensity ~ 6.4×10^{18} W/cm^2). Fig. 1 (a) shows the variation of the emission flux in each gate (4 ns) window, with a typical plasma emission snapshot at a delay of 4 ns, placed inset as an example. Fig. 1 (b) shows the flux in each differential window between 0 – 1.8 ns. A peak is observed at Δt ~ 0.5 ns, which is attributed to Cherenkov radiation [Fig. 1 (b)]. Corresponding snapshot of the detected emission at t ~ 0.5 ns is placed inset. Further experiments at higher laser peak intensities are in progress, and interesting observations are expected.

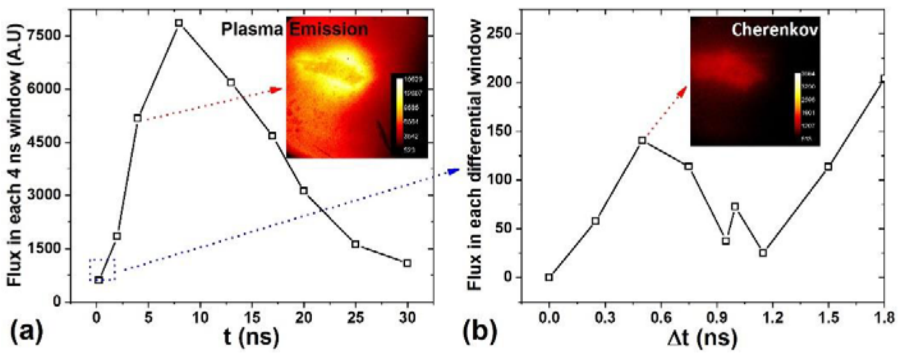

Fig. 1. (a) Plasma emission flux in each 4 ns gate window, obtained from the ICCD. Typical emission snapshot at 4 ns delay, shown inset. (b) Emission in each differential window, showing the Cherenkov peak at 0.5 ns. Corresponding snapshot of Cherenkov emission, shown inset.

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Astrophysically Relevant Magnetic Turbulence with a Table-Top Intense Laser

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The ubiquity of turbulence manifests itself on both terrestrial and galactic scales with turbulent flows abounding in magnetized plasmas such as the interstellar medium, the solar wind and the magnetosheath of planetary magnetospheres [1, 2]. Although the origin and manifestation of turbulence may be diverse, it is often characterized by phenomenological power-law scalings in the Fourier energy spectrum in the so-called “inertial range”.

We report results from recent experiments, where we probe the megagauss magnetic fields generated in intense laser-solid interactions at irradiances of ~10^{18} W/cm^2 at near-solid densities of ~10^{22} /cm^3. At initial time-scales, the energy spectrum shows a -5/3 scaling [3] in the k-spectra, whereas ~20 ps after the incidence of the main interaction laser pulse, the k-spectrum shows two distinct power-law scalings, separated by a spectral ‘kink', which becomes progressively more prominent at longer time-scales (up to ~ 75 ps), indicative of the dynamic involvement of ions. Similar spectral kinks have been observed previously in solar flare loops [4] as well as in spacecraft observations of the solar wind [5, 6]. Our results portray dynamic turbulent mechanisms in highly non-equilibrium regimes, providing an experimental test-bed for turbulent mechanisms of astrophysical significance, which can be tailored and simulated in a laboratory with a table-top laser.

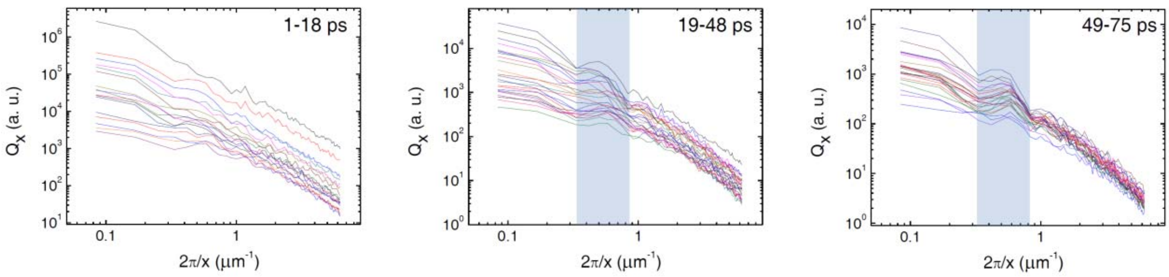

Fig. 1. The temporal evolution of the magnetic energy turbulent spectra

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Laboratory Studies of Astrophysical Processes

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For astrophysics research, traditional methods include observations and theoretical simulations. Large telescopes on the ground or space telescope are used to observe the celestial bodies in different wave bands. However, for some celestial and astronomical phenomena, the studies are limited sometimes since the observational data are scarce, objects are too far away from the Earth to observe, or evolution time of some objects is too long to get a comprehensive understanding in a limited period. With high-power laser systems, scientists are able to create the extreme conditions of physical experiments in the laboratory presently. Such experimental conditions are unprecedented, and can be used to simulate some representational celestial objects and phenomena, which allow scientists to study many important and critical astrophysical issues in laboratories. A new field of research, high energy density laboratory astrophysics (HEDLA), is developing rapidly [1].

Plasma outflows or jets exist widely in universe. Plenty of astrophysical processes, like magnetic reconnection, shock waves, jets, etc, are produced in the interactions of outflows. In this talk, we will present our recent experimental studies of the interactions between two laser-produced plasma outflows at Shenguang II laser facility, which can delivery energy up to 2 kJ. The main results are below,

1) Magnetic reconnection (MR) is believed to play an important role in many different plasma phenomena including solar flares, star formation, and other astrophysical events. The loop-top x-ray source in solar flares is one of the most famous observation evidences for MR model. Mega-gauss (MG) magnetic fields could be generated in hot, high-density plasmas by irradiating a solid target with high-power laser beams. During the laser pulse the magnetic field is quasi-steady and approximately "frozen" in the plasma expanding laterally. Based on this quasi-steady state of the magnetic field, we reconstruct the topology of magnetic reconnection in laboratory by using Shenguang II laser facility. The similar results of loop-top x-ray source in solar flares are observed. By applying the scaling law of magnetohydrodynamics they found the physical parameters of both systems have highly similarity.
2) Most astronomical and astrophysical shock waves are collisionless, which means that the shocks are not formed by coulomb collisions. We will present the generation of collisionless shockwaves in the interaction between two counter-streaming laser-produced plasmas. Numerical simulations indicate that the shockwaves are excited by electrostatic instability. We also observe formation of plasma filaments, which is believed to be caused by Weibel instability.
3) Jet deflection is an interesting astronomical phenomenon that collimated jets usually propagate away from their initial trajectories. When two high-density plasmas jets propagating perpendicular to each other, we observe large angle deflection of the jets. This may throw light on the understanding of the fantastic HH 110/270 system.

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Efficient generation of Hard X-Ray in an Interaction of Intense Femtosecond Laser with a Metal Nano-Coated Dielectric

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Hard x-ray emission in intense laser-matter interaction studies is a topic of great interest due in significant part to its various applications [1].We measure the hard x-ray yield from Ag nano-coated thick BK-7 glass target interacting with an intense femtosecond laser and compare the results with those from an uncoated BK-7 target. The enhancement in integrated hard x-ray yield is measured as a function of thickness of Ag nano-coating which was varied from tens of nanometer to hundreds of nanometer. The effect of laser polarization on hard x-ray yield is studied. Maximum enhancement (20x) is observed for a coating thickness of 35 nm for a p-polarized pump laser of relativistic intensity ($\sim10^{19}$ W/cm^2). For the coating thicknesses of more than 100 nm, the x-ray enhancement factor is found to be flat. The x-ray yield from uncoated BK-7 target is found to be the same for the two polarizations of the pump laser. Additionally, it is observed that the X-ray enhancement for coating thickness of 42 nm is greater for the p-polarized pump laser as compared to that for s-polarized pump laser. We compare our results with those from earlier studies [2, 3] and discuss the implications.

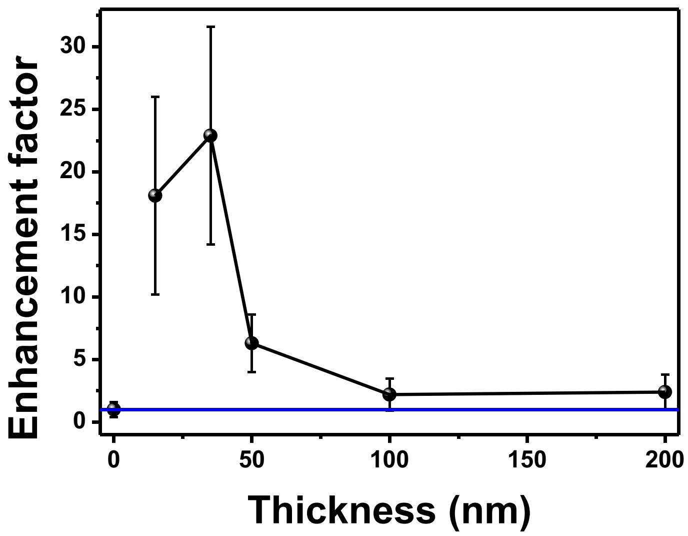

Fig.1. x-ray enhancement factor as a function of thickness of silver coating on an optically polished BK-7 target. Blue line corresponds to enhancement factor of unity.

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Particle Induced K- α X-Ray Emission from Laser Produced Proton Beam

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Heating of thin foils with high energy proton / ion beams of extremely short duration, low emittance, high brightness, and high peak current, is a subject of considerable importance to create isochoric state, warm dense matter, particulate evolution in a dense matter, laser driven fast ignition, as well as generation of monochromatic x-ray source with low bremsstrahlung. In such an experiment, an MeV energy proton beam generated by the interaction of fs duration laser pulse with foil target, is made incident on a second foil separated from the former one. This leads to rapid ionization of the foil atoms via collisions with the proton / ion beam. Removal of an electron from an inner electronic shell results in characteristic x-rays emission, which is used to characterise the isochoric state.

We have performed particle induced x-ray emission experiments using laser produced proton and ion beams. 1- 2.5 MeV protons and several hundred keV ions of different charge states of carbon were generated by mildly relativistic (~10^{18} Wcm-2), short-pulse (50 fs) laser interaction with foils of Al and Ni with thickness varying between 5 - 25 μm. Double foil target geometry was used, where a second foil of 7 μm thick Cu was kept at a distance of 100 μm from the first one (i.e. Al or Ni). Proton and ion beam generated from the first foil bombards the second foil. The particle induced x-rays emitted from second foil were characterized using a dispersion-less spectrograph working in the energy range of 1–20 keV. The x-ray spectrum consists of K_α (8.05 keV) and K_β (8.9 keV) lines of Cu, riding on a continuum of bremsstrahlung radiation. It is observed that the K_α peak position in single foil geometry is blue shifted, broadened, and has higher intensity compared to that of the line radiation from the double foil. The x-ray emission from the double foil target was studied as a function of the thickness and the atomic number of the first foil, and the laser intensity. It is observed that with increase in the laser intensity, the flux of the characteristic line radiation from the second foil increases. In the thickness range of 5-25 μm, the Cu K_α x-ray intensity from the second foil decreases monotonically with the increasing foil thickness. For the same thickness foil of 5 μm, Ni gave 5 time higher x-ray flux than Al. The observations were explained from the high flux and energy of the proton beam observed in the case of Ni foil compared to the Al foil of same thickness (5 μm). Theoretical calculations based on a variety of cross section models show that for protons energy less than 10 MeV, the cross section for K-shell ionization in copper increases with proton energy, which is in good agreement with the observed experimental results. The experimental details, the results, and our current understanding on the same, will be presented.

Intensity Dependent Confinement of Laser Produced Barium Plasma in a Transverse Magnetic Field

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Laser produced barium plasma produced using Nd:YAG laser pulses was investigated by optical time-of-flight spectroscopy in the absence and presence of 0.45 Tesla transverse magnetic field. The plasma was studied at two different pressures of 10^{-5} Torr and 10^{-1} Torr with Ar ambient at different laser intensities from 1.5 GW/cm^2 to 3.8 GW/cm^2.Temporal profiles of Ba I 553.5 nm (6s6p $^1P_1 \rightarrow 6s^2\ ^1S_0$), as well as Ba II 413.0 nm (6d $^2D_{5/2} \rightarrow$ 6p $^2P_{3/2}$) lines were recorded at 6 mm distance from the target surface.

The ionic profiles of 413.0 nm line have shown magnetic confinement in presence of magnetic field at 10^{-5} Torr as well as at 10^{-1} Torr pressures as shown in Fig.1. The profiles became narrow in presence of magnetic field as the fluence increases. This can be understood by the diamagnetic nature of the laser produced plasma in presence of applied magnetic field. When the laser plasma expands in an external magnetic field, the kinetic energy of the plasma is converted into magnetic potential energy and diamagnetic current arises because of $\mathbf{E} \times \mathbf{B}$ drift of magnetized electrons. Because of the diamagnetic current, $\mathbf{J} \times \mathbf{B}$ force acts on the plasma which compresses the plasma into thin layer and hence the temporal profile becomes narrower. The confinement is more at higher fluences due to increase in kinetic energy of plume.

At a pressure of 10^{-1} Torr, a fast component was observed in the ionic profile which can be attributed to the recombination of Ba $^{2+}$ ions to form Ba$^+$. In the absence of magnetic field, the peak position of the profile is almost constant at all laser fluences. This means, when we increase the laser fluence, the density of highly ionized states increases but there is no much change in the density of neutral atoms. In the presence of magnetic field, as the fluence increases, the peak position shifts towards the lesser time delays which indicates the increase of velocity of ions with fluence in presence of magnetic field.

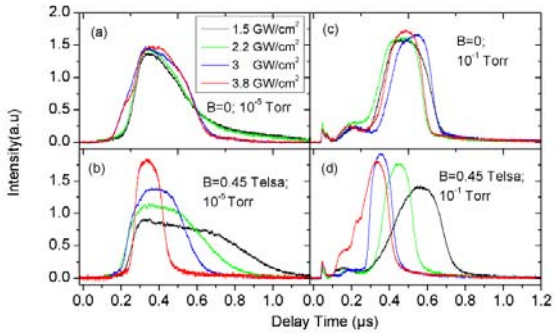

Fig. 1. Temporal Profiles of Ba II 413.0 nm line in (a) at 10-5 Torr in the absence of B field (b) at 10-5 Torr pressure in presence of B field (c) in 10-1 Torr pressure in the absence of B field (d) in 10-1 Torr pressure in the presence of B field

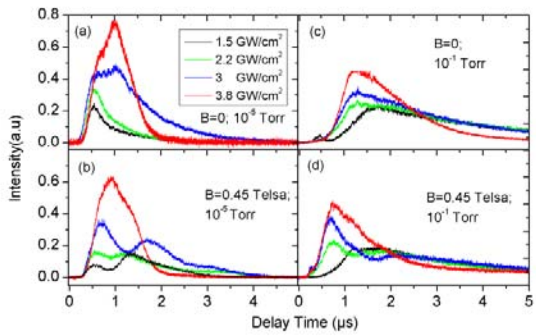

Fig. 2. Temporal Profiles of Ba I 553.5 nm line in (a) at 10-5 Torr in the absence of B field (b) at 10-5 Torr pressure in presence of B field (c) in 10-1 Torr pressure in the absence of B field (d) in 10-1 Torr pressure in the presence of B field

The scenario is completely different for case of neutral line Ba I 553.5 nm. The profiles are broadened in 10^{-1} Torr compared to 10^{-5} Torr in the absence as well as presence of magnetic field due to the collissions with the Ar atoms as shown in Fig. 2. Enhancement of emission intensity is observed in case of 10^{-1} Torr compared to vacuum in the absence as well as presence of magnetic field which is due to the confinement of plasma due to the ambient gas.

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On Feasibility of Observing QED Cascades in Laser Pulses

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We have considered the interaction of a high-energy electron beam with a laser field formed by two counterpropagating focused femtosecond laser pulses. Non-linear Compton scattering and electron-positron pair production by the emitted photons lead to development of an electromagnetic cascade ("shower-type" cascade) which collapses very quickly however due to significant energy losses by the initial and secondary electrons and positrons. Nevertheless, the laser field accelerates the low-energy charged particles trapped in the focal region and thus gives rise to development of electromagnetic cascade of another type ("avalanche-type" cascade) predicted earlier in Refs. [1, 2]. We show that this effect of collapse and revival of electromagnetic cascades can be observed at the energy of the initial electron beam of the order of several GeV and intensity of the colliding laser pulses of the order 10^{24} W/cm^2. This means that the effect can be already observed at novel laser facilities that are now under construction (ELI) or are planned for construction in near future (ELI, XCELS). Moreover, we claim that in general the proposed experimental setup provides the most realistic and promissory way to observe the "avalanche-type" cascade.

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High resolution and high dispersion Thomson parabola along with Time-of-flight Detector for Ion Spectrum Measurement of various target materials

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Hot plasma is produced when a solid target is irradiated with intense laser in vacuum. Properties of the generated plasmas depend strongly on the laser and the target parameters and on the target irradiation geometry. A high resolution and high dispersion Thomson parabola spectrometer comprising of Time-of-Flight diagnostics has been developed for simultaneously resolving protons and low-Z ions of energy from 1keV to 1MeV/nucleon and incorporated in the Laser plasma experimental chamber. The Thomson parabola consists of two permanent magnets mounted inside the housing through linear magnetic feed-through which are connected to micrometer for the adjustment of the magnetic field by changing the spacing between the magnets. The magnetic field can be varied from 150 Gauss to 2 kGauss. Two copper electrodes were connected with –ve and +ve polarity of electric field. The voltage difference between two electrodes can be varied from 0 V to 10 kV. The shaping of the ion beams was done with the help of 2 mm aperture in ring type ion collector and a 100 µm diameter pinhole kept 2 mm before the magnetic shoes. The ion energy and charge state has been optimized with respect to the laser parameters such as laser pulse duration and wavelength, various targets including low density foam targets has been done. The angular distribution of charge states and the corresponding ion flux have been measured. The energy spectrum for each charges corresponding to the target normal has also been measured. It is evident from the TPS images that, the ion energy and flux are highly directional towards the target normal. It is also seen that the angular spread of the higher charge states are less.

Hydrodynamic Studies at HP&SRPD, BARC

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High Pressure & Synchrotron radiation Physics Division is engaged in High Energy Density Physics using indigenously developed 30 J / 300 ps. A short pulse laser (1J/1ps) has been commissioned for the x-ray probe pulse generation. This will be used for the x-ray imaging of shocked material. This will be upgraded to hundreds of TW in near future. More than fifteen plasma diagnostics have been developed for laser produced X-ray emission studies, ion emission studies and laser driven shock studies. Various experiments have been done on x-ray generation and laser driven high pressure (shock) studies in single and layered targets: pressure was measured up to 30 Mbar. Stable and enhanced acceleration and studies on instabilities of laser ablated low Z ablator targets, interaction of low density foam with intense laser for inertial confinement fusion (ICF) research, X-ray back-lighter characterization for material opacity measurements etc. We have also installed 2J/ 8 ns Nd:YAG laser along with the high resolution Raman spectrometer (2 cm-1) for the time resolved Raman spectroscopy of the dynamically shocked material. In this paper, we will present a few recent experiments done using these facilities.

Fusion Energy by Ultra Intense Laser Initiated Nuclear Reactions with Aluminum Targets

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Ultra Intense Laser UIL interaction with Al27 target could possibly give rise to a nuclear rection of the target nuclei with the accelerated target charged ion in the laser field. The residual radioactive nuclei of Mn 52 and Mn 51 could well be due to evaporation of deuterons and tritons from the created compound nucleus according to the nuclear reaction:

Al27 (Al27, H2) Mn52 and AL27 (Al27 + H3) Mn51

We here with report simulation of compound nucleus formation followed by particle evaporation applying Mont Calro code PACE-4 to estimate the possible cross-section for forming highly excited compound nucleus Fe54 leading to the final Nuclei Mn52 and Mn51. The results shown in the figure below indicate that the highest cross section of such possible two reactions is peaking at Al27 ions projectile energy ≈ 60 MeV (2.222 MeV/ A) and 70 MeV (2.593 MeV/A) respectively.

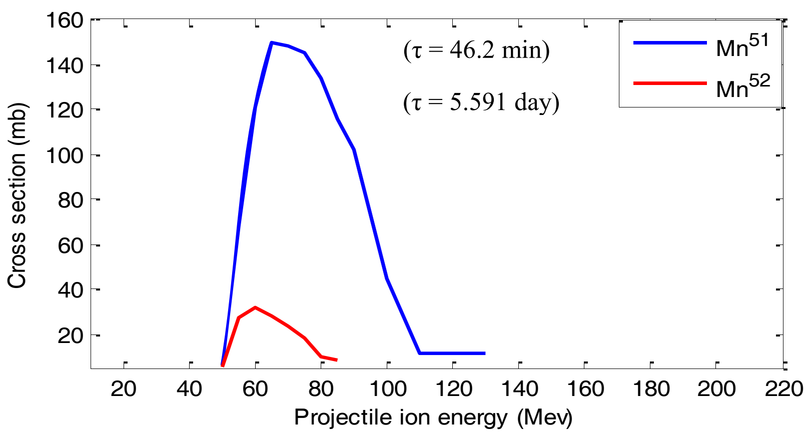
The cross sections for production of the neutron deficient Mn nuclei resulting from the two above mentioned nuclear reactions of Al27 + Al27 are also estimated. The estimated cross-section of Mn52 and Mn51 positron emitters shown in figure indicate maximum values of approximately 30 and 150 mb at the aluminum ion energies mentioned above respectively. The nuclear reactions leading to Mn positron emitters are expected to also provide deuterons and tritons with the same cross-sections.

The energies of these particles (H2 and H3) are calculated considering the newest standard Tables of the Atomic Masses. Possible acceleration of these emitted particles in the laser field is also expected.

The Possibility of a new approach of fusion of the deuterons and tritons without implosion during the confined short laser pulse duration is proposed.

In this approach an intense laser field equal or above 100 Peta Watt/cm2 would be needed. Simulation calculations for the form factors will be reported.

The design of the experimental set up to be applied to attain such Fusion energy and overcome probable difficulties will be elaborated.



Theoretical studies on Laser Driven Atomic Clusters

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Atomic clusters, intermediate to gas and solid, contain both the advantages of solids and gaseous targets when irradiated by high intense lasers [1]. The clusters are excellent absorbers of incident laser light. The absorbed energy is redistributed among Mev ions, Kev electrons and Kev X-rays. Laser-driven particle acceleration, coherent and incoherent X-ray generation, nuclear fusion in deuterium clusters are few of the important application of laser-cluster interaction. Various theoretical models like nanoplasma model, molecular dynamic (MD), particle-in-cell (PIC) *etc.* are used to study the dynamics of laser driven clusters. We have developed a three dimensional time dependent MD simulation model to study the laser–cluster interaction [2]. The ionization of the cluster atoms is carried out by optical field [3] and collisional ionization [4] using Monte–Carlo method. The motion of the particles is governed by the laser electromagnetic force plus the coulomb force of other charged particles. The present MD code is validated against various published theoretical and experimental results. For example, we have studied the interaction of 125 fs, 800 nm laser pulse with peak intensity of 10^{16} W/cm^2 with deuterium (R_0=100Å), argon and xenon (R_0=50Å) clusters. As the atomic number of cluster material increases, the average degree of ionization also increases. It is found to be 12 and 8 from Xe and Ar clusters respectively which is close to the published results. The mean kinetic energy of ions is found to be 58, 35, and 5 keV for Xe, Ar, and deuterium clusters, respectively. These results are in good agreement with the studies of Petrov et al [5].

By using MD simulation, we have also studied the energy absorption by atomic clusters [6] and reaffirmed the existence of linear resonance at electron density of $n_e = 3n_c$ [1], where n_c is the critical electron density. Our simulation parameters are Ar cluster of radius 30Å, a laser pulse of intensity $8 \times 10^{16}\, W/cm^2$ with FWHM pulse duration varying from 10 fs to 120 fs. Both mean kinetic energy of ions and energy absorbed by the cluster have shown an optimum value at pulse duration of 25 fs. The presence of optimum pulse duration is a consequence of maximum absorption of laser energy due to the closest vicinity of peak of laser intensity time profile to the resonance condition ($n_e = 3n_c$) at the time of cluster expansion.

Recent experiments [7] with few cycle laser pulses have revealed the anisotropic emission from Ar clusters is anisotropic i.e. the ion yield is higher along perpendicular direction of laser polarization than parallel to it. Detailed MD studies are performed on Ar clusters with simulation parameters: cluster radius ~ 16-58Å, laser intensity ~ $5 \times 10^{14}\, W/cm^2$ - $3 \times 10^{16}\, W/cm^2$ and pulse duration ~ 5-100 fs [8]. For a fixed cluster size of 58Å and laser intensity of $4.5 \times 10^{15}\, W/cm^2$, we observe an optimum pulse duration of 10-20 fs for which the anisotropy manifests itself prominently. For this optimum pulse duration, the oscillating inner electron cloud shields the ions more effectively along the direction of laser polarization than perpendicular to it. Consequently more ions are emitted along the perpendicular direction at the time of cluster explosion.

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Effect of defocusing a PetaWatt Laser into Gold Cone-Wire Targets

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An experiment was carried out to examine the coupling of a high energy PetaWatt laser into a gold cone-wire target. The experiment was carried out using the Vulcan PetaWatt laser, and utilised Cu K-alpha spectroscopy and imaging to provide information on the coupling of laser generated hot electrons into the copper wire. The results showed that defocusing tended to soften the electron spectrum whilst approximately maintaining the coupling from the laser to the hot electron population. The experimental results are presented alongside the results of a number of models and simulations including ray-tracing, PIC and VFP codes the results of which support the experimental conclusions. These results are of interest from the standpoint of Fast Ignition Inertial Confinement Fusion where the generation of an overly hot electron spectrum is detrimental to laser-fuel coupling efficiency.

Simulation of Fusion Evaporation of Compound Nuclei Created in Ultra Intense Laser Interaction with Carbon Targets

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Compound nucleus creation in Ultra Intense Laser UIL interaction with materials could be possible through Fusion-of the target nuclei with the accelerated target charged ion in the laser field. The residual radioactive nuclei in the remaining target material could well be due to evaporation of protons, neutrons, deuterons etc. from the created compound nucleus.

We here with report simulation of compound nucleus formation followed by particle evaporation applying Monto Calro code PACE-4 to estimate the possible Fusion cross-section for carbon nuclei forming excited Mg^{24} compound nucleus. The results shown in fig. 1 indicates the highest cross section of such possibility peaking at carbon ions projectile energy ≈ 30 MeV (2.5 MeV/ A).

The cross sections for production of neutron deficient nuclei resulting from the Fusion-Evaporation process of C^{12} + C^{12} are also estimated. The estimated cross-section for Na^{22} ($\tau = 2.6\ y$) and O^{15} ($\tau = 2.034\ min$) positron emitters shown in fig. 2 indicate maximum values of app. 100 and 80 mb at carbon ion energies of 60 MeV (5 MeV/A) and 86 MeV (7.17 MeV/ A) respectively. The reactions leading to these positron emitters are C^{12}(C^{12}+ d) Na^{22} and C^{12} (C^{12}+2 α + n) O^{15}

The acceleration of possible contaminant O^{16} ions to produce Fusion-Evaporation reaction of O^{16} + C^{12} creating Si^{28} compound nucleus could participate in producing the same positron emitters shown above. The simulation results for the Fusion- evaporation cross- sections attain maximum values at accelerated oxygen ions 110 MeV (6.88 MeV/A) and 158 MeV(9.88 MeV/ A) for Na^{22} and O^{15} respectively.

The simulation results help greatly in choosing the power of the UIL as well as the design of the experimental set up to be applied in verifying the Fusion-Evaporation Phenomena.

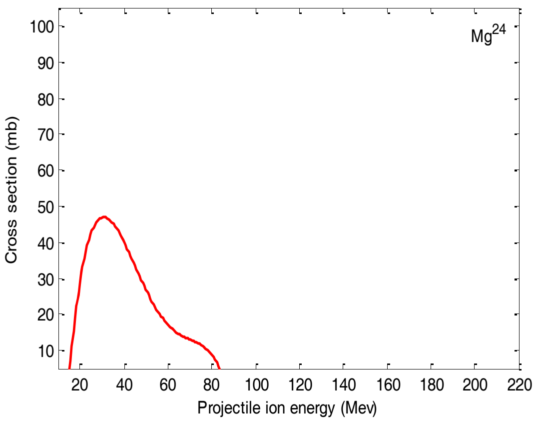

Fig.1: Cross section for the production of Mg^{24} calculated by PACE-4 evaporation code for $C^{12} + C^{12}$

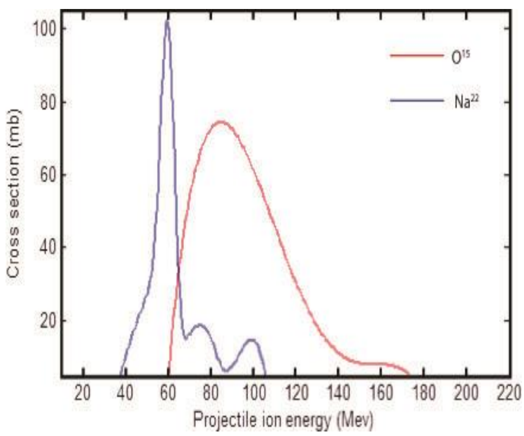

Fig.2: Cross section for the production of Na^{22} & O^{15} calculated by PACE-4 evaporation code for $C^{12} + C^{12}$

Investigation of Strong Terahertz Radiation Generation by Hollow Gaussian Laser Beam in Magnetized Plasma.

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In this paper we are proposing a scheme of terahertz waves generation by the non linear interaction of the self focused Hollow Gaussian Beam (HGB) with Electron Plasma Wave(EPW) in a collisionless magnetized plasma. When the laser beam propagates in the plasma along the direction of static background magnetic field then a non linear ponderomotive force acts on it (considering paraxial approximation), as a result of this the beam starts suffering oscillatory convergence and divergence, thereby getting focussed in the plasma. When this self focussed laser beam interacts with EPW it drives a non linear current in the transverse direction, thereby producing THz radiations. In this study we have analyzed the role of the order of the HGB and effect of static background magnetic field on the generation of THz radiations. The generated waves are found to be highly sensitive to both of these parameters and we found that by using this theory the power level of the generated radiations come out to be of the order of Gigawatts.

Dynamics of Hot Dense Plasma Excited by Intense Femtosecond Laser

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We investigate dynamics of hot dense plasma excited by nonrelativistic and relativistic intensity femtosecond lasers. We observe a periodic oscillation of a probe reflectivity in the THz frequency regime when a nonrelativistic ($\sim 10^{17}$ W/cm^2) pump laser interacts with a dense plasma. Additionally pump-probe Doppler spectrometry [1] was adopted to track the instantaneous motion of the critical-density-layer inside the plasma from where the probe laser gets reflected. A one-to-one correlation has been found in the simultaneous measurements of probe reflectivity and its Doppler shift. A similar oscillation in the reflected probe spectrum is observed in a three stage numerical simulation. On the other hand, at relativistic pump laser intensities ($\sim 10^{18}$ W/cm^2) we clearly observe a laser driven shock-like structure moving deeper into the solid target which was independently investigated by a set of numerical simulations and found to have a good agreement with the experimental results.

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Probing High Intense Femtosecond Laser Produced Hot Electron Transport inside BK7 Glass Using Pump-Probe Shadowgraphy Technique

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We present studies of fast electron transport through a bulk transparent medium and the associated plasma dynamics using pump-probe shadowgraphy. An 800 nm p-polarized pump laser of 30 fs pulse duration is focused onto an optically polished BK7 glass with peak intensity in the range of $10^{18} - 10^{19}$ W/cm^2. A 400 nm shadowgraphic probe is used to transversely probe the hot electrons generated by the interaction. The high resolution images are resolved even within ionization cloud and filamentary transport is clearly seen. We have observed very long electron jets of ~600 μm in 3.7 ps probe delay. The longer time scale plasma expansion speed towards vacuum side is consistent with our previous result ~10^7 cm/s [1]. At this high intensity, a low contrast ratio laser pulse can generate a pre-plasma before the arrival of the laser pulse peak intensity and completely change the interaction mechanism between the laser pulse and the initial target. Experimental results using low contrast (10^{-6}) and high contrast (10^{-9}) pump lasers are also illustrated here.

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Terahertz Generation by the Beating of Two Laser Beams in Collisional Plasmas

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The role of two laser beams at beat wave frequency is studied for the high power and efficient terahertz (THz) radiation generation in collisional plasma. The nonlinear current at THz frequency arises on account of temperature dependent collision frequency of electrons with ions in the plasma and the presence of a external static electric field and density ripple. Optimization of laser-plasma parameters gives rise to the radiated THz amplitude of the order of 10^{-2}

Laser Pulse Amplification by Stimulated Brillouin Scattering

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A theoretical model of laser pulse amplification by stimulated Brillouin scattering is presented. The amplification of laser pulses by plasmas is based on a coupling of three waves: two transverse electromagnetic waves and a longitudinal plasma response. The plasma response via ion-acoustic wave called Brillouin amplification. This process requires that the resonance condition for energy (frequency x) and momentum (wave-vector k) is fulfilled. The laser pulse interact with counter propagating seed laser pulse via stimulated brillouin scattering. The seed pulse takes the energy of the main laser pulse and gets amplified via SBS process. The theoretical results are compared with simulation results which are of good agreements.

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Stabilization of Rayleigh Taylor in Laser Fusion by Strong Coupling Effects

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The Rayleigh Taylor instability is one of the most virulent instabilities in laser fusion. The strong mixing between the hot and cold fluids due to this instability during compression makes the inertial confinement scheme inefficient. Suppression of such an instability would, therefore, be very useful.

It is demonstrated that the parameter regime for such a hydrocarbon plasma to lie in strong coupling regime can be readily achieved in experiments on laser compression of matter for inertial fusion. Modeling the strongly coupled plasma of the ablation driven piston by a Generalized Hydrodynamic (GHD) model (often employed in the context of strongly coupled plasma systems) it is shown that there is a stabilization of the Rayleigh Taylor mode. Numerical simulations also confirm this conclusion. This suggests a new mechanism for containing the instability. The experimental verification of such a suppression effect would be desirable.

Proton Acceleration Studies from Nanostructured Thin Foils

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Structured targets in the nanometric or micrometric scale absorb laser energy more efficiently compared to conventional polished targets via the local field enhancement due to the lightning rod effect and the surface plasmon resonance [1]. This property results in enhanced hot electron generation which is used routinely for bright x-ray sources. After the electrons have transported through the thin foil target, it gives rise to a strong charge separation electric field at the target rear. This field provides the accelerating field for protons by the Target normal sheath acceleration mechanism [2]. As more energy of the laser is coupled to the electrons, the sheath is expected to be higher in magnitude and ion acceleration is expected to enhance [3].

Particle-in-cell simulations carried out on nanoparticle coated targets have yielded an optimum particle size to be 100 nm for maximum laser energy absorption. Production of metal (Cu, Al, Ag) nanoparticles of average size 100 nm in diameter poses a technical challenge inherent to the standard conventional sputtering technique. However, tantalum exhibits a peculiar property of producing clusters of 100-200 nm average size which are formed by the coagulation of 6-10 nm nanoparticles during flight towards the substrate. A 2 μm thick tantalum foil coated with nano-clusters is used as the target. The proton acceleration is studied using a Thomson parabola spectrometer at a laser intensity of 1.5×10^{19} W/cm^2 at the TIFR high contrast 100 TW Ti:Sapphire laser facility. The nano-cluster density was varied systematically over there orders of magnitude. The proton cut-off energy is observed to increase very rapidly as the cluster density is increased before it saturates. A three-fold enhancement in the highest proton cut-off energy has been observed compared to the unstructured foil by the introduction of the nano-clusters.

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Laser Driven Plasma Accelerator: Towards Stability and Applications

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Laser driven plasma accelerators are very promising for providing compact high energy particle sources (eg. electron beam). With the development in laser technology new milestones in energy gain of electron beams have been achieved in last couple of years. However, significant attention is required to achieve unprecedented beam parameters, in order to make these particle sources available for practical applications. For several applications it is required to synchronize these electron beams with another independent physical, chemical or biological processes. The primary requirement for such a synchronization is low divergence and high precision in the pointing of these electron beams.

It has been shown that plasma generated by intense laser pulses, embedded in an external static magnetic field, could dramatically change the divergence and pointing stability of such electron beams [1]. In particular, an external magnetic field could allow steering of the electron beams with high accuracy and control within few degree around the laser pulse propagation direction. Such characteristics of laser driven electron beams could revive hopes towards the real practical applications of these compact high energy particle sources.

We will will present some results on the stability of electron beams generated by laser driven plasma accelerators, and their possible application towards imaging of dense warm matter and compact radiation sources.

Key words: Laser plasma accelerator, beam stability, external static magnetic field.

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PIC Computer Simulation of Intense Laser Pulse Interaction with Multicluster-Plasma Targets

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A number of salient phenomena have been observed in the laser irradiation of cluster targets. These include the Coulomb explosion of the clusters, enhanced emission of x rays, generation of energetic electrons and energetic ions. There are indications that some strong nonlinear interaction of laser and clusters do occur upon the intense short pulse irradiation. The laser interaction with clusters is far stronger than that of the same intensity laser with other preparations of the same materials such as gas and/or usual plasma and solid with planer surface structure. A cluster medium is characterized by its material (the charge state Z, and density, size (the radius, assuming circular structure), surface and internal structure(for example, multilayer coating using different materials), packing function, spatial configuration or distribution of clusters (order or random distribution). In relation to the interaction with laser field, following parameters such as cluster size to wavelength, collisionless skin depth to cluster size. A difference of cluster medium from conventional plasmas is in variety of controllable parameters which characterize the interaction. Such a large number of parameters widens applications utilizing the laser-cluster interaction. In this work we analyze the laser -cluster interaction in order to understand the cluster fusion. For this purpose by using our two - dimensional (2D) particle - in - cell (PIC) number code we investigate the ultra short high irradiance laser pulse interaction with targets where the multicluster cloud is imbedded in an underdense plasma or the clusters are located in a vacuum region preceding the plasma layer. Single bunch formation of an electron beam generated from nonlinear laser wakefields was also shown in numerous PIC simulations. The wake wave breaking occurs when the laser pulse pushes the plasma electrons both in the forward and sideways directions. As a result the wakewave takes the form of a plasma cavity.

One characteristic of high intensity laser-plasma interactions is the formation of an electron density cavity moving with the group velocity of the laser pulse. The cavity's transverse size is determined by the laser pulse width and its length is of the order of the relativistically strong Langmuir wave wavelength. In this limit, the wavelength depends on the amplitude of the Langmuir wave, which in turn depends on the laser pulse intensity. On the other hand the high intensity laser pulse is subject to self-focusing which changes its intensity. Therefore, the difference in the laser intensity influences not only the wake amplitude but also the wake position relative to the laser pulse. This is considered to lead to variations in the features of the electron acceleration in addition to the increase and decrease of the electron energy. Here we systematically study the interaction of a short-pulse moderate to high intensity laser with an underdense plasma slab. Also discussed are the properties of the fast electron distribution in phase space, aiming at a better understanding of the formation of their energy spectrum. We consider the terawatt – petawatt range laser pulse interaction with a sub millimeter underdense plasma slab.

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Development of a Table-Top uCT Based on Laser Electron Acceleration

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Relativistic electrons are important requirement in several fundamental research fields. The development of ultashort, high-power (>100 TW) laser sources enables us to down scale both the cost and size of large, conventional accelerator facilities to the university laboratory scale. The acceleration of electrons happens via focusing an intense laser pulse onto a low density gas plasma. The electrons are accelerated in the large electric field which is created by the electrons being pushed aside, while the heavy ions remain stationary [1]. The transverse motion of the electrons during the presence of the laser pulse creates a synchrotron-like radiation. The high brightness and spatially coherent radiation can be used as high resolution phase-contrast x-ray imaging [2].

Recently we demonstrated the reconstruction of a high resolution 3D image of a femoral trabecular bone using a laser driven X-ray source on Astra-Gemini laser in the Rutherford Appleaton Laboratory (UK).

In this presentation the recent progress in development of a table-top laser system with high repetition rate and ultrashort pulse duration is shown for carrying out electron acceleration experiments on a laboratory scale for medical imaging purposes.

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Effect of Gamma-Ray Emission on Hole-Boring at Ultrahigh Intensity Laser-Solid Interaction

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The impressive progress in laser technology open bright prospects in generation ultrahigh intensity optical radiation. Upcoming laser facilities like ELI or XCELS may reach intensity level 10^{23} W/cm^2 and higher. The laser-solid interaction at such intensity level may be accompanied by the hole-boring effect when the radiation pressure pushes the laser-produced plasma towards. Beside of the fundamental significance of hole-boring it plays a key role in laser-driven ion acceleration. Relativistic correct model of the hole boring have been developed recently [1]. However, at laser intensity higher than 10^{23} W/cm^2, the electrons become very efficient radiators of X-rays and γ-quanta while the particle dynamics is governed by radiation reaction. The radiative and QED effects can strongly affect hole-boring scenario [2,3].

The effect of radiation reaction and gamma-ray emission on hole-boring and ion acceleration is studied. It is shown that the efficient gamma-ray emission can strongly affect the hole-boring velocity. A simple analytical model for hole-boring with consideration for gamma-ray emission is developed. The model predictions are compared with results of PIC-MC simulations.

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Energetic Molecular Ions from Intense Laser-Cluster Interactions

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In the recent years, laser acceleration of ions through coulomb explosion of clusters has been shown to generate MeV energy ions. In this submission we report the observation of molecular CO^+ ions with kinetic energies extending upto 3 keV from Coulomb explosion of $\{CO_2\}_{36000}$ clusters irradiated with moderately intense ($3*10^{16}$ W/cm^2), 40 fs, 800 nm pulses. The resulting energetic charged fragments were analyzed in a high resolution Thomson Parabola spectrometer. Charge-resolved kinetic energy (KE) distributions reveal that the average charge over a CO_2 molecule in the cluster plasma is ~ 12. Using a uniform charging model, this translates to an electric field of ~ $6*10^9$V/cm at distance of 1 nm from the centre of the cluster, large enough to trigger dissociation of the CO^+ ion. The unexpected presence of the CO^+ ion indicates its formation deep in the cluster core. Using a model involving non-uniform charging of the cluster and subsequent Coulomb explosion with appropriate laser and cluster parameters we numerically obtain KE distributions close to the experimental KE distributions.

A Computational Study of the Effect of Higher-Order Transverse Modes in Laser Plasma Based Electron Acceleration

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Laser wakefield acceleration (LWFA) technique in general assumes a Gaussian transverse spatial intensity profile for the laser pulse that generates the plasma wakefield for accelerating electrons. The effect of tailoring the transverse laser intensity profile in terms of higher order Laguerre-Gauss (LG) modes was studied with three-dimensional particle-in-cell simulations. Specifically, the LG01 and LG10 laser modes were utilized to drive and optimize the wakefield generation in the plasma medium and study their effect on electron injection and acceleration dynamics in comparison to a standard Gaussian laser beam.

Laser-Driven Plasma-Based Electron Acceleration in Nitrogen and Argon Gas Jets

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An experimental study on laser-driven electron acceleration in nitrogen and argon gas jets has been carried out using the Ti:sapphire laser system at Laser Plasma Division of RRCAT, which delivered 3 TW laser pulses of 45 fs duration on the gas jet target. The laser was focused at about 1 mm above the gas jet nozzle, to an intensity of ~ 2×10^{18} W/cm^2 at the focus. In the nitrogen gas jet, the laser pulse was observed to be stably self-guided over a length of about 450 µm, and high-quality, stable electron beams were produced at an electron density of 3×10^{19} cm^{-3}. The electron beam had virtually background-free quasi-mono-energetic energy distribution, with peak energy ~ 25 MeV (average), charge ~ 30 pC. The beam divergence and pointing variation were ~10 mrad. In the case of argon gas jet, although the laser pulse was self-guided over a much longer length (700 µm to 900 µm), the electron acceleration was highly unstable. In this case, a collimated electron beam with divergence ~ 40 mard, pointing variation > 15 mrad, beam charge ~40 pC, and peak energy < 10 MeV was occasionally observed at an electron density $>10^{20}$ cm^{-3}. The differences in laser pulse guiding and electron acceleration in the two gases can be understood in terms of the differences in ionization dynamics and acceleration mechanisms involved in the two gases. The details of the experiment will be presented and our current understanding of the mechanisms involved will be discussed.

Microscopy of Coulomb Explosion of Clusters in Intense Laser Fields

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Interactions of rare gas clusters with intense laser fields in the regime of 10^{15} - 10^{16}W cm^{-2} are probed using a non-uniform charging model of the cluster species. Moving beyond the usual practice of theoretical investigations being made in isolation from the experimental measurements and seeking a convergence of the results thus obtained to the latter, we report a first attempt in making theoretical analysis of the laser-cluster interaction dynamics in conjunction with the experimental observations in toto. The method adopted by us distinctly minimizes the necessity of over-simplification of the model and, also, drastically reduces the requirement of computational resources. A comparison with the experimental measurements shows very good reproduction of the integrated charge-resolved spectrum of ion propensity distribution and ion kinetic energy spectra.

Electron Injection Dynamics in the Sharp Density Transition Regime of Laser Wakefield Acceleration

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The downward plasma density transition configuration is one way of achieving controlled injection of electrons in the technique of Laser Wakefield Acceleration (LWFA). Using three-dimensional PIC simulations, we have explored in detail the mechanism of electron injection in the sharp density transition regime (transition scale length is much less than the plasma wavelength). In this regime, we find that the injected electrons originate from the high density side just before the density downward ramp and are both on-axis as well as off-axis with respect to the laser and wakefield propagation direction.

High Brightness, High Energy Electron Beams from Density Transition and Subsequent Acceleration in a Plasma Channel

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We study, using three-dimensional simulations, the combined effect of a gradual downward density transition followed by a transverse plasma channel. The purpose of density transition is to induce controlled electron injection, whereas the subsequent plasma channel is to aid in extended guiding of laser pulse and thereby enhanced acceleration of electrons. The effect of various plasma channel parameters on the final electron beam quality is explored. We show that with this technique it is possible to produce high brightness, high energy electron beams, that can have application to short-wavelength free-electron lasers.

Target Normal Sheath Acceleration of Protons by Laser Mode Converted Nonlinear Surface Plasma Wave

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The mode structure of a large amplitude surface plasma wave (SPW) over a vacuum – plasma interface, including relativistic and ponderomotive nonlinearities is deduced. It is shown that the SPW excited by a p- polarized laser on a rippled thin foil target has larger amplitude than the laser and causes stronger target normal sheath acceleration of protons. Further, the SPW covers a larger surface area, hence, is more effective for target normal sheath acceleration. Protons accelerated by the SPW can reach energies $\varepsilon_i \sim 4\times$ times the ponderomotive energy of electrons. For the parameters of Ceccotti et al.'s experiment [1] one gets 4 times energy enhancement due to the excitation of SPW when 60% laser energy is mode converted into SPW. Experimentally they have observed 2.5 time energy enhancement. Substantial enhancement in proton energy is possible for optimal values of the laser amplitude.

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Direct, Real-Time and Sensitive Plasma Density Diagnostic by Quadriwave Lateral Shearing Interferometry

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Laser Plasma Wakefield Accelerators (LPWAs) [1-3], make use of the extremely intense accelerating fields produced during the interaction of an ultra-intense, ultra-short laser pulse with a sub-critical plasma. This plasma results from laser-ionization of a gas jet, or by discharge in a capillary. The properties of the accelerated electron bunch is highly dependent on the plasma density profile. The injection in the accelerating cavity is critically improved by steep gradients [4] and tuned plasma profile [5] . Beyond electron acceleration, gas jets are broadly used in high-intensity laser physic because they can be probed, and shot with high rep. rate. Such jet are of high interest in short X-Ray pulse from plasma-laser ,[6], ions acceleration and magnetic solitons [7], or all optical Compton source [8], emphasizing the importance for control and diagnostic of the plasma profiles.
Electronic density is usually mapped by two-arms-interferometry : the optical index of the medium is retrieved from the interference fringes between the reference arm and the arm crossing the plasma. In a classical Mach-Zehnder set-up, the fringe pattern gives discontinuous phase information, unwrapped by complex wavelet transform algorithms, and often results in remaining discontinuities on noisy data, and low resolution.

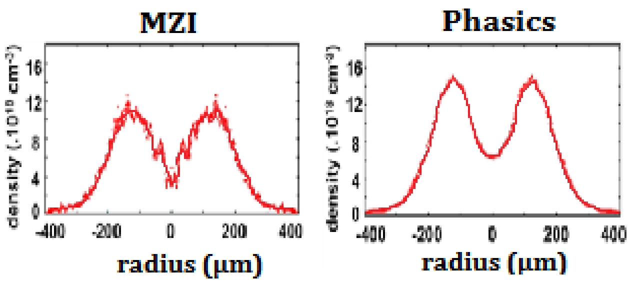

Fig. 1. Density profile of a jet of 20 bars of Argon with intern gradient from insertion of a wire in the gas jet. Left) Mach-Zenhder set-up Right) 4-waves shearing interferometry.

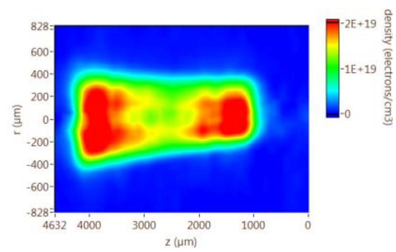

Fig. 2. One-shot density map of a plasma channel from interaction of short pulse (20fs, 1J) into an Helium gas jet (3mm diameter nozzle).

We designed and demonstrated a fully integrated density diagnostic, for both plasma and neutral gas, based on a commercial quadriwaves shearing interferometer. Such interferometers [9] are used in laser laboratories as laser wave-front sensors : a 2D diffraction grating with a phase chessboard modulates the laser field and the resulting grid pattern is recorded on a CCD camera. The phase gradients are derived by Fourier analysis of the grid deformation. The signal/noise ratio is 8 times better than with a classic Mach-Zehnder set up[10], with a phase rms of few nanometers. For axis-symmetric jet geometry, the index distribution is derived from the phase projection by Abel inversion. We developed a robust Abel inversion algorithm, finding inversion axis and deriving density map with minimal discontinuities. It allows fast in-line density measurements, exhibiting thin structures like shock front in supersonic flows. Further development would be of high interest for the community, such as tomography for characterization of non-symmetric gas profile, or tomographic reconstruction of the full magnetic map of laser-plasma interaction[11].

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Effect of Relativistic Self-focusing of High Power Laser Beam on Co-existing Stimulated Raman and Brillouin Scattering.

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We present a theoretical model to study the coexistence of stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) at relativistic laser power. At high laser power, the relativistic mass correction for the plasma electrons becomes important and the plasma refractive index gets modified which leads to the self-focusing of the laser beam. This self focusing phenomenon affects the back scattering processes and at the same time the pump filamentation process also gets modified in the presence of the coexisting SRS and SBS due to the pump depletion.We have also studied the effect of pump depletion and relativistic filamentation process on the back-reflectivity of scattered beams (SRS and SBS).

Simplified Model to Study Transient Self-focusing of Laser Beam in Plasma

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In this paper we are presenting the numerical simulation for the coupled system of equations governing the dynamics of laser and Ion Acoustic Wave (IAW) in collisionless plasma, when the coupling between the waves is through ponderomotive non linearity. When the pump laser is perturbed by a periodic perturbation in the direction perpendicular to the direction of laser propagation, the laser and IAW spectra show spatial harmonics. The magnitude of these harmonics changes with time and leads to localization of laser beam in spatial domain. This localization changes with time. The nonlinear dynamics of this localization is investigated in detail. To have the physical insight in the numerically obtained results we develop a simplified model.

Effect of Multiphoton Ionization on Performance of Crystalline Lens

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This paper presents a novel model for propagation of laser pulse in human crystalline lens for the eye surgery. The model contains transverse beam diffraction effect, laser induced optical breakdown for creation of plasma via multiphoton ionization process, the gradient index (GRIN) structure and the nonlinearity due to Kerr effect. Multiphoton ionization process depends on nonlinear absorption of laser light therefore laser beam gets attenuated. Plasma introduces the nonlinearity in the crystalline lens due to which propagation of beam get affected. Microscopic cavitations bubbles are generated due to laser plasma interactions at the focusing point and these cavitations bubbles can retain the elasticity of crystalline lens which can cure presbyopia.

Laser Induced Rescattering Photoelectron Spectroscopy of CO_2 Molecule

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When atoms and molecules are irradiated with high intensity laser pulses electrons are released in the continuum through the tunneling process. Now the electron is driven back and forth in space by the laser field. Depending on its time of birth, there is a possibility that the electron can 'revisit' the position of the parent ion. The returning electron then can either recombine with the parent ion to release a high energy photon which is called as high harmonic generation (HHG), or it can elastically rescatter off the ion core. From both these processes the structural information can be extracted. The structure retrieval from HHG has been very broadly studied in last few years [1 and ref. therein]. In contrast to HHG, the retrieval of structural information with the rescattered electron is less studied.

Rescattering photoelectron spectroscopy (RPS) is similar to photoelectron diffraction measurement in which the molecule under study acts a source of electron and the scattering target. Pioneering work on N_2 and O_2 was done by Merkel et al [2]. In the talk I will elaborate on the technique of RPS and present our recent results from the experiment which we performed in Tohoku University, Sendai on RPS. The experiment was performed on CO_2 molecule with 800nm wavelength having 35fs pulse duration and with 1250nm and 1300nm having 100fs pulse duration. We measured angle-resolved high energy rescattering photoelectron spectra of randomly oriented CO_2 and extracted the angular differential cross-section (DCS) of electron scattering from CO_2^+. We found that the angular DCS extracted from RPS at 800nm and the RPS at 1250 and 1300 nm wavelength are quite similar which indicates that the extracted DCS are independent of the wavelength and the pulse duration. Also the experimentally extracted DCS shows a good agreement with *ab initio* calculations of the field free DCS of electron scattering from CO_2^+. Further DCS dependence on rescattering electron momentum distribution shows a few minima in the distribution for large angle scattering. It may be due to the interference between two shape resonances as predicted in theoretical calculations, but other resonance effects like channel closing resonance, which are not incorporated in the present simple formulation, may be responsible for them. Further study is required to explain the minima.

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High Harmonic Generation Controlled by Molecular Alignment and Ellipticity of Laser Field

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We demonstrate experimentally that pre-aligned molecules produce observable spectral redshift or blueshift on the high harmonic generation (HHG) through optimization of molecular alignment. We distinguish two effects of molecular alignment on the phase modulation of the harmonics: one is from the gradient of alignment degree and the other is the plasma density varied by the molecular alignment. The finding provides an insight on the spectral distribution of molecular harmonics and a method for fine-tuning the harmonic spectrum [1].

It has been reported that enhanced HHG from aligned molecules is produced at the non-zero ellipticity of driving intense laser fields in the near-threshold energy region [2], but with on the quantum mechanical explanation. We also study the ellipticity dependence of the near-threshold harmonics by means of time-dependent density function theory (TDDFT) for the simple molecular system of elongated H_2 molecules. It is found that the anomalous maximums (AM) can be well simulated as those observed in experiments of atoms and aligned molecules [3]. This identifies the possibility to create elliptical harmonics with high efficiency.

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Charge-State Resolved Kinetic Energy Spectra from Intense Laser Cluster Interaction – What can we learn from the Ions?

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The interaction of intense femtosecond laser pulses with nanoscale aggregates, or clusters [1], has been studied with increasingly curious behaviour emerging from these systems ranging from near-perfect laser pulse coupling and nuclear fusion [2], dopant-induced ionization [3] to the serendipitous observation of MeV neutrals [4]. However, much of what we know about the dynamics ensuing during the interaction of these systems with the laser pulse(s) relies on the information available either from optical absorption measurements, photoelectron spectra or one-dimensional ion kinetic energy spectra without charge-state resolution. The recent introduction of Thomson parabola spectrometers has paved way to multi-dimensional charge-state resolved kinetic energy spectra throwing up, for the first time, an opportunity and a challenge to gain deeper insights into the dynamics and structure these highly-charged aggregates. We discuss some new insights gained from such complete studies which will become indispensable in future investigations of laser-cluster interaction in all intensity regimes including the super-intense case.

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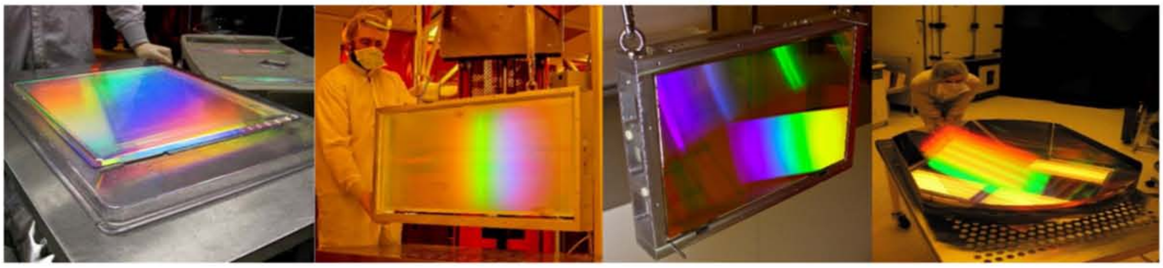

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Operations and First Experiments with the BELLA laser

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The BELLA laser system at Lawrence Berkeley National Laboratory is the first high repetition rate (1 Hz) petawatt class laser in the world producing more than 40 J in pulses less than 40 fs. The laser was acquired from THALES [1] to allow laser plasma acceleration (LPA) [2] experiments that aim at exploring the physics of linear and non-linear interactions of intense lasers with plasmas towards the development of a 10 GeV module. Previous experiments had demonstrated that GeV electron beams can be produced using 40 TW laser pulses to power a 3 cm long capillary discharge based plasma channel [3].

In this talk we will review the performance of the BELLA laser [4] and experimental results that have been obtained with the laser during the past 18 months. As the key physics in the LPA studies are primarily dependent on laser intensity, the key parameters are laser pulse energy, pulse duration, laser beam profile and their stability. For experiments where the laser beam is focused onto the entrance of a capillary discharge waveguide or other small target, pointing stability is also essential. Results will be presented on the stability of those parameters, on controlling the laser spatial mode at focus using a deformable mirror to obtain high Strehl ratio beams and on detailed measurements of the laser pulses shapes. The impact of these important parameters on the acceleration of electron beams by guiding the laser beam in capillary discharge based preformed plasma channels will be discussed.

This work is supported by the DOE, Office of High Energy Physics under contract DE-AC02-05CH11231. The BELLA Project was funded from the American Reinvestment and Recovery Act (ARRA).

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Enhanced Laser Wakefield Electron Acceleration Achieved by Applying Chirp-Controlled PW Laser Pulses

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With the advance of high-power laser technology, charged particle accelerations through ultra-intense laser-plasma interactions have been pursued widely for their potential as unique sources of high energy charged particles including electrons, protons and ions [1]. Laser wakefield acceleration (LWFA) of electrons is a promising scheme as a compact electron accelerator for generating multi-GeV electron beams [2]. The energy and quality of electron beams from LWFA are strongly affected by the beam loading mechanism used in an acceleration cavity and the propagation characteristics of driving laser pulses in a target plasma. To obtain high quality multi-GeV or even higher energy electron beams, it is crucial to adopt targets with long interaction length (> 1 cm). In this regime, stable beam injection and stable laser pulse propagation are critical tasks for efficient electron acceleration. In order to achieve these goals, we investigated electron acceleration by controlling laser chirp and by optimizing target geometry.

In the bubble regime of LWFA, particle-in-cell (PIC) simulations have been performed to look into the details of interaction dynamics while comparing with the experimental results performed with the PW laser at CoReLS. As the interaction dynamics occurring in the relativistic regime are highly nonlinear, the PIC simulation is a powerful tool to examine detailed interaction processes. We performed multi-dimensional PIC simulations while controlling the chirp of PW laser pulses propagating through staged targets. The laser beam propagation characteristics were investigated for a range of plasma density and for different frequency chirp conditions. The electron beam injection dynamics were studied by varying the plasma density of each stage, and the conditions for enhanced electron energy could be found (Fig. 1). The chirp condition of laser pulses was found to play an important role in propagation, and the condition for stable electron acceleration, depending on plasma density, was obtained. The positive chirp case was preferable in the low density regime, while the negative chirp gave a better result in the high density regime. We propose to use properly chirped pulses, depending on plasma density and interaction length, for stable generation of high quality electron beams.

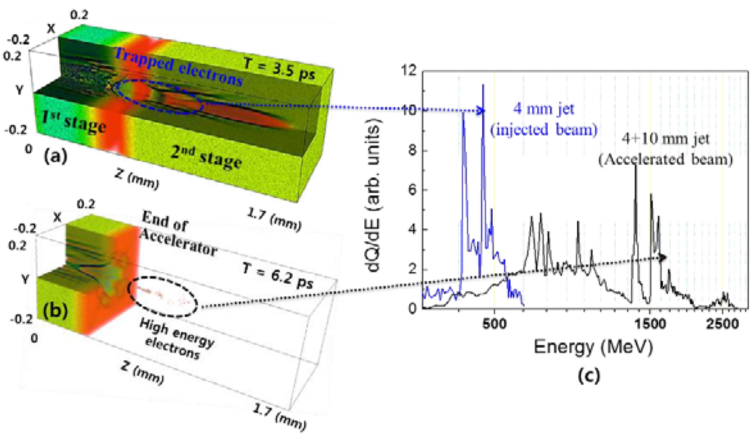

Figure 1. Electron density profiles at (a) t = 3.5 ps and (b) t = 6.2 ps, and (c) electron energy spectra of the injected beam and the accelerated beam in the dual-stage accelerator obtained from 3D PIC simulations.

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Laser Driven Radiation Pressure Acceleration of Ions with Thin Foils

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Acceleration of particles by intense laser matter interaction is a rapidly evolving field of research. The ion beams driven by the laser differ from conventional accelerators due to their higher brightness, laminarity and their ultra-short burst duration. These properties of laser driven ion beams mark them as potential candidates for a broad number of scientific and medical applications. Laser driven ion beams typically have a broad energy spectrum, modest conversion efficiency at high energies, large divergence, and a $E \; \alpha \; I_0^{1/2}$ [1] scaling of maximum proton energy (E) with peak laser intensity (I_0). Radiation pressure acceleration (RPA), [2] is currently attracting a substantial amount of experimental and theoretical attention due to the predicted superior scaling in terms of ion energy and laser-ion conversion efficiency. This paper presents experimental evidence of narrow band features in the ion spectra emerging from thin (nano meter scale) foil irradiation by VULCAN petawatt laser pulses focused to 10^{20} W/cm^2. In particular, carbon ion peaks centered at energies up to 7 MeV/nucleon are produced for the first time, with nearly an order of magnitude higher particle flux than previously reported. The possibility of achieving spectral peaks beyond 100 MeV/nucleon, a key requirement for hadron therapy, by tuning currently achievable laser and target parameters, will be discussed on the basis of the observed experimental scaling and supported by 2D particle-in-cell (PIC) simulations.

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Tuesday Session 1

Simultaneous Focussing, Energy Selection and Post-Acceleration of Laser-Driven Proton Beam

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The key to the growing interest in laser based ion accelerators lies in their cost effectiveness and compactness, which, coupled to ongoing technological developments, makes the prospects for all-optical accelerators very promising and appealing. Where intense laser driven proton beams, mainly by the so called Target Normal Sheath Acceleration (TNSA) mechanism, have proper ties such as brightness, laminarity and burst duration, overcoming some of the inherent shortcomings, such as large divergence, broad spectrum and slow ion energy scaling poses significant scientific and technological challenges. A novel target geometry has been envisioned in order to create a traveling pulsed charge device, by exploiting transient charging of laser irradiated target [1], to act simultaneously as an accelerating, focusing and energy selection device. By varying physical parameters of the target, experimental data show control and optimisation of proton beam parameters and potential for in-situ post-acceleration. Where a collimated, quasi-monoenergetic (~10% energy spread) proton beam of ~10^8 particles at 10 MeV was delivered by a 10TW laser, the technique may provide the platform for a practical 'table-top' accelerator.

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Multi-Stage Ion Acceleration from the Thin Foils Irradiated by Ultra-intense and Short Laser Pulses

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The schema of multi-stage laser proton accelerator with a few foils and laser pulses is discussed. It is shown, that for optimal distance between targets mono-energetic ions energy distribution is obtained. The two-stage scheme allows obtain higher acceleration efficiency and energy of ions, than acceleration by one pulse with the energy equal to total energy of two pulses. By means of analytical model the optimum distance between targets, second laser pulse delay time and pulse intensities are defined. Analytical model results are confirmed by 2D PIC-simulations of ion bunch, moving through laser spot on a foil surface. Such schema can significantly enhance proton energy and improve ion spectrum.

High Repetition Rate kJ-class Nanosecond to Femtosecond Lasers

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High energy pulsed lasers (those with energy above 100 J) traditionally require laser amplifiers with aperture greater than 10 cm. In solid state gain media, such as Nd:glass or Nd:YAG such high energy pulses, when pulse durations are nanoseconds or shorter, demand amplifiers in disk geometry with the gain medium oriented at an angle to beam propagation (typically Brewster angle). This is the amplifier format of such high energy lasers as the National Ignition Facility at LLNL, the Omega Laser in Rochester and a host of other high energy and high peak power lasers around the world.

The next generation of multi-petawatt lasers, whether they be Ti:sapphire lasers pumped by Nd:glass lasers or amplification directly in Nd:glass, will be used for experiments which would benefit greatly from augmented repetition rate. Because these lasers inevitably require hundreds of joules to many kilojoules of energy (either in 527 nm pump pulses or in the chirped pulse amplifier beam itself) these next generation lasers will require new technology for thermal management. While at moderate repetition rate (< 0.1 Hz) the average power generated is modest, the large aperture of these high energy lasers presents a challenge not amenable to traditional cooling schemes.

Here we describe an approach we have developed to cool large aperture Nd:glass flashlamp pumped slab amplifiers. We will present data on the performance of one such amplifier constructed with 18 cm clear aperture, suitable, when fitted with Nd:phosphate glass, for amplification of 10-30 ns pulses up to 1 kJ or 2-4 ns chirped pulses up to 200 J. This amplifier utilizes a novel liquid cooling geometry in which coolant is flowed up the faces of the pumped laser glass slabs. In this geometry we have characterized wavefront quality and gain at repetition rates up to 0.07 Hz. We have also operated a laser system (see figure below) at the 100 J level at 1 shot per minute using these amplifiers.

The approach we have adopted to manage heat deposition in large aperture slab amplifiers is illustrated in figure 1. Coolant liquid flows in thin laminar flow channels up the faces of the pumped slabs. We have constructed modules of 18 cm aperture in this manner and demonstrated small signal gain up to 1.23 per module with induced wavefront aberrations at one shot per minute of less than one wave RMS. The implementation of this amplifier design in a high energy laser is illustrated in the photo of figure 2, where a Ti:sapphire pump laser designed to produce 400 J pulses at 527 nm is shown (built for the Apollon 10 PW laser project at LOA in France). Preliminary performance data on this laser at 100 J will be presented, illustrating the capability of this approach to amplify multi-hundred joule pulses at one shot per minute with excellent beam quality. We will then describe how this technology can be deployed to produce rep-rated kJ-class Nd:glass lasers operating with 100 fs pulses at 10 PW.

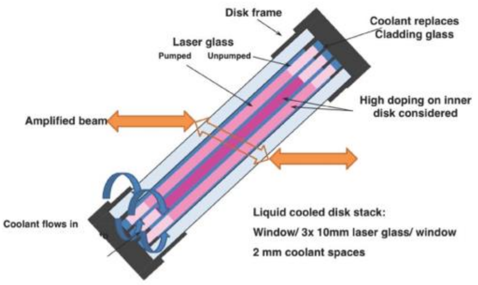

Figure 1: Diagram of National Energetics liquid cooled disk amplifier module

Figure 2: Liquid cooled disk amplifiers in the 600 J Apollon pump laser

A New Class of Metal Diffraction Gratings Tuned for Maximum Efficiency and Bandwidth for the Next Generation High Intensity Petawatt Lasers

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The past few years there has seen steadily growing interest related to the development of high energy Petawatt lasers (HEPW) and science around the world [1-7]. Most of the facilities being planned or constructed aim at the generation of laser-driven, secondary sources such as generating compact particle beams and incoherent and coherent light sources from THz radiation up to hard x-rays. The optimum source for most of the aforementioned applications rely on a femtosecond architecture in which tens of femtosecond pulses are amplified to tens of Joules using chirped pulse amplification in Ti:Sapphire as the gain media or optical parametric amplifiers. In the present state of the art, large-aperture ultrafast laser systems employ holographic, 1200 to 1480 lines/mm gratings created by gold overlayed grooves in photoresist (plastic) pioneered at LLNL [8]. However, the residual underlying photoresist is thermally unstable and can lead to volatile organic compound contamination of the vacuum compressor chamber leading to reduced damage thresholds or diffraction efficiency over time. Directly into the substrate etched grating structures address this problem but show lower diffraction efficiency and are more difficult to fabricate.

We have developed a new class of gold-overcoated diffraction gratings for laser pulse compression, consisting of a refractory etched dielectric grating layer over which gold is deposited. The architecture employs a metallic etch-stop layer that is also a release layer for wet chemical removal. This type of grating has several distinct advantages over the current state of the art:

1. The photoresist layer with its inherent low thermal stability has been eliminated.
2. The sidewall angle of the grating ridges is engineered to give optimal efficiency and bandwidth.
3. Spatial uniformity is improved since the grating ridge height is defined only by the thickness of one dielectric layer, which is typically deposited in a very well controlled process.
4. The grating can be stripped and substrate recycled an indefinite number of times during processing without the need to repolish, enabling a large reduction in cycle time and cost.

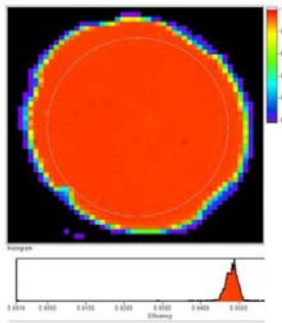

Figure 2: Diffraction efficiency map. The average diffraction efficiency is 94.8% approaching the theoretical limit (95.2%).

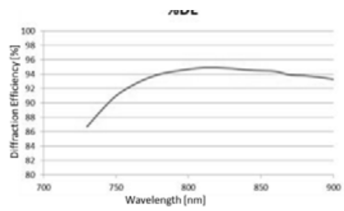

Figure 3: Diffraction efficiency vs wavelength for the same grating

We have fabricated several gratings samples on 4” substrates and with a groove density of 1480 l/mm demonstrating characteristics above and with excellence performance. These gratings show improved diffraction efficiency approaching the theoretical limit and present an improved bandwidth. Figure 1 shows the typical spatial distribution of diffraction efficiency at 800nm and under Littrow angle achieving a diffraction efficiency of 94.8±0.26% (theoretical limit = 95.3%). Figure 2 shows the spectral bandwidth for the same grating. In this talk we will describe the new grating design and present the latest performance data. This work performed under auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

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Hybrid Metal/Dielectric Diffraction Gratings for PW Lasers

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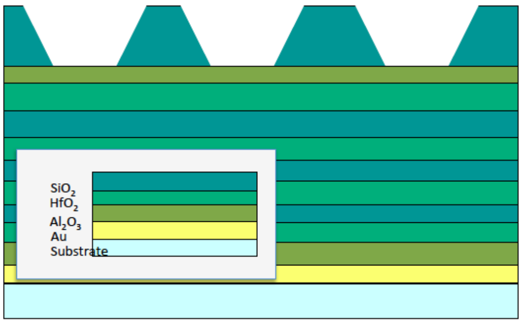
The development of diffraction gratings that exhibit ultralarge spectral tolerance is a challenge for the realization of high powerfull laser chains. In this talk, we report the design and fabrication of hybrid metal/dielectric gratings that exhibit ultralarge spectral efficiencies when etched in a top layer made of silica.

The gratings under development for the APOLLON project must exhibit a high diffraction efficiency in the -1st order in the range [720;920]nm. We will present in this talk an optimization technique that permits to reach a diffractive efficiency higher than 95% when averaged over the whole spectral range, together with a reflectivity of the multilayer stack down to 1% at the interferogram recording frequency. The optimization technique relies on the use of a strongly limited number of layers allowed by the use of a hybrid metal/dielectric coating [1-2].

The final design is composed of: $Au/Al_20_3/(HfO_2\text{-}SiO_2)^3/HfO_2/Al_20_3/SiO_2$. The mirrors have been coated by REOSC on both pyrex and silica substrates (120×140 mm2) using an electron beam deposition technique. Their optical properties have been measured by REOSC under the conditions of the interferogram recording and in the operating frequencies. The laser induced damage thresholds (LIDT) were measured at the AZUR facility hosted by LP3 that delivers 11fs pulses centered around 820 nm.



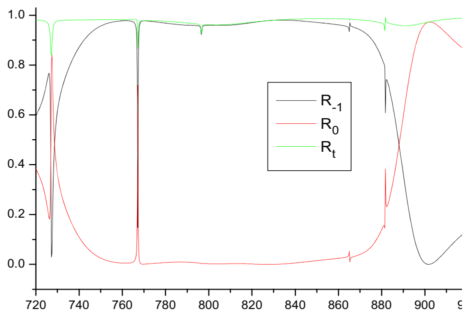


Fig.1. (Left) Sketch of the hybrid metal/dielectric grating: A gold layer is inserted between the substrate and the dielectric stack. This strategy allows for the use of a low number of dielectric layers and a large spectral tolerance. (Right) Simulated reflected efficiency in the -1st order of the hybrid metal/dielectric grating with respect to the wavelength in nm.

For the next step, HORIBA Jobin Yvon will manufacture, under a worldwide exclusive license of the patent [3] a diffraction grating structure on the top of the optimized MMLD stack.

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Femtosecond Laser-Induced Damage of Optical Thin Films: from Fundamental Laser/Film Interactions to Design and Manufacturing

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The laser damage resistance of optical components is a main concern for the development of high power short and ultrashort pulse lasers. In these laser systems, there are enormous technological challenges to produce multilayer optical coatings that can limit pulse lengthening, spectral distortion and exhibit high laser-induced damage thresholds (LIDT). In practical terms, accomplishing this requires specialized and new generation of multilayer optical coatings and components.

Progress on this particular topic requires available experimental data on the LIDT of optical coating materials and fundamental knowledge of the laser damage mechanisms. Despite common characteristics with bulk materials, the laser damage of dielectric thin films has peculiarities that need to be taken into account: specific optical, mechanical, thermal, and electronic properties affecting the resistance of components under laser exposition, these properties being very dependent on the deposition conditions.

In the presentation we will report on our recent work [1-5] about the LIDT of various optical materials (simple oxides or fluorides and binary mixtures of high and low index materials) and the dependence of LIDT with material parameters (intrinsic properties, manufacturing conditions, defects) and operational conditions of the laser (wavelength, pulse duration, number of pulses and repetition rate,...). These data will be compared to physical-based models that describe the ionization process in dielectric materials. From this knowledge, we will discuss on design strategies for enhanced laser damage resistance.

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Ultra-short Pulse Laser-Induced Damage Thresholds of Broadband High-Reflective and Low Dispersive Coatings

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The peak power handling capability of ultra-short pulse lasers is main concern for new facilities, like those for the French *APOLLON 10P*, and European *Extreme Light Infrastructure* (ELI) projects. Indeed, these last generation lasers require large (Ø 1m) and resistant optical components with optimized thin-films coatings. In this context and in the framework of a joint project, LOA, Fresnel Institute and Reosc are working together to develop high performance coatings for ultra-short pulse laser applications.

In the femtosecond regime, the damage of dielectric materials can be understood as a result of electronic processes. The electronic structure of materials is then particularly significant. As a consequence of these processes it is possible to increase the Laser-Induced Damage Threshold (LIDT) by adjusting the Electric Field Intensity (EFI) distribution in the stack of High-Reflective (HR) coatings [1]. LIDT of many currently used oxides, often deposited by Ion-Beam Sputtering (IBS), are well known and a correlation with the band gap energy was shown [2].

With these results we decided to study the LIDT of oxides-made stacks with Electron Beam Deposition (EBD) processes compatible with 1-meter class optics. Several dielectric (MLD) and hybrid metal-multidielectic stacks were design and coated at Reosc.

Samples were irradiated at Fresnel Institute by a 500fs KYW:Yb pulsed laser delivering 1mJ at 1030nm [3], at the LOA by a 40fs (resp. 150ps) Ti:Sa pulsed laser delivering 1.5mJ (resp. 3mJ) in a Gaussian spectrum 20nm FHWM centered at 790nm and at the LP3 by a 11fs Ti:Sa pulsed laser delivering 50µJ in a Gaussian spectrum 130nm FHWM centered at 790nm [4]. Irradiated areas are optically inspected under a Nomarski microscope and any visible modification of the surface is considered as damage. A statistically distribution of the damages gives the LIDT as the mean of the highest fluency class undamaged and the lowest fluency class damaged. Single pulse and multi pulses tests were performed.

We present on one hand the measured spectral characteristics of the coated samples like reflectivity and Group Delay Dispersion (GDD) and on the other hand the LIDT tests results. Moreover, we discuss about the relationship between this results, the intrinsic LIDT of used materials and the electric field distribution inside the stacks (eq. 1).

$$LIDT_{stack} = \min\left(\left|\frac{E_{inc}}{E_{max}}\right|^2 * LIDT_{intrinsic}\right)_{materials} \quad (1)$$

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Actuator-Position Optimization and Holographic Correction for Large-Scale Deformable Gratings

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Surface-deformation induced wavefront error on large-scale diffraction gratings prevents short-pulse laser systems using such gratings for compressing chirped pulses from realizing transform-limited laser pulses [1]. The design and optimization of the actuator layout for a 1.5-meter scale adaptive grating was performed using an integrated finite-element-analysis and genetic-optimization model. The initial design was first constructed, tested, and selected from a few designs with different total number of actuators. The deformable-optics model was constructed in ANSYS®, which predicts the influence function of each actuator and the surface figure created by a particular actuator design. The residual wavefront error was used as a merit function. Actuator layout designs are optimized through genetic optimization by passing on elite populations, mutating or combining the surviving configurations through generations [2]. Figures 1(a) and 1(b) show the initial and optimized actuator positions for correcting a parabolic wavefront error with a peak-to-valley of 1.5 λ. Figures 1(c) and 1(d) show the residual wavefront errors of the initial and optimized designs. The actuator layout design was improved through the optimization with actuators under forced symmetric constraints [3].

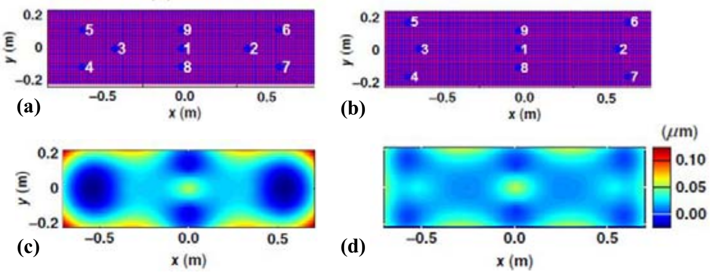

Fig. 1. (a) Initial 9-actuator design; **(b)** Optimized 9-actuator design; **(c)** Residual wavefront error of initial design (RMS = 0.032λ, PV = 0.202λ); **(d)** Residual wavefront error of optimized design (RMS = 0.015 λ, PV = 0.084 λ).

A solution was also developed to compensate for the surface sag errors by varying the grating line spacing locally. The one dimensional formula for the grating line density as a function of surface sag has been derived. A FRED-Matlab integrated optical model of a pulse compression system including two pair of identical parallel 1.5-m diffraction gratings and an F/2 off axis parabola was built. This model, capable of locally varying grating groove spacing and incorporating surface sag errors, was used to analyze the effectiveness of the correction on the focused pulse spatially and temporally. Figures 2 (a) and (b) show the phase of the central and end wavelengths of the shot spectrum with and without a holographic correction, respectively. Figure 2 (c) shows the result calculated from the full FRED-Matlab model – a Fourier transform-limited pulse was achieved with the holographic correction.

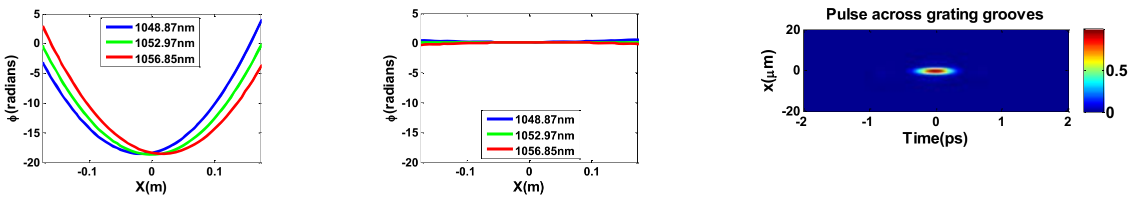

Fig. 2. (a) Spectral phase across beam without holographic correction; **(b)** Spectral phase across beam with holographic correction; **(c)** Normalized intensity of focal spot.

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Design and Operation of Laser Damage Test-Bench with Sub-15 fs Ultrashort Pulses

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Laser damage and ablation of optical materials and components is a key point for safe operation of high energy ultrashort laser facilities (PW laser systems and beyond) and enhanced development of micromachining processes. Indeed, laser damage of dielectric material in ultrashort regime (down to < 15 fs) has been shown to be highly deterministic [1] which is favorable to the definition of industrial processes requiring fine tuning of the laser ablation phenomenon. It was also shown that laser damage and ablation took place at rather low irradiation fluences compared to longer pulse durations [2,3] posing the problem of the fragility of optical materials and components used in high peak power laser systems. Moreover, the mechanisms of laser-matter interaction remain largely unclear and scarcely studied at such short pulse durations (<< 30 fs) and further experimental and theoretical developments are desirable to clarify all the electronic aspects of the interaction (characteristics of the free electron-hole plasma developing at the material surface in strongly nonequilibrium thermodynamic conditions) on the damage ablation phenomenon.

Additional complexity arises when considering pulses of extremely short pulse duration down to few optical cycles. Such pulses have extremely broad spectrum difficult to manipulate and are highly subject to beam distortions due to their high intensity rapidly yielding to deleterious phase modulations. The difficulty to manipulate them severely increases in dense media and can also take place in air [4]. In that context, specific studies need to be performed to characterize the propagation of the ultrashort laser beam in various regimes of laser fluences and intensities to infer precise data on damage and ablation of optical materials and components.

The purpose of this work is thus to measure reliably the laser-induced damage threshold (LIDT) at the surface of materials exposed to single pulses of pulse duration < 15 fs (using 1on1 protocol), providing feedback to builders and suppliers of intense laser infrastructures as well as to the scientific community involved in ultrashort laser damage. We also aim to determine laser-induced ablation threshold (LIAT) of materials and related characteristics (like morphology and affected zone) to help the development of micromachining processes based on ultrashort lasers. Our presentation will first be devoted to the description of a laser test-bench operated in air (later in vacuum) and able to study laser – matter interaction with femtosecond pulses down to pulse duration of a few optical cycles (< 15 fs). We then characterize the propagation of ultrashort pulses to estimate the onset of nonlinear effects in air (with measurement of the nonlinear index n_2) and to determine the exact conditions in which the LIDT and LIAT thresholds are measured. Finally, we illustrate the accuracy of our approach by measuring LIDT and LIAT fluences of materials extensively used in optics and photonics (like for instance fused silica).

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Petawatt Laser System and High Field Science at CoReLS

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Femtosecond petawatt (PW) Ti:sapphire laser becomes an crucial tool for producing high energy charged particles (GeV electrons and 100-MeV protons) and high energy photon (x-ray and γ-ray) sources [1]. Several groups in Asia and Europe are further developing multi-PW and 10-PW lasers for fundamental research and applications in bio-medical science, nano-science, and many other fields [2]. The Center for Relativistic Laser Science (CoReLS) is conducting experiments on electron and proton acceleration and x-ray generation through relativistic laser-matter interactions using 1-PW and 1.5-PW beam lines. And, the center is upgrading the 1.5-PW beam line to 4-PW (20-fs pulse duration, 80-J output energy) level for the investigation on high field science. In this talk, the upgrade status to 4-PW power level is presented, and the recent experimental results on electron and proton acceleration using PW beam lines [3, 4] are briefly summarized. Finally, experimental plans using 4 PW laser pulses are introduced in the talk.

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PetaWatt Lasers and Beyond

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Ultra high intensity laser pulses are required by researchers for a growing number of applications. The advent of Titanium Sapphire (TiSa) as a laser material has overcome many limitations existing with the Neodymium doped glasses in terms of installation size, cost and repetition rate. This is due to its superior bandwidth and thermal properties allowing much shorter pulses. The Chirped Pulse Amplification (CPA) concept [1] has made possible the amplification to high energy levels while keeping a very short pulse duration. Thanks to these breakthroughs several research teams worldwide have built installations based on the TiSa technology, some of them delivering peak power above PetaWatt level [2] [3] We report on the performance of 2 Ti:Sa based PetaWatt laser systems entirely designed and built by Thales and installed respectively at Berkeley in 2012 and in Romania in 2013. Ongoing project of 2 beams of 10 PW lasers for ELI-NP will be also presented.

A 1 Hz PetaWatt laser system has been built, installed and commissioned at Lawrence Berkeley National Laboratory by Thales Optronique in September 2012. This laser system is based on a double CPA configuration with a 2 crystals XPW filter [7][8] inserted between the 2 CPA in order to increase the temporal contrast by 4 orders of magnitude at least. The 2 final power amplifiers are pumped by high energy frequency-doubled Nd:YAG lasers (GAIA HP with 14 J of green) allowing operation at a repetition rate of 1 Hz. An output energy level before compression up to 70 J has been obtained. The initial PetaWatt laser shot at 1 Hz has been produced with an energy per pulse after compression of 42.4 J and a pulse duration of 40 fs. Through the use of a deformable mirror placed immediately after the final amplifier, Strehl ratio as high as 0.92 has been reached. This laser system is now in full operation since end of 2012 and routinely produces laser beam to drive ongoing laser plasma acceleration experiments.

Another PetaWatt laser system has been demonstrated and commissioned in November 2013 at INFLPR in Romania for the CETAL project. This laser system works at a repetition rate of 0.1 Hz as frequency-doubled Neodymium glass lasers (ATLAS 25 with 25 J of green in a single beam) are used to pump the final amplifier stage. A careful amplification design to minimise gain-narrowing effects as well as insertion in the early part of the second CPA of a AOPDF device to correct high orders of residual spectral phase have led to produce a beam with 52 nm spectral width (FWHM) resulting in a 23.7 fs (FWHM) compressed pulse duration at full laser power measured with a one-shot autocorrelator. Then the 26.5 J energy level reached after compression allowed to produce a 1.12 PW peak power.

Thales Optronique is involved since July 2013 in the construction of 2 laser beamlines delivering 10 PetaWatt each at 1 shot per minute for the ELI-NP (Extreme Light Infrastructure – Nuclear Physics) located in Romania and operated by IFIN-HH (Horia Holubei Institute of Nuclear Physics) Institute.

Design of the beamlines will be presented as well as the main technical challenges to reach the expected performance like a further reduction of pulse duration close to 20 fs through the insertion of new solutions like spectral filters [8] to compensate accurately gain-narrowing effects.

We have demonstrated the performance of 2 different PetaWatt laser systems recently implemented and the evidence of their effectiveness for doing high level science. The TiSa technology will be again used to build the next generation of higher peak power lasers, 10 PW class, therefore extending capabilities of such lasers.

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Spatial, Temporal and Digital Properties of the CAN Laser

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Since its inception over more than 50 years, the laser was the tool of choice to investigate the atomic physics. We propose to investigate the possibility for the CAN laser to study for the first time the subatomic regime, i,e. nuclear and particles physics [1,2]. We aspire to demonstrate that this laser has excellent spatial and temporal properties that could be handy for the study of dark matter or laser-induced vacuum polarization effects. Other examples requiring an impressive control over the fiber synchronization includes the Electron Acceleration by Coherent Laser Pulse in Periodic Plasma Structures which could be soared using CAN heuristics capabilities.

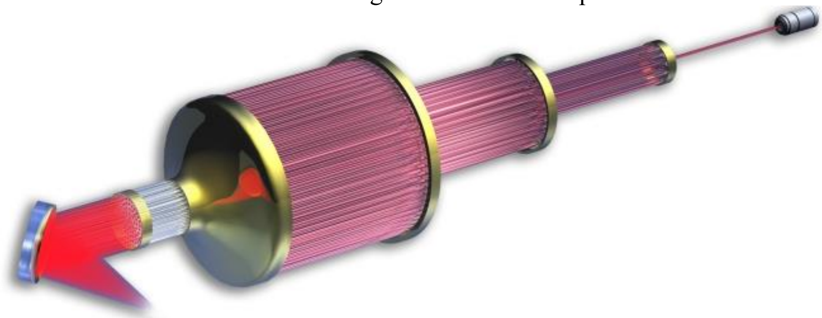

Fig. 1: CAN, a novel architecture for the generation of high peak power pulses at tens kHz rate.

The 10-100 TW peak power of the CAN laser relies on a novel architecture based on a network of several thousands of coherent single mode fiber amplifiers. This novel architecture offers the following important characteristics:

1. A very high Average Power

The Yb^{3+} doped fiber lasers are diode pumped and offer large surface area/active volume ratio making possible the generation of high peak power pulses at tens kHz rate (Fig 1.). An improvement in average power of 3 to 4 orders of magnitude over conventional CPA laser is expected [3].

2. A very high Temporal stability

Being the sum of tens thousand identical lasers the temporal fluctuation will be attenuated of a single amplifier by 10^2-3.10^2 leading to the increase of the signal to noise ratio to 10^5-3.10^6.

3. Very good Spatial characteristics

The coherent combining of a large number of fiber amplifiers will guaranty a very smooth far fied distribution with low divergence. An improvement of 10^2-3.10^2 in the RMS smoothness is expected. Phase noise correction of each fibers will also enable a good pointing stability in the lateral and the axial directions.

4. A Digital laser with Heuristics capability

Because CAN is composed of thousands fibers, it exhibits digital properties. The adaptive wavefront of each channel enables beam shaping. For instance, a top-hat beam can be generated. Moreover, phase correction of the beamlets operates at kHz level [4]. This makes feasible the desirable modification of the beam shape with time. Furthermore, the laser can modify his wavefront to seek for optimum particle energy and efficiency. An example could be in laser-plasma-produced electron or proton beams. The most sophisticated code can not simulate the complexity of the laser–plasma interaction with fidelity. A heuristic approach is necessary. Using CAN we would look at the proton output and seeks for the optimum. This method could be applied to scientific, industrial, and societal grand challenge as: future colliders, high flux neutron sources, or applications such as nuclear transmutation, energy-specific gamma beams as well as in medicine nuclear pharmacology and proton therapy.

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Diagnostics and Controls for Temporal Structure of the BELLA, High Repetition Rate Peta-Watt Ti:Sapphire Laser

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The world's first petawatt class high repetition rate (1 Hz) laser system was acquired from THALES, and implemented in the Berkeley Lab Laser Accelerator (BELLA) facility [1] to explore the physics of laser plasma interactions, with an emphasis on development of a 10-GeV class Laser Plasma Accelerator (LPA). Here, we report on diagnostics and controls of the temporal structure of BELLA laser pulses.

Temporal pre- and post-pulse structures in the nanosecond regime are monitored by nanosecond photo-detectors at several key locations of the system, allowing us to monitor pre-pulses originating from the oscillator (~75 MHz pulse train) and the regenerative amplifier (round-trips in the cavity). For the picosecond regime, a third-order correlator SEQUOIA, from Amplitude Technologies, is used to diagnose. Measurement results as well as future improvement of the laser pulse contrast will be discussed in the presentation.

The femto-second pulse structure was measured by GRENOUILLE [2] and Wizzler [3]. Although online single shot measurements based on GRENOUILLE have an intrinsic uncertainty with respect to the front or rear of the pulse due to the use of a second harmonic crystal as non-linear element, a more precise evaluation was made possible by scanning the compressor grating separation. This multi-shot measurement based on the GRENOUILLE agreed with single shot measurements based on the Wizzler. For the BELLA pulse diagnostic, the Wizzler showed an advantage in accuracy of single shot measurements, while the GRENOUILLE had a potential to monitor pulse front tilt and spatial chirp [4, 5]. The on-target pulse shape was found to have temporal structure about ~+/- 100 fs of the main pulse. The structure can be cleaned by tuning compressor grating angle at a cost in achievable peak power.

The planned improvement of the laser temporal shape and shot-to-shot stability will be discussed in this presentation.

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Upgrade of Pumping Laser for Multipetawatt PEARL-X Setup

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We have made the computational modeling of pumping laser for multipetawatt OPCPA laser complex PEARL-X and have shown the possibility of creation of compact based on Nd:glass rod pumping laser with kilojoule radiation energy level and pulse-repetition time 10 minutes.

Most of high-intensity laser systems have the pumping laser as the component, which limits output radiation energy. Therefore multipetawatt complex parameters and usability directly depend on pumping laser parameters (pulse energy, quality of radiation, pulse-repetition frequency).

Pumping laser of existing in IAPRAS complex PEARL [1] is based on Nd:glass rod amplifiers with diameters from 10 mm to 100 mm [2]. Pulse diameter is gradually increased by keplerian telescopes, which also organize image transfer to avoid diffraction divergence, separation of near by amplifires to avoid a self-excitation of system and filtration of small-scale modulation to avoid self-focusing.

We have measured parameters (gain value and distribution, depolyarization, etc.) of unique Nd:glass rod amplifier with diameter 150 mm (fig.1) [3].

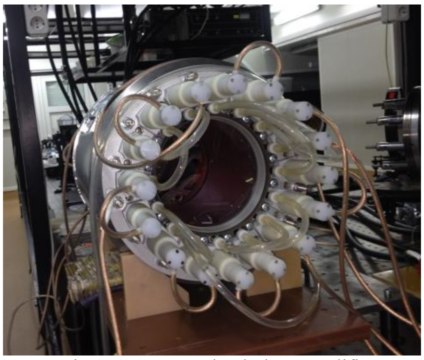

Fig.1. 150 mm rod Nd:glass amplifier

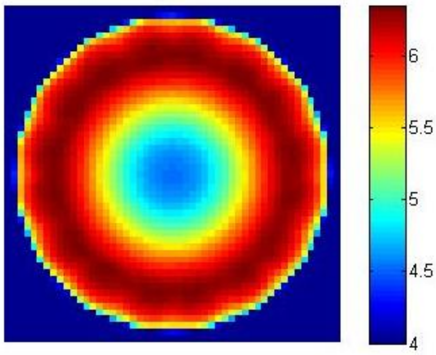

Fig.2. Output beam energy distribution, J/cm^2

Based on experimental measurement of each using amplifier gain (it's distribution in cross-section) [3,4] we have investigate various possible optic schemes and have chosen few of them according to the optimum between beam energy and quality and compactness of the pump laser. Detailed calculations where made for chosen schemes.

We show the possibility of making pumping laser using optical table 15 square meters (using extremely short telescopes [5]). Pulse parameters are: wavelength 1054 nm, pulse duration 1 ns, energy up to 1 kJ, repetition rate 6 pulse per hour. Pumping laser output radiation have good quality better than 2 diffraction limit and fill factor more then 0.8 (fig.2).

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Spectral Filtering for 10 PW TiSa System. Demonstration on a 100 TW, 23 fs System

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We present the validity of spectral filtering at high energy for obtaining short pulse duration of 23 fs on a TiSa 100 TW system. The different steps that are the amplification simulations, the required spectral shaping and the coating design have been validated. Extension to 10 PW TiSa laser, will be presented.

Standard TiSa laser systems with energy above 1 joule exhibit a pulse duration ~30 fs if no attention is paid to spectral management. For obtaining shorter pulse duration, spectral shaping has been applied on the laser front-end at low energy level. One solutions used years ago is regenerative pulse shaping (Fabry-Perot etalon or Acousto Optic Programmable Dispersive Filter). A second one is to strongly shape the spectrum of the seed pulse by SLM or AOPDF system. These solutions have shown a high potential for 100 TW systems but their efficiency is limited for multi-PW peak power.

A solution that shows high possibilities is the spectral filtering at a high energy level. Such a solution relies on the use of mirror which presents a reflectivity as a function of the wavelength. In order to have the required mirror implanted in the laser chain, we have developed a set of precise simulation tools; amplification process that gives the spectral function of the mirror and the mirror coating design for obtaining that shape. The amplification process is computed for the complete laser beam, taking into account not only the spectral gain if the laser medium but also all the components that exhibit a spectrally variable behavior. The coating design is computed based on a genetic algorithm and has as targets the spectral function and a flat spectral phase. Such a routine has been applied for a 100 TW class laser system. This is a double CPA laser, with a XPW temporal filter. The potential output energy is > 2 joules at repetition rate of 0.1 Hz. The system has been characterized in terms of pulse compressibility and spectral phase using a "Wizzler" measurement tool.

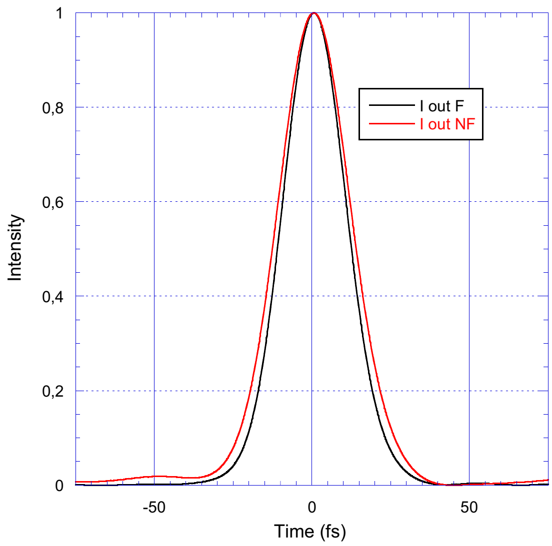

Figure 1: measured temporal pulse profiles of spectrally (black) and non spectrally (red) filtered schemes

Figure 1 shows the measured temporal shapes of amplified pulse with or without spectral filtering. The output pulse duration is respectively 23.5fs and 26.7fs FWHM. The complete set of simulation tools will be presented and their application to Appolon-10P laser system will be detailed.

High-Quality Spatial Modes for Petawatt Class Lasers

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Berkeley Laboratory Laser Accelerator (BELLA) facility is a petawatt class laser used for laser plasma acceleration of electrons [1]. This will be achieved using plasma channels enclosed in sapphire on the order of hundreds of micrometers in diameter. Precisely shaping the incoupled beam not only properly guides the laser through the plasma channel, but also protects the sapphire structure from the >40 J of laser energy. The 1 Hz repetition rate of BELLA allows for a feedback control system to be implemented, producing the highest quality beam of any petawatt laser.

The adaptive optics system, developed by Imagine Optic, consists of a Shack-Hartmann wavefront sensor and a deformable mirror for beam sensing and control, respectively. The deformable mirror is mechanically actuated and has been specifically designed for high power laser applications [2]. Individually moving the pistons in the deformable mirror and detecting its effect on the wavefront generates a transfer function that relates piston movement to the coefficients of the Zernike polynomials. This process can be done using both an alignment diode beam or a low energy pulsed beam to capture the subtle differences in the two. Because the deformable mirror uses mechanical motors for actuation of the adaptive optic, they must reset to a base state at every move to ensure its position accurately. This action precludes movement of the mirror at high energies in order to protect the compressor gratings and introduces some operational challenges.

The deformable mirror produces a beam at focus shown on Fig. 1. The beam at focus has a Strehl ratio of 0.821 and propagates without astigmatism. Additionally, as the energy of the beam is ramped up, the deformable mirror allows for manual correction of lower order modes introduced by the amplifier crystals. This includes manual adjustment of the focus location and astigmatism correction as seen in Fig. 2. This is done in an open-loop fashion without disruption of the higher-order modes.

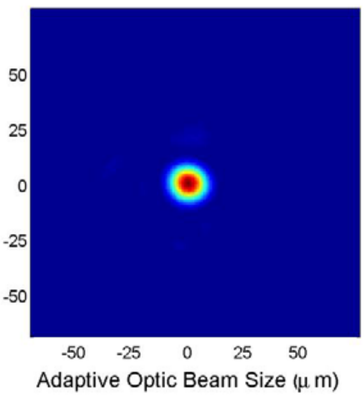

Fig. 1: Beam at focus with deformable mirror correction.

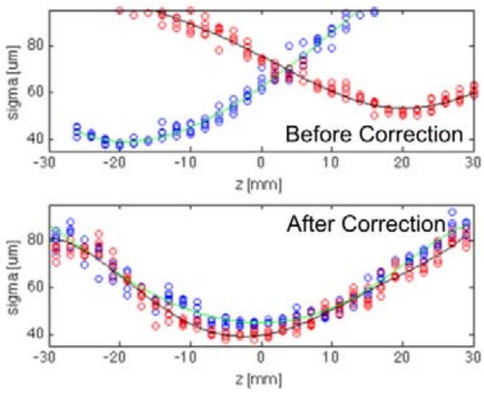

Fig. 2: Spot size through focus. Manual astigmatism correction achieved with deformable mirror.

The work on the spatial quality of the beam represents one facet of delivering the ideal beam to the plasma acceleration structure. In addition, significant work has been done to tailor the temporal profile of the beam [3], which has resulted in the first 4 GeV electrons generated from a laser plasma accelerator [4]. The following presentation discusses the operational challenges associated with implementing a deformable mirror system in a petawatt laser facility and the techniques associated with generating a high-quality spot.

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Instant Phase Matching Broadband Non-Collinear Optical Parametric Amplification: a Candidate Front-End for the Future Laser Wake-Field Accelerator

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Abstract: Ultra-short pulse has been proved to be a very useful tool for accelerating electron close to GeV now. But limited by gain narrowing effect, conventional CPA technology is quite hard to get less than 30fs at high energy level. Non-collinear optical parametric amplification (NOPA) looks more and more attractive for generating super-broad bandwidth pulse, which is possible to be compressed to ultra-short pulses. Previous NOPAs, pumped by 400nm pulses, were using BBO crystals to reach shorter signal pulse durations. But the associated spectral bandwidths are still strongly linked with higher order nonlinear effects, which make it quite difficult to get higher energy with short pulse duration. Here we proposed to use pre-chirped few nm bandwidths around 515nm pumped pulses to amplify ultra-short pulses centered 800nm based on BBO crystal, which applied instant phase matching technology to increase the energy transfer efficiency. For different geometry configurations of experiment setup, if pump laser have no angular dispersion, with S curve chirp requirement, we have possibility to get more than 170nm perfect phase matching amplification bandwidth, which will support less than 10fs for good compression while pump pulses have 1.6nm bandwidth. While if pump laser have small angular dispersion, just for a little bit divergent pump beam at an appropriate input direction compared with signal, we can get continuous amplification for the whole signal spectrum. Otherwise, we will meet some spectrum amplification missing, which would be useful for the measurement. The continuous amplification will produce two different type of chirps, one for hyperbolic and the other for quadratic curve, while the pump pulse has linear chirp. For such of case, we can also get over 170nm bandwidth amplification, which is also suitable for 10fs relying on the good compression. This design is well adapted for BBO crystal. But the idea could be also used for other crystals. The whole process is also quite similar as the evolution of the Rayleigh-Taylor instability.

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30 mJ All-Solid-Stated Picosecond Laser Amplifier

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In recent years the all-solid-stated picosecond lasers with high energy have attracted an increasing interesting since wide applications, such as for laser fine processing and pump sources for high power femtosecond lasers. In this presentation we reported a high energy picosecond Nd:YVO4 laser amplifier pumped with laser-diodes (LD). Output energy as high as 30mJ with the pulse width of 20 ps was obtained at 1064 nm with a repetition rate of 1 kHz. The whole laser system consisted in an oscillator and a series of LD pumped amplifiera. First, stable seeding pulse with 16 ps duration was generated from a homemade mode-locking Nd:YVO4 laser oscillator at a repetition rate of 80 MHz, then it was boosted to pulse energy of 1.5 mJ by a regenerative amplifier which was pumped by a quasi-continuous wave LD at a repetition rate of 1 kHz. Finally, three single pass power amplifiers based on 12 mm-long Nd:YVO4 crystals were used to further improve the pulse energy and ensure a good beam quality. Under the pumped energy of about 70 mJ, output laser energy of 30 mJ was achieved, corresponding to a conversion efficiency of about 40.7 %

Direct Focal Spot Correction with Phase Retrieval Adaptive Optics

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Adaptive optics is now commonly used in ultra intense laser facilities in order to compensate for the spatial phase distortions and provide the final user with diffraction limited focal spot. Adaptive optics systems correct for phase distortions using a deformable mirror which shape is controlled in closed loop by dedicated software using the measurement from a wavefront sensor as a feedback.

Standard set up aims at minimizing the aberrations measured by the wavefront sensor (Fig. 1.). In this case, any aberration created downstream of the wavefront sensor, for instance focusing optics aberration, is not corrected and degrades the focal spot quality. Several improved strategies are possible in order to get diffraction limited focal spot [1]. We present a simple, direct and automated method using a standard focal spot camera and phase retrieval algorithms [2] in order to measure and correct wavefront directly on the focal spot itself. This method is implemented in the Pharao adaptive optics software which is dedicated to laser applications.

Compared to focal spot wavefront measurement using a wavefront sensor, this method is simple as it does not require additional hardware or any manual operation. Also, contrary to other stochastic algorithms using focal spot camera, it is direct and deterministic as the aberrations are directly measured and compensated in a single step without iterations. Eventually, it is fully automated as Pharao software automatically changes the focus using the deformable mirror to obtain the images necessary for the phase retrieval algorithm, calculates the focal spot aberrations, and corrects the wavefront.

This strategy is an effective way to correct simply and automatically the focal spot aberrations for any type of setting or focusing optics; it eases the tedious alignment of fast off axis parabola, and eventually allows to reliably get diffraction limited focal spot.

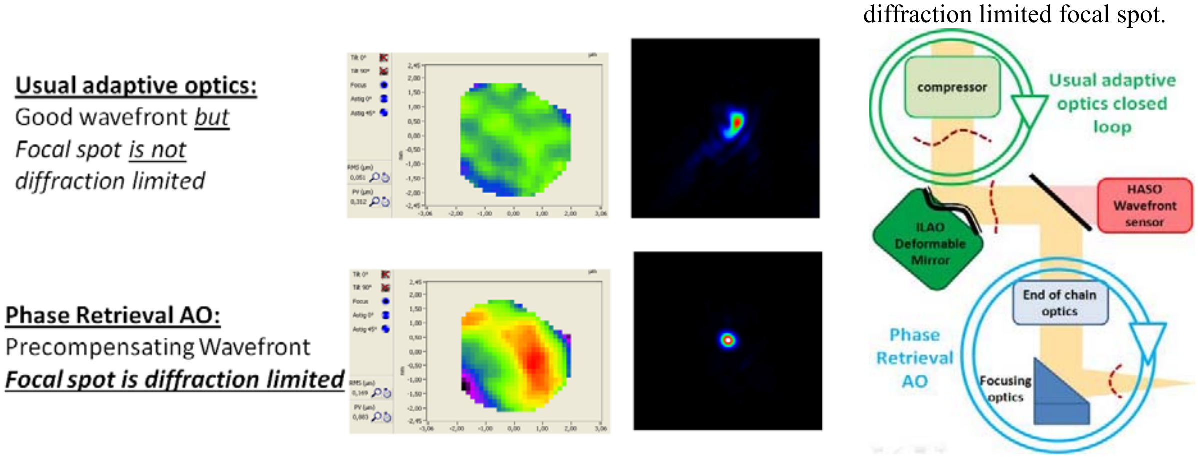

Fig. 1. Usual adaptive optics leads to low aberration wavefront on the wavefront sensor but focal spot is not diffraction limited (top left). Phase Retrieval adaptive optics leads to wavefront precompensation downstream aberrations and diffraction limited focal spot (bottom left). Usual adaptive optics corrects for aberrations located upstream of the wavefront sensor while Phase Retrieval adaptive optics corrects for aberrations located downstream of the wavefront sensor (right).

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Tuesday Poster 4

Parametric Study of Subpicosecond Laser Induced Damage Threshold in Optical Thin Films: Influence of Number of Pulses and Photon Energy.

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We investigate multiwavelength (1030nm, 515nm and 343nm) and multipulse laser damage in the femtosecond regime.
When submitted to pulses of different photon energies, optical material's laser-induced damage threshold (LIDT) decrease with the photon energy. This can be explained by the Keldysh theory [1] of photoionization. The higher the photon energy, the lower the number of required photons needed to cross the energy gap; which implies the need of less energy to reach the LIDT. In the case of multipulse it have been established a decrease of the LIDT with the number of pulses [2] [3] This decrease is due to the appearance of modifications of the material [4] which take place under laser irradiation up to the point where damage (defined as a visible modification through a Nomarski microscope) occurs.
The study of the combined multipulse and multiwavelength effects is essential for understanding the initiation of laser-induced damage, and helps in designing optical thin films with high LIDT. We focus our study on commonly used materials in optical thin films. Our work covered basic optical thin film materials: Niobia (3.4 eV), Hafnia (5.17 eV) and Silica (7.5 eV). For the sake of comparisons, we used films from different film deposition technologies.
Independently from the photon energy, the LIDT of optical material in thin films form is a linear function of material's energy gap. This trend of the dependence of the LIDT according to the material energy gap has been observed at 800nm [5] and 1030nm [5]. When plotted for the different photon energies, we observed a power function dependence of the slope and the offset. We present also a comparison of the multipulse thresholds and incubation or fatigue effects at the different photon energies. The multiple pulses optical material's LIDT decreases with the number of pulses N, and stabilized at a minimum value from a certain value of N which depends on the material, the photon energy and the deposition technology.
Numerical simulations based on non-linear ionization processes (photo and impact ionization) and thermodynamical considerations are conducted for understanding the photon energy dependence of damage threshold, and its influence on fatigue effect on the thin film materials.

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In Situ Peak Intensity Measurement up to 10^{29} W/Cm^2

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Over the last two decades, studies in ultra-intense laser matter interaction have opened doors to exciting fields like laser wakefield acceleration of electrons, multi-MeV ion acceleration, non-linear QED effects like laser induced positron generation, etc. To understand and model these complex phenomena, one needs a careful measurement of peak intensity at the laser focus, which is extremely difficult to perform. Although ultra-intense laser facilities around the world at present routinely report performing experiments at intensities exceeding 10^{20} W/cm^2, reliable intensity measurement with error bars have remained elusive. Indirect measurement of intensity involves measuring pulse energy delivered at the interaction region, measuring focal spot of fully amplified beam, and laser pulsewidth of the fully amplified pulse.

Link *et. al.* demonstrated that peak intensity up to 10^{20} W/cm2 can be measured using strong field ionization of deeply bound atomic states [1]. However, as that method relies on collecting high charge state ion species created by field ionization at laser focus, Coulomb explosion of ions due to rapidly escaping electrons from focus at higher intensities render this method ineffective. More recently, Har-Shemesh et. al. [2] has described another method of directly measuring peak intensity of laser focus using non-linear Thomson Scattering, valid up to 10^{23} Wcm^2. This complex method involves relativistic frequency upshifting of laser by scattering a relativistic electron beam at the laser focus, which relies on generating relativistic electron beams via another ultra-intense laser pulse synchronous with the pulse whose peak focal intensity is to be measured.

In this paper, we present a simple method to directly measure peak intensity of a focused laser pulse, up to 10^{29} Wcm^2 using direct laser acceleration (DLA) of protons/carbons from an under dense target. Localized under dense target will be generated at the interaction region via H_2 or CH_4 gas jet and differential pumping, so that target density at the interaction region stays around 10^{15} cm^{-3}, and falls off to high vacuum level away from focus. This way, any plasma formation at the interaction region is suppressed. The choice of target is significant, as H and C become fully ionized by ~10^{15} and ~10^{18} Wcm^2 respectively, all the electrons are born much earlier than peak field is reached, and is driven out of the focus by a combination of ponderomotive force and non-paraxial fields. At intensities exceeding 10^{22} Wcm$^-$

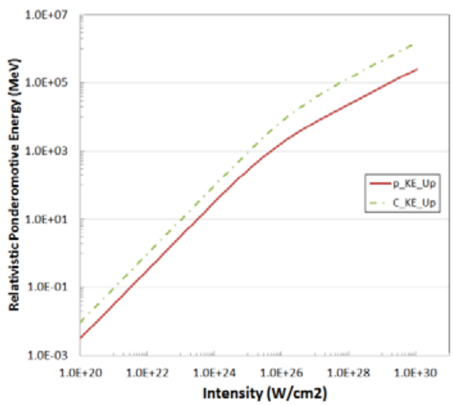

Figure 1. Relativistic Ponderomotive energy of proton and carbon 6+ in ultrastrong fields

^{2}, proton ponderomotive energy becomes significant (~300 keV), as shown in Fig.1. As detecting and measuring MeV ions using various spectrometers has advanced significantly, detecting 10^3 – 10^4 ions accelerating from focal volume has become feasible. For proton/ion energy exceeding GeV, detection techniques based on secondary particle/Cerenkov radiation generation developed at high energy particle accelerators can be used. A fully relativistic model with realistic proton/carbon density distribution within a non-paraxial laser focus will be presented at various intensities, and coulomb effect on the ion trajectories due to loss of electrons in laser focus will be discussed.

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Extracting During Pumping Ti: Sapphire Amplifiers for ELI

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For the new generation of the ultra-high power lasers with tens of PW of output power, the kJ- energy level has to be reached. There are two already proven solutions for the duty amplifiers in such systems, Optical Parametrical Amplifiers (OPA) and laser material amplifiers (Ti:S, doped Glass, etc.). Both types of systems possess advantages and shortcomings. OPA places severe requirements on the temporal and spatial shape of the pump beam, as well as on its pointing and energy stability. The current kJ level laser amplifiers are subjected to severe losses due to Transverse Amplified Spontaneous Emission (TASE), and Transverse Parasitic Generation (TPG). These effects cause significant depletion of the inverted population, leech stored energy, and hence limits the extractable energy [1]. It was demonstrated that Extracting During Pumping (EDP) [2, 3] can significantly reduce parasitic losses due to both TASE and TPG, making an EDP laser amplifier to become an efficient candidate for the next generation of CPA-laser systems. The EDP-method has been applied on several Ti: sapphire booster amplifiers of PW-scale, and has allowed output energies in excess of 72 J with the current record power of 2 PW from a single channel [4, 5]. In this paper we study the concept of EDP amplification for the 10-100PW level laser systems.

In the three pillars of ELI, several PW-class lasers have been planned to build. The HF PW laser of ELI-ALPS (and the L2 laser of the ELI-Beamlines) with 2 PW peak power and <20 fs pulse duration, while the L4 of the ELI-BEAMLINES as well as the ELI-NP lasers aiming at 300 J / 10 PW lasers. The 200 PW laser facility is still on the roadmap of the ELI consortium. To achieve these parameters, we have elaborated the simulation especially for the geometry [1] of Ti:S amplifiers: the diameter of pump area and crystal - 8 and 9 cm; the pump energy – 170 J; the input and output energy are 10J and 90J, respectively. The dependence of calculated losses connected with TASE for this crystal with thickness 3cm (purple) and 2cm (blue) from the time of the pump presented on figure. The loss for EDP-amplifier is lower 5% as seen from the figure (compare green curve with blue one). Main parameters for ELI-BEAMLINES and ELI-NP amplifiers are: the diameter of pump area and crystal - 19 and 20 cm; the pump energy – 960 J; the input and output energy – 60 and 600 J; the losses – also under 5%.

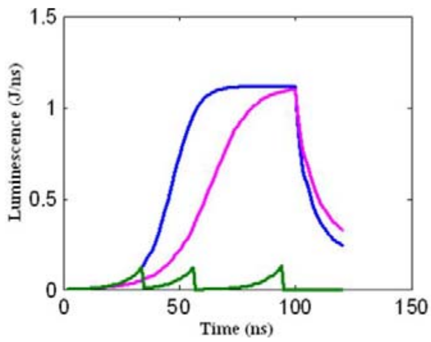

Fig. 1 The temporal evolution of the losses of high power ELI amplifiers: for conventional amplifiers (3 cm (purple) and 2 cm (blue) Ti:S crystals, and for the EDP amplifier (green).

Hence, the technique of EDP-amplifiers is modelled to keep the amplification level of at hundreds Joules by reducing the losses. Besides, in this report we also present the design of EDP power amplifiers, as an alternative to the stimulated backward Brillouin scattering method, for the 200 PW class system dreamed for the fourth-high intensity pillar of the ELI facility.

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Thermal Originated Drift and Noise of Carrier-Envelope Phase in Ti:Sapphire Based Amplifiers

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The pulse-to-pulse change of the carrier-envelope phase (CEP) of few-cycle laser pulses defines ultimately the accuracy of phase-related experiments in high harmonic and attosecond pulse generation, coherent beam combination, and precise frequency metrology [1]. Several experimental studies highlight the role of the mechanical stability of the elements in a chirped pulse amplification (CPA) system, especially the stretcher-compressor stages [2,3]. The resulting CEP noise of 250-350 mrad of commercial multi-kHz repetition rate CPA systems has been recently improved to 100 mrad with the use of a fast detection system [4].
The subject of our study was to characterize the effect of amplification in Ti:Sapphire crystal on the CEP of the pulses, i.e. measure the CEP change of the amplified pulses relative to the incoming ones by using spectrally resolved interferometry [5]. In this way, the CEP noise of the pulses entering the sample amplifier is completely indifferent, ensuring a measurement with high accuracy and low noise. The multipass Ti:Sapphire amplifier has been incorporated into the sample arm of a Mach-Zehnder interferometer with equal arm lengths (Fig. 1. a.).

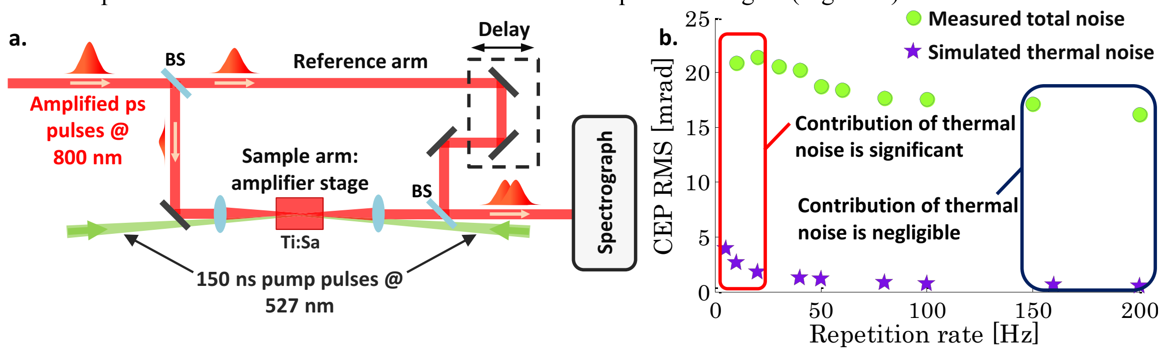

Fig. 1. a. Experimental setup with the Mach-Zehnder interferometer (BS beamsplitter). b. Measured total CEP noise (o) and simulated thermal CEP noise (☆) for one pass in a Ti:Sapphire amplifier at different repetition rates with 20 mJ pump energy. Crystal length was 5 mm.

Experiments with two different Ti:Sapphire amplifiers were made to examine the effect of incorporated crystal length on CEP, different crystal water cooling mounts were also investigated. We measured the noise and drift of the CEP upon the variation of the seed pulse energy, the pump energy, the repetition rate, and the cooling of the crystals. Results show that the noise basically increases linearly with the pump pulse energy, but independent of the seed pulse energy. Simulations on thermally induced CEP changes were also performed. By using finite element method, we modeled the thermal instabilities in the crystal. With the use of numerical temperature data the changes of the CEP of pulses were calculated from the temperature dependency of the crystal's refractive index. We have found that the thermal instability of the amplifier crystal under pumping is responsible for the drift of CEP, additionally at lower repetition rates it can increase the noise of the CEP (Fig. 1. b.), as well.
We can conclude that the significant part of the CEP noise is related to mechanical vibrations of the optical elements in the amplifier. The drift of the CEP can be limited effectively with precise cooling techniques close to room temperature and also with cryogenic cooling. Furthermore, noise of the CEP can be also kept under control by working at high repetition rates and close to the gain saturation. Most affected systems are potentially the low repetition rate, high pump energy amplifiers, since the CEP noise gradually increases in these cases, because of the cooling instabilities between the consecutive seed pulses.

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ASUR Ultra-Intense Laser Platform: Radioprotection and Dosimetry Measurements

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High peak-power ultra-intense lasers (>> TW and PW laser class systems) are now flourishing everywhere in the world (see http://www.icuil.org/). Upon operation, these ultra-intense laser sources can achieve extremely high intensities on target (>> 10^{16} W/cm²) inducing secondary sources of radiation (hot electrons, X-rays and γ-rays, protons and heavy ions, neutrons, etc.) and significant acceleration fields (> GeV/m) [1]. This class of laser allows scientists to explore and develop a new and promising avenue of research for the creation of new sources of compact, short and intense particles ("burst of particles") for many fundamental and applied applications in particle physics, astrophysics, energy (fusion) , plasma physics and condensed matter, medicine (proton therapy, imaging, ...), etc.

In the context of routine and safe operation of both facilities and their users, the question of radiation protection has to be addressed carefully. The problems are multifold: i) such laser facilities provide ultra-high intensity on targets with pulse duration in the femtosecond range (< 50 fs typically), potentially leading to the generation of deleterious particle and radiation beams of high energy (> MeV) and of short pulse duration making hard their protection and their detection (accuracy and reliability of the measurement); ii) the facilities may also be operated with high repetition rate for obvious scientific and applicative interests but it makes particularly crucial the problem of the dose (ICRP recommendation limit of 20 mSv per year) and dose rate which may to be observed for the operation of such installations (see recommandations of ICRP: http://www.icrp.org/).

In this paper, we will present the radioprotection strategy we implement for the ASUR (multi-TW and multi-beam line facility, [2]) installed in LP3 laboratory. In particular, this laser facility is able to deliver on target an intensity up to ~ 2.5 10^{19} W/cm² at the repetition rate of 100 Hz making particularly crucial the problem of the induced dose rate and of the safe management of the facility (operation, protection). We will thus present an ensemble of calculations able to provide an estimation of the dose generated during experiments at ultrahigh intensity. These numerical estimations served as a basis for determining a solution for radio protection, which was implemented in the laser platform. We will then show our first results of dosimetry measurements, realized under various intensity conditions (with I up to ~ 2.5 10^{19} W/cm²) and which give us a feedback on the problem of radioprotection safety encountered with high peak-power ultra-intense laser facilities.

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Long Pulse on LULI2000 : Advanced Phase Modulation Technique for Stimulated Brillouin Scattering Suppression

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LULI2000 is one of the most energetic laser facilities in Europe. Since its first shot in 2003, LULI2000 has been used by world-wide plasma scientists and has made an important contribution to laser plasma physics and Inertial Confinement Fusion studies. Composed of high-energy 3-beam neodymium glass chains, it delivers pulses in the ns (<5 ns) and ps regime at 1053 nm with an energy level up to 2 x 1 kJ. This multibeams facility is capable of combining kJ/ns pluses with high energy sub-ps ones.

We discuss in this paper new techniques to increase the nanosecond pulse duration of kilojoule class laser chain. World-wide kilojoule class lasers are mainly limited to 5 ns because of the large fluence on optics causing transverse Brillouin gain. This effect can cause severe optical damage to the final amplifiers and lenses. Megajoule class laser facilties (LMJ & NIF) have address this problem by using phase modulation (i.e. frequency modulation) to increase the seed spectrum and thus limiting the Brillouin gain. Ideally, this pure phase modulation does not change beam intensity. A drawback of this phase modulation is that during it's propagation, the FM is partly converted into AMs due to spectral filters induced by the different components of the chain [1]. In a kilojoule class facility such as LULI2000, those intensity modulations are mainly due to linear spectral filters and thus can be entirely compensated thanks to inverse transfer function. Those intensity modulations needs to be controlled to get good experiments (AM can amplify instabilities of the plasma) and nevertheless AM migh also damage the optics.

We are developing at LULI2000 a new front end ready for SBS suppression by phase modulation. An original system for precompensating the FM/AM conversion is tested by using an active spectral filter (Mazzler) inside our REGEN cavity. This new technique will allow LULI2000 to operate nanosecond pulses up to 20 ns with more shot-to-shot stability and a multi pulse shaping capability. We will present a full characterization of the new fibered oscillator, then the progress of the ongoing laser developments, including the regenerative amplifier filtered by the Mazzler and the investigation into the possibility of using more powerful fiber amplifiers instead of REGEN (pulse >20 ns limited by the lenght of the REGEN).

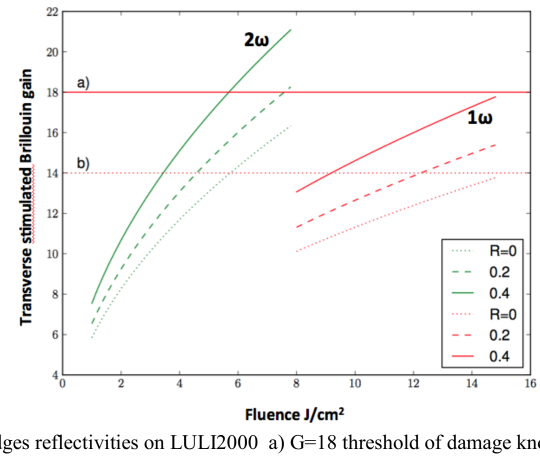

Fig. 1. Brillouin gain for various edges reflectivities on LULI2000 a) G=18 threshold of damage known on Phebus laser b) G=14 security threshold: gain divided by a factor of 100 ~ e^4

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Comparison of Three Angular Dispersion Measurement Methods

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In a laser beam, angular dispersion can be described as the variation of propagation direction regarding the different spectral components. Most often considered as a default, this angular dispersion can lead to pulse distortions such as pulse front tilt or lengthening of the pulse duration [1]. Since this effect is more pronounced for shorter pulse durations and for high stretching-compression ratio chirped pulse amplification (CPA) lasers, considerable efforts have been paid during the last decades to measure it and correct for [2-6]. On the contrary, the control and knowledge of angular dispersion have been recently demonstrated as essential in generation of single attosecond pulses and energetic terahertz waves [7,8].

In this study, comparative results about the accuracy, the measurement limitations, and the ease-of-use of the three methods based on linear optical elements are given. The novel two-dimensional (2D) angular dispersion measurement method applies a Fabry-Perot etalon (FPE) to create well-designed spectral components, which are then imaged on a CCD chip by an objective [6]. Alternatively, an acousto-optical programmable shaper of the laser system, if available, can be used to generate the separate spectral components, so that the FPE can be omitted. A simple method to measure propagation direction angular dispersion is based on recording the intensity distribution spatially and spectrally of the focused beam [4]. The last method under testing allows to measure phase front angular dispersion by spectrally and spatially resolved interferometry, based on the combination of a two-beam interferometer and a two-dimensional spectrograph [2].

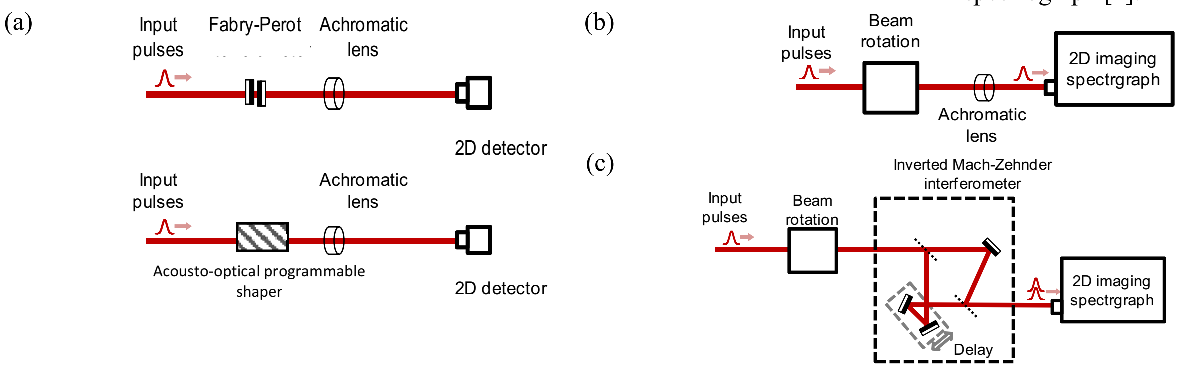

Fig. 1 Schematic layouts of the methods: (a) two versions (FPE and AOPDF) of the 2D angular dispersion measurement technique, (b) the imaging spectrograph measurement technique, (c) the spatially and spectrally resolved measurement method.

We have found that all angular dispersion methods present exceptional accuracy. The 2D technique gave a precision of 0.12µrad/nm, while the method with the imaging spectrograph provided an accuracy of 0.1µrad/nm. The inverted beam Mach-Zehnder interferometer has been experienced to be as accurate as 0.05µrad/nm [2,4-6]. Regarding alignment and ease of use, the 2D technique experienced to be the most convenient one. Unlike the other two, it measures the angular dispersion in a single-shot without the requirement of beam rotation. Hence, the requirements and circumstances of the given measurement determine the choice of the measurement method.

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Off-Axis Parabola Alignment using a Closed-Loop

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For high-peak-power lasers generating ultra-short pulses, off-axis parabolas (OAP) are usually used in spatial filters of the amplification chain and as a focusing optics after the compressor. In fact, temporal delay could be generated by longitudinal chromatism induced by lenses. On the other hand, beam focusing by off-axis parabolas after pulse compression could avoid non-linear effects generated within transmittive optics. Nevertheless, such optic is quite hard to correctly align and thus a lot of time is required to achieve a good focusing quality.

In order to obtain a good alignment of an off-axis parabola in a short time, we propose an alternative method to control its position through a closed-loop instead of the usual focal spot monitoring with a CCD camera. This new method is inspired from the adaptive optics used for laser beam wavefront control. Composed of a deformable mirror and a wavefront sensor, such systems improve considerably laser wavefront quality [1]. Excellent focal spot closed to diffraction limit can be obtained. In a similar way, we study the wavefront aberrations of a beam reflected by a misaligned off-axis parabola. By minimizing the defaults of the wavefront comparing the targeted one, we can effectively optimize the parabola position and achieve its alignment.

Simulations carried out with the software Zemax allow us to predict the wavefront deformations due to each degree of misalignment especially by the longitudinal translation, and the transverse rotations (see Figure 1). The impact of the parabola parameters (focal length and off-axis angle) on these deformations has also been studied. The simulations were well confirmed experimentally using a high quality CW collimated beam, an off-axis parabola (f = 750 mm, off-axis angle = 6°) and a high transverse resolution sensor. The wavefront deformation measured close to the parabola focal plan is minimized in several iterations. The experimental results of the closed-loop are very promising and show a very fast convergence of the loop and a good stability.

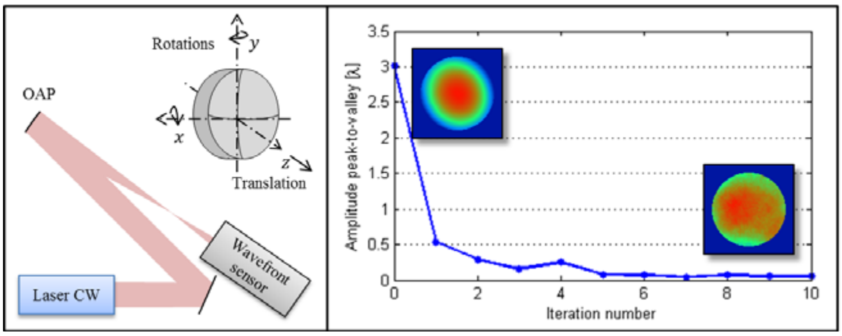

Figure 2. Experimental set-up and representation of the 3 degrees of misalignment studied (left) and evolution of the residual wavefront deformations during the closed loop (right)

Off-axis parabola alignment using a closed-loop proposes a new way to realise an automatic OAP alignment for high-peak-power laser systems. In this presentation, we describe the procedure of the closed-loop including its parameters, the software and experimental setup as well. The simulations and the experimental results carried out at the LULI facility, as well as the study of the limitations will provide an exhaustive overview of this innovative and reliable method for parabolic mirror alignment.

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Time Multiplexed Pulse Amplification Approach for v Enhanced Extraction Efficiency of Laser Amplifier

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Most of the high energy high power laser systems [1,2], worldwide use complex setups to generate an energetic laser beam. This leads to their enhanced cost and it is difficult to align these laser systems and keep them aligned. The concept of space multiplexing of laser beams is applied in the developing large laser systems like the National Ignition Facility (192 beams) in USA, Orion (12 beams) at AWE, UK etc. While the extraction efficiency of a single pass laser amplifier (Fig.1a) is limited, it can be further enhanced in a multi-pass laser amplifier (Fig.1b) as they operate at near saturation. In any case, the laser energy cannot be extracted beyond the damage threshold limit. A typical space multiplexed laser amplifier is given in the Fig.1c.

In this paper, we propose a new scheme of time multiplexed amplification (TMA), wherein two or more time delayed laser pulses are sent into an amplifier (either in single or multi-pass architecture) working in linear amplification regime (Fig. 1(d)). In such a scheme, the stored laser energy in the gain medium is sequentially extracted by different pulses at different time intervals. The maximum number of pulses can be estimated from the ratio of the total stored energy to energy extracted by a single pulse. In this scheme, the total laser energy will be much larger than the energy limited by the damage threshold. Implementation of TMA scheme in single-pass amplifier is easier due to alignment simplicity, minimization of back reflection and enhanced pulse contrast.

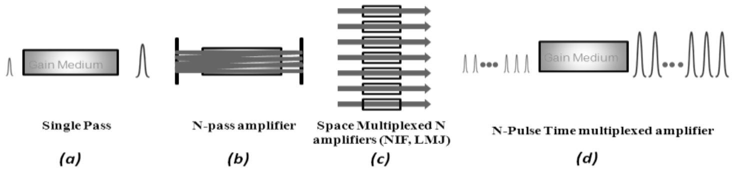

Fig. 1. Schematic of space and time multiplexed amplifier system

We have proposed and validated such a scheme experimentally on an existing all Nd:phosphate glass laser system, consisting of a regenerative amplifier, a 25 mm 4-pass laser amplifier, and a 50 mm 2-pass laser amplifier, using two ~9ns duration pulses separated by ~20ns. The two pulses were amplified up to ~7 J which is nearly equal to the sum of the energies extracted by the two pulses individually. The temporal and spatial profiles are shown in the Fig.2a and 2b respectively.

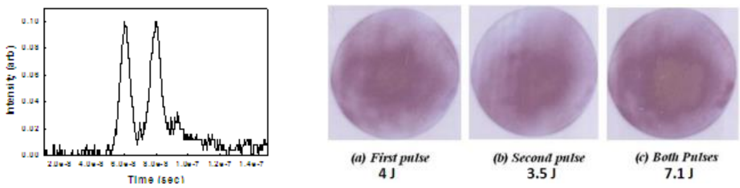

Fig. 2. Time Multiplexed Amplification based laser system with spatial and temporal profiles

Acknowledgements are due to members of the electronics team for smooth operation and maintenance of the control system and power supply of the laser.

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Flat-Top Apodization of Laser Beams by Means of Acousto-Optics

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Spatial profiling of laser beams is an urgent problem in design of high-power laser systems. One of the common methods of solving this problem is using soft-edge diaphragms [1, 2]. Traditional soft-edge diaphragms are fabricated as stationary amplitude masks that suppress diffraction of laser beams by the edges of the aperture. This design principle sufficiently limits adaptivity of the soft-edge diaphragms.

In the report, we propose a novel adaptive method of flat-top diffraction-free spatial shaping of laser beams based on acousto-optic (AO) Bragg interaction. For implementation of this method, transformation of laser beam plane wave spectrum due to angular selectivity of isotropic Bragg diffraction is used.

Diffraction of divergent laser beams by divergent ultrasound in the strong-field limit was studied in Ref. [3]. According to that results, distribution of diffracted laser field $E^d(x,z)$ can be expressed as

$$E^d(x,z) = \frac{\pi}{\lambda} E_2^0(z) \int_{-\infty}^{\infty} E_1^0(x-x') J_0\left(2\pi \frac{W}{\lambda} \sqrt{\left(\frac{L\lambda}{2\Lambda}\right)^2 - x'^2}\right) \mathrm{rect}\left(\frac{\Lambda}{L\lambda} x'\right) dx', \qquad (1)$$

where $E^0(x,z) = E_1^0(x) E_2^0(z)$ is the spatial distribution of input laser beam along orthogonal coordinates x and z; W is the ultrasonic power parameter; λ and Λ are the wavelength of light and ultrasound; L is the length of AO interaction. For the incoming Gaussian laser beam with the waist radius w_0, Eq. (1) in the weak-field limit can be integrated analytically. The result is expressed as

$$E^d(x,z) \sim \exp\left(-\frac{z^2}{w_0^2}\right)\left[\mathrm{erf}\left(\frac{x}{w_0} + a\frac{\pi}{4}\right) - \mathrm{erf}\left(\frac{x}{w_0} - a\frac{\pi}{4}\right)\right], \qquad (2)$$

where $a = 2\lambda L/(\pi w_0 \Lambda)$. According to Eq. (2), the diffracted field has a flat-top shape along the diffraction plane and remains Gaussian in orthogonal plane. Thus, an AO Bragg cell can be considered as adaptive one-dimentional soft-edge diaphragm. The edge width in the field distribution is determined by the parameter a. To perform rectangular beam shaping, a two-coordinate Bragg cell can be used.

During AO interaction in weak-field limit, the angular spectrum of the diffracted field is a product of the angular spectrum of incoming light and the angular spectrum of ultrasound. As a result, the angular spectrum of the diffracted field is always narrower, than the angular spectrum of the incoming light. That makes the principal difference with diffraction of light by the aperture, when the angular spectrum always widens. Thus, controlling of the spectral components of the ultrasonic field one can affect the spatial distribution of the diffracted light.

Experimental Bragg cell was designed and fabricated from dense flint glass. The experiments were performed with single-frequency emission of frequency-doubled Nd:YAG laser at the wavelength 532 nm. Adaptive amplitude apodization of the laser beam distribution corresponded to the theoretical predictions.

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Spectral Broadening and Self-compression of Down-chirped Fs Pulses in Transparent Bulk Kerr Media

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Discussed in this presentation is a new phenomenon of spectral broadening and self-compression of down-chirped visible pulses propagating in bulk materials with cubic nonlinearity at intensities close to 1 TW/cm^2. For the first time, this phenomenon was observed in our previous paper [1], when down-chirped 475 nm pulses with an energy of 0.2 mJ and Gaussian beam profile of 0.4-0.5 mm in diameter propagated through a 2.3-mm-thick fused silica plate. Spectral broadening was accompanied by temporal self-compression of the pulses down to 40 fs pulse-width, which is practically twice shorter than the duration of a 70 fs transform-limited pulse corresponding to the initial spectral width (Fig.1).

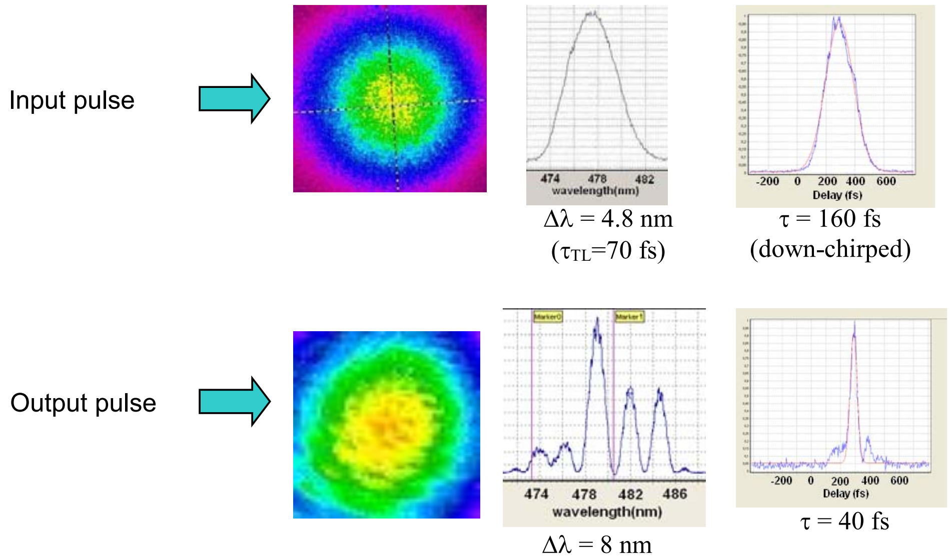

Fig. 1. Beam profiles, spectra, and autocorrelation functions for the intensity of incident beam 1 TW/cm^2: top row – parameters of the incident beam, bottom row - parameters of the beam passed through a 2.3-mm-thick fused silica plate.

In this presentation we will give new experimental results on scaling this phenomenon to 0.7 mJ and discuss these observations on the base of Generalized Nonlinear Schrödinger Equation. Numerical results agree quite well with the experimental observations and show that the dominant mechanism of nonlinear broadening and formation of a banded spectrum structure is self-phase modulation (SPM). In particular, simulations of spacing between successive bands in the spectra and dependence of the spacing on intensity are in good agreement with the experimental results. We also discuss the role of four-wave parametric amplification in the formation of the banded spectrum structure. It was also shown that the pulse self-compression mainly due to the self-focusing effect. Spectral broadening of down-chirped visible pulses was also experimentally observed in such Kerr materials as MgF_2, LiF, CaF_2 и BaF_2.
Results obtained in this studies offer a novel technique of fs pulse self-compression which is much simpler than well known methods based on filamentation in gases and in gase-filled capillaries. Moreover, they help to understand the influence of negative chirp on the propagation of intense femtosecond pulses in normally dispersive media with Kerr nonlinearity.
Scalability of this phenomenon towards higher energies and its applications will also be discussed.

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Laser-Plasma Source of Frequency-Tunable Few-Cycle Mid-Infrared Pulses

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We examine a new method for generation of the coherent few-cycle mid-infrared pulses. The method utilizes the gas ionization by ultrashort incommensurate two-color laser pulses. These incommensurate two-color pulses contain the fields at two different frequencies. One of the frequencies is detuned from the doubled value of the other one. Such incommensurate pulses can be obtained with the use of the nonlinear crystal (for example, BBO or KDP) or with the use of the optical parametric amplifier. In the latter case, the main (in the respect of intensity) field component has greater central frequency than the weaker field has; and the frequency of the weaker field can be reasonably easy tuned around the halved value of central frequency of the main field, which stays fixed [1].

We calculate the electron current which is excited by such two-color pulse in a gas during ionization through the use of the semiclassical approach both analytically and numerically and find out that the low-frequency component of that current can have central frequency in the mid-infrared range, which can be controlled by tuning the frequency of the weaker optical field. The full-dimensional simulations based on the quantum-mechanical approach (the solution of the 3D time-dependent Schrödinger equation) support the results obtained from the semiclassical approach. We estimate energy radiated by that current and discuss the possibilities of employing the phenomenon for creating the tunable source of coherent few-cycle mid-infrared pulses.

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Ultra-High Contrast Pulses with the All-Diode Pumped Laser POLARIS

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Over the last more than ten years we gained experience on building and running the femtosecond DPSSL POLARIS, producing high pulse energies, and using it tightly focused for laser-matter interaction experiments. Moreover, by playing with innovative technologies like new relay-imaging multipass amplifier schemes, cryogenic cooling, new laser materials, different pump beam homogenization principles, pulse cleaning concepts, or tiled grating compression considerable improvements could be shown. Some of these technologies are already implemented in the laser, giving every day proof of its performance. Here the most promising technologies and the current status of the POLARIS laser system will be reviewed. Actually, the POLARIS laser delivers pulses of 145 fs with an ultra-high temporal contrast of 2 × 10−13 at the 100 ps time scale (fig. 1). This contrast was achieved by the implementation of a double chirped-pulse amplification scheme comprising a cross-polarized wave generation pulse cleaning. Actually a peak intensity in excess of 3.5 × 1020 W/cm2 can be generated by tightly focusing together with adaptive wavefront correction. The given pulse parameters of POLARIS predestine it as a scientific tool well suited for sophisticated experiments as exemplified by measurements of accelerated proton energies. With the final amplifier recently added to the laser chain POLARIS now consists of six different diode pumped amplifiers. The first five of them are equipped with an Yb-doped fluoride phosphate glass, where in the last amplifier an Yb:CaF2 crystal is used. In the ramp up phase of this amplifier pulses are not yet compressed and did not yet reached the final goal for energy. Nevertheless, an output energy of 16.6 J was achieved so far. A higher pulse energy is expected in the coming months as the beam profile is improved and the new laser crystal with higher damage threshold anti-reflection coatings is installed. So far all amplifiers are operated at room temperature. But it can be envisioned that cryogenic cooling can increase the optical-to-optical efficiency of the laser. This helps to relax the diode-pump requirements like peak power and brightness to which another example laser installation, that amplifies bursts of fs pulses to the joule level, bears witness. Results from this system are also given.

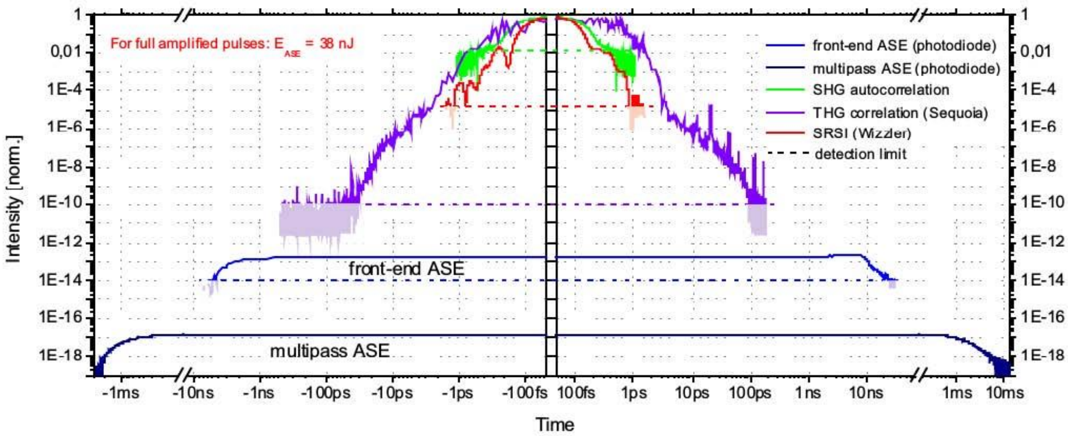

fig. 1: High dynamic temporal characterization of the amplified and compressed laser pulses from a couple of measurement devices.

High Energy Lasers Using Diode Pumped Laser Amplifiers

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Joule class laser systems have become important tools in high intensity science. These laser are often used as Ti:Sapphire and OPCPA pump sources. Creating a diode pumped, 2-20J, 10-100Hz laser generally requires dJay evelopment of custom laser amplifiers. Laser amplifiers are now available on the commercial market that greatly reduces the cost and development time of these types of laser systems. Diode pumped laser amplifiers that are capable of over 7 Joules stored energy, with aperture sizes of up to 25mm are discussed. Joule class laser systems built with these high energy modules are detailed and a design methodology is also presented.

Comparative Study of High-order Harmonic Yield Generated through Various Types of Carbon Plasmas

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Laser-ablated graphite plasmas have been found to be a highly efficient nonlinear medium for generating coherent source of extreme ultraviolet (XUV) radiation, compared to those from other plasmas or gaseous medium. Using Ti:sapphire lasers available at the Advanced Laser Light Source (ALLS), multi-μJ harmonic energy has been observed in each of the $11^{th} – 17^{th}$ harmonic order of graphite plasma [1]. Harmonic properties such as high conversion efficiency and low beam divergence make graphite plasmas a promising medium to develop tabletop source of extreme ultraviolet radiations.

In this paper, we present our results on high-order harmonic yield generated through various types of carbon plasmas from target materials with different crystalline structure and carbon compositions, to find a suitable target for harmonics generation. Three different types of carbon, such as graphite, glassy carbon and diamond are used as target material for harmonics generation. It is observed that harmonic yield generated through graphite plasma and glassy carbon is almost same. However, the results obtained using laser-ablated diamond plasma are interesting. No harmonics are observed during the initial few shots of laser-ablation. Then, very weak harmonics appeared on the detector. However, at this time it is observed that the surface of the target material has turned black. This indicates that diamond may undergo phase transition and converted into graphite first and then plasma generated from graphite is used to generate harmonics. Moreover, we have also observed that harmonic yield from diamond target is lower compared to graphite/glassy carbon targets (**Fig. 1(a)**).

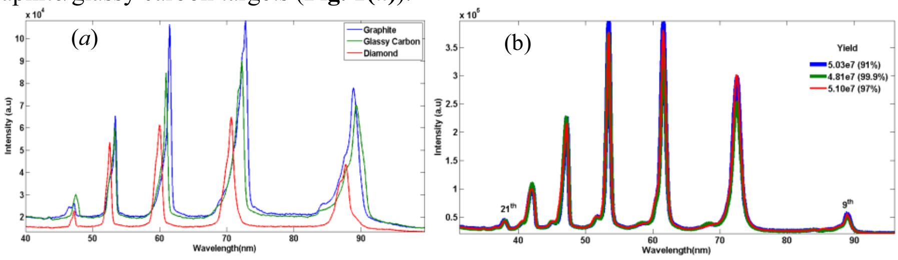

Figure 1: (a). Harmonic intensity comparison of plasmas generated through graphite, glassy carbon and diamond targets. **(b).** Comparison of harmonic intensities of graphite plasma with different composition (91, 97 and 99.99%).

Recently our group has demonstrated that stable and intense high-order harmonics can be generated using pencil lead as the target material [2]. The disadvantage of pencil lead is that it contains non-uniform distribution of carbon particles and different types of impurities are present in the target. To find the optimum target material, we used material with three different types of carbon compositions (Graphite of 90, 97 and 99.9%) for plasma ablation. It is observed that harmonics of same intensity can be generated through all these three types of graphite materials (**Fig. 1(b)**) and harmonics yield have less dependence on impurities present in the target material.

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Development of an Energetic Sub-Picosecond Laser-Plasma X-Ray K_α Source with a High Pulse Repetition Rate

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We report our latest results on the development of a bright hard x-ray quasi-monochromatic K_α source, generated by interaction of intense (~10 TW) and energetic (>100 mJ) ultra-short laser pulses (25 fs) with a solid target at high pulse-repetition rate (100 Hz). The source is characterized by a micrometric size (comparable to the size of a laser focal spot) and sub-picosecond duration. The source exhibits an isotropic x-radiation with a dominant K_α line emission (at photon energy determined by target material) in addition to a weak bremsstrahlung continuum. This allows employing the source in many applications, such as bio-medical imaging, achieving a high spatial resolution, as well as a high image contrast, when the phase-contrast technique is applied [1]. Furthermore, for fast x-ray diffraction applications, the high temporal resolution (femtosecond scale) is crucial to investigate fast changes in the local structure of condensed matter and to probe the atomic motion during the phase change [2]

In recent years, many new bright and ultra-short x-ray sources with pulse duration of less than 100 fs are put into operation worldwide. The most intense of them are based on the emission of charged accelerated particles. One approach employs the bunch "slicing" technique in a synchrotron beamline (SLS...); another one uses coherent emission of particles accelerated in free electron laser (FEL) systems (LCLS, FLASH ...) [2]. However, such installations are huge and costly. While the intensity of x-radiation produced by compact sources based on the electrons accelerated by laser wake field (betatron radiation) is relatively low. At the same time, intense secondary sources of K_α x-ray emission, which require electromagnetic fields of 10^{18} W/cm^2 peak intensity, can be generated by modern compact femtosecond laser systems commercially available on the market.

Being focused on the target surface, an intense fs laser pulse creates plasma, where the electrons are accelerated by the laser field via different absorption mechanisms. We consider the regime of intense non relativistic interaction (10^{16} - 10^{18} W/cm^2) and high-contrast p-polarized fs pulses, which result in the vacuum heating (Brunel effect) as dominant mechanism of plasma absorption, leading to characteristic energies of accelerated "hot" (suprathermal) electrons of tens keV and higher. Coming in collisions with atoms of the target material, the hot electrons are scattered producing spectrally-continuous bremsstrahlung radiation and create the vacancies in the atom inner shells, resulting in the characteristic line emission. At hot electron energies of several times the K-shell ionization threshold, the K-shell ionization cross-section reaches its maximum and the K_α emission is dominant due to the highest rate of the K-shell population. Owing to a very rapid energetic relaxation of hot electrons in the target material, the produced x-ray pulse has sub-picosecond duration.

Photon fluxes of K_α emission of up to 10^{10} photons/s have been attained using laser systems delivering few mJ per pulse with 1-kHz repetition rate [3]. We expect to reach higher K_α photon fluxes (up to 10^{12}photons/s) using the laser system "ASUR" at our laboratory [4]. Note that "ASUR" is a unique high-contrast (10^9 @ns and 10^8@10ps) laser system delivering 10TW/250mJ/25fs pulses with 100 Hz repetition rate (designed by Amplitude Technologies).

Measurements of the main source characteristics (source size, spectrum, efficiency) will be presented. Experimental setup includes a vacuum interaction chamber with a silver-coated off-axis parabolic mirror (metal substrate, f/3.5, f=150 mm), which concentrates an intense fs laser pulse into a small spot at the surface of a motorized rotating disk target in Mo (K_α photon energy 17keV) or Cu (8keV). The interaction chamber is coupled to the final vacuum compressors through a separate vacuum chamber, where an adaptive deformable mirror is installed. Available diagnostics for controlling the x-ray source characteristics include X-PMTs, X-spectrometers and X-CCDs.

Preliminary experiments (performed to the date of abstract submission) on the x-ray generation by Molybden target show the production of more than 10^9 x-photons under single laser pulse of 100mJ energy focalized into a spot diameter of 6 µm FWHM (without use of the deformable mirror).

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Recent Developments of Soft X-Rays Lasers on LASERIX and New Perspectives

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Multi-terawatt laser systems are ideal tools for jitter-free pump-probe experiments with highly different wavelengths. In this context, plasma based soft x-ray laser are interesting short wavelength probe for surface interferometry, plasma physics or warm dense matter studies. During the last two years, LASERIX really focused on developing new pumping schemes for transient collisional soft-X rays laser (SXRL) generation. The classical configuration for SXRL is a two steps process. First, it involves creating plasma column at the surface of a solid target with a nanosecond laser pulse focused with a cylindrical optic. Then, it consists in exciting a coherent XUV laser transition by pumping highly charged and stable ions with a short picosecond pulse. Since the population lasts a few picoseconds, the short pulse energy front is tilted to about 45° in order to synchronize pumping and amplification along the plasma column, leading to the well-known Grazing Incidence Pumping (GRIP) scheme [1].

Previous works partly conducted on LASERIX in collaboration with PHELIX (GSI, Darmstadt) have shown the interest of the Double GRIP (DGRIP) scheme, which consists in creating a prepulse having a large positive spectral phase induced by an additional stretcher at the beginning of the laser chain before amplification [2]. After compression the DGRIP scheme offers a long pulse for plasma creation followed by the short pulse for collisional excitation, both in the same beam, allowing then more compact, stable and convenient system. We have improved, simplified and extended the principle in order to generate up to two prepulses of different spectral phase with no need of additional stretcher [3]. Existence of a low energy short prepulse appears to help excitation of the preformed plasma allowing better SXRL energy. Additionally, we experimented plasma creation with an additional Q-Switch laser [4] instead of using an un-stretched part of the CPA pulse as usually done on collisional SXRL lasers. Such a configuration allows an easy control of the delay between plasma and pump pulses with Q-Switch triggering, and gives the availability of the entire CPA energy for the short pump pulse. Moreover, this scheme guarantees a clean short pulse without any prepulse, contrary to DGRIG, which can be required for certain experiments needing for example a femtosecond resolution [5]. Previous experiments led with an old Nd:YAG laser (providing 140mJ-6ns pulses at 2ω), showed very good and reliable SXRL in Ti, Ag and Mo. The third important development made on LASERIX concerned direct high order harmonic (HH) seeding generated in a low pressure Ne cell into a SXRL plasma on Ti. This offered to demonstrate a 10 times amplification at 32.6nm of a very good quality beam which is simple to obtain thanks to the Nd:YAG laser configuration. We plan to develop this new beamline in order to be able to provide amplified HH for external users.

LASERIX is now integrating a new experimental room lent by LAL (Laboratoire de l'Accélérateur Linéaire) while waiting for its definitive building expected to be at CEA-Orme des Merisiers. We have fit out a 80m^2 low-cost clean room in order to install the 3J-10Hz part of the CPA driver laser together with one XUV beamline containing both SXRL and HH beams. We took advantage of this reorganization for upgrading the laser with support of Amplitude technologies by inserting a MAZZLER into the regenerative amplifier, mainly in order to tune the central output wavelength for HH accordability. We will make the most of the new location, close to the Photoinjector test line PHIL of LAL, to collaborate on the study of femtosecond photoexcitation in one photon (UV) and multiphoton (IR) modes by sending a low energy beam sampled from the output of the front end towards the accelerator. That part of the beam will be also used for testing recycling cavities in collaboration with LAL for the ELI-NP project. For the next two years, the main goal for LASERIX is to pursue its major activities regarding CPA laser designs for SXRL excitation, designs of XUV beamlines and applications.

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The High-Energy Density Instrument at European XFEL

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Free-electron laser facilities provide new applications in the field of high-pressure research including planetary materials. The European X-ray Free Electron Laser (XFEL) in Hamburg will start user operation in 2017 and will provide photon energies of up to 25 keV. With a photon flux of about 10^12 photons/pulse, with a pulse duration of 2-100 fs and a repetition rate of up to 4,5 MHz during 600µs long bursts with a repetition rate of 10Hz, rendering up to 27000 pulses per second, this facility will provide unique opportunities to study material under extreme conditions. The high-energy density science instrument (HED) is one of the six baseline instruments at the European XFEL. It enables the study of dense material at strong excitation and high pressures, studying structural and electronic properties of excited states with hard x-rays. Besides the use of the x-ray FEL beam as a possible pump and/or probe, it will be equipped with a high contrast PW-class ultra-high power -, a temporal shaped ultra-high energy, KJ-class and a mJ-class MHz repetition rate, matching the X-ray burst structure, laser facility. Probing of the laser-generated excited states will be performed with the x-ray free electron laser.

A Laser Beam Circulator for Gamma-Ray Generation

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Compton scattering process between a relativistic electron bunch and a high power laser pulse is today the most efficient technique to generate high-energy gamma ray beams. However, the main drawback of this physical process is its small cross-section which has to be compensated for by the use of a laser power at the limit of the existing technology to provide a high flux of gamma rays.
The European Collaboration EUROGAMMAS [1], just won the bid of the Extreme Light Infrastructure – Nuclear Physics – Gamma Beam Source (ELI-NP-GBS) [2]. In this context a novel generation of gamma source is expected with performances up to 2 orders of magnitudes above the present state of the art in terms of spectral density, bandwidth and peak brilliance.
A state of the art low emittance electron-beam linear accelerator [3], and high intensity and power laser system are being implemented in order to reach the ELI-NP-GBS specifications. Even with these technologies, the laser pulse has to be circulated to interact several times with the multi-bunches electron beam at a constant crossing angle. The Laboratoire de l'Accélérateur Linéaire (LAL, Orsay, France) is in charge of the design and commissioning of the optical system at the interaction point, which manage the laser recycling and interaction efficiency for gamma generation [4].
After a short overview of the ELI-NP-GBS project, the accelerator and the high-performance laser system required for this project are introduced. The accelerator chosen for this project is a hybrid technology between a photo-injector in S-band and accelerating cavities in C-band. The velocity bunching technique is used to produced the very low emittance and low energy spread electron beam required [5]. The laser system is composed of three state of the art lasers with repetition rate of 100 Hz: one Ti:Sapphire and two Yb:Yag delivering up to 500 mJ per pulse. Then, the presentation is focused on the optical system and its design optimization. This laser beam circulator allows recycling the laser beam 32 times while the optical performances and the crossing angle (with the electron beam) are preserved. The interaction points are located in a cube of hundred micrometers on each side. Among the final expected performances of the laser beam circulator it could be cited the polarization transport and the optical aberration free of the laser pulse. To conclude, other possible high-intensity laser applications of our new optical system are presented.

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Gamma Rays and Pair Production During Symmetric Irradiation of a Plasma Target by Two Ultra-Relativistic Circularly Polarized Laser Pulses

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The upcoming ultra-high power lasers [1] can strongly modify habitual laser-plasma interactions, mostly due to the QED (quantum electrodynamics) processes. First of all, the radiation reaction effects can add significant conductivity, cause formidable absorption (~50%) of laser energy and its transformation into MeV or even GeV photons [2]. Second, these high energy photons can initiate avalanche like electron-positron pair production. This process can decrease maximal photon energy and the rate of photon production due to increasing plasma density and as a result the suppression of laser field penetration into plasma [3]. But if the particles are expelled faster from the strong field region than they are created, then pair production isn't so crucial, moreover it can increase the part of laser energy converted into the photon energy. These scenarios depend on focusing geometry and intensity of laser radiation.

The present paper concerns the study of gamma ray generation and as well pair production during the plasma target interaction with two counter-propagating circularly polarized laser pulses. Based on the previously developed one-dimensional self-consistent model of ultra-relativistic laser-plasma interaction [4] that permits defining optimized parameters with respect to the efficient gamma ray generation, we have carried out three-dimensional computer simulations by using the PIC-code PICADOR [5] with modules of synchrotron emission and electron positron pair production. It has been shown that, at tight focusing geometry, 3D effects are crucially important for the interaction dynamics. Firstly, the electrons compressed in the longitudinal direction by the incident laser pulses are expelled from the high intensity field region due to the transverse ponderomotive force. We have demonstrated that by varying the transversal size of a plasma target relative to the diameter of the laser beam it is possible to suppress electron escape. Secondly, non-uniformities of plasma and electromagnetic field lead to generation of a magnetic field due to the inverse Faraday effect, and its amplitude may be comparable to that of the transverse magnetic field of the laser pulse. Moreover, these non-uniformities may give rise to instability resulting in spatial modulation of electron distribution with a subwavelength scale and destruction of the compressed electron layer. By properly choosing pulse duration we can avoid the negative influence of this process on laser energy conversion into gamma-rays. In the third place, electron-positron plasma production in strong enough laser fields interacting with matter can play an appreciable or even crucial role. Although electrons can escape from the strong field region there is a high probability to generate hard photons, which decay and produce electron-positron pairs. So, this process can provide enough particles for highly efficient gamma-ray conversion in a strong field. The performed PIC-code simulation allowed finding the required transversal size of the plasma target and laser beam, pulse duration for given plasma target thickness and laser intensity to maximize the conversion efficiency, which can be about 40% for the laser intensity of $\sim 10^{24}$ W·cm^{-2}.

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Demonstration of Femtosecond Plasma-Based Soft X-Ray Lasers Using Near Critical Density Waveguiding Techniques

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Laser- based soft X-ray Laser (sXRL) plasma amplifiers seeded with High order Harmonic Generation (HHG) arouse great interest due to their ability to deliver the high energy per pulse within a narrow linewidth in the XUV region [1-3]. Using gas target, the pulse duration has been to date limited so far to 5 ps due to the intrinsically limiting narrow gain bandwidth [4].
We report the latest effort aimed at overcoming previous bottlenecks to yield femtosecond-scale x-ray laser pulses. Our method is based on seeding near critical density gas laser-driven-plasma amplifier using High order Harmonic generation (HHG). Increasing plasma density simultaneously leads to an increase of output performance and shorter pulse duration. However, to permit the propagation of the high intensity-pumping laser into the gain media, guiding techniques is needed. This was performed using an optically preformed plasma waveguide based on the ignitor-heater scheme.
The femtosecond-scale plasma-based XRL gain was achieved with a transient collisional excitation scheme in Ni-like krypton at 32.8nm. The waveguide was characterized using optical techniques. The gain dynamic of the amplifier was probed using a high-harmonic seed signal and the x-ray laser pulse duration was inferred to be lower than 400 fs for a krypton neutral density of few 10^{20} cm^{-3}, which is the shorter plasma-based x-ray laser pulse ever reported so far. Experimental results will be compared to intensive modeling including the propagation of the laser and the amplification of the seed HHG by combining a Bloch-Maxwell treatment with collisional-radiative description of the atomic kinetics [5]. Our calculations show that, although complicated structures may arise after amplification, the duration of the amplified soft x-ray pulse is in good agreement with our experimental measurements.
Tailoring the plasma waveguide for higher densities yields promising prospects for further sXRL pulse duration shortening.

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Some Comments on Future Development of MJ-level High Power Laser Driver

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The construction of National Ignition Facility (NIF) in US has been completed recently, and its further enhancement of output energy is expected to meet the physical needs of ignition. At the same time, The Laser Megajoule facility (LMJ) in France is also under construction, of which the output capacity and physical experiments results are to be verified.

According to ignition physics, the MJ-level (for example, 3MJ) laser driver is the key verification platform to develop demonstrative experiments of ignition. Based on the experiences in the construction of SG high power laser facility series in China, in this paper, we propose the following four key issues on designing and constructing a laser driver which can achieve the MJ-level (more than 3MJ) output and provide a long-term stable operation.

a)To analyze and design the total energy output of the laser driver and the spatial layout of the target range, in order to meet the physical research needs with certainty and uncertainty factors in ignition physics.

b)To match the fundamental frequency output with the triple frequency output, in order to gain an optimized configuration for the laser system.

c) To achieve the high efficiency output of the fundamental frequency.

d) To upgrade the load of optics for triple frequency.

Random Phase Noise Effect on the Contrast of an Ultra-High Intensity Laser

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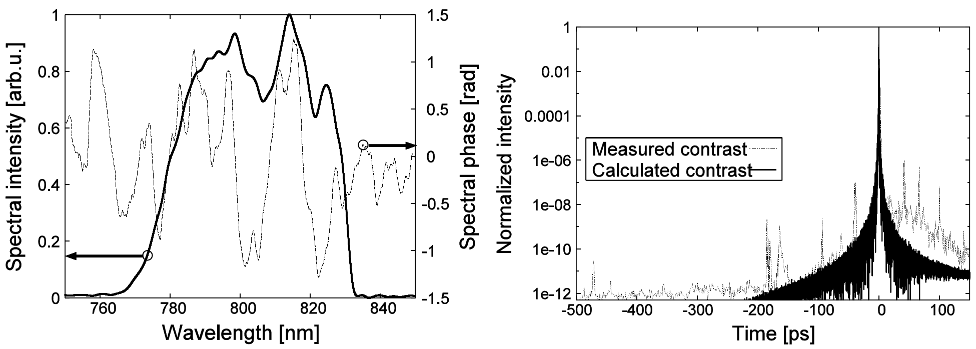
The advent of ultra-intense laser pulses generated by Ti: sapphire chirped-pulse amplification (CPA) laser systems provides great opportunities for experimental study of relativistic laser-matter interaction in small-scale laboratories. Recently, femtosecond high intensity lasers are breaking through to the 100 TW or even petawatt (PW) power level. Consequently, the laser focused intensities have reached up to 10^{20} W/cm^2 or even to 10^{22} W/cm^2.

In order to reach these intensities, great effort has been directed to increasing the pulse energy and reducing the pulse duration. For many experiments, increased peak intensities require a commensurate improvement in temporal contrast. The temporal contrast is a critical characteristic of femtosecond high intensity laser pulses where it is important to avoid any modification of the target, such as pre-plasma formation, before arrival of the main femtosecond laser pulse. Here, a pedestal covering ±10's of picoseconds of the main pulse, which is independent of amplified spontaneous emission (ASE), is investigated.

In CPA lasers, the laser beam is expanded and spectrally resolved on the optics surfaces in a stretcher and compressor. The surface quality of the large grating in a compressor has an influence on the spectral phase noise, which reduces the temporal coherence of the main pulse and generates a pedestal. The effect of the random phase noise on the contrast is analyzed using the experimental observation of the contrast in the J-KAREN laser [1]. We have calculated the temporal contrast using both the random phase noise with an amplitude of λ/4 peak to valley, which is a reasonable surface quality for the compressor grating used in our system, and the typical experimental spectrum. Figures 1 (a) and (b) show the spectral phase noise, the spectrum and the resulting temporal contrast, respectively. This random phase noise generates a pedestal in ±100 ps range, which is in fairly good agreement with the experimental observation.



(a) (b)

Fig. 1. The effect of random phase noise on the contrast. (a) spectral phase noise with the amplitude of λ/4 and a typical measured spectrum, (b) calculated temporal contrast corresponding to the phase noise with the experimental contrast in the J-KAREN laser.

The random phase noise can be a good explanation for the pedestal observed in our contrast measurement. Thus, we concluded that the spectral phase noise generated in the grating in a compressor is the most probable factor causing the pedestal. As the ASE contrast gets even higher, for example, than 10^{12} for the experiment with the focused intensity of over 10^{22} W/cm^2, the spectral noise factor becomes more important because the pedestal could exist for more than 100 ps around of the main pulse.

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Specificity of Contrast Formation in OPCPA at Multipetawatt Level

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High contrast of amplified pulses is the basic requirement for the majority of laser systems operating with chirped pulse amplification and intended for experiments with target irradiation. For achieving ultrahigh contrast it is important to get an insight into the physical features of pulse profile formation at amplification in OPCPA systems. Apart from apparatus effects such as cut-off in the field distribution at the gratings edge or the presence of small-sale defects in the grating structure, there are two main causes of contrast deterioration due to amplification process itself. They are increase of spontaneous noises in the amplification band and nonlinear distortions of the pulse spectrum (or, which is the same, of the amplitude and phase of the chirped pulse). The goal of this paper is detailed theoretical investigation of formation of the contrast of ultrashort pulses at OPCPA amplification for petawatt power levels and development of recommendations on choosing the architecture of laser complexes.
An example of contrast degradation during OPCPA calculated in our model is presented in the Fig.1. The reason of it is an essential change in the chirped pulse profile at amplification. Pulse rectangularization occurs – as the pump is depleting a plateau is formed in the central part of the pulse and its slopes become steeper. An ideal compressor provides the Fourier-transform of the signal with the above shape $A_1(\Omega, z_{output})$ to the compressed pulse $A_{comp}(t, z_{output})$. This means that the radiation intensity at the pulse wings after the compressor is falling much slower as compared to the Gaussian pulse, i.e., saturation of parametric amplification appreciably deteriorates the near-time contrast.

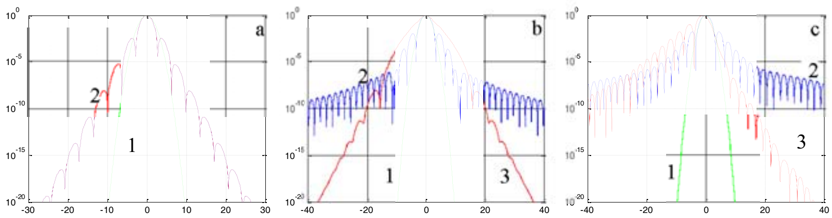

Fig. 1. Pulse amplitude profiles $A_{comp}(t,z_{output})$ over time (in fs) in arbitrary units after amplification and compression, that are depicted on logarithmic scales for different dependence of wave vector mismatch Δk versus frequency deviation Ω from strict parametric synchronism: a – $\Delta k(\Omega)=0$, b – $\Delta k(\Omega)=\Omega^2$, c – $\Delta k(\Omega)=\Omega^3$; 1(green) – without amplification, 2 (blue) – with amplification with phase compensation in compressor, 3(red) – without amplification with phase compensation in compressor. The saturated gain in the final amplifier stage is 420 (a), 360 (b), and 370 (c), respectively.

The statement about contrast deterioration associated with chirped pulse profile rectangularization becomes stronger with decreasing the spectral amplification band, which is illustrated by Figs. 1 b,c. Even with compensation of nonlinear spectral phase in compressor (blue curves), the decrease of intensity in time at the wings is slower than in the case without wave mismatch (a). The point is that the wave mismatch (quadratic or cubic) decreases the rate of energy accumulation over distance for spectral components with larger Ω. Consequently, the chirped pulse profile becomes even steeper but now due to its effective cutting at the periphery. If we do not introduce compensation of nonlinear phase incursion, the picture of the formed contrast will depend on the type of wave mismatch. Quadratic mismatch lifts up the wings of the compressed pulse symmetrically at the leading and rear fronts, and cubic mismatch lifts up one of the wings and lowers the other.
The effect of contrast deterioration due to nonlinear shaping of the spectral amplitude can be compared with amplified parametric luminescence and apparatus (grating) effects. We demonstrated that at the nanosecond pump and chirped pulse duration, total gain values $G \cong 10^{11}$-10^{12} and several tens of femtosecond compressed pulse duration, parametric luminescence is the main source limiting the far contrast at the time beyond 10 ps from the pulse maximum, while the discussed nonlinear shaping effect is responsible for contrast degradation at the shorter time scale.

Complete Modeling of Broadband Amplification, Compression and Focalisation of the PETAL Laser Beam

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Petawatt Aquitaine Laser (PETAL) [1] will allow unique experiments in the field of ultrahigh intensity sciences, extreme plasma physics, astrophysics, radiography, and fast ignition by a combination of its own multipetawatt kilojoule beam and the nanosecond multikilojoule beams of the Laser Megajoule (LMJ). The PETAL facility is designed by the french Commissariat à l'énergie Atomique et aux énergies alternatives (CEA) to deliver energy of 3 kJ in 500 fs at the wavelength of 1053 nm and is an additional short pulse beam to the Laser MegaJoules (LMJ) facility [2]. PETAL energy will be limited to 1 kJ at the beginning due to the damage threshold of the final optics.

We present a complete modeling of the PETAL laser chain with the Miró code [3]. Amplification, compression and focalisation are studied. All the components are included with transmission and phase profiles. Precise gain and loss values of the amplified section have been obtained with experimental measurement of the PETAL amplified section. The global calculus is performed under broadband spectrum with temporal adaptive mode to treat stretched pulses.

Broadband amplification is calculated with the Nd:glasses experimental spectrum data for LG750 and LG770. Some aspects like focalisation on the spatial filters have been studied with an analytic formalism. Full description of the chromatism compensation component (CROCO) has been done with Fresnel lens combined with convex thick lens. Such function need to be studied both with adaptive temporal and spatial mode.

The double pass first stage compression (1680g/mm) is implemented with cylindrical deformable mirror in order to compensate the wavefront distortions of the gratings under vacuum. The second compression stage (1780g/mm) is composed of four pairs of gratings in single pass. Segmentation, propagation and recombination of the four beams are considered with respect to the phase delay between the gratings [4]. Independent alignment of each pair of gratings is used to optimize compression duration and peak intensity of the focused beams with the 7.8m off-axis parabola.

At the conference, we will present numerical results and validation of the simulation, underlining some subtleties of use of the code.

This work is partially being performed under the auspices of the *Conseil Régional d'Aquitaine ("maître d'ouvrage" of the PETAL construction project)*, of the *French Ministry of Research* an of the *European Union* and with the technical supports of the *Institut Lasers et Plasmas*.

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Extended Ultrashort Capability at L2I: a Versatile Facility for Laser-Plasma Experiments

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The Laboratory for Intense Lasers (L2I) is a leading facility in laser research and development in Portugal, having been recently selected to a top group of research infrastructures of strategic relevance. It is dedicated to experimental research in high intensity laser science and technology, ultrashort diagnostics and laser plasma interaction, with emphasis in plasma particle accelerators, high harmonic generation and advanced radiation sources. Additionally, it plays an important role in the education of young researchers, providing them with advanced training in high power laser technology. Through the host institution, Instituto Superior Técnico, L2I researchers also ensure the Portuguese experimental participation in the Laserlab-Europe consortium.

The main laser of L2I is a hybrid Ti:sapphire-Nd:glass system operating at 1053 nm, based on the chirped pulse amplification technique. It laser is capable of providing up to 15 terawatt pulses at a repetition rate of one pulse / 15 minutes, and has been the main workhorse for high power laser experiments.

Over the past years we have been developing a diode-pumped laser program, with the objective of improving the experimental capability of the laboratory. This was mainly motivated by the need to increase the shot repetition rate at the 100 mJ level. The work has also led to an evaluation of ytterbium-doped media suitable for hybrid amplification at 1050 nm [1] and to the development of compact pre-amplifiers based on a single chirped volume Bragg grating for pulse chirping [2].

In parallel we have carried an OPCPA program based on ultrabroadband, noncollinear amplification in the nonlinear crystal YCOB [3], with the aim of providing mJ-level, sub-20 fs pulses for experiments.

In this work we describe the implementation of three-beam capability at L2I, in particular evaluating the performance of the recently developed ultrabroadband OPCPA system. With the successful conclusion of a dual-stage, diode-pumped amplifier based on $Yb:CaF_2$ and Yb:YAG operating at 1030 nm / 100 mJ / 1 Hz, making this beam available for experiment, we have recently started the development of a high-energy, frequency-doubled pump pulse for OPCPA.

The new configuration is designed for the following possibilities: (a) 15 TW at 1053 nm, (b) 100 mJ at 1030 nm, and (c) 20 mJ, 20 fs at 900 nm. This last stage is now under characterization and optimization, and will be made available for users in the near future.

Acknowledgments

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Control of the Laser Pulse Shape in Strong Saturation Regime.

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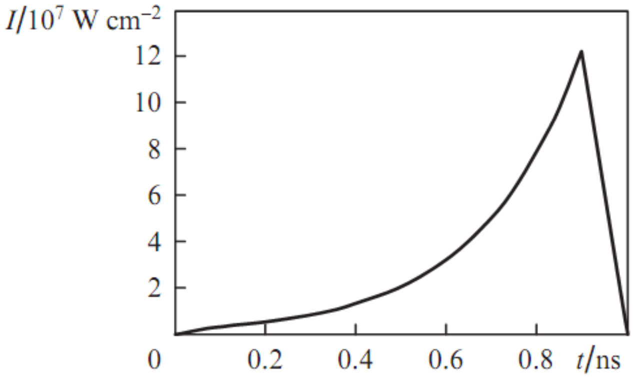
One of the main parameters of pulsed laser amplifiers is the accumulated energy efficiency (the ratio of the energy, extracted from the amplifier, and the energy, stored in the population inversion).
For pulses with a sharp leading edge, e.g., rectangular pulses, the saturation-induced distortions can be significant: the pulse becomes triangular with a sharp leading edge and a mildly sloping trailing edge, while the effective pulse duration is reduced. To produce a rectangular pulse at the amplifier output, one has to choose properly the shape of the input one. The stronger the saturation, the greater the distortions, and the more difficult the problem of tailoring the appropriately shaped pulse at the input [1].
In the report the parameter is proposed that allows easy estimation of the shape distortion degree for sharp-front pulses, amplified in the regime of strong saturation. Parameter is the ratio N of the gains at the leading (G_0) and the trailing (G_{end}) edge of the pulse.

$$N = G_0^{\eta} = \exp\left(\frac{E_{out} - E_{in}}{E_s}\right).$$

where η is the stored energy efficiency coefficient; $E_{in,\,out}$ is the energy density of the pulse at the input and output of the amplifier, respectively; E_s is the saturation energy density [2].
We also propose the method for reducing the laser pulse shape distortion and tailoring quasi-rectangular pulses at the output of laser amplifiers with a large gain and high efficiency. The idea of the method consists in decomposing the input pulse into two (or more) replicas conserving the total pulse energy both at the input and the output of the amplifier. As a result, the distortions of each replica appear to be much smaller than the distortions of the initial pulse. The efficiency of the method is demonstrated by the example of calculating the six-stage optical neodymium glass amplifier. It is shown that even using only two replicas allows the reduction of the pulse shape distortion by several (six) times.



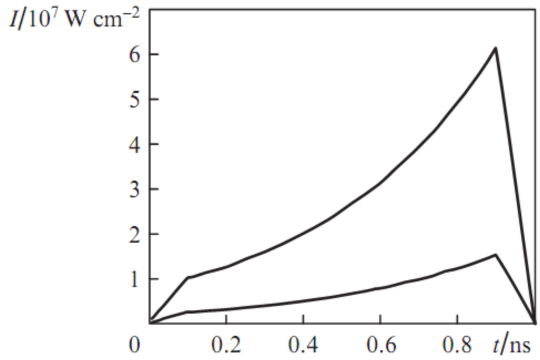


Fig.1 Fig.2
The shape of single (Fig.1) and two (Fig.2) pulses at the input of the amplifier with optimisation of the output pulse shape.

The additional advantage of using two and more pulses is an essential reduction of the cubic nonlinearity effect, which is the major factor limiting the output energy of neodymium glass lasers having the pulse duration ~1 ns . This means a possibility to increase the output energy without enlarging the amplifier aperture.

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The Current State of Affairs in the THL-100 Multi-Terawatt Laser System of a Visible Range

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This paper reports the modernization results of THL-100 multi-terawatt hybrid laser system of visible range [1-3]. Also the laser system consists of a two basic parts - Start-480M titanium-sapphire starting complex and photochemical XeF(C-A) amplifier with a 24-cm aperture – both parts were improved. The purpose of upgrade was the increase of output laser system power. For it the energy of a starting complex was increased at 4 times by the use of additional titanium-sapphire amplifier which is pumped by second harmonic (532 nm) of Nd:laser with 0.7 J energy and 10 ns pulse duration. Also the dimensions of a grating compressor and prism stretcher were increased to ensure the optimal radiation intensity. In addition the quality of laser beam of a starting complex was improved by means of using of the spatial filters. To decrease the nonlinear effects in XeF(C-A) amplifier the thickness its input window of was decreased with 40 mm to 3 mm. The plane-parallel plate of output window was changed on wedge with 1 degree angle to decrease the interference effects of output laser beam. The femtosecond laser beam was amplified in the XeF(C-A) amplifier formed by The 32 round mirrors used in a multipass optical scheme (33 passes) of the XeF(C-A) amplifier have been replaced with new. The mirrors reflectance was 99.7 %. A photo of the XeF(C-A) amplifier is shown in Fig. 1.

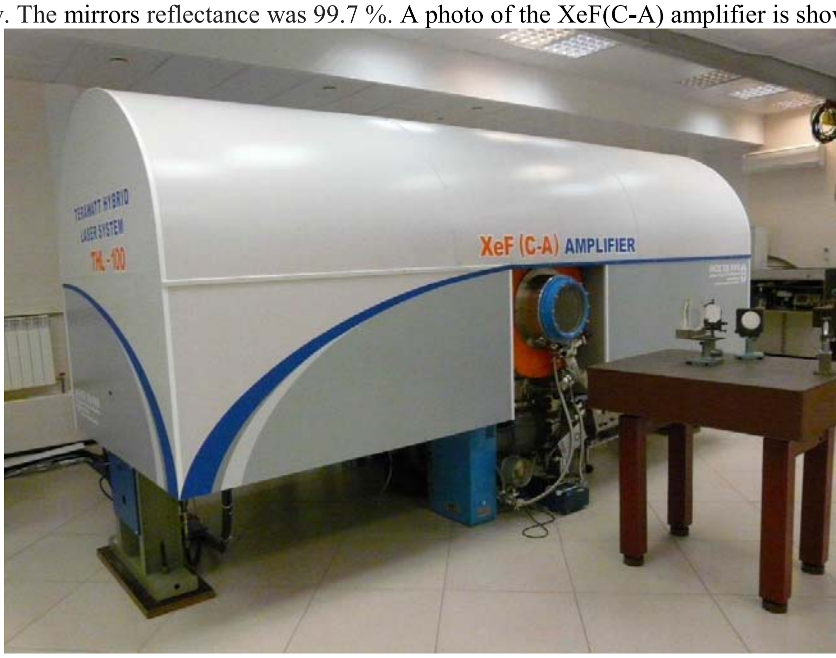

Fig.1. General view of the XeF(C-A) amplifier.

The laser beam parameters of the titanium-sapphire starting complex and photochemical XeF(C-A) amplifier after modernization will be reported on the conference.

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Pointing Stability Challenges after 25-M Beam Propagation under Vacuum on CETAL Laser Facility

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Over the past years, the ultra-intense laser field has continued to flourish as demonstrated by a growing number of scientific and technological projects. In particular, Europe's commitment towards ultra-high intensity physics is exemplified by the involment of several European countries pooling research, network resources and experience to succeed in the completion of different (multi) PetaWatt-class laser facilities. Some institutes such as INFLPR (National Institute for Laser, Plasma & Radiation Physics) in Romania has already paved the way and just fully funded the procurement of the 1.12 PW CETAL laser. The latter is typically dedicated to experiments involved in fields of high-intensity laser-matter interactions. This facility is at the state of the art in term of laser source and such laser is generally associated to beam transportation line (BTL) to achieve the beam to the target chamber. At this stage, scarce laser source manufacturers do not generally supply the beam transport. Beamline is either made by institutes themselves or public tenders can be an alternative solution. Precisely in this Romanian project, French company ARDoP was awarded for the delivery a turn-key system, including the design, material supply and installation on site. Basically, one of the main challenge of CETAL transportation line is to ensure the optical performances (before focusing) to be as close as possible to the laser source; namely after propagating over several meters from the compressor exit. The pointing stability requested must be fewer than µrad RMS over 500 shots, which is actually one of these challenging parameters to be fulfiled, and wavefront quality must be better than lambda. The 810 nm CETAL beam of 25J, with a pulse duration less than 25 fs, at a rep rate of 0.1 Hz has to be transported over 25 meters of propagation, including a periscope system with beam deviation at 30 degrees. Beam diameter is 160 mm at FWHM and has to be transported under vacuum at 10^{-5} mbar. These technical conditions imply appropriate vaccum, mechanical and optical design which has been simulated through a CAD software so as to minimize the risks. This resulted in a beam transport line including five 230 x 310 mm^2 mirrors and one F/20 aperture off-axis parabolic mirrors. All the optical parts are integrated into motorized mounts wich are controlled and remotely. CETAL beam transport line has now been finished to be installed. Final acceptance tests clearly show that overall optical performances are fulfiled in term of pointing stability and wavefront deformation after propagation.

Keywords: Ultra-short laser pulse, high-intensity laser, pointing stability, wavefront deformation, laser beam propagation

Restricted Analysis of Focal Length Selection in the Final Optics System

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Now the high power laser driver is mainly limited by the load capability of the whole system, especially the final optics system. Final optics system is the key part in high power laser driver. The optimization design of the system is mainly used to improve the load capacity and the target irradiation uniformity. In final optics system, there are many optical elements such as vacuum window, triple frequency converter, wedged focus lens, beam sampling grating, debris shield and so on. Among all the optical elements, the focus lens is the most critical, because it is the only non-planar component which causes space compression and beam property changes. Thus, to optimize the design of the final optics system, the focal length of the focus lens is the first and most important parameter. In this paper, the restricted factors of the focal length selection in final optics system are mainly analyzed. To begin with, the influence of focal length on the near field beam quality is studied in order to improve the load capacity. It is shown that by increasing the focal length, the modulation can be reduced. Moreover, to design a system with ultimate load, a specific focal length should be chosen for a specific input intensity. Then, the influence of focal length on quasi far field property is studied to improve the target irradiation uniformity. It is shown that the longer the focal length, the more insensitive the spot characteristic on the change of defocused distance would be. And the anti-deformation ability of the optical field of the longer focal length is also stronger than that of the shorter focal length. Therefore, as long as the space and cost permit, a longer focal length is better. In addition, the spatial temporal characteristics of optical field on the hohlraum wall are very important for understanding and controlling the laser plasma interaction process in the indirect driven inertial confinement fusion research. So in the last part of this paper, the spatial temporal characteristics of optical filed on the hohlraum wall are also studied.

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Effect of Target Debris on the Laser Induced Damage Threshold (LIDT) of Silver Coated Optics

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Silver coatings are used in final focusing arrangements due to the limitations of dielectric coatings with respect to operating angle ranges and bandwidths. For large high power facilities using large optical components debris protection is extremely difficult and a typical facility will operate with no target debris protection for the final focusing optic. We present experimental data demonstrating the effect of target debris on the Laser Induced Damage Threshold (LIDT) of silver coated optics and the impact to their operational lifetime.

Tens of Picoseconds Pulse Duration High Average Power 1kHz Repetition Rate Chirped Pulse Amplifier for OPCPA Pumping

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One of the most promising ways of achieving laser radiation of high peak intensities that can be used to generate high order harmonics and attosecond pulses is Optical Parametric Chirped Pulse Amplification. While this technique is well developed it is still a challenge to create a pump source that would both work at high repetition rates and have relatively high average output power. Our goal was to develop a laser amplifier system that could serve as an effective source for an OPCPA system. In this work we present new ps pulses amplification approach based on chirped pulse amplification [1] of narrow spectral band pulses.

The main limiting factor in amplifying of tens of ps duration pulses is non-linear effects in amplifier media caused by high pulse intensity. Due to narrow spectrum of pulses of tens of picosecond, in the past it was not practical to use chirped pulse amplification technique. In [2, 3] authors proposed to use hyper-stretcher/hyper-compressor in high energy ps pulses amplifier which was used for gamma-ray generation. This technology looks very attractive as it permits to saturate amplifiers and extract as much energy as possible while amplifying ns pulses. Despite attractiveness of this method it faces serious problems of total losses in stretcher and compressor due to quite low reflectivity of used diffraction gratings. However, due to recent achievements in diffraction grating technology - very high efficiency in narrow spectral band and high damage threshold [4], it is feasible to apply hyper-stretcher/hyper-compressor technique to realize chirped pulse amplification technique even for narrow spectrum pulses. To test feasibility of this technology we performed some experiments. In our experiments we used a three-stage amplifier setup that was already tested with non-chirped pulses of ~50ps duration [5]. To increase the extractable output power of this amplifier setup we've seeded it with chirped pulses from fiber-optic master oscillator.

The fiber oscillator had outputs at 1030 nm and 1064 nm of precisely synchronized pulses. 1030nm output is intended to use as seed for CaF2:Yb channel which has to serve as a broad spectrum source for an OPCPA system. The 1064 nm output with ~0.3 nm spectral width producing chirped pulses with ~600 ps pulse width, was used to seed regenerative amplifier. Nd:YVO4 based regenerative amplifier working at 1 kHz repetition rate amplified seed pulses to average powers of about 2.9 W. Due to spectral narrowing amplification caused the pulse width to shorten to ~300ps. Seed pulse stretching allowed us to have a more powerful input signal to power amplifier without inducing self-focusing or other unwanted nonlinear effects in the amplifier system and still achieve short pulse widths at the output of the system after compression. Average output power of 106 W at repetition rate of 1 kHz was achieved. After amplification the pulse width was ~270 ps. In this time span we obtained spectrum width which supports the pulse compression down to ~10 ps duration. The compressor of traditional lay out using two double pass dielectric reflectance gratings was designed and constructed. After preliminary compression experiments we obtained ~16ps pulses after regenerative amplifier and one amplification stage. Full power compression experiments are in progress.

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Development at B.A.R.C of Chirped Pulse Amplification Technique for High Peak Power Production With Nd: Glass Laser Systems.

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The motivation for development of powerful ultra-short pulse generators is due to their diverse applications in the areas of fundamental research. High power short pulsed laser systems are continually being developed and improved upon as a tool to investigate physics in the extreme condition. With the advent of the chirped pulse amplification (CPA) technique the total laser system has become more compact. At BARC we have built and assembled two CPA systems based on Nd:glass as the active medium. The best performance of a CPA system requires the optimization of three key factors. They are , energy extraction, pulse duration and pulse contrast ratio. The practical limit of maximum energy extractable is determined by the damage threshold of the compressor gratings available commercially. The pulse duration is determined by the output spectrum and the ability of the compressor to reconstruct the Fourier transform of the spectrum properly. Therefore the methods of reducing gain narrowing is important. The pulse contrast ratio needs to be controlled so that the main pulse intensity is increased and the pre-pulse intensity should be minimized. Therefore amplified spontaneous emission during the amplification process needs to be reduced. Of all these factors, we have worked on the gain narrowing and its mitigation in the laser chains that have been built.

In the building of the Nd: glass chains, the concept that has been used is that the seed pulse spectral peak is shifted from the amplifier active medium gain profile peak, and at the same time keeping a large overlap of the seed pulse spectrum and the active medium gain profile. The aim of this shift is to achieve a wider output spectral bandwidth in the amplified pulse. In one CPA system that was built, the components were the following – (a) 100MHz, 200fs, Nd:glass (fluoro-phosphate) oscillator with a centre wavelength of 1056nm and an output spectrum of 7nm FWHM, (b)double pass stretcher, (c) a single pulse selector, (d) a regenerative amplifier with Nd:glass(silicate) as the active medium with a centre wavelength of 1060nm, (e) double pass linear amplifier, (f) single pass linear amplifier and (g) a double pass grating compressor. The maximum gain narrowing takes place in the regenerative amplifier. This 4nm shift between the oscillator spectrum central wavelength and the regenerative amplifier gain profile central wavelength could reduce the gain narrowing . The final spectral bandwidth of the amplified pulse was 3.8 nm FWHM. The pulse width measured after compression was 1.7ps and the peak power reached is nearly 0.1TW. One more CPA system that was assembled consists of the following components (a) 75MHz 200fs Nd:glass (phosphate) oscillator with a center wavelength tuned to 1057nm and an output spectrum of 7nm FWHM, (b)stretcher, (c)regenerative amplifier with Nd:glass (phosphate) as the active medium with a centre wavelength of 1054nm, (d)pulse selector, (e) a ten pass ring amplifier with Nd:glass (silicate) as the active medium and a centre wavelength of 1060nm, (f) a double pass linear amplifier and (g) a double pass compressor. In this case the 3nm shift between the oscillator spectrum central wavelength and the regenerative amplifier gain profile central wavelength could reduce the gain narrowing to a lesser extent. The spectrum after the regenerative amplifier had a center wavelength at 1054.2nm and the bandwidth was 2.9nm FWHM. Since the ring amplifier had a Nd:glass(silicate) active medium , the lost bandwidth could be restored and the final amplified pulse had a spectral bandwidth of 4.9nm. The pulse width measured after compression was 1ps and the peak power reached was 1.0TW.

Next addressing the issue of pulse contrast we have found in our analysis that spectral profile tailoring changes the contrast ratio and peak power. The combined effect of third order dispersion (TOD) and gain narrowing brings about a marked increase in the contrast ratio. So compensation for TOD in materials is brought about by gain narrowing in the material during the amplification process.

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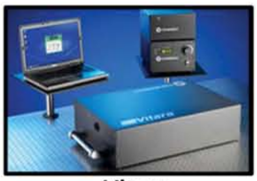

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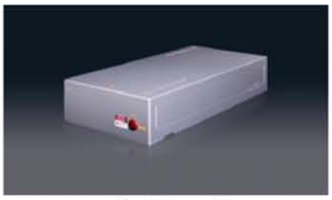

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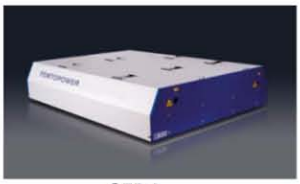

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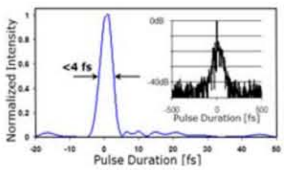

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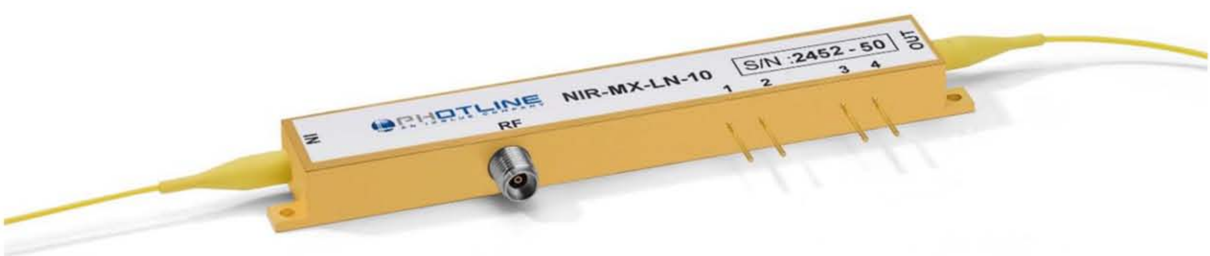

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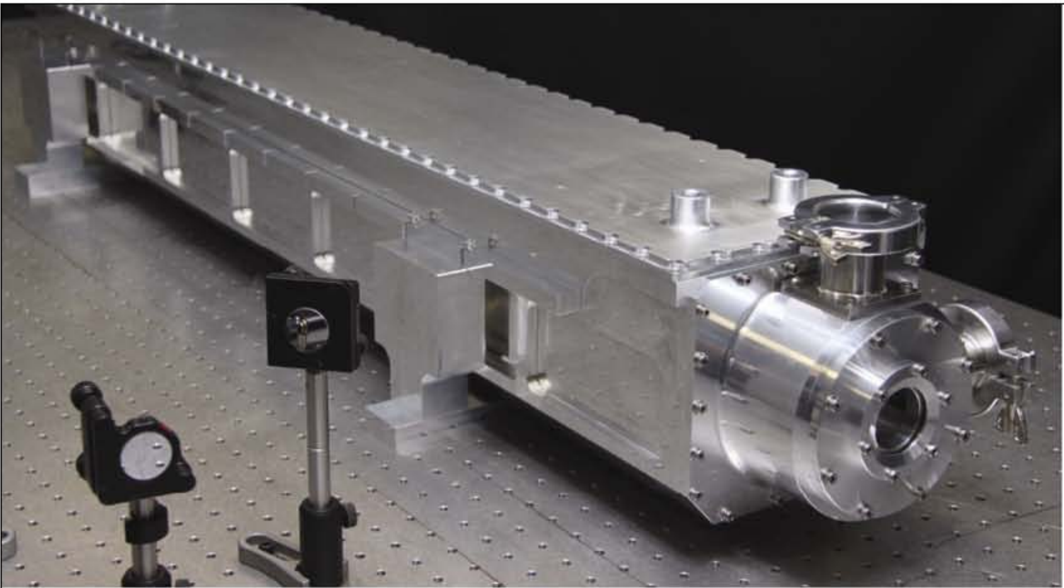

The New Frontier of Extreme Light

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A new frontier of extreme light at Exawatt level is discussed. This frontier has approached to us much closer than we thought till only recently. While we at IZEST [1] are working on kJ laser applications for extreme light, we now see the possibility to create fs super-PW optical laser pulses from PW lasers [2]. Such laser pulses can be further converted into (1~10) EW (≥10keV) X-ray laser pulses in attoseconds (as) via the known method [3]. Such X-ray laser pulses simultaneously achieve the highest intensity and shortest laser pulses, in fact consistent with the Conjecture [4], opening the new laser frontier at EW multi-keV in as (or perhaps even zeptoseconds).

Among applications derived from this frontier physics, we introduce a class of novel ways to accelerate (and manipulate) particles in fields ever higher than any in the past [5]. In the first version the intense X-ray laser propagates in a crystal in which X-rays induce intense wakefields in the medium of crystal electrons (LWFA in a crystal). In the second version we inject this intense X-rays into vacuum in which X-rays navigates the vacuum as a nonlinear medium, creating an accelerating structure akin to the plasma fiber accelerators. We suggest to utilize such coherent X-rays to drive acceleration of particles. Such X-rays may be focusable far beyond the diffractive limit of the optical laser wavelength. In the ideal pancake 1D pulse the energy gain may exceed PeV over the range of 10's of meters. Once we preaccelerate ions to beyond GeV, such ions are capable of being accelerated in the above LWFA to similar energies over likewise distances. Such high energy proton (and ion) beams can induce copious neutrons, which can also give rise to intense compact muon beams and neutrino beams. These beams may be portable. Very efficient and high-energy gamma rays can be also emitted by this accelerating process, both by the betatron radiation as well as by the radiative-damping dominant dynamics with the brilliance many orders of magnitude over the brightest X-rays sources over a very compact size. With this exceptional new physical parameters enabled by this technology we envision a whole scope of new physical phenomena, which include the possibility of laser pulse self-focus in the vacuum, neutron manipulation by the beat of such lasers, zeptosecond spectroscopy of nuclei, etc. Further, we introduce the second concept now vacuum as the nonlinear medium, the Schwinger Fiber Accelerator, which is a self-organized vacuum fiber acceleration concept, in which the self-focusing and defocusing and repeated processes of these in vacuum form a modulated fiber that guides this intense X-rays within it. (*Many aspects of this work in collaboration with G. Mourou.)

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Absorption of High-Contrast, High Intensity Femtosecond Laser Pulses by Solids

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The interaction of intense femtosecond laser pulses with solid targets leads to conditions relevant to extreme high-energy-densities [1]. There are numerous spin-offs of matter excited under such extreme conditions, like generation of ultrafast x-rays, or acceleration of electrons to relativistic energy [2] for the fast ignition scheme of the inertial confinement of laser fusion [3]. High intensity ultrashort lasers can achieve this scenario because the ionized solid does not get enough time to expand within the femtosecond pump pulse duration, leading to coupling of laser energy close to the solid density. However, all the ultrashort lasers based on chirped pulse amplification technique (CPA) suffer inherently from the prepulses, strong enough to ionize the target well before arrival of the main pulse, making intensity contrast a very critical parameter of a given laser. Therefore it is important to understand basic absorption mechanisms of high-contrast relativistic intensity lasers with solid target. However, there have been very few studies in this regard [4-5].

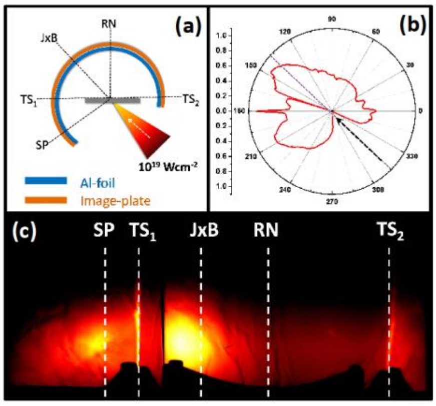

Fig. 1: Angular distribution of fast electrons measured at peak intensity of 10^{19} W/cm^2

In the present work, we addressed the crucial issue of absorption of intense, high-contrast light pulses through a comprehensive and decisive study involving (a) polarization dependent absorption of 30 fs laser pulses, over intensities spanning four orders of magnitude (10^{15} -10^{19} W/cm^2), (b) influence of the intensity contrast by a controlled (and monitored) change by two orders of magnitude, (c) angular distribution measurements of fast electrons to investigate preferred direction of acceleration, and (d) motion of the critical surface inferred from the spectra of second harmonic emission from the laser plasma. For maximum intensity of 2×10^{19} W/cm^2, absorption for *p*-polarized laser was found to be nearly 77%. The dominance of $\boldsymbol{J} \times \boldsymbol{B}$ mechanism over other collisionless mechanism was verified using preferential acceleration of fast electrons along the laser axis (Fig. 1). Moreover, the Doppler spectrum of the second harmonic emission shows a consistent trend of red shift *i.e.* inward push of the critical surface with increasing laser intensity.

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Generation of Fast Electron Assisted by Two-Plasmon-Decay in Intense Femtosecond Laser-Solid Interaction

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The absorption of femtosecond laser pulses in solid target is facilitated mainly by various collisionless mechanisms, such as resonance absorption or vacuum heating [1]. The ineffectiveness of collisional (inverse-bremsstrahlung) or parametric instability processes in short-pulse interaction regime is ascribed to the sub-wavelength nature of the preplasma scale. However, recently it has been shown that even moderate preplasma scale length (of the order of the laser wavelength) can lead to the two-plasmon-decay (TPD) instability. The signature of TPD is the emission of 3/2 harmonic (532 nm for Ti:Sapphire lasers), and it can be dominant absorption mechanism for femtosecond laser solid interaction[2-4].

We present a systematic way of switching the TPD process on and off based on two laser parameters (a) by varying the laser fluence incident on the target, keeping pulse duration constant, and (b) by varying the pulse duration at fixed laser fluence. We show that in comparison to the short pulse, the appearance of TPD signal (emission of 532 nm) can occur at much lower intensity for longer duration. In the non-TPD regime (absence of 532 nm emission, occurring mostly for low fluence experiment) a short pulse seems to be more efficient in generation of fast electrons than a long pulse, for the same fluence. However, this trend gets inverted in TPD regime (associated with a strong emission of 532 nm line coming from plasma), where long pulse generates hotter and brighter flux of fast electrons than a short pulse at the same laser fluence. Moreover, onset of TPD was investigated by varying the intensity contrast of laser in three regimes - 10^{-5}, 10^{-7} and 10^{-9}. The details of the experimental findings and their relevance to TPD are discussed in this paper.

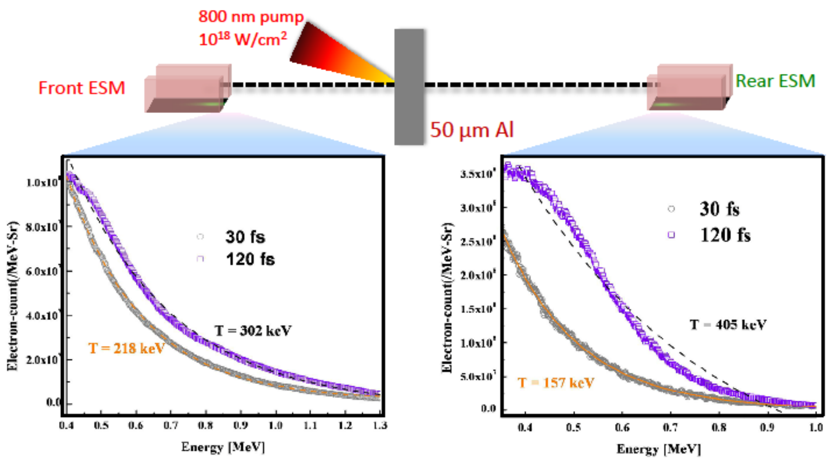

Figure: Comparison of fast electron energy spectra captured at the front (left) and rear (right) side of the target for short (30 fs) and long pulse (120 fs).

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Ultra-Bright Source of GeV Photons Based on Anomalous Radiative Trapping in the Ultra-Intense E-Dipole Laser Fields

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Today's high-intensity laser systems can cause ultrarelativistic motion of electrons, providing various opportunities for conversion of optical energy into other forms, such as streams of charged particles and photons with high energy. Laser systems of the next generation will enable another fundamental mechanism of nonlinearity – an electron's significant recoil due to emission of photons, so-called radiation reaction.

Until recently it was commonly assumed that radiation reaction can only lead to effective energy dissipation in the system of laser-plasma interaction, without causing significant changes in the dynamics of the system. However, recent theoretical studies have shown that a strong influence of radiation reaction can lead to profound counterintuitive changes even in the dynamics of a single electron. A strong enough effect of radiation reaction on an electron, moving in the field of a plane standing electromagnetic wave, leads to complex highly nonlinear dynamics, which cause a rapid "pulling" of the particle to the electric field spatial maximum, where the electron experiences the greatest possible influence of the field. This behavior contradicts the intuitive expectation that a system usually tries to minimize the impact on itself, and dissipation can only support this tendency. That is why the effect was called *anomalous radiative trapping* (ART), as opposed to *normal radiative trapping* (NRT), which corresponds to electron localization in the vicinity of the electric field spatial minimum when radiation reaction contributes weakly in case of lower wave amplitudes.

Electrons trapped by the ART effect are driven by the oscillating electric field of maximal possible amplitude, which causes the particles' synchronous oscillation and emission along the electric field vector. This unique energy coupling between the electromagnetic field and the particles' kinetics, accompanied by the presence of a preferential direction of emission, provides an unprecedented opportunity for creation of an ultra-bright collimated source of photons with energies extending to the GeV level.

It is important that the mechanism of the ART phenomenon is very robust. This allows to achieve entrapment of particles in the symmetric geometry of the so-called e-dipole wave (inverse emission of a dipole antenna). This kind of field structure is very interesting from the practical point of view. By virtue of the optimal energy focusing, it makes possible to reach the required level of intensity using several laser pulses focused from different directions, assuming parameters of laser systems now in development. However, for intensities triggering the ART regime, the process of particles capturing and trapping is accompanied by a growing avalanche of electron-positron pair production. Generation of a large enough number of particles can lead to the essential depletion/scattering of laser radiation forming the e-dipole wave that can eventually break the ART regime.

This paper presents the results of theoretical investigation of the ART phenomenon in the presence of the electron-positron pair production process and their mutual influence in the geometry of the e-dipole wave with varying intensity and duration. On the basis of the results we formulate general conclusions about the possibility of triggering and maintaining the regime of ART at the multichannel laser facilities of next generation. In particular, our calculations indicate that produced electrons and positrons are immediately trapped by the ART mechanism, which happens until the number of particles in the central trapping state reaches 10^9 . Further growth of the particles number causes reduction of the field strength in the central point and decrease of particles and emitted photons energy. This means that by choosing the appropriate initial density and laser pulse duration one can reach the instant of the peak field strength, maintaining the ART regime for a large number of particles, and produce a well-collimated beam of photons with the highest possible energy for the setup of this kind. Based on the simulations performed for the parameters of the upcoming large-scale facilities we propose a concept of an ultra-bright, well-collimated source of photons with energies up to several GeV.

Intense THz Pulses from Laser Plasma Interaction on Solid Surface

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Intense THz pulse generation can open new frontiers of THz science, such as nonlinear THz spectroscopy and THz nonlinear optics. A strong half-cycle electromagnetic pulse in the THz region can be used as the streaking field for temporal measurement of femtosecond charged particle bunch from the modern accelerator. They can also be used for temporal measurement of extreme ultraviolet (XUV) pulses from free electron laser[1]. Today, there are a large number of techniques available for THz pulse generation [2–4]. However, most of them do not generate sufficiently intense THz pulses for the above-mentioned applications.

THz pulse generation from laser plasma interaction has drawn considerable attention, because extremely intense THz pulse have been predicted via these process [5–7]. THz field of GV/cm has been predicted via interaction of high-intensity lasers with low-density plasmas at relativistic intensity [8]. Intense THz pulse emission from laser-plasma interaction has been investigated from gaseous targets (low-density plasmas) [9], foil targets [6] and solid targets (high-density plasmas) [7]. Recently, THz pulse emission from high-intensity laser irradiation of bulk targets has attracted scientific interest. Conditions inside plasmas from bulk targets can be very different and can simultaneously support different mechanisms of THz emission, such as electromagnetic mode conversion and oscillating surface current.

In this paper, we have experimentally studied intense THz pulse generation from intense laser-plasma interaction on solid surface (bulk target) at relativistic intensities. A 40 fs, 800 nm Ti:sapphire laser pulse (from the ALLS 10Hz beam line) with maximum energy of 350mJ on target is focused on a polished bulk Cu target (size: 5cm × 5cm × 3mm) using an f/4 off-axis parabolic mirror to a spot of 20 µm diameter. Maximum intensity on target is 2.7×10^{18} W cm^{-2}. High-field THz pulse is emitted as a result of the laser-plasma interaction. THz radiation in the specular direction has been collected by using off-axis parabolic mirror and is detected by a calibrated pyroelectric detector. In this experiment, we investigate the mechanism responsible for THz emission from the interaction of high-intensity laser and solid-density plasma. We have also optimized conditions favourable for THz emission by engineering the laser pulse as well as the target surface condition. Detailed analysis and modelling of the experimental results are still going on and will be presented at the conference.

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Prospects of Deformable Mirrors and Adaptive Optics Implementation for High Power Laser Systems

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Adaptive optics is a technique that allows correcting wavefront distortions in order to reach diffraction limit in optical systems. Adaptive optics was initially developed for astronomers in order to correct for atmosphere turbulence, and it has expanded its applications over the past 20 years in applications such as military applications, microscopy, free space communication, retinal imaging and high power and ultra intense laser facilities.

Nowadays, adaptive optics is a standard feature of most ultra intense laser facilities. It allows providing the final user with diffraction limited focal spot. First, ultra intense laser users have used deformable mirrors and adaptive optics set up developed for other applications. The market of high power laser facilities is expanding very quickly and so are the technical solutions dedicated to the specific needs and constraints of ultra intense laser users.

The current technologies and solutions of deformable mirrors, wavefront sensors and adaptive optics implementation will be reviewed. Projects such as multi petawatt ultra intense lasers require specific features that will drive the future industrial developments dedicated to these applications. Many features are already showing up, like for instance, the number of actuator of the deformable mirror, the correction speed and the integration of the adaptive optics in the control command system of the facility. These features and others will be detailed and their implications in terms of performance of the next generation of deformable mirrors and adaptive optics implementation will be discussed.

Eventually, this presentation will allow drawing the outlines of what could be the future of adaptive optics solutions for high power laser systems.

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Combined Deformable Mirror Performances

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Bimorph DMs showed good performances of the wavefront correction in laser systems with sub PW level of intensitiy [1]. Some applications need the DMs of far big sizes while it intended to correct for beams in multi cascade laser system (for example 400x400 mm). As the big bimorph DM is rather thin, the surface shape is usually not perfect and stable. We propose the design of large scale DM using both bimorph and stack actuator technologies.

A 220x220 mm deformable mirror using 12 PZT stacks actuators and 60 bimorph electrodes showed a good initial corrected flatness about lambda/30 RMS [2]. The good performances of this experimental sample persuaded us to increase the size of such DM. Now we consider the big combined DM with active size 400x400 mm that is usual one for many modern output laser beams. The ratio thickness to aperture of the DM substrate was 1/50 . Number of bimorph electrodes was 100, stroke of deformation for each one was +/-12 µ. The bimorph substrate was glued on the tops of PZT stack actuators. The stacks are arranged inside of the thick metal baseplate and supported substrate at the periphery outside of the bimorph electrodes. The number of stacks was 20, they provided the displacements for +/- 9 µ. These actuators support the DM inside of the holder and allow to change the surface shape either by open and/or closed loop control. So they could be used to initially flatten the surface.

The recent results of study of the prototype of such DM will be presented.

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Dark-Field and Laser Performance Diagnostics for a 100J 10Hz Amplifier System

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The demand for high-energy diode-pumped solid-state lasers (HE-DPSSL) has increased in recent years, with several systems in development around the world capable of producing energies of 10 J or greater. The laser output needs to be increasingly flexible to satisfy the requirements of potential applications, including OPCPA pumping, laser driven particle sources, laser peening and shock compression. As the power and repetition rate of HE-DPSSL systems increases and the layouts become more complex the need for diagnostics escalates.

One of the major issues in operating high power lasers concerns the laser induced damage threshold of optical elements. To diminish the risk of undetected damage causing significant problems throughout the laser chain the dark-field diagnostic is an essential addition to laser diagnostics suites. A dark-field diagnostic can be deployed to detect damage to critical components and also provides a non-intrusive method to monitor the growth of any damage observed. Early detection of damage can mitigate some of the serious effects, for example subsequent damage to other optics throughout the laser system [1].

A dark-field system has been installed on the DiPOLE laser; a laser system constructed as part of a project to develop a high-energy, high repetition rate DPSS laser amplifier [2,3]. The current laser system has achieved an output energy of 10 J at a 10 Hz repetition rate by using a cryogenic gas cooled multi-slab amplifier. This 10 J amplifier contains four ceramic Yb:YAG discs as the gain medium, cooled by a stream of helium gas at typically 150 K and 10 bar. The nominal beam size is 20 x 20 mm^2 and the amplifier is pumped by two pulsed laser diode sources. The multi-pass extraction optics around the main amplifier are of a simple bow-tie type that include image relaying.

The gain media in any laser system are critical and expensive components. In DiPOLE the ain media are also difficult to access using conventional imaging techniques, particularly in enough detail to distinguish damage. The dark-filed system is designed to overcome this difficulty. Figure 1 is a dark-field image captured on the DiPOLE laser system. The layout of this dark-field design will be described and some initial results shown. As a result of the success of this diagnostic, a test system has been built offline to develop an improved layout which would allow continuous operation. In future the dark-field will be linked to control software which will shut off the laser when damage is detected as a system safety measure. This development activity will be described, with some initial results discussed.

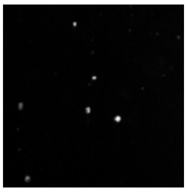

Figure 1 Image showing the damage detected on the DiPOLE system by the dark-field diagnostic

Finally, in order to characterise the laser performance multiple diagnostics are required to record key parameters including energy, spatial, spectral and temporal parameters. An overview of the diagnostics on DiPOLE and the proposed diagnostics for the upgrade to the 100J amplifier system, will be discussed briefly.

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Measurement of Spatial-Temporal Couplings in High Power Femtosecond Laser Beams

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As femtosecond laser systems deliver more powerful and therefore larger beams, features like spatial-temporal couplings are to be expected [1]. Spatial-temporal couplings (STC) in femtosecond laser beams occur when the temporal structure of the beam is dependent upon the spatial coordinates. Such effects can be introduced by something as simple as a singlet lens, but their impact on the peak intensity at focus can be dramatic.

First thought of mostly as imperfections of the laser systems, these couplings are now exploited –when properly controlled- to achieve more complex laser-matter interactions [2]. Therefore, in order to optimize and use the existing facilities to the full range of their capabilities it is crucial to be able to measure these couplings. This is especially true for laser systems that produce spatially large beams such as the 80 mm laser beam of UHI-100, the 100 TW, 25 fs laser at CEA Saclay. We have performed simple measurements yielding partial information on the spatio-temporal structure of the beam, that have revealed that residual STC are indeed present on UHI100 (see e.g. Fig.1a).

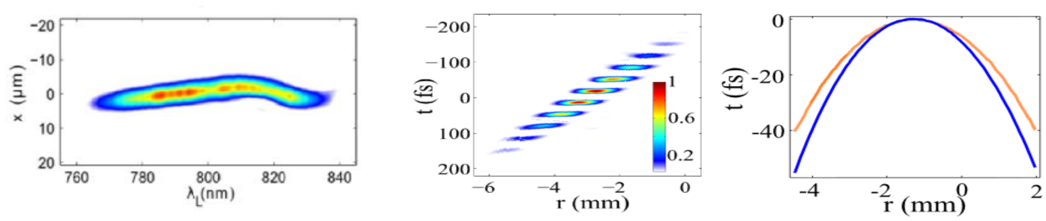

Figure 1: a) (Left) Spectrum versus spatial transverse position in the focal plan of UHI100, measured using an imaging spectrometer; b) (Center) Reconstructed E-field of a 100 GW fs laser with RED-SEA-TADPOLE; c) (Right) Example of reconstructed pulse front (blue) and wavefront (orange) obtained with RED-SEA-TADPOLE, showing pulse front curvature induced by a singlet lens.

In order to get a better understanding of these residual STC, we have then worked on different techniques to measure the full spatio-temporal structure of lasers such as UHI100. Figures 1b and 1c shows the results of measurements performed with RED-SEA-TADPOLE, a modified version of SEA TADPOLE [3], suited to such high power beams. Fig.1b shows the E-field of a beam with pulse front tilt, i.e. for which the wavefront and pulse front are not parallel. On Fig.1c, we can observe pulse front curvature, a case where the pulse front and wavefront have different curvatures. Despite these successful measurements, a serious complication in using SEA-TADPOLE is related to phase fluctuations in the optical fibers, which have to be corrected. Furthermore, due to the size of the beam, many laser shots are needed for the measurement.

To address these issues, we are developing a new range of techniques called TERMITES. These are based on simple designs that perform spatial interferometry between a test and a reference beam. Our implementation of a TERMITES apparatus has led to the very first full reconstruction of the electric field of a 100-TW beam in the (x, y, t) domain. Our data analysis focuses on highlighting spatial-temporal couplings.

This talk will describe the geometry of the devices we are using, will present and discuss the results of measurements performed on the UHI laser in Saclay, and discuss the possible extensions to larger laser systems.

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Tilted Transmission Grisms for Pulse Compression with Dispersion Control up to the Fourth Order

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The spread of double-CPA architectures in high-intensity Ti:Saphire laser systems has renewed the interest in bulk stretchers and, subsequently, in grism-based compressors. The additional complexity of the double-CPA architecture and the high sensitivity of the nonlinear stage to all possible fluctuations of the spectral phase and pulse energy plead for schemes as simple, as compact, as stable as possible for CPA1. Additionally, the coherent pulse contrast and the carrier-envelope phase stability are key parameters of CPA1.

The use of bulk stretchers considerably simplifies the design, footprint and stability of mJ-level CPAs. With the help of internal reflections, it is possible to reach stretching factors of a few thousands within compact devices (Fig.1 left). Bulk stretchers provide rock-stable CEP stability, high throughput and avoid spectral clipping issues.

To compensate for the positive GDD and TOD introduced by the bulk stretcher, a Treacy compressor cannot be used since, for a grating pair, GDD is negative whereas TOD is positive. As soon as 1968, it was shown that TOD could be cancelled or reversed by using transmission gratings engraved on the surface of prisms [1-2]. We have previously demonstrated that assemblies of high index prisms and transmission gratings could compensate for both the GDD and TOD of long bulk stretchers and retain favourable properties for a multi-mJ-level pulse compression device [3-4-5-6] However, the large level of fourth order dispersion (FOD) introduced by the compressor had to be compensated by an acousto-optic dispersive filter.

In this talk we introduce an additional degree of freedom: the prisms are tilted with respect to the planes of the gratings (Fig.1 center). We demonstrate both numerically and experimentally that with this new design, a grism compressor can also compensate for the FOD of a bulk stretcher. As a proof of concept, we measure the spectral phase of a ~1.47 m SF57ultra bulk stretcher combined to a tilted-grism compressor over the 720-900 nm bandwidth and show that the residual phase is mainly limited to the fifth order.

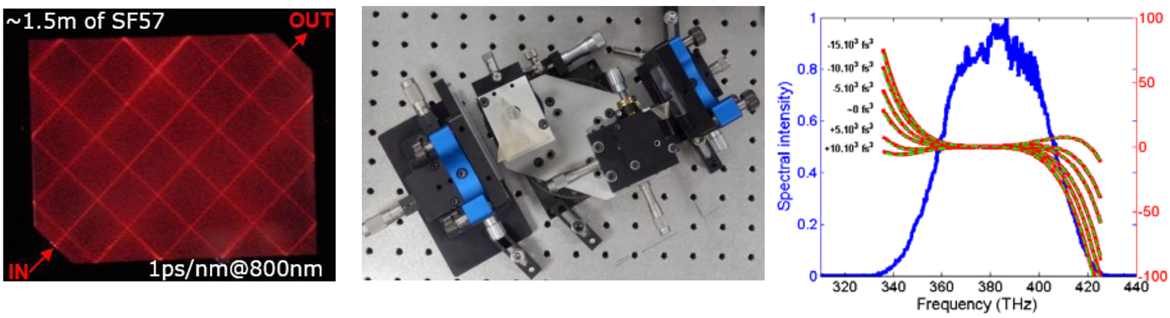

Fig.1: Left: view of the bulk stretcher (HeNe beam). Center: top view of the grisms setup Right: TOD tunability

Tilted-grism compressors based on transmission gratings and high index prisms (Fastlite patent pending) open the path to efficient and broadband compression schemes with adjustable GDD, TOD and FOD. Such bulk stretcher/ grisms compressor combinations can be used as dispersion management modules in CEP-stable, mJ-level CPA systems, as well as dispersion tweaker in large-scale, high-intensity laser facilities.

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High-contrast, CEP-stable double CPA laser system

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To date, most relativistic-intensity laser-plasma experiments have been carried out on a single-shot basis using Joule class CPA laser systems. A less explored regime consists in focusing few-cycle pulses down to wavelength-scale spot sizes in order to reach relativistic intensities at higher repetition rates using mJ energy CPA lasers. In particular, this regime allows the exposure of solid plasma targets to waveform-controlled few-cycle pulses with near-relativistic intensity [1]. However, reaching the relativistic regime requires a very high temporal contrast. Here we present the first CEP-stable, multi-mJ double-CPA architecture with high-energy nonlinear temporal filter [2].

The first CPA unit is based on a commercial CEP-stabilized Ti:Sapphire CPA (Femtolasers), delivering 1.4 mJ, 30 fs pulses. This is followed by a cross-polarized wave (XPW) generation filter for temporal cleaning, pulse shortening and spectral broadening [3]. About 300 µJ pulses are routinely generated. The broadened XPW Gaussian spectrum supports sub-10 fs pulse duration (110 nm FWHM spectral bandwidth). At this stage, typical long-term energy stability is around 2% rms and the CEP stability is kept below 200mrad rms.

For the second CPA the dispersion management has to be carefully designed to minimize CEP instabilities and B-Integral accumulation. The pulses are stretched to 45 ps duration by means of a bulk stretcher (SF57 glass) and a Dazzler (Fastlite). The stretched pulses are then amplified to 12.8 mJ energy in two Ti:sapphire amplifiers pumped with a combined average power of 45W at 1 kHz. Pulse compression is then achieved in a compact and custom designed grism compressor (Fastlite), which allows compensation of both 2nd- and 3rd-order spectral phase of stretcher and amplifier material [4]. The beam diameter is 22 mm. To avoid any nonlinear effect, final compression is achieved by chirped mirrors (-2000 fs^2). The overall transmission of the compressor is then 67%.

The compressed pulses have an energy of 8 mJ with 1% rms stability and 22 fs duration (Wizzler, Fastlite) (fig. 1a,b). Despite spectral gain narrowing in the amplifiers, the output pulse duration is shorter than that out of the first CPA, thanks to the spectral broadening in the XPW filter. Good spatial quality is also observed (fig. 1e).

The compact bulk stretcher und grism compressor allows robust CEP stabilization and the CEP drift of the double-CPA chain is stabilized down to 240 mrad rms over 45min (fig. 1c).

High-dynamic range 3ω-correlation measurements show a temporal contrast enhancement of more than 3 orders of magnitude compared to the first CPA, leading to a final contrast of 10^{11} at -25 ps from the pulse peak (fig. 1d).

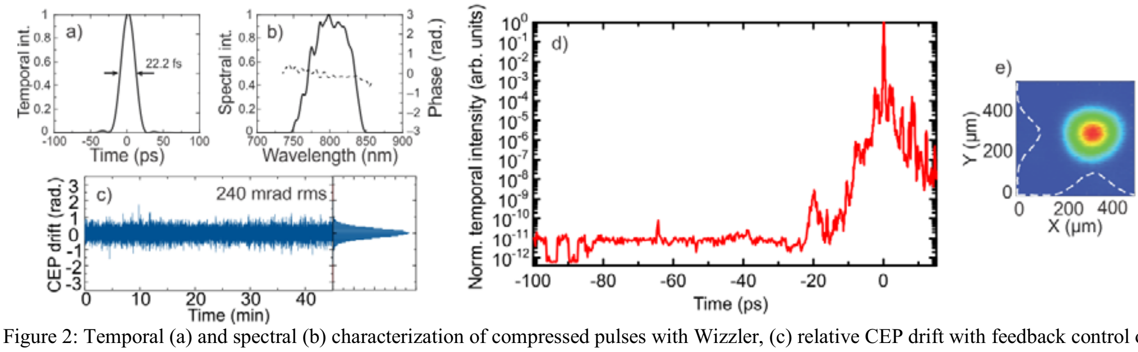

Figure 2: Temporal (a) and spectral (b) characterization of compressed pulses with Wizzler, (c) relative CEP drift with feedback control on the oscillator, (d) measured temporal contrast with Sequoia (Amplitude Technologies), e) typical beamprofile in focus.

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Alignment Optimization of Off-Axis Parabolas using a Wave Front Sensor

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Tuning the alignment of off-axis parabolas (OAP) for optimized performance can be achieved using high-resolution interferometry in the laboratory. However, it is often impractical to use interferometry for alignment optimization during installation in the field. In practice, alignment feedback is most often obtained by imaging the focal spot on a CCD camera. However this method lacks precision.
Without adequate alignment sensing, the true performance potential of high accuracy OAPs cannot be obtained. The following paper illustrates a technique and supporting data for demonstrating how a compact wave front sensor can be used in typical OAP installations for obtaining equivalent laboratory optimized alignment feedback. Two case examples; one short focal length and one long focal length are studied and comparative interferometric and wave front sensor data are presented.
In this study, we will characterize off-axis parabolas produced at Aperture Optical Sciences Inc. with a Phasics SID4HR wave front sensor. The demonstrated method will measure the beam directly after focus without any relay lens, which drastically reduces the measurement uncertainties for fast parabolas.


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Extreme Light Infrastructure – Nuclear Physics Laser Facility Status

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Extreme Light Infrastructure – Nuclear Physics pillar, to be running in 2017 in Romania, is part of the distributed pan-European facility infrastructure ELI on the ESFRI Roadmap, together with the ELI-Hu pillar in Hungary dedicated to attosecond science and with the ELI-Beamlines pillar in Czech Republic, dedicated to secondary radiation sources development. The main area of research for ELI-NP is related to nuclear physics and applications. The facility includes a narrow bandwidth gamma beam system based on Compton backscattering and a high power chirped pulse amplification laser system with two arms having common front-end.

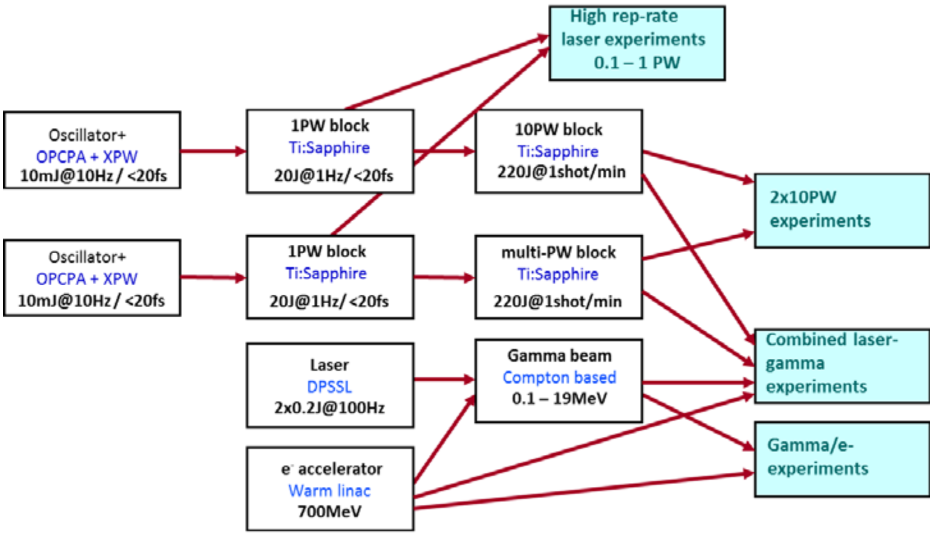

Fig. 1. ELI-NP facility block scheme

The envisaged laser parameters of the two arms laser system with 10 PW peak power will be presented. Status of beam transportation lines to interaction chambers will be reviewed. Specific technologies such as plasma mirror for contrast enhancement, all reflective circular polarization system and adaptive optics are planned for implementation.

The Current Status of the Apollon-10P Project

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Apollon laser facility will provide 10 PW peak power pulses (150J/15fs) at a repetition rate of 1 shot/minute with an intensity capacity surpassing $2{\cdot}10^{22}$ W/cm^2. Such characteristics will allow the generation of ultra-intense and ultra-short sources of particles (electrons, protons...), coherent and high energetic X rays in regimes never studied so far. The integration of Apollon will begin before for the end of 2014 and will take place in a recently renovated building (l'Orme des Merisiers, Saclay, France). A simplified schematic of Apollon is shown in figure 1.

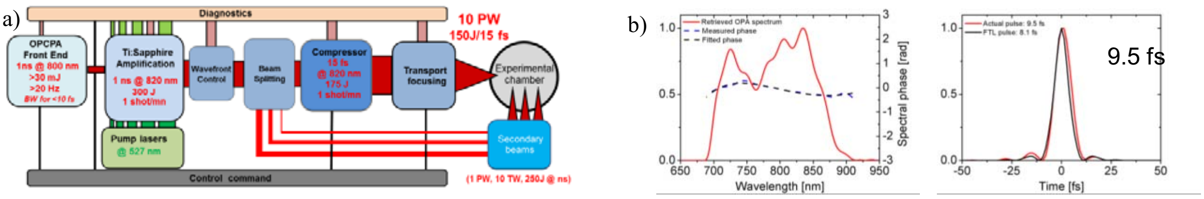

Fig. 1 a) Simplified schematic of the Apollon-10 PW laser. b) Measurement of the compressed ps-OPCPA pulses of the Apollon Front End: spectral profile and phase (left) and pulse intensity (right).

The front-end of Apollon is based on the OPCPA technology targeting the generation of 30 mJ, high temporal contrast, ultrashort pulses (sub-10 fs). For the OPCPA pump lasers, joule-class diode pumped Yb-doped crystal (Yb:YAG and Yb:CaF_2) systems are used [1]. Extremely high contrast is obtained with the combination of an XPW (crossed polarized wave) based injector [2] and a first high gain (x10^3) OPCPA operating in the picosecond regime. In recent experiments about 1 mJ pulses at the output of the first OPCPA stage have been compressed to 9.5 fs (figure 1b) with a CR measured to be better than 10^{-12} (limited by the dynamic range of the 3rd order autocorrelator). Completion of the final amplification stage and commissioning of the front-end is scheduled for the end of 2014.

The power amplification section (PAS) is based on 5 multipass Ti:Sapphire amplifiers to obtain 300 J before compression. For this, the largest Ti:Sapphire crystals in the world have been developed for Apollon (Φ175 mm). A commercial pump system (Continuum & National Energetics) will be used for the three last amplification stages. This laser uses liquid cooled flashlamp pumped large Nd-glass multi-slab amplifiers with the capacity of 800 J at 1 shot/minute. The first module of the pump system (400 J), will be delivered in 2014. For the preservation of the spectral width and form, necessary for the generation of high quality 15 fs pulses, optimized spectral filters have been designed to fight against gain narrowing and red-shifting due to saturation [3]. Off-axis parabolic telescopes with intermediate spatial filtering are used for relay imaging between the amplification stages, associated to a high dynamic range deformable mirror installed at the end of the PAS, to assure a high beam quality (Strehl ratio>50%).

The main beam line compressor of Apollon employs four 1480 gr/mm gold coated gratings of 910×455 mm² manufactured by Lawrence Livermore National Laboratory. The diffraction efficiency of these gratings is better than 92% and their wavefront error lower than λ/3 PtV over the whole effective surface. The design of the compressor assures the compensation of the 3rd and partially the 4th order spectral phase accumulated in the chain. The residual higher order spectral phase is actively controlled by a Dazzler in the Front End. The compressor will be implemented in a large stainless steel vacuum chamber (6.2x3x3.1m^3) specified to provide vacuum level of 10^{-7} mbar and cleanliness of ISO6.

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Status and Implementation of J-KAREN Laser Upgrade

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The J-KAREN laser system [1] is the flagship system at the Kansai Photon Science Institute (KPSI) of the Japan Atomic Energy Agency (JAEA). The system features a number of innovations, which make it unique. In particular, they include a double CPA architecture, OPCPA preamplifier, two saturable absorbers, and acousto-optic programmable dispersive filter (AOPDF) improving the contrast; cryogenically-cooled power amplifier removing severe thermal effect such as thermal lensing; diffractive optical elements improving the beam profile; extremely high intensity on target with high contrast; possibility of daily operation during long experimental campaigns; and more. The system produces the capability of ~600 TW peak power at single-shot with ~10^{12} temporal contrast.

We have started the upgrade of the J-KAREN laser toward over PW level at a 0.1 Hz repetition rate. The upgraded system is now called J-KAREN-P laser. Figure 1 represents the schematic diagram of J-KAREN-P laser system. The current booster amplifier is pumped by a single-shot Nd:glass green laser. This current amplifier stage (named booster amplifier-1) will be pumped with ~50 J of two commercial Nd:glass green lasers at a 0.1 Hz repetition rate. The pulses are further amplified in an additional Ti:sapphire booster amplifier (named booster amplifier-2), which uses a 120 mm diameter Ti:sapphire crystal, that will be pumped at 0.1 Hz with ~100 J from four commercial Nd:glass pump lasers. Based on the Frantz-Nodvik simulation, the achievable broadband energy is calculated to be over 60 J.

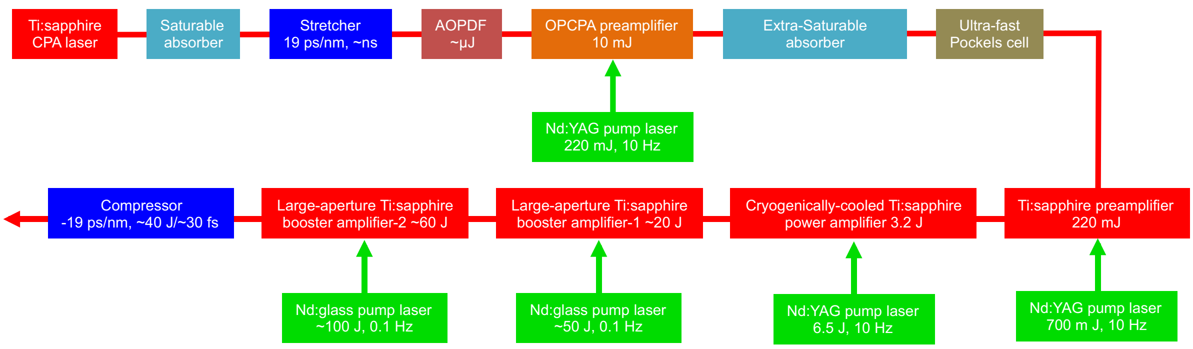

Fig. 1. Schematic of the J-KAREN-P laser system

Assuming ~70 % of the compressor throughput and ~30 fs for the recompressed pulse duration, in accordance with measurements in similar laser systems, the peak power is expected to be over PW level with the repetition rate of 0.1 Hz. The focal length of the thermal lens of booster amplifier-1, as an example, is investigated. A 3D finite-element approach (FEM) using Comsol multiphysics software is chosen to model the thermal and stress effects in booster amplifier-1. We have evaluated the impact of the increased repetition rate on thermal lens. The thermal focus length for the amplifier at 0.1 Hz is estimated to be a few km, thus there is no need to consider the thermal lensing effect. Increase in the repetition rate will lead to more a severe thermal issue. This should be helpful and useful as a reference for future higher repetitive systems.

We suppose that the implementation will be finished at the beginning of 2015. As a first step, J-KAREN-P laser will be used for ~200 MeV proton generation and ~1 keV ultra-short x-ray generation.

[1] Hiromitsu Kiriyama, Takuya Shimomura, Michiaki Mori, Yoshiki Nakai, Manabu Tanoue, Shuji Kondo, Shuhei Kanazawa, Alexander S. Pirozhkov, Timur Z. Esirkepov, Yukio Hayashi, Koichi Ogura, Hideyuki Kotaki, Masayuki Suzuki, Izuru Daito, Hajime Okada, Atsushi Kosuge, Yuji Fukuda, Mamiko Nishiuchi, Masaki Kando, Sergei V. Bulanov, Keisuke Nagashima, Mitsuru Yamagiwa, Kiminori Kondo, Akira Sugiyama, Paul R. Bolton, Shinichi Matsuoka and Hirofumi Kan, "Ultra-intense, high spatio-temporal quality petawatt-class laser system and applications," Appl. Sci. 3, 214-250 (2013).

Orion Facility Overview and Status Update

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In April 2014, the Orion Facility, at AWE in the UK, completed it first full year of experimental operations. Using its ten long pulse (ns) beam lines and two CPA-based petawatt beams, a diverse range of experiments has been conducted. These include long pulse-only campaigns to investigate, for example, material strength, implosions, and laboratory astrophysics (the latter as part of our academic access programme). There have also been several short pulse campaigns for which reliable short pulse operation has been essential, both at the fundamental and second harmonic.
This presentation will provide a reminder of the Orion architecture and discuss some of the issues encountered during commissioning. It will also give an overview of some of the experimental campaigns that have successfully utilised Orion's ultrahigh intensity capability. These include, for example, laser driven radiography, proton radiography (including the influence of temporal pulse contrast) and electron/position spectroscopy.
Laser improvements currently under development at the facility will also be discussed. These include a doubling of the available short pulse energy at the second harmonic, from 100J to 200J, by utilising a greater fraction of the 600mm fundamental beam. Two square sub-apertures will be taken and combined coherently at the target plane using a single focussing parabola.

Few Cycle, Phase Controlled Laser Sources for the Attosecond Facility of the Extreme Light Infrastructure

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The Attosecond Light Pulse Source (ALPS) facility of the pan-European Extreme Light Infrastructure (ELI) project is designed to build a laser based research infrastructure in which light pulses of few optical cycles in the infrared or mid-infrared spectral range are generated and used for basic and applied research. These pulses will be used as driving source for the generation of even shorter extreme ultraviolet pulse with durations that can be as short as a few tens of attosecond.

Four laser sources are under implementation for the ELI-ALPS infrastructure, operating in different regimes of repetition rate, peak power, and spectral range. All four light sources deliver pulses with unique parameters: unparalleled fluxes, extreme broad bandwidths, and sub-cycle control of the generated fields. The high repetition rate (HR) system delivers TW peak power, < 5 fs pulses at 100 kHz. The 1 kHz repetition rate future single cycle (SYLOS) system provides 20 TW pulses with a pulse duration of <5 fs. The petawatt-class high-field (HF) laser would operate at 5 Hz repetition rate with close to 15 fs pulse duration. The performance of the above laser systems operating with central wavelength in the range of 700- 900 nm is complemented by the mid-infrared (MIR) laser system, which provides sub-3 cycle laser pulses at 100 kHz repetition rate with over 10W average power.

This exceptional performances will give way to a set of secondary sources with incomparable characteristics, including light sources ranging from the THz to the X-ray spectral ranges, and particle sources. The laser and secondary sources foreseen at ELI-ALPS will push the frontier of attosecond science in three main directions as coincidence measurements, investigations of highly nonlinear processes in the XUV and X-ray spectral range, and ultrafast valence-shell and core electron dynamics.

In this talk the unique technical solutions of the laser sources are discussed, along with the control command systems and infrastructure issues.

On the Correlated Emission of High-Harmonics and Fast Electron Beams from Relativistic Plasma Mirrors

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Plasma mirrors driven by ultra-short laser pulses constitute an ideal test bed for building simple physical models of relativistic laser-matter interactions, which in turn can be optimized in order to develop innovative ultrafast energetic particle and short-wavelength radiation beams for applications. In particular, we are interested in the synchronized emission of fast electrons expelled from the plasma toward vacuum, and high-order harmonics of the incident laser frequency (associated in the time domain to trains of attosecond pulses [1]) generated in the specular direction. These two observables are strongly correlated because it is a fraction of the fast electron population that is responsible for the harmonic emission. Here, we show the first correlated study of fast electron and high-harmonic emission from plasma mirrors driven at 1-kHz repetition rate using our recently developed high-contrast double-CPA laser system [2].

In our experiments, 3-mJ, 22-fs pulses are focused at near-relativistic intensities (a_0 ~1) in order to generate plasma mirrors at kHz repetition rate on a moving optical glass target. Harmonics emitted in the specular direction are analyzed using an XUV spectrometer and fast electron beams emitted anywhere between target normal and specular direction are recorded on a Lanex screen facing the target. Both harmonic and fast electron signals are recorded in pump-probe fashion as a function of time delay between a weak pre-pulse (FWHM = 10-µm, I ~ 10^{15} W/cm^2) used to generate a uniform pre-plasma expanding at around 70-nm/ps and the main high-intensity pulse driving both harmonic and electron emission.

Fig. 1 below shows the difference in behavior observed for different focusing/intensity regimes. When the main pulse is weakly focused (FWHM = 3-µm, I ~ 1 x 10^{18} W/cm^2), electrons appear at later time delays when the plasma has already expanded, in anti-correlation with the harmonic signal, which decays exponentially as a function of pump-probe time delay. Fast electrons are emitted over a wide range of angles between 0 and 30° with respect to target normal. When the main pulse is focused more tightly (FWHM = 1.7-µm, I ~ 3 x 10^{18} W/cm^2), a brighter and less diverging electron beam is generated in the direction of target normal, the intensity of which decays as the plasma expands, this time in correlation to the decaying harmonic signal. Experiments are currently underway to optimize the correlated emission of harmonics and electrons using relativistic-intensity waveform-controlled few-cycle pulses in order to produce, for the first time, fully synchronized sub-fs electron and XUV beams for applications.

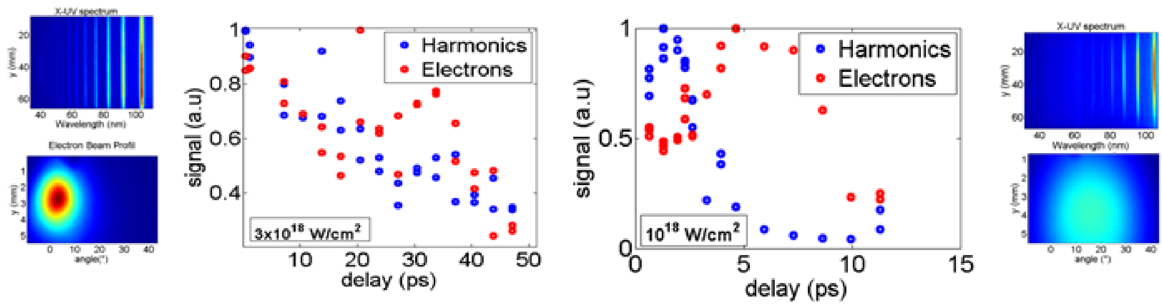

Fig.1 Left : Strong focusing .Harmonics and electrons are shown for 0ps delay of the prepulse.
Right: Weak focusing .Harmonics and electrons are shown for respectively 3ps and 6ps delay of the prepulse.

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Relativistic High Harmonic Generation on Solid Surfaces and Plasma Optics

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As ultrashort laser pulses become intense enough, any reflective optics turns into an active plasma medium. These short lived mirrors, usually indicated as plasma mirrors (PM) are exciting source of scalable intense XUV attosecond pulses in time domain [1], manifesting as harmonics of the laser fundamental in the frequency domain [2]. These coherent sources can be tuned and optimized by a new technology that allows reproducible sub wavelength control of the PM density gradient [3]. At extreme high intensities light can even bend the reflective plasma mirrors imprinting its signature on the emitted coherent XUV beam. Latest intestigations [4] allow continuous control of beam divergence by careful handling of laser spatial phase. Controlling relevant spatio-temporal couplings at the focus of a high power laser [5] has remarkably led to the generation of an isolated attosecond XUV pulse via attosecond light house effect [6] opening the possibility for XUV-XUV pump probe experiments from surface harmonics.

Given the brightness, versatility and numerous potential applications [7] of such an attosecond light beam the importance of spatial and temporal metrology of such a source cannot be overemphasized. For example complete spatial characterization would allow us to understand the XUV HHG beam spatial coherence properties as well as give access to insight on the generation process itself. A stumbling block in their complete spatial characterization is the indeterminacy associated with retrieving the spatial phase information from intensity measurements in the far-field angularly resolved harmonic spectra. Innovative in-situ solid density plasma structuring has allowed us very recently to overcome this problem and access this essential information [8].

All these latest advancements would be utilized for the implementation of the surface harmonic beamlines at ELI Attosecond Light Pulse Source [9] built in Hungary. The laser and secondary sources foreseen at ELI-ALPS will push the frontier of attosecond science. We would discuss all these developments finally culminating in the ELI-ALPS SHHG beamlines. We would also shed light on the new scientific applications, hitherto impossible, that would be enabled by access to such a source.

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Route to Isolated Intense Attosecond Laser Pulse with Efficient High Order Harmonic Generation

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Recent developments in attosecond source and have provided the access for direct measurement of electron dynamics in chemical reactions etc [1]. In this presentation we report the generation and measurement of attosecond laser pulse driven by carrier envelope phase (CEP) stabilized sub-5-fs laser. The isolated attosecond pulses with the central wavelength at 82 eV are obtained. Streaking trace shown the duration to be 160 as, which was constructed as an attosecond beamline for further application. Based on the work, we will further introduce the update work of attosecond beamline with intense output pulse, new development on attosecond laser driven will be prospected and overviewed.

In our experiment, the sub-5-fs laser pulse with CEP stabilized [2] is focused into the neon gas target to produce high order harmonics at XUV range. A Zr foil at thickness of 150nm was used as a filter for transmission of attosecond XUV beam and block of IR beam. The IR beam transmits through the pellicle and formed an annular beam. Then both XUV and IR are focused by the two-segment-mirror consist of Mo/Si multilayer coating inner mirror and a silver-coated out mirror with the same focal length. By overlapped the XUV and IR at the focus spot interacting with the second neon gas target, ionized photoelectrons were generated and collected by a time-of-flight (TOF) electron spectrometer. Fig.1 shows the streaking trace with the scanned delay range of 16 fs in steps of 100 as. The obtained photoelectrons are centered at an energy of ~ 80 eV with ~15 eV shift of the electron peak. Based on frequency-resolved optical gating measurement for complete reconstruction of attosecond bursts (FROG-CRAB), we reconstructed the attosecond pulse with the pulse duration of about 160 as.

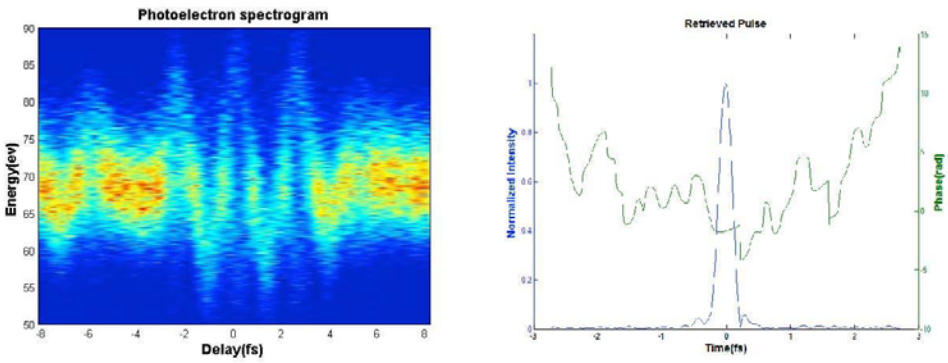

Fig.1. Attosecond streaking spectrogram (left) and retrieval of duration of attosecond pulses (right)

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Post-Compression of Terawatt Pulses for the Generation of High Energy Attosecond Pulses

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In the last few years, major effort has been devoted to decrease pulse duration at the output of the CPA laser chains via numerous post-compression technique. Some of them allowed the production of few femtosecond pulses, however most of the time the output energy is limited to the mJ level. Very few techniques are suitable to high energy input pulses and produce Terawatt sub-10-fs post compressed pulses [1,2]. We performed gas ionization based post-compression of TW laser and investigated high-order harmonic generation with multi-mJ post-compressed pulse.

The experiments were performed with Ti:Sapphire Terawatt laser delivering 50 fs - 70 mJ pulse at 10 Hz repetition rate. The laser pulses are then post-compressed by the use of the optical-field-ionization (OFI) of helium gas in a guided geometry (capillary based) [1]. Since OFI is very fast and highly non-linear, large spectral broadening can be obtained with low helium gas pressure (few mbars) compatible with high energy input pulses. Our post-compression set-up uses glass capillary of 420 µm inner diameter and 40 cm long associated to 4 chirped mirrors (-50 fs² per bounce) to recompress the pulse at the capillary output close to the transform-limited duration. This approach allows us to obtain sub-10-fs TW pulses with an energy of 10 mJ (see Fig. 1) and clean spatial profile suitable for HHG. The whole post-compression set-up is under vacuum to be able to recompress the full energy of the pulse without propagation issues and thereby the pulses can be used directly for HHG without propagation in any windows.

The high-order harmonics are generated with the 10 fs pulse focused into a synchronized argon gas jet by a 2 meter focal length spherical mirror. We generate the harmonics at high intensity (>10^{15} W/cm²) to get a high XUV photon flux. The high-order harmonic beam is characterized by a single-shot XUV imaging spectrometer consisting of 500 µm entrance slit, gold concave grating and dual microchannel plates. Since infrared pulse duration could be adjusted from 50 fs to 10 fs with helium pressure in the capillary (see Fig. 1) while maintaining TW peak power, dipole saturation and ionization gating on the XUV beam characteristics have been clearly identified. Indeed, the generated harmonics with the post-compressed pulses exhibit broad spectral bandwidth with spatio-spectral structures (see Fig. 2) originating mainly from both the dynamic and the spatial distribution of the emitting dipole. Those effects are clearly identified in simulations where similar spatio-spectral structures are reproduced. During this talk, I will give details on the TW post-compression technique and I will present and discuss experimental and numerical results on the high-order harmonic generation when high intensity and ultra-short IR driving pulses are used.

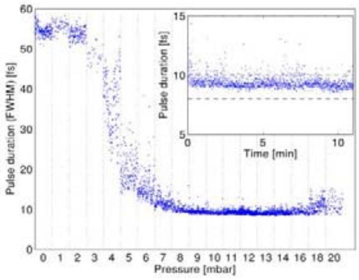

Fig. 1. Pressure dependence of the pulse duration (fwhm) showing a single shot response on the pressure of Helium gas in the capillary.

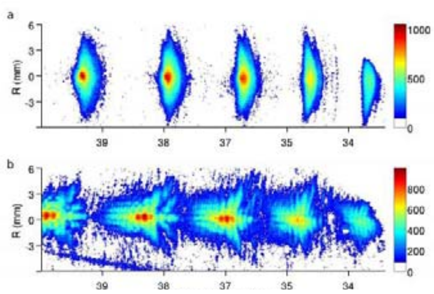

Fig. 2. Spatially resolved single shot harmonic spectra generated in argon. (a) is a reference spectrum obtained with 50 fs long pulse, (b) is generated with 10 fs 10 mJ pulses.

We thank LAPHIA, the European Community and the Conseil Regional d'Aquitaine for financial support.

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Ultrahigh Photon Flux XUV Source by High Harmonic Generation of a High Power Fiber Laser

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The process of high-harmonic generation (HHG) is a well-established method for generating coherent extreme ultraviolet radiation with tabletop setups. Despite rapid progress in the applicability of this radiation there are remaining challenges. In particular, there are numerous applications that require an increased repetition rate and photon number to make available multidimensional studies or faster data acquisition [1]. This ambitious goal has been addressed by high-harmonic generation in enhancement cavities [2], which has already shown impressive power levels of several tens of microwatt in a single harmonic at several MHz of repetition rate, which is however limited to low photon energies (<30 eV) [2,3].

In this contribution we present an alternative approach: HHG with state-of-the-art ultrashort-pulse high-power fiber laser systems, which represent a power scalable and robust concept. The laser system that is used for the experiment is a fiber chirped-pulse amplifier that incorporates coherent combination (CC-FCPA) for power scaling and is similar to the system presented in [4]. Here, we operate the CC-FCPA at ~270 µJ, 340 fs and variable repetition rate (up to 600 kHz). Temporal post-compression of the pulses is achieved by a 1.1 m long hollow-core fiber filled with 4 bar of krypton and subsequent compression by chirped mirrors. The resulting ~30 fs, ~130 µJ pulses are focused to a focal spot diameter of ~90 µm (~f/40), generating a peak intensity of ~ 10^{14} W/cm^2. A cylindrical nozzle provides the target gas (Kr, Xe) for HHG. A crucial point for detection of the XUV radiation is the separation of the high average power fundamental and the high-order harmonics. We employ two grazing-incidence plates (GIPs) which reflect ~16 % of the XUV but transmit most of the infrared [5] in combination with two additional aluminum filters (1 µm thickness). The harmonics are spatially and spectrally analyzed by a CCD-equipped grating spectrometer. The recorded signal is then corrected for the measured losses of the involved optical components and detection system. Figure 1 shows the experimental results obtained with the laser operating at 80 W (after nonlinear compression) and 600 kHz. The strongest harmonics H23-H27 own an average power of >100 µW, which corresponds to >10^{13} photons/s. Using krypton gas a broad plateau of strong harmonics (>30 µW) in the range of H23-H39 (45 nm-26 nm) is observed. To our knowledge, this is the highest photon flux generated in that wavelength range by a table-top setup. Such a source opens new possibilities in multi-dimensional surface science and imaging techniques.

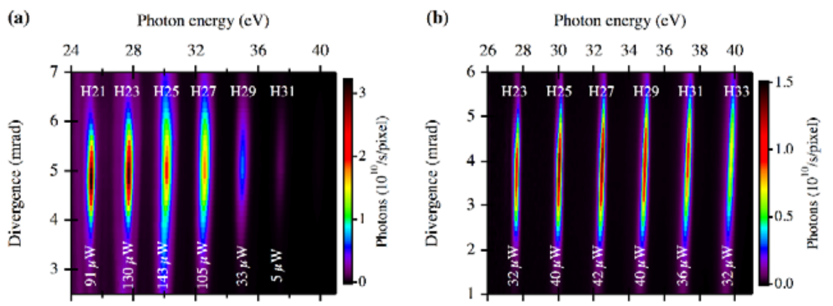

Fig.1. Spectrum of the high harmonics generated in a) xenon and b) krypton and the corresponding average power.

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High Power Laser-Driven X-ray Sources for High Energy Density Science

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To meet the increasing requirements of examining and understanding high-energy-density (HED) science phenomena on extremely short space- and timescales, it is necessary to develop novel and accessible light sources. We are developing one of the most promising applications of laser-wakefield accelerators—betatron radiation—to probe HED plasmas with unprecedented time resolution. This unique broadband, collimated (<30 mrad) source of hard x-rays (1–100 keV), with sub-ps pulsewidths, is produced by electrons accelerated and wiggled in the wake of a high intensity laser pulse in a plasma [1–3]. When a short laser pulse with an intensity $I > 10^{18}$ W/cm^2 is focused inside a plasma, the laser ponderomotive force expels the plasma electrons away from the strong intensity regions to form an ion bubble in the wake of the pulse. Electrons trapped at the back of this structure are accelerated and wiggled by the focusing forces to produce broadband, synchrotron-like radiation in the keV energy range. Studies have implied that betatron x-rays have a source size of a few microns, a divergence of less than 100 mrad, a pulse duration of less than 100 fs, and a broadband spectrum in the keV energy range. Betatron x-rays are also directly related to the electrons emitting them, and thus the radiative properties of the source can be a diagnostic of the LWFA acceleration process.

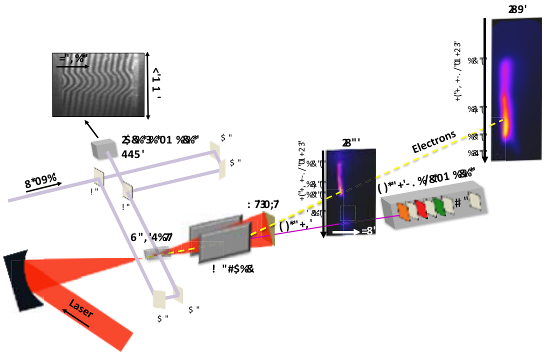

Fig. 1: Experimental betatron x-ray radiation setup at the LLNL Jupiter Laser Facility.

We will review experiments performed on petawatt-class lasers Titan and Callisto at the LLNL Jupiter Laser Facility, and at the LCLS-MEC high power laser of the SLAC National Accelerator Laboratory. The experiments recently performed using the Callisto laser system (200 TW, 60 fs, 12 J) are depicted in Fig. 1 [4].

We will also discuss ongoing applications of this novel x-ray source as a probe for HED science experiments at these facilities, as well as how these could be implemented on future multi-petawatt lasers currently being built around the world.

Acknowledgements

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Single-Shot Visualization and Control of Ultra-intense Laser-Plasma Interactions

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Abstract: Laser-plasma acceleration is now entering an era of petawatt lasers, tenuous plasmas and multi-GeV electron energies. I will review initial results in this regime, and discuss plasma diagnostics needed to understand, optimize and scale them.
OCIS codes: (350.5400) Plasma; (020.2649) Strong field laser physics; (280.5395) Plasma diagnostics

35 years ago, Tajima and Dawson proposed the idea of accelerating charged particles by surfing them on charge density waves propagating at light speed through underdense plasma in the wake of an ultra-intense laser pulse [1]. Two decades of intensive experimental research starting in the early 1990s yielded a generation of self-injecting laser-plasma accelerators (LPAs) of only centimeter length [2] that produced nearly monoenergetic electron bunches with energy as high as 1 GeV [3]. Petawatt (PW) laser technology is now opening the era of multi-GeV LPAs [4,5]. With PW drivers, self-injection has been observed at plasma density as low as $n_e = 10^{17}$ cm^{-3} [6], and electrons have been accelerated quasi-monoenergetically up to several GeV with sub-milliradian angular divergence. I will review these early results. Yet this is clearly only the beginning. Simulations predict that PW pulses of currently available parameters are capable of accelerating electrons quasi-monoenergetically to ~10 GeV and beyond with negligible dark current [7]. Conversion of multi-GeV LPA beams to coherent, ultrafast x-rays, demonstrated on lower energy LPA beams, is yet to be explored. Advanced diagnostics that enable direct 4D spatio-temporal visualization of the plasma structure and accelerating electrons will be critical in guiding us into this exciting future. I will review recently developed methods for visualizing such objects directly in the laboratory in a single shot. Frequency-domain holography (FDH) has yielded detailed snapshots of linear [8] and nonlinear [9] plasma wakes, but averages over their evolution as they propagate. Transverse shadowgraphy has yielded multi-shot movies of evolving wakes [10], but averages over transverse structure and shot-to-shot fluctuations. Recently we developed all-optical streak camera methods to image selected projections of evolving light-speed objects over mm [11] to meter [12] propagation lengths in one shot, and applied them to visualize dynamics of TW- and PW-laser-driven plasma wakes [13]. In these methods, the evolving object imprints a phase streak onto an obliquely propagating probe pulse. By using multiple probes, each crossing the object's path simultaneously at different angles, the techniques in Refs. [11]-[13] can be generalized to produce a single-shot, multi-frame movie using tomographic reconstruction algorithms [14]. I will describe recent developments with such techniques suited for imaging evolving plasma wakes in tenuous plasma that underlie the new generation of multi-GeV LPAs.

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Investigation of a Picosecond Pedestal of Recompressed CPA Pulses

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The technologies developed during the last years to improve temporal contrast related to amplified spontaneous emission (DCPA [1] and temporal filtering with XPW [2]) applied to Petawatt laser systems allow to reach extreme values of temporal contrast of above 10^{11} for repetitive systems and > 10^{14} for single shot operation in combination with plasma mirrors [3]. This technology is scalable to the level of temporal contrast of at least 10^{15} for repetitive systems and can be improved for additional nearly four orders of magnitude for single shots. This low ASE level is sufficient for the next generation of ultra-intense laser systems.

The features (pedestal) appearing at the leading front of recompressed pulses on a picosecond scale are the typical characteristics of modern high intense pulses. For most of high intensity laser systems this pedestal appears above the ASE level at several tens of picoseconds preceding the pulse peak and grows to the level of 10^{-4} in the vicinity of the pulse maximum. In literature, sometimes, this pedestal is associated with 'coherent contrast'. The energy accumulated in the pedestal (and intensity) could be an issue for most of modern laser-matter interaction experiments. Contrary to ASE the origin of these features is poorly investigated and understood.

We report on a comparative investigation of the pedestal appearing at the leading and trailing fronts of the recompressed pulse depending upon the type of the stretcher/compressor used in the system, master oscillator, B-integral accumulated in the system and spectral chirp generated by the stretcher. Three types of stretchers were investigated and two types of master oscillators. Two of the stretchers are based on reflection and transmission diffraction gratings, one with prisms. The investigations were done with a high ASE contrast mJ CPA system (1.5 mJ, 25 fs, ASE contrast ~ 10^9) implementing a multipass amplifier. The pulse stretched by a prism stretcher and a stretcher with transmission diffraction gratings had duration of ~ 12 ps (recompressed by bulk media), while for the reflection – diffraction grating based stretcher had the duration of ~ 120 ps. In this case the pulse was recompressed by the diffraction grating- based compressor. We found that the observed leading and trailing pedestals of the recompressed pulse obtained after careful optimization of high orders of dispersion and system 'cleaning' do not depend on the value of B-integral accumulated in the system, thus demonstrating that they are most likely not

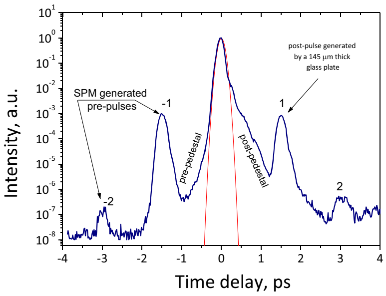

Fig1. Artificial pre/post pulses generated by SPM; picosecond pedestals.

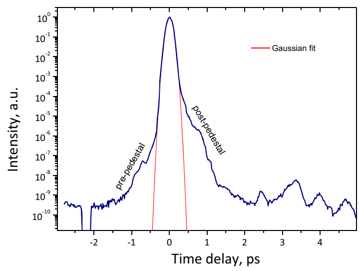

Fig.2. The 'best' laser pulse obtained after system optimization.

coherent to the main pulse. It was found that despite of absence of measurable angular chirp, or other reasons that might lead to a spatially inhomogeneous temporal distribution within the laser beam the detected by the cross-correlator picosecond pedestal is dependent on the beam aperture. In the optimized case we succeeded to reach a very short pedestal (< 2 ps) at the leading front of the laser pulse (see Fig.2). Results obtained with different stretcher-compressor configurations will be reported, reasons of appearance of non-coherent pedestals on a picosecond time scale, as well as the impact of the cross-correlator used for characterization of pulses will be discussed.

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Contrast Improvement via Cross-Polarized Wave Generation in Anisotropic Crystals

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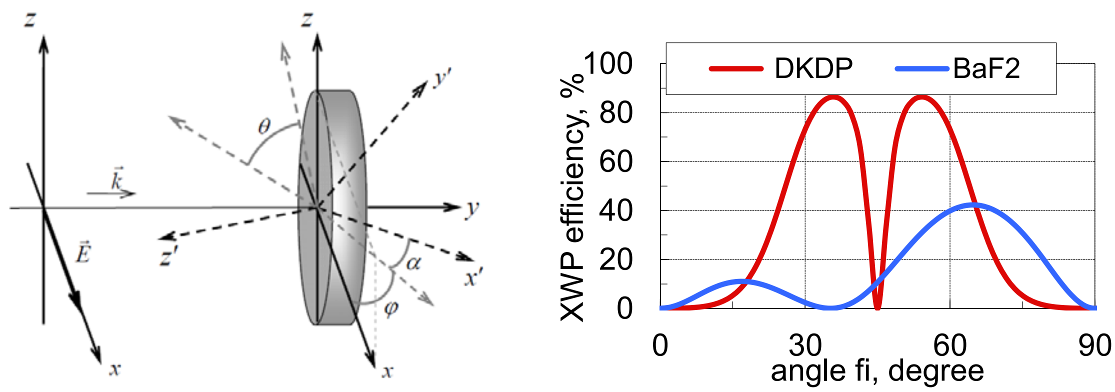
Two crucial aspects in building a petawatt laser system is the pulse duration and the temporal contrast of the output laser pulses. Cross-polarized wave (XPW) generation based on third-order nonlinear susceptibility is one of promising methods of temporal contrast improvement of femtosecond laser pulses. Usually an isotropic crystal like BaF_2 uses as a third order nonlinear media. In this talk we overview some scheme of XPW generation and propose high-efficient XPW generation in anisotropic crystals. In particular we study uniaxial KDP and DKDP crystals (42m point group symmetry).

Generation efficiency of XPW in a DKDP crystal depending on the orientation of the crystal was studied. Crystal orientation was specified by three Euler angles (ϕ, θ, α), defining the mutual arrangement of the coordinate system associated with the polarization of the laser radiation and the coordinate system associated with the crystallographic axes of the crystal (Fig. 1a). XPW generation efficiency was considered with the help of a system of differential equations, describing linear birefringence; nonlinear processes such as self-phase and cross-phase modulation and generation of orthogonally polarized wave; diffraction effects were omitted. We demonstrated that XPW generation efficiency in DKDP and KDP crystals sufficiently depends on crystal's orientation.

The results for the case when the optical axis z' of the crystal is oriented along the axis of radiation propagation (θ = 90°, α = 0°) are shown on Fig.1b. Maximum of efficiency equal to 85% can be achieved for certain values of the angle ϕ when B-integral (cubic nonlinear phase) is 2, which is quite modest value below small-scale self-focusing. The maximum of efficiency in the scheme with the commonly used cubic crystal BaF_2 with optimal orientation [101] is equal to 42% only (Fig. 1b). Thus, even the simplest orientation of DKDP crystal provides a more efficient generation of XPW that can be due to greater difference in values of the diagonal and nondiagonal components of χ^3 in DKDP crystal as compared with BaF_2.

We also discuss arbitrary crystal orientation and also optical schemes with two anisotropic crystals with 90 degree angle between their optical axis. The obtained results show grate benefits of usage anisotropic crystal over isotropic ones. Additional advantage of KDP and DKDP crystals is fact that their huge aperture allows using them at the output of petawatt lasers. Taking into account 85% efficiency (see Fig.1b) we propose to use XPW based on these crystals in usual single-CPA lasers avoiding the bulky double-CPA technique.



(a) (b)

Figure 1. Definition of Euler angles ϕ, θ, and α, (x,y,z) – light propagation basis (a); and dependence of XPW generation efficiency on angle ϕ for BaF_2 and DKDP crystals for B-integral equals 2 (b).

Reducing the Contrast Pedestal in CPA Lasers

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The contrast pedestal is a well-known feature in the intensity profile of compressed ultrashort laser pulses. It appears in third-order cross-correlation plots as a triangular shape, rising from the ASE baseline a few tens of picoseconds before the pulse peak, and typically reaching a level of 10^{-5} to 10^{-4} of the peak intensity close to the main peak [Figure 1]. The pedestal has a very damaging effect on laser interactions with solid targets, because it generates pre-plasma that completely alters the subsequent interaction, or in many cases destroys the target altogether. Using a plasma mirror is perhaps the only way to reliably eliminate the pedestal [1], but this comes at a significant cost in energy, so removing or reducing the pedestal by other means is highly desirable. In previous work [2] we showed that the pedestal is generated by the gratings in the pulse stretcher, and that it can be reduced by using better-quality gratings. We now present results showing that the use of transmission gratings in the stretcher makes a further significant reduction in the contrast pedestal.

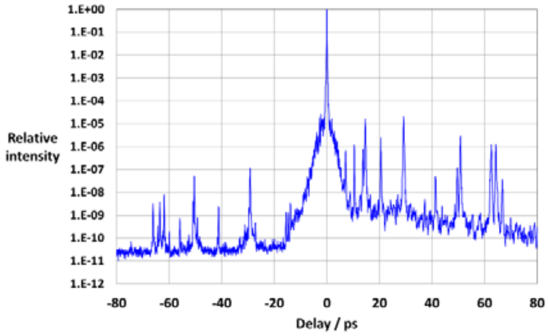

Figure 1. Typical contrast trace showing the pedestal

We built two pulse stretchers, one with transmission and one with reflection gratings, in order to compare the relative sizes of the pedestal produced by each. For both we used gratings with 1480 grooves/mm, the same as in the pulse stretcher of the Gemini laser at the CLF [3]. The largest readily available size of transmission grating was 70 mm, which gave a maximum stretched pulse length of around 160 ps. To recompress the pulses we used a pair of reflection gratings in double-pass, with a plane mirror to retro-reflect the beam. The same compressor was used to compress the pulses from both stretchers. The contrast was measured with a Sequoia third-order cross-correlator, the standard instrument for such measurements.

The experiments used the residual kHz beam from the front end of Gemini. This consists of a kHz pulse train from which single pulses have been switched out at 10 Hz to seed the Gemini laser. The rejected pulses are available for other activities whenever the laser is operational.

The principal result is shown in Figure 2, which is a direct comparison of contrast scans recorded with the two different stretchers, in each case after the compression of the pulse had been optimized. As can be seen, the transmission grating stretcher has a pedestal that is 1-2 orders of magnitude smaller than the one produced by the reflection grating stretcher. The input pulse is also shown.

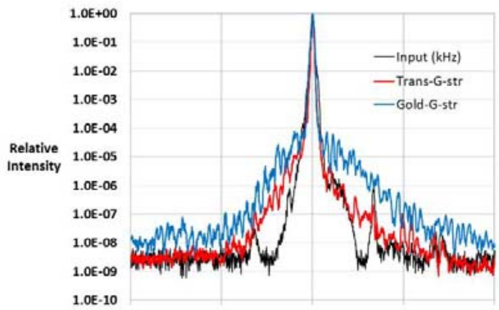

Figure 2. Comparison of contrast traces with gold grating and transmission grating pulse stretchers and the input pulse.

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3 mJ, 4 fs, CEP-stable pulses from long hollow fibers

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Ultrafast light-plasma interactions pave the way to particle acceleration and XUV/X-Ray generation. Sub 2-cycle CEP-stabilized pulses are of particular interest as these facilitates the generation of single attosecond pulses and allow to probe the electron dynamics on an attosecond timescale. Upscaling the currently available pulse energy would allow higher XUV photons yield and could allow attosecond-pump, attosecond-probe experiment. [1]

One way of generating sub 2-cycle pulses is to spectrally broaden optically amplified pulses by self-phase modulation (SPM) in noble gas filled hollow core fibers (HCF). With this technique over octave spanning bandwidth can be achieved at the mJ energy level allowing pulse compression to sub 5fs.

For controlled spectral broadening, self-focusing and ionization needs to be avoided. We will show that for up-scaling the peak power, the effective length of the waveguide and the mode area have to be increased proportionally. An innovative design has made this scaling possible, utilizing stretched flexible capillaries [2].

Here we present, using a combination of circularly polarized light and a long HCF filled with He in a pressure gradient mode, the generation of 4 fs, 3 mJ, CEP-stabilized pulses with 1 kHz repetition rate. We believe this is the highest pulse energy achieved to date for CEP-stabilized sub-5 fs pulses at kHz repetition rate.

8 mJ, 23 fs pulses of a 1 kHz high-contrast, double-CPA Ti:Sapphire amplifier system [3] were circularly polarized and subsequently spectrally broadened in a 2-m long, 450 µm inner diameter HCF. A regular, over octave spanning spectrum, supporting a transform-limited duration of 2.6 fs, was achieved at an optimal He pressure of 1.8 bar with an output energy of 3.5 mJ and excellent beam quality (fig. 1a). Subsequently the pulses were compressed by chirped mirrors and characterized by a home-made single-shot SHG FROG (fig. 1c-e) revealing a pulse duration of 4.27 fs, and by a D-Scan device (Sphere Ultrafast Photonics) giving a duration of 3.9 ± 0.1 fs.

Finally the CEP-stability was verified using a home-made f-to-2f interferometer with a slow feedback loop. The CEP was stabilized at an RMS error of 250 mrad before, and 360 mrad after the HCF (fig. 1b).

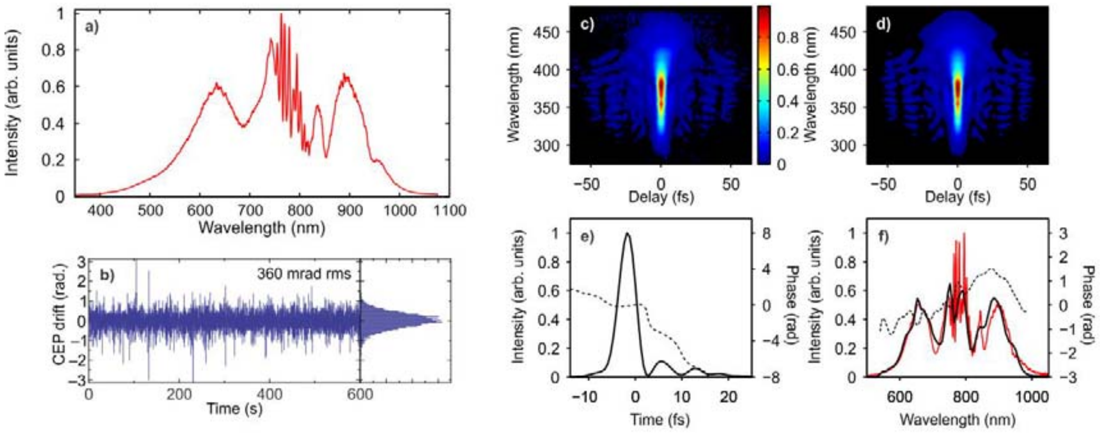

Figure 3: (a) output spectrum, (b) CEP stability at the output of the fiber, (c-e) SHG FROG: Measured (c) and retrieved (e) traces with the retrieved temporal (e) and spectral (f) intensities shown. Dashed lines represent the phase, the red line the measured spectrum before the FROG.

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Technology Development for Ultra-intense OPCPA

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Optical parametric chirped-pulse amplification (OPCPA) with kilojoule Nd:glass lasers pumping deuterated potassium dihydrogen phosphate (DKDP) provides broadband gain [1] and the potential for focused intensities exceeding 10^{23} W/cm^2. A mid-scale (15-fs, 7.5-J) optical parametric amplifier line (OPAL) is being constructed at the Laboratory for Laser Energetics (LLE) to demonstrate technologies that are scalable to a kilojoule system pumped by OMEGA EP.

The ultra-broadband front end produces the seed using white-light–continuum generation in a YAG plate that is pumped by a Yb-doped fiber system (250 fs, 11 μJ). Three noncollinear optical parametric amplifier (NOPA) stages made from β-barium borate (BBO) crystals amplify the portion of the spectrum from 810 to 1010 nm with a gain of 5×10^7 to 5 mJ. The pulses are stretched to 1.5 ns for amplification in the remaining NOPA stages using a cylindrical Offner stretcher (COS) [shown in Fig. 1(a)] [2]. A linear phase-conjugate imaging technique using a spatial light modulator has been developed to relay the apodized beam from NOPA3 through the long working distances of the COS. The 1.5-ns stretch is a trade-off between subsystems best suited to small stretches (e.g., NOPA's, stretchers) and those suited to longer stretches (e.g., pump lasers, compressors).

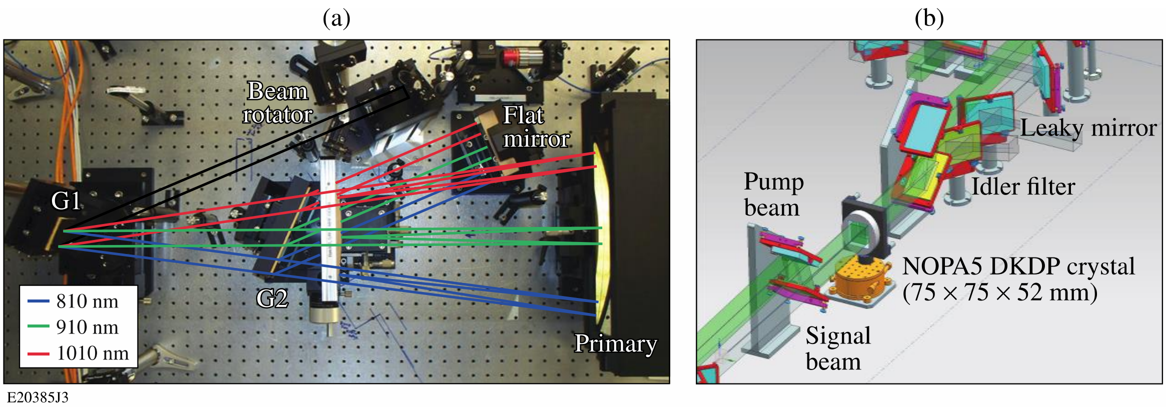

Fig. 1: (a) The COS with select rays overlaid. A beam rotator is used after the first pass for symmetric imaging through the remainder of the system and to double the stretch to 1.5 ns. (b) The NOPA5 design, showing the two-level configuration chosen to match the capabilities of the optical coatings.

Several types of custom coatings have been designed at LLE for the OPAL project [3]. High reflectors, leaky mirrors, antireflection coatings, and an idler-blocking filter with suitable damage thresholds and dispersion properties have been developed. Dichroic mirrors that reflect the 527-nm pump pulses and transmit the broadband seed are used for the final amplifier stages (NOPA4 and NOPA5). Figure 1(b) shows the design of NOPA5. The Multi-Terawatt laser is being reconfigured using switchyards so that it can pump NOPA5 using narrowband, 50-J, 1.5-ns pulses at 527 nm.

In conclusion, a laser development program is underway to demonstrate technologies suitable for an OPAL pumped by OMEGA EP. The presentation will review progress on the 7.5-J, 15-fs mid-scale system.

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Thursday Session 3

Development of OPCPA Technologies for Multi-PW Applications

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In this paper we report on the performance and development of a medium-sized aperture OPA to test and evaluate OPCPA technologies for Multi-PW applications. The design of the OPA is based upon that developed for the envisaged Vulcan 20PW upgrade project which will use OPCPA amplification to generate pulses of 400J and 20fs. This will be achieved by amplifying the output from a custom front-end system in 3 further stages of amplification. The first of these stages is designed to have a small signal gain of ~90 in a KD*P crystal that is 64mm long and has an aperture of 40mm. The subsequent stages will have 200mm apertures. Whilst we await funding for the full upgrade we have been building the first stage of this amplification scheme to; develop OPCPA technology for Multi-PW applications, test and evaluate the scheme developed for the Vulcan 20PW upgrade which requires coatings with complicated transmission and reflection profiles to deal with the signal, pump and idler wavelengths, test different deuteration levels of KD*P to benchmark the model and to identify the most suitable crystal, compare the performance of fast and slow growth crystals and to confirm the optical modeling used in the design of the beam expansion schemes.

We have developed a dedicated area to test and evaluate the performance of this first stage of amplification and the associated key components. A schematic of this stage and how it relates to the 20PW front-end is shown in Figure 1 (left). The 20PW front-end and the component test lab are in adjacent laboratories and have been coupled together using vacuum relay pipes. The pump source for the area is derived from the output of a dedicated rod amplifier chain that is seeded by a diode-pumped temporally shaped long pulse oscillator. The output from this system is then amplified to over 30J and shows very good spatial uniformity and is relayed into a crystal for doubling. The IR is frequency doubled to form a pump beam for a single OPCPA stage. The fluence of the pump is comparable to the planned fluence that will be used in the Vulcan 20PW upgrade.

The seed at 910nm for this system uses a beam that is relayed from the existing front-end [1]. The seed is generated using the technique of chirp compensated OPA [2]. This is stretched to 1.8ns in a single mirror grating stretcher and then amplified in two stages of LBO to the Joule level. This is then imaged into the OPA crystal under test using a vacuum relay pipe that expands the beam from 20mm diameter to 45mm diameter using achromatic doublets. The OPA scheme is arranged so that the signal is transmitted through the pump injection mirror. After the crystal the undepleted pump is reflected off a mirror and the idler and signal beams transmitted. At the next mirror the signal beam is reflected and the idler transmitted and blocked in a beam dump. To diagnose the beam after amplification the residual reflection of the signal and idler from the pump separator after the crystal is used. This is followed by a second mirror that transmits the pump and reflects the signal and idler and the beam imaged into a diagnostics package. In this way all of the wavelengths are attenuated before being diagnosed.

After amplification the seed that is returned to the front-end laboratory for re-compression is derived from the reflection off a series of glass wedges and then relayed through a pipe and injected into an air-compressor.

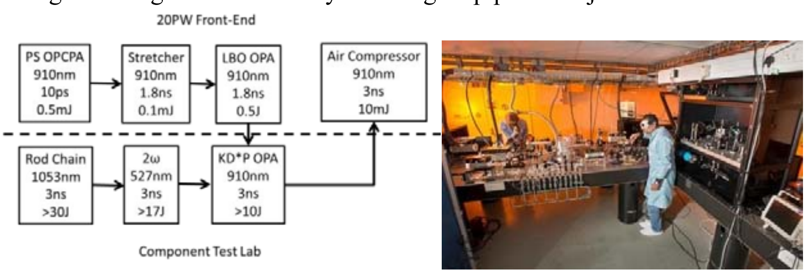

Figure 1. Schematic of the components that have been assembled to test multi-PW OPCPA technology (left) and a photograph of the completed component test laboratory (right).

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Overview of the Ultra-intense Laser Activity at RRCAT, Indore

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Raja Ramanna Centre for Advanced Technology, Indore, is involved in development of high power Nd:glass lasers as well as use of ultra-short pulse Ti:sapphire lasers for studying laser-matter interaction at ultra-high intensities.

On the laser development side, we shall describe the optical parametric chirp pulse amplification based 600 fs Nd:glass laser system.

It is well known that when ultra-short laser pulses are focussed to ultra-high intensities, they can produce a number of energetic particles like hot electrons, MeV energy protons, ions, neutrons, neutrals and even negative ions. In addition to generation of energetic particles with multi-MeV energy, ultra-short pulse lasers can also be used to accelerate electrons to hundreds of MeV to few GeV energy. At RRCAT, we have been working on laser-matter interaction at ultra-high intensities using a 10 TW, 45 fs Ti:sapphire laser. Our studies on ultra-high intensity laser plasma interaction include, electron acceleration in laser plasma wake-field produced in gas jets or plasma plumes, and proton / ion acceleration in thin foil targets. We have so far obtained well collimated, stable, mono-energetic electron beams with energy up to 50 MeV with gas jets. We have also demonstrated acceleration of electrons in "plasma plumes" to ~12 MeV. With the operation of the 150 TW, 25 fs laser in our lab, we hope to reach higher electron energies soon.

Recently, we have also carried out ion acceleration studies in thin foil targets and have achieved proton beams of energy up to ~3 MeV, in aluminium foil targets. We have observed an interesting feature on quasi-mono-energetic ions of gold with constant energy of various charge states, in gold nano-particle embedded composite targets. We have also observed for the first time the emission of negative ions from solid target-laser interaction. We have also carried out some parametric work on hot electron generation and K-α generation from foil targets.

In this talk, I will present our results on the above topics which have been obtained in the last few years and discuss our present understanding of the processes involved.

Pre-Pedestal Generation by Post-Pedestal in High Power CPA Lasers

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Understanding the nature of pre-pulses existing in high-power lasers is critical in super-intense laser-matter interactions because the pre-pulses can change the characteristics of laser-matter interactions, especially in the case of high-density targets. A laser pulse in a Chirped Pulse Amplification (CPA) laser has three kinds of pre-pulses, such as femtosecond pre-pulses, ASE, and pre-pedestal. The origin of both femtosecond pre-pulses and ASE is well known and, hence, there exist effective techniques to remove such unwanted pre-pulses. It is however difficult to remove the pre-pedestal due to its unavoidable and unknown causes. V. Bagnoud *et al.* [1] and K. –H. Hong *et al.* [2] reported that the spectral phase noise or spectral phase distortion, coming from the limited surface quality of optical components in a stretcher or a compressor, produced such pedestal. Recently, Chris Hooker *et al.* reported that the origin of the pre-pedestal and post-pedestal was mainly related to scattering from the stretcher grating of a CPA laser [3]. Here we show experimentally using a high-contrast laser that a significant pre-pedestal can be generated by a post-pedestal due to the refractive index nonlinearity of an optical material.

To investigate the generation of the pre-pedestal by the refractive index nonlinearity, experiments were performed. An 1-ns stretched laser pulse from a preamplifier [4] was sent through a SF10 block, having large n_2, and compressed by a grating compressor. The diameter of the incident laser pulse was ~ 3 mm, and the beam profile was close to Gaussian beam. The laser pulse energy is 26 mJ and attenuates before the incidence on the SF 10 block. The measured third-order cross-correlator signals are shown in fig. 1. When the laser pulse did not pass through the SF10 block, the pedestal shape was asymmetric. Also, the pre-pedestal did not exist before -25 ps, but the post-pedestal existed even after 80 ps, as shown in Fig. 1. As the laser pulse energy E_p increased from 2.3 mJ to 12.5 mJ, and the pass length L increased from 14 cm to 28 cm, corresponding to the increase of B-integral value, the shape of the pedestal became symmetric, and the pre-pedestal extended up to -70 ps. In addition, the contrast ratio became worse by up to two orders of magnitude at -25 ps. These experimental results represent that the pre-pedestal is also generated due to the refractive index nonlinearity as femtosecond pre-pulses can be generated due to the refractive index nonlinearity [5, 6].

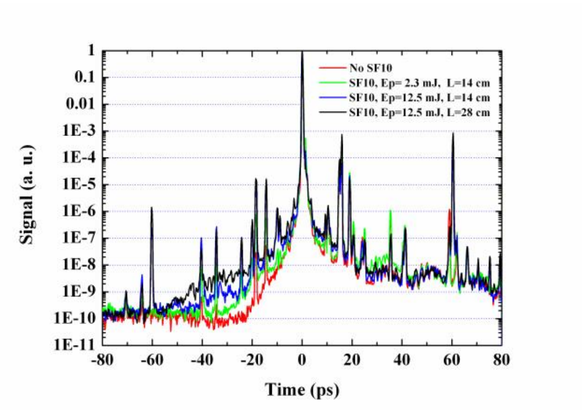

Fig. 1. Pre-pedestal generation of a laser pulse propagating through a SF10 block with high nonlinearity

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Intracavity Gain Shaping in a mJ Level, High-Gain Ho:YLF Regenerative Amplifier

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Ultrashort multi-mJ laser pulses at 2 µm are of great importance to e.g. advance HHG in the water window energy range and THz generation [1]. A Ho:YAG regenerative amplifiers were recently demonstrated with mJ-level pulses energies [2], but required complex optical parametric amplifiers for seeding. Here we report on a compact Ho:YLF chirped pulse amplifier system seeded with a home-built Ho:fiber oscillator. To compensate for gain narrowing, intracavity gain shaping was employed as a simple and flexible solution. In a proof of principle experiment, we inserted an un-optimized etalon in the cavity of the regenerative amplifier and were able to significantly decrease the compressed pulse duration.

The basis of the setup was a prototype Ho:YLF regenerative amplifier followed by a single pass amplifier (both from Q-peak Inc.) [3]. The amplifier was seeded with a home-built Ho:fiber oscillator; (whose details can be found in [4]) stretched and compressed with chirped volume Bragg gratings (CVBG) exhibiting a stretching factor of 19 ps/nm. The seed spectrum was centred at 2.05 µm with a bandwidth of 19 nm at FWHM. A total amplification of ~10^7 was achieved leading to an output energy of 1.3 mJ at 1 kHz. The pulses were compressed using a second identical CVBG with an efficiency of 88% leading to a pulse energy of 1.1 mJ. The beam profile observed with a camera showing an output beam diameter of 1.3 mm (inset Fig.1.a). To measure the pulse duration, we generated the second harmonic in a BBO crystal and then used a commercial auto-correlator at 1 µm. We derived a pulse duration of 3.5 ps for the 2 µm pulses assuming a $sech^2$ pulse shape (See Fig. 1.a). For gain shaping, a 120-µm thick uncoated (reflection of 4%) fused quartz-etalon was placed inside the cavity. The wavelength dependant transmission of the etalon re-shapes the effective gain [5]. The etalon was tuned to provide maximum loss at the gain peak of 2050 nm and minimum loss at 2065 nm. To compensate for the reduced overall gain and the additional losses the output coupling was reduced from 11% to 2%. The result of this gain shaping technique is not only observable by the reduced pulse duration of 2.5 ps (see Fig. 1.a) but also by broadened optical spectrum (See Fig. 1.b). An optimized configuration with a single face reflection of 28% and a thickness of 150 µm can almost double the gain-bandwidth to ~22nm as shown by simulations in Fig.1.c. Thereby, approaching the Fourier- limit, such method of gain shaping can generate sup-ps pulses

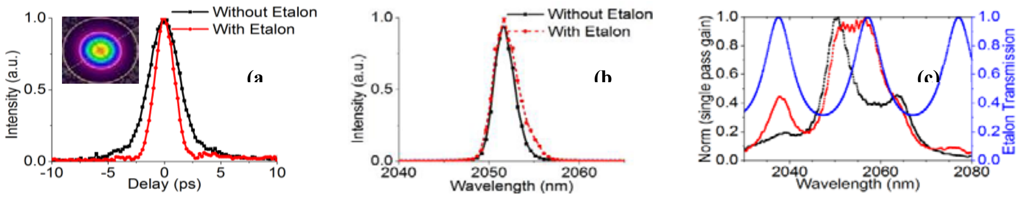

Fig. 1 (a) Autocorrelation trace of the corresponding frequency doubled pulses; in the inset, a far-field beam profile of the regen output after compression is shown. (b) Spectrum without and with the etalon (c) Simulation results of single pass gain spectrum shaping with (red) and without (black) the etalon of 28% reflectivity.

In summary, we demonstrated a compact Ho:fiber/Ho:YLF-amplifier system with an amplification factor of 10^7 delivering 1.3 mJ pulses at 3.5 ps. Intracavity gain shaping was applied for the first time to a Ho-based amplifier system leading to a reduction of the compressed pulse duration to 2.5 ps. Further reduction with an optimized intracavity filtering is planned for the near future. The authors would like to acknowledge the contributions of Anne-Laure Calendron, Peter Krötz and Alex Dergachev.

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ELI-Beamlines: Development of Next-Generation Short-Pulse Laser Systems

B. Rus, P. Bakule, D. Kramer, J. Thoma, J. Naylon, M. Fibrich, J.T. Green, G. Korn, B. Le Garrec, J. Novák, F. Batysta, R. Antipenkov, T. Mazanec, R. Baše, D. Peceli, L. Koubíková, P. Hříbek, J. Hřebíček, J.C. Lagron, J. Polan, M. Košelja, T. Havlíček, A. Honsa, Ch. Zervos, P. Korouš, M. Laub
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Overview of the laser system being built for ELI-Beamlines will be presented. The ELI-Beamlines facility will be a high-energy, high repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. The facility will make available for users high-brightness multi-TW ultrashort laser pulses at kHz repetition rate, PW 10 Hz repetition rate laser pulses, and kilojoule nanosecond laser pulses for generation of 10 PW peak power. These systems will allow meeting requirements of international user community for cutting-edge laser resources for programmatic research in generation and applications of high-intensity X-ray sources, in particle acceleration, and in dense plasma and high-field frontier physics. The ELI-Beamlines high repetition rate lasers will extensively employ the emerging technology of diode-pumped solid state lasers (DPSSL), to pump OPCPA and Ti:sapphire broadband amplifiers. We will describe in detail architecture and status of development of the kHz beamline based on ps OPCPA driven by thin-disk laser units, and development of the ns OPCPA based beamline using cryogenic Yb:YAG laser as the driver. We will also describe progress on the 10 Hz HAPLS (High Repetition Rate Advanced Petawatt Laser System) beamline using Ti:sapphire pumped by gas cooled Nd:glass DPSSL system.


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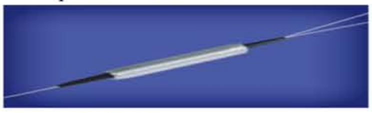

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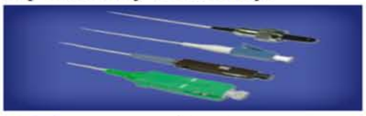

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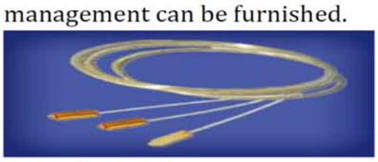

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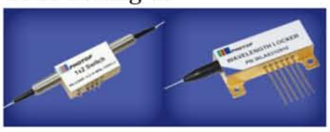

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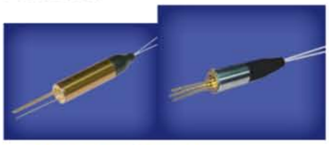

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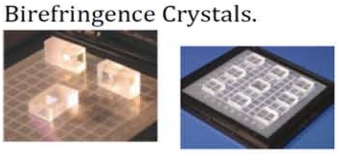

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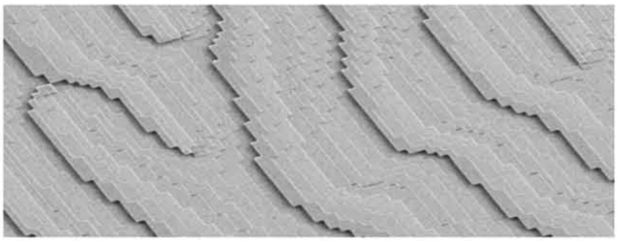

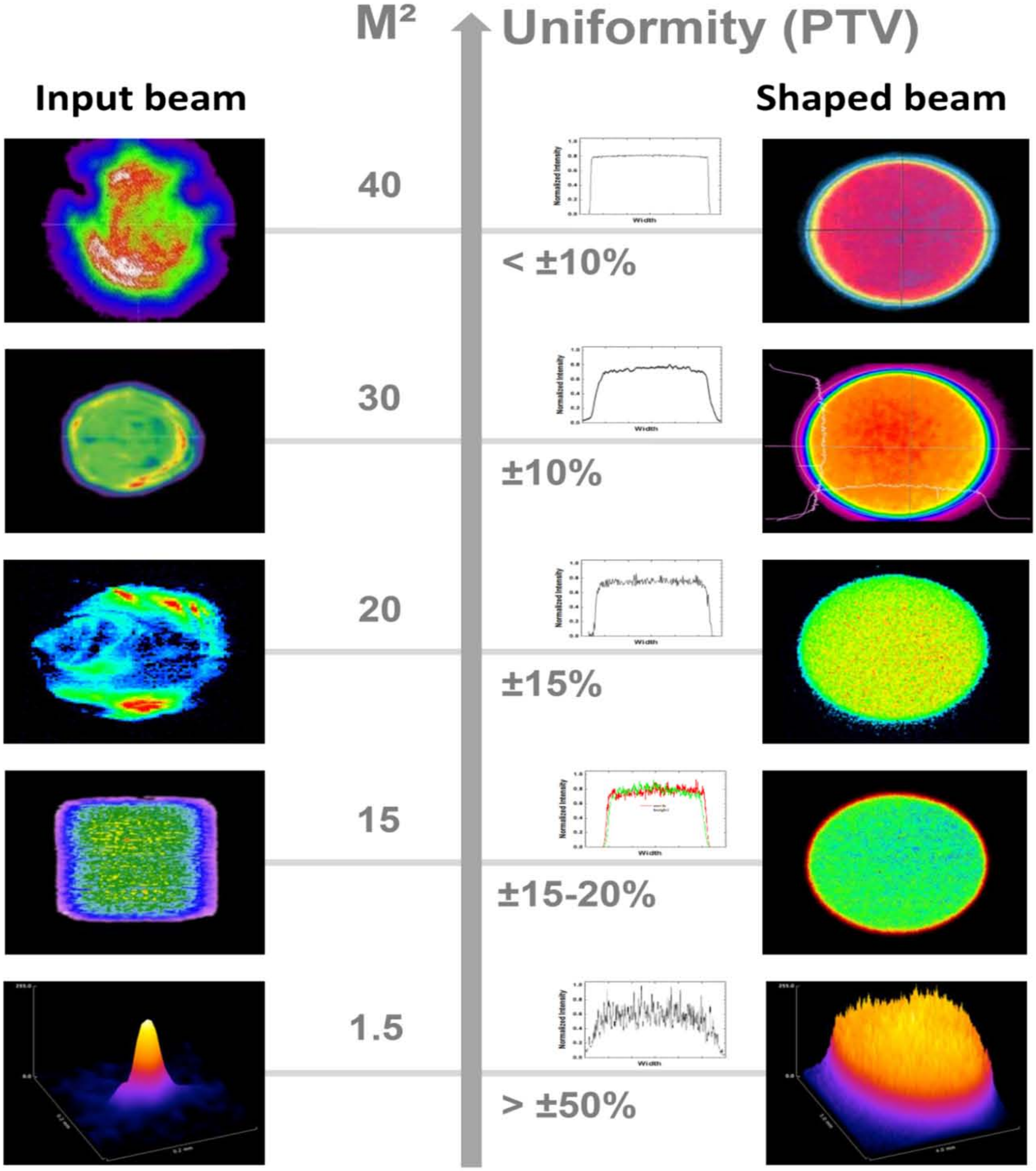

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High Energy Single Cycle Compressor: Path to Zeptosecond-Zettawatt Physics

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Abstract: We present a new compression technique that has the potential to compress high energy pulses of up to a few hundred Joules into pulses as short as one optical cycle at 0.8µm, and producing true ultra-relativistic λ^3-pulse [1]. This could act as the first stage in a scheme that promises to ultimately compress to Zeptosecond- Zettawatt pulses heralding a new regime in laser-mater interaction.

Generation of a single cycle, high energy pulse: The compression technique relies on self phase modulation in bulk material and the top-hat nature of a well designed and constructed PW laser. The pulses that have been used in our simulation correspond to the output of the PW laser, generating 27J in 27fs called CETAL in the Institut National de Laser, Plasma et Radiophysique (INFLPR) in Bucharest.
The simulation of this simple technique based on the experimental spatial profile provides a spectacular reduction in pulse duration of more than 10 times, transforming a PW laser into one of greater than 10PW. Furthermore, the compression system can also be adapted to the 10PW of ELI-NP to boost its power to more than 100PW or 0.1EW.

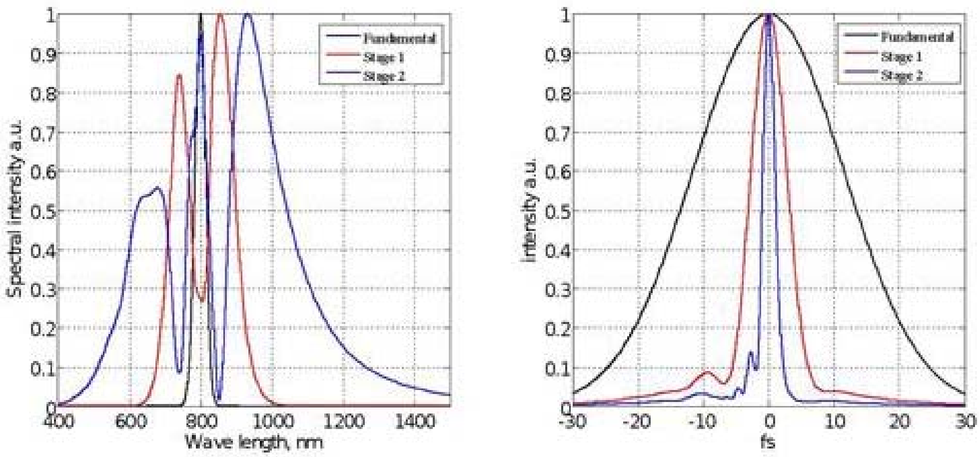

Fig 1. Generation of a single-cycle pulse from a 1PW laser system[1]. Single-cycle pulse from a top hat PW laser is produced by a double self-phase modulation compressor.

This result becomes extremely relevant to the so-called Relativistic-λ^3 regime where relativistic-intensity few cycle pulses are focused on a λ^2 area. As demonstrated [2] the enormous power density will drive the critical surface inwards at the light frequency and ensure the compression mechanism. As the critical surface moves relativistically in and out as well as sideways, the reflected beam, composed of compressed pulses, is broadcast in specific directions and provides an elegant method to isolate individual pulses. The pulse duration T of each individual pulse according to [2], scales like T=600 (attosecond)/a0 . Here a0 is the normalized vector potential, which is unity at 1018W/cm2 and scales as the square root of the intensity. Assuming in our case an a0 of 5000, then pulses of 100 zs could be produced and recent simulations suggest pulses as short as a few zeptoseconds. Even with estimates for a low efficiency of 1%, the peak power could be in the zettawatt regime.

Nonlinear vacuum physics [3]: As the pulse is compressed into a extremely short duration, even a modest efficiency leads to sizable nonlinearities in the quantum vacuum. Although the value of n2 for vacuum is 18 orders of magnitude smaller than a typical optical transparent medium, such as glass, the critical power (Pc= λ2 /n2) scales as the inverse-square of the photon frequency. As an example if the vacuum critical power is 1024W for 1.0 µm light [3], it should be 6 orders of magnitude less for a one attosecond pulse with 1keV radiation, or 1018W.

Under this condition the vacuum critical power could be attained with a single joule. For a 10PW laser with 250J input energy this corresponds to only .4% efficiency. It is quite fascinating to imagine that filaments in vacuum analogous to those produced in air [4] could be generated. Their sizes would be limited by “vacuum breakdown” or pair creation as the intensity approaches 1029W/cm2 corresponding to a filament of 10-5 cm diameter.

Acknowledgements: T. Tajima, E. Khazanov, A. Sergeev, N. Zamfir, R. Dabu, I. Morjan

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Broadband Stimulated Raman Backscattering in Plasmas

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1. Introduction By-passing technical complications on the way towards Exawatt/Zetawatt Laser systems requires the use of Raman amplification in a laser driven plasma. During the last years a number of experiments demonstrated the possibility of this approach. The aim to reach high efficiency at very high energy levels still requires a large step forward.

2. Experiment In experiments at the JETI 30 TWatt laser at Jena issues of the seeding laser and the amplification bandwidth were studied at an energy range up to 1 Joule. For this purpose, a wide-band short laser pulse was produced in a hollow-fibre scheme followed by a chirped-mirror compressor. This resulted in a wide spectrum with a shifted component in the 900 nm range, well suited for the demonstration of plasma amplification. The pulse duration was below 20 fs, and the energy was reaching up to 150 micro-Joule. The plasma amplification region was realized using an optimized gas-jet pumped by the remaining 500 mJ pulse from the Jeti laser, stretched to around 600 fs.

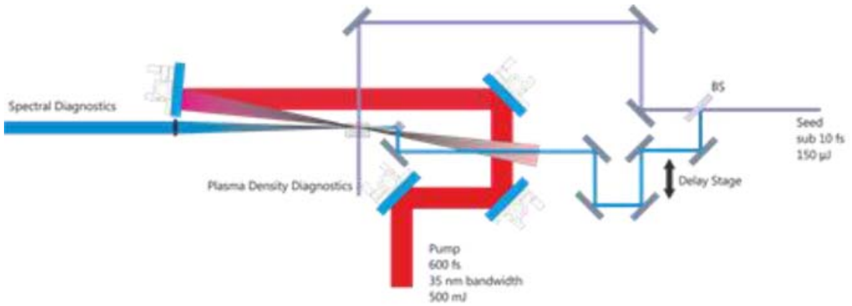

Figure 1: Scheme of the experiments at the JETI laser

3. Results In the experiment at JETI strong amplification of the red-shifted part of the pulse was observed. Experiments towards high-efficiency high-energy Raman amplification using existing lasers might already reach into the Petawatt range. One possible candidate to host a combined effort is the PHELIX laser at GSI Darmstadt. PHELIX uses 31.5 cm glass amplifiers from the former Nova and Phebus chains in combination with a Ti:Sapphire front-end. The performance was enhanced by adding an ultrafast-OPA stage and spectral shaping to the front-end. The system can deliver pulses of 400 fs duration and 200 J energy onto the target. At a power level of 0.5 Petawatt this laser can evaluate steps to reach multi-Petawatt performance by plasma amplification.

Friday Session 1

Tunable Plasma-Wave Laser Amplifier

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Exploring the physics at the laser-intensity frontier is an exciting challenge. Present-day petawatt-class lasers provide on-target focused intensities of 10^{22} W/cm^2. Raman amplification opens a potential route for focused intensities in the range 10^{23} to 10^{25} W/cm^2 as well as providing a cost-effective route for high-energy petawatt laser pulses. At the Laboratory for Laser Energetics (LLE), we plan to perform a careful and systematic experimental investigation, aided by state-of-the-art numerical modeling, into the physics of Raman amplification and the associated laser–plasma instabilities that are notorious for limiting the efficient energy extraction.

Raman amplification is a process by which a long energetic pump pulse transfers its energy to a counter-propagating short seed pulse through a resonant electron plasma wave. A recent comprehensive series of large-scale multidimensional particle-in-cell simulations has identified the optimal parameter space for this interaction [1]. This regime is dictated by limiting the growth of other parametric instabilities in the plasma and the study suggests that controlling these processes is not straightforward, as has been demonstrated by many experiments over the past decade [2–4].

Figure 1 shows the seed wavelength plotted versus the resonant plasma density for a pump of 1054 nm. The optimal regime outlined in Ref. [1] is marked by dashed lines between ω_p / ω_0 of 0.05 and 0.07, where ω_p is the plasma frequency and ω_0 is the pump laser frequency. The regimes previously studied have been significantly limited by the available laser wavelengths and techniques required to shift those wavelengths into resonance with the mediating electron plasma waves [2–4]. At LLE, the optical parametric amplifier line is being designed to produce a seed pulse with a tunable central wavelength between 1110 nm and 1300 nm. Alongside a Nd:glass laser to produce the 1054-nm pump with 50 J of energy, a tunable plasma-wave amplifier will be designed to access the optimal parameter space for Raman amplification where the plasma density is scaled from 2.5×10^{18} cm^{-3} to 5×10^{18} cm^{-3}, while the corresponding seed wavelength will be tuned to maintain resonant matching conditions (Fig. 1).

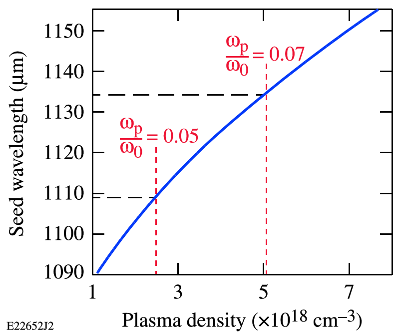

Figure 1 : The resonant seed wavelength for a pump wavelength of 1054 nm is plotted versus the resonant plasma density.

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Gain Dynamics of X-ray Plasma Amplifier Spurring CPA Soft X-ray Laser

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Emergence of ultrafast coherent soft x-ray lasers driven by LINAC (i.e. free-electron lasers) have opened new paradigm in coherent nano-imaging at the femtosecond time-scale leading to major breakthroughs in biology, solid state physics, astrophysics [1]. The primary challenges for all the soft x-ray lasers to ensure nano- femto-imaging are pulse energy, pulse duration, beam coherence and wave front. In parallel to huge and costly free-electron lasers we developed compact laser-driven soft x-ray lasers. Seeded soft x-ray laser by injecting high harmonics into a plasma amplifier has attained full spatial and temporal coherence [2, 3] but with limited shortening of the pulse duration [4] and not so efficient energy amplification [5] limiting their interest for coherent femto- nano- imaging. Our recent simulation work [6] based on a time-dependent Maxell-Bloch model revealed this matter out. We have showed that using a sequence of two amplifiers seeded by an ultrafast high harmonic soft x-ray pulse, one may increase the output energy by a factor of ten while reducing the pulse duration by 25 times (intensity enhancement by 250 times) leading to a source comparing well with most advanced soft x-ray free-electron lasers. However, we demonstrated also that the saturation influence of plasma amplifier remaining low, it is impossible to further increase the output energy and thus to reach the optimal parameters for coherent femto- nano- imaging. Consequently, we explored the possibility to increase the stored energy not with larger amplifiers that demonstrated their limit but in plasma with much longer lifetime. Our modelling showed the possibility to tremendously increase the output coherent energy (1,000 times) by transposing the Chirped Pulse Amplification (CPA) to the soft x-ray domain [7]. High harmonic pulse is first stretched 1,000 to 10,000 times then amplified and finally compressed to ~100 fs [6]. The key issue of this technology is the ultrafast gain recovery time uniquely observed in our modelling of plasma amplifiers. We thus set an x-ray pump/x-ray probe experiment to measure the nonlinear response of a plasma amplifier perturbed by a strong high harmonics pulse [8]. The detected fast gain recovery time of 1.5-1.75 ps is in excellent agreement with our theoretical prediction, confirming our proposal of generating GW fully coherent soft x-ray lasers by seeding a CPA stretched soft x-ray high harmonic into plasma amplifier.

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Laser-Plasma Undulator Based on Wakefield Excitation in a Plasma Channel

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A novel type of undulator based on control of the focusing forces inside the Laser Plasma Accelerator [1] is proposed. Controlling the focusing force can be achieved by inducing laser pulse centroid oscillations in a plasma channel [2,3]. The period of such a plasma undulator is proportional to the Rayleigh length of the laser pulse and can be sub-millimeter range. Schematic of the plasma undulator is presented on Fig. 1. A short laser pulse depicted with red color is propagating through the plasma channel and exhibits oscillatory motion due to an initial centroid displacement. Plasma wakefields created in the plasma density also follow the oscillatory motion. An electron beam is injected behind the laser pulse and is depicted by a collection of points. The lower panel shows the focusing field as seen by the electrons. The periodic focusing force serves as an undulator and the oscillating electrons produce radiation. The electron trajectories inside the plasma undulator are examined and expressions for the undulator strength are derived. Multimode and multicolor laser pulses [4] are considered for greater tunability.

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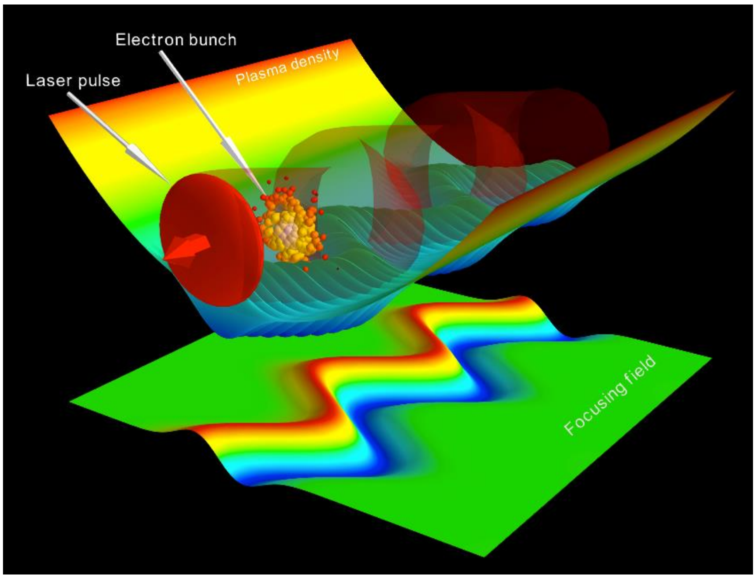

Fig. 1. Schematic of the plasma undulator

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ICAN: High Peak and High Average Power Ultrafast Lasers via Coherent Amplification Networks

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Progress in laser wake field acceleration has been rapid in recent years, arousing interest in laser-based accelerators as a practical technology. Laser sources for wake field acceleration remain at present only able to operate at repetition rates of 1Hz or less. The International Coherent Amplification Network (ICAN) project, a collaboration between Ecole Polytechnique Paris, France, University of Southampton UK, Fraunhofer IOF Jena, Germany, and CERN, aims to leverage the ability of optical fibre-based lasers to deliver very high average powers in order to increase the repetition rates to tens or hundreds of kHz. The main obstacle is the ability of the optical fibres to produce the very high peak powers necessary. ICAN draws on the technology for fibre networks to amplify and split a seed pulse into many replicas, which can each be amplified to relatively high energy. These replicas can be coherently recombined to produce pulses with the very high energy and very high repetition rate required for practical applications. Progress toward ICAN lasers will be reported, along with potential architectures and issues.

Beam Combination with a Dual Beam Ti:Sapphire Femtosecond Amplifier

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Ultra-high intensity lasers are used in a variety of applications. The coherent combination of separate laser beams into a single beam offers an attractive route to power scaling of ultra-high intensity lasers because it offers the advantage that it reduces the requirements for laser amplifiers to a more modest level. The coherent combination of free space lasers has been demonstrated in the CW and nanosecond pulsed regimes [1-2]. To our knowledge the combination of femtosecond pulses has only be achieved through fiber lasers where there is a significant control of the beam parameters or through the use of tiled gratings for spectral combination [3].

Having previously reported on the successful test-bed demonstration of the locking of two beams together using a PHASICS [4,5], wave-front sensor we now report on a proof-of-principle experiment conducted on the Astra-Gemini laser facility. In this paper we will present the results of the beam combination from high intensity dual beam bulk optical amplifiers, which to our knowledge, has never been reported to date. The Astra-Gemini [6], laser represents an excellent candidate for demonstrating the beam combination experiment; as it is a dual beam facility (comprising a North beam and a South beam) with each beam being seeded by a common source and capable of up to 0.5 PW. In order to create the conditions for beam combination the two normally circular aperture beams were converted into semi-circle beams, this is required so that the wave-front sensor can compare the relative phase between the two beams. There is a delay line in the South beam that enabled control of the relative timing between the South and North beams so that they can be synchronized at the target chamber

Measurement of the temporal overlap was achieved by using a specially designed autocorrelator; giving simultaneous autocorrelations of the individual beams and the combined beam. The far-fields of both the North and South beams were measured and are shown in Figure 1 with their respective x and y measurements.

Beam combination was confirmed by the measurement in the y direction being halved spatially as shown in Figure 2 as compared to the individual spatial beam focus sizes. These results were achieved with the Astra-Gemini in the 10 Hz, 0.5 J mode of operation. To our knowledge this the first time beam combination has been achieved on a bulk optics amplifier.

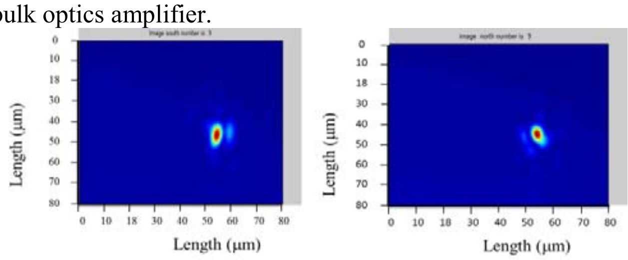

Figure 1 North beam fwhm in the x direction 19.2 pixels (4.1 μm) and in the y direction 45.7 pixels (9.52 μm)and South beam fwhm in the x direction 15.3 pixels (3.18 μm) and in the y direction 47.0 pixels (9.79 μm)in the far field; before beam combination

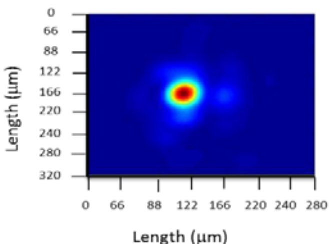

Figure 2 Beam combination with a fwhm in the x direction 16.9 pixels (3.52 μm) and in the y direction 19.9 pixels (4.14 μm)

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Approaching TW-Peak Powers at >10 kHz Repetition Rate by Temporal Combining of Femtosecond Fiber Lasers in a Stack and Dump Cavity

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Novel accelerating-concepts are currently under development in different international projects such as ICAN or ICUIL-ICFA. One promising approach is laser wakefield acceleration. However, in order to transfer this technology to large-scale facilities and, thus, to be able to compete with classical accelerators, extreme laser parameters are necessary. The required pulse energies are as high as 32 J with pulse peak powers of ~100 TW and a repetition rate of ~15 kHz [1], which results in an average power of 480 kW. Unfortunately, these laser parameters are not accessible with state-of-the-art laser technology. On the one hand, bulk systems can achieve very high pulse peak powers, but their wall-plug efficiency is typically <1% and they cannot handle high average powers very well. On the other hand, fiber-based amplifiers are well known for their high average powers even in the fs-pulse regime, but they are typically limited in pulse energy. Now, the concept proposed herein shows a way to take advantage of the

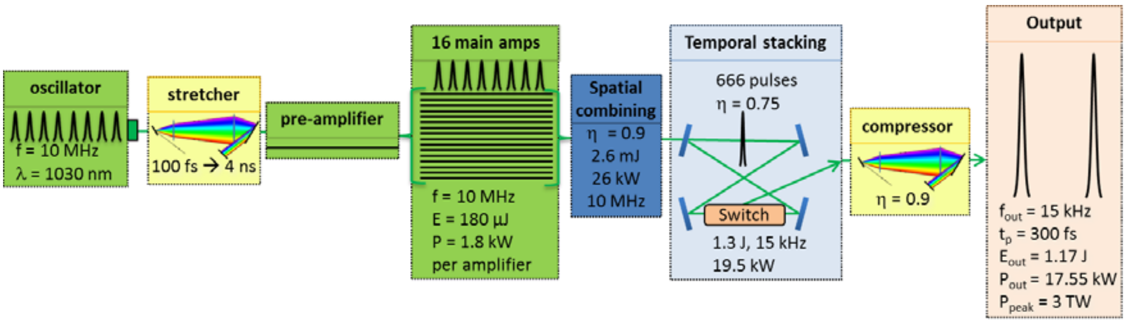

Fig. 1 Schematic Setup of a prototype system employing a Stack and Dump cavity within a common CPA-system.

very high repetition rates of fiber laser systems to achieve a combination of average power and peak power which is not otherwise accessible. The basic idea is to use a high repetitive (typically 10 MHz) chirped-pulse-amplification setup and additionally employ an enhancement cavity to stack the stretched pulses in the temporal domain before the compression. Such passive enhancement cavities are ideally suited for this task since a power enhancement of several orders of magnitude with very high average powers has been shown. With ps-pulses 670 kW of intracavity average power have been recently obtained [2]. The key challenge is the switch, since for the desired parameters no additional losses within the cavity can be tolerated. Hence, for the suggested approach, the enhanced pulses will be switched out of the cavity using a rotating chopper wheel [3] as a lossless, all-reflective switch with, for example, 15 kHz repetition frequency. Hence the MHz-level repetition rate of the incoming pulses is reduced to kHz-level which increases the pulse energy by the same factor while the average power is almost maintained. A schematic of a Joule-class 15-kHz system employing such a Stack and Dump cavity is depicted in Fig. 1. This setup is currently under development. Further power scaling can be achieved via additional parallelization of such systems to enable even higher output parameters enabling novel applications for ultra-fast lasers.

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Coherent Pulse Stacking Amplification

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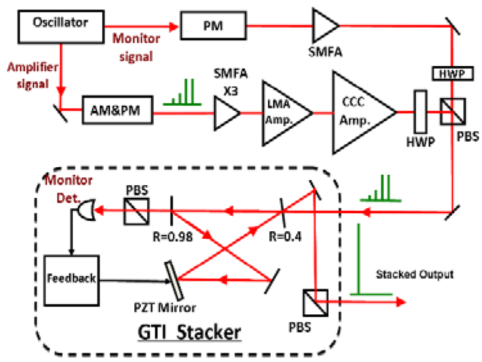
Coherently combined fiber CPA arrays are being considered as a possible path towards future multi-kilohertz repetition rate TW and PW systems. The serious challenge is that, due to detrimental nonlinear effects, pulse energies achievable from an FCPA typically are nearly two orders of magnitude lower than the stored extractable energy, and consequently a simple linear addition would require up to 10^3 - 10^4 of parallel fiber channels. Here we propose and demonstrate a coherent pulse stacking (CPS) technique, which has the potential to increase FCPA pulse energies by more than two orders of magnitude, thus reducing the required array size by a similar factor.

Coherent pulse stacking is achieved by tailoring amplitudes and phases of all the pulses in a pulse burst which then enters a reflective resonant cavity (e.g. a Gires-Tournois interferometer (GTI) - see Fig. 1), so that they destructively interfere at the partially-reflecting front mirror and are stored as a single pulse inside the cavity, until the final pulse in the burst constructively interferes with the intra-cavity pulse at the front mirror and extracts all the stored energy from the cavity in a single output pulse. Suitable multiplexing of several such reflective resonant cavities can coherently stack a large number of pulses with energy enhancement reaching into the range of >100 times. Here we experimentally prove the idea using a single GTI cavity with R=40.6% front-mirror reflectivity, and demonstrate the theoretically predicted pulse energy enhancement of ~2.5 times.



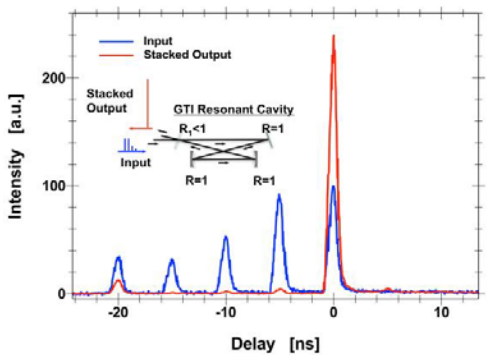


Fig. 1. Experimental coherent pulse stacking amplification system. AM&PM: amplitude&phase modulators; SMFA: single-mode fiber amplifier
Fig. 2. Experimental result at 1W average power: Input five-pulse burst and the solitary output pulse from a GTI stacker.

Tailored pulse bursts can be produced directly from a periodic train of oscillator pulses, by "carving them out" with an amplitude modulator (AM), and imprinting the required phase with a phase-modulator (PM) (Fig.1). As a result the whole system, except the final pulse-stacking stage, could be monolithically integrated. In this experiment we use a five-pulse burst (each pulse is 1ns long), with the two last pulses being of equal amplitude (Fig. 2). Inter-burst repetition rate can be arbitrarily chosen, and in this experiment is set at 10kHz. Pulse bursts are amplified in a fiber amplifier chain with a 55μm chirally-coupled-core fiber (CCC) based final power-amplifier stage, with the total burst energy reaching 1.2 mJ at 12W average power. For coherent pulse stacking the GTI resonator length has to be precisely controlled using a PZT mirror to match the pulse repetition period to within a fraction of an optical cycle. A small part of the original oscillator signal is branched-off to provide a GTI-monitor signal for cavity-length locking using a scheme similar to the Pound–Drever–Hall locking technique. The amplified signal and the monitor signal share the GTI cavity by polarization multiplexing, as shown in Fig.1.

With the GTI stabilized, a stable coherently-stacked solitary pulse is achieved at the output, as shown in Fig. 2, with a pulse energy enhancement of ~2.5, defined as the pulse energy ratio between the output stacked pulse and the most intense input pulse. The stacking contrast, defined as the pulse energy ratio between the output stacked pulse and the most intense "suppressed" output satellite pulse, is measured to be ~17dB. Note that the first weak pulse in the burst can never be suppressed and, if needed, can be minimized by choosing a longer burst sequence. The demonstrated CPSA technique is fully compatible with a CPA scheme, as well as with coherent fiber-array combining, and therefore offers a potential path towards multi-Joule fiber based laser systems.

ICAN: A Novel Laser Architecture for Space Debris Removal

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The development of a revolutionary fiber-based laser architecture will enable novel applications in environments which have hitherto been impossible with traditional systems. Such an architecture has been developed by the International Coherent Amplification Network (ICAN) project.

Here we present an analysis of utilizing a space-based ICAN laser for the purpose of tracking and de-orbiting hyper-velocity space debris. The phasing together of many diode-pumped mono-mode fiber lasers can yield pulses with very high efficiency (>30%), beam quality ($M^2=1$), high average power (kW) and repetition rate (kHz). In addition, the excellent heat dissipation for fibers and precise beam maneuverability and focusing via phase control provides a system very adapt to the problem of orbital debris remediation.

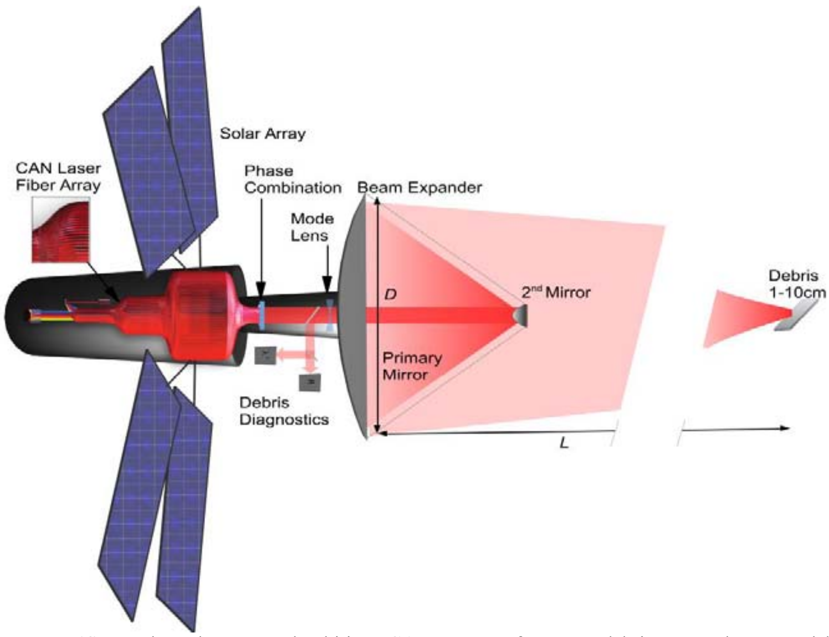

Fig. **Error! No sequence specified.**: The solar-powered orbiting ICAN concept for space debris removal. Powered by the solar array, the amplified beam from the combined array of fibers is expanded via the telescope to aperture D~2m which enables focusing to large distances, L>100 km , while the fiber phase combination controls the focusing distance of the beam. Reflected light from the debris is also collected by the telescope and enables precise diagnostics for its size and velocity.

For different design parameters such as fiber array size, it is shown that such a system would be sufficient to de-orbit small 1-10 cm debris in counter-propagation within a single instance via laser ablation. The concept for the system is also designed to actively scan and catalog the debris using the reflected light. Two different payload designs are presented: (i) as a solar powered satellite and (ii) as a module housed on the International Space Station (ISS). In the latter case, operation in tandem with the wide-angle Jem-Euso telescope as a debris tracker on-board the ISS is discussed.

Spatial-Temporal Multiplexing for Overcoming Limitations in Non-Linear Compression

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Non-linear compression (NLC) is a well-known concept for increasing the bandwidth of laser systems and thus allowing for the creation of shorter pulses [1]. The basic setup consists of a medium where the intensity of the incoming beam is high enough to cause spectral broadening via self-phase modulation (SPM). The use of an optical waveguide, e.g. a gas filled capillary [2-4], is a preferred solution here to have a homogenous distribution of the accumulated phase across the whole beam. This element is then followed by a compressor that reduces the pulse duration. While the concept of non-linear compression has already been employed in a variety of experiments, there are fundamental limitations depending on the medium. These include effects like optically induced damage, self-focusing and ionization. While it is possible to mitigate these problems in some cases by increasing the mode-field diameter, this is not always a solution and might even cause additional detrimental effects such as the loss of single-mode operation.
To overcome these limitations, we propose the technique of coherent combination of multiple pulses. This approach has already been successfully used with laser amplifiers [5]. There are basically two different approaches that can be pursued.

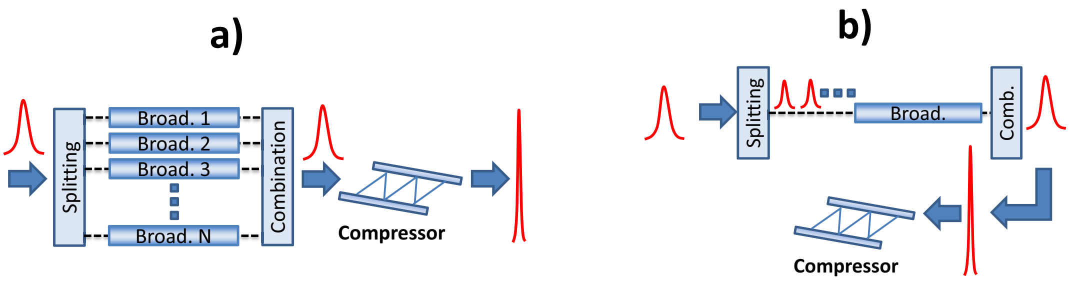

Fig.1. Schematic setup of a) spatially separated broadening in parallel waveguides and b) using temporally divided pulses

In figure 1a) the combination of multiple parallel waveguides is shown. The input pulse is split up into multiple channels, therefore, reducing the peak-power of each pulse replica. They are then broadened in separate waveguides that can be pushed to their specific limits. This concept offers a scaling mechanism for peak-power and average power at the same time. The broadened pulses are finally recombined and the combined pulse is compressed in a common compressor. The second setup is shown in figure 1b). Here, temporally separated replicas are created which are then broadened in a common waveguide before recombination and compression takes place. Again, the peak-power of the replicas is reduced and therefore a scaling mechanism for the total peak-power is realized. It should also be noted that the combination of both concepts provides a multi-dimensional scaling opportunity. We will present theoretical investigation and experimental results, where the self-focusing limit for solid-core fibers has been overcome, for both of the proposed schemes.

Friday Session 2

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A Path Towards Joule-Class Femtosecond Pulses at >10kHz Repetition Rate

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Undoubtedly, the laser parameters required for the acceleration of particles to high energies are challenging for any existing laser architecture. So far, impressive results have been achieved by using large-scale titanium-sapphire systems [1]. Such bulk lasers are capable of generating the necessary pulse energies and peak powers (TW…PW), but are typically limited in efficiency and repetition rate. In the last decades, alternative solid-state-laser geometries such as slab, thin disk and fiber have emerged. So far, these systems cannot compete in terms of peak power with large-scale bulk lasers, but for many applications this is more than compensated for by their intrinsic advantages such as excellent beam qualities, high average powers and high efficiencies. Especially rare-earth-doped fibers have established themselves as an attractive and power scalable solid-state laser concept.

Here we discuss the concept of coherent pulse combination in order to close the peak-power gap between fiber- and bulk systems. We suggest a laser system that simultaneously achieves the immense peak power today only accessible with bulk lasers, and the high average power, beam quality and efficiency resulting from the fiber geometry. In principle, coherent combination of ultrashort pulses can be performed in the spatial and in the temporal domain. Of course, these two techniques are compatible to standard power-scaling methods such as chirped-pulse amplification and, therefore, allow for going beyond existing limitations. The spatial and the temporal approach have in common that the incident stretched femtosecond pulse is split into *N* replicas, subsequently amplified (with the intensity in the amplifier reduced by a factor of *N*) and, finally, recombined and compressed. There exist a plethora of different possibilities for a spatial separation and combination of laser beams. So far, the most powerful ultrashort-pulse laser systems (that already outperforms single-emitters [2]) use polarization beam-splitter cubes (PBSs) for pulse splitting and combining. Recently, also temporal splitting and combing to high pulse energies has been demonstrated by using cascaded PBSs and free-space delay lines [3]. A schematic setup of a laser system under development employing temporal and spatial multiplexing is depicted in Fig. 1. It is capable of generating efficiently 1 J femtosecond pulses at a repetition rate of 15 kHz (i.e. 15 kW of average power).

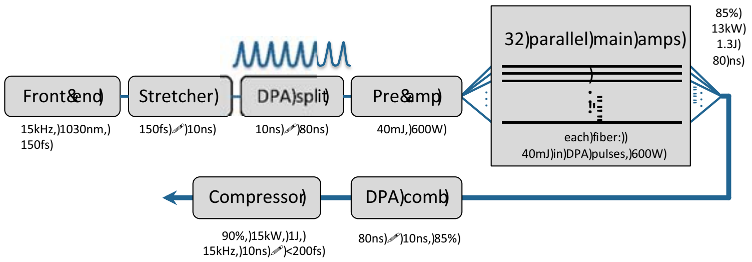

Fig. 1. Schematic setup of a fiber-based 1 J system using multidimensional pulse combining.

The pulses are generated from a front-end consisting of a fs-oscillator emitting at 1030 nm central wavelength and a pulse picker generating the desired final repetition rate of 15 kHz. After temporal stretching and splitting into 8 replicas, the pulses are pre-amplified and spatially distributed into 32 parallel main amplifiers. Each of these amplifiers includes an Yb-doped short-length large-mode-area fiber emitting an average power of 600 W and an overall pulse energy of 40 mJ (i.e. 5 mJ per replica). Afterwards, the individual beams are spatially combined with 85% efficiency and, finally, temporally combined and compressed. At the system output, pulses with an energy of 1 J and an average power of 15 kW can be sent to the experiment.

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Friday Session 2

Prospects of J-KAREN Upgrade and High Field Science

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The J-KAREN laser is a Ti:sapphire laser system with chirped pulse amplification (CPA) at the Kansai Photon Science Institute, Japan Atomic Energy Agency. J-KAREN can deliver a laser energy of 8 J on target with the pulse duration of 40 fs. Thanks to the double CPA, the laser system has a high contrast ratio of 10^{11}. The focused intensity is 10^{21} W/cm^2 with the f/2 optic and its value has been confirmed by the achievement of electron energy from an irradiated thin foil [2]. Currently, the laser system is being upgraded to ~ PW level on target at the repetition rate of 0.1 Hz. The challenge is to achieve the focused intensity of 10^{22} W/cm^2 with a f/1.4 optic employing two deformable mirrors. Two target chambers are prepared mainly for short-focus (f/1.4) with multiple vacuum ports and for long-focus f/10 or f/20.

In order to check the total performance of the upgraded laser system, we are preparing for two pilot experiments: ion acceleration using a thin foil target and keV coherent X-ray generation. A theoretical estimate shows that a more than 100 MeV proton beam can be accelerated at the power level of 800 TW [3]. We also have developed (present? are developing, future? will develop) an on-line ion spectrometer consisting of a movable slit, a dipole magnet with electrodes, and a phosphor screen read by a CCD to optimize the ion signals.

The coherent X-rays we focus on involve a new mechanism based on relativistic harmonics generation [4]. In this regime, the high density electron spikes formed near the laser pulse front propagating in a tenuous plasma emit high order harmonics of the drive laser frequency. A simple estimate shows the highest harmonic number scales as $\sim I^{3/2}$, where I is the laser intensity, a keV class X-rays are expected with our new laser system. We have designed (present? are designing, future? will design) a high resolution X-ray spectrograph with bent crystals.

The current scope of high field science is physics relevant at the peak intensity of 10^{22} W/cm^2. One of the interesting topics is to study the radiation reaction regime. With our modeling with the Landau-Lifshitz equation a strong laser to gamma ray conversion is expected with the interaction of the infrared laser pulse with a thin foil with the optimum scale length density [5]. Another approach is examining the elementary interaction of an electron with an intense electromagnetic wave. This test is complementary to the gamma flash, since the process is simplified. To do this, we have several options for electron beams of 100 keV by a thermionic gun, 150 MeV by a microtron accelerator, and GeV by laser wake field acceleration [6].

The first pilot experimental campaign will begin in 2015. The current status of the laser upgrade and preparation for the experiment is also given in the talk.

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Ultra-Short Pulse Duration, High Temporal Contrast, High Repetition Rate Multi-TW/PW Laser Systems Development

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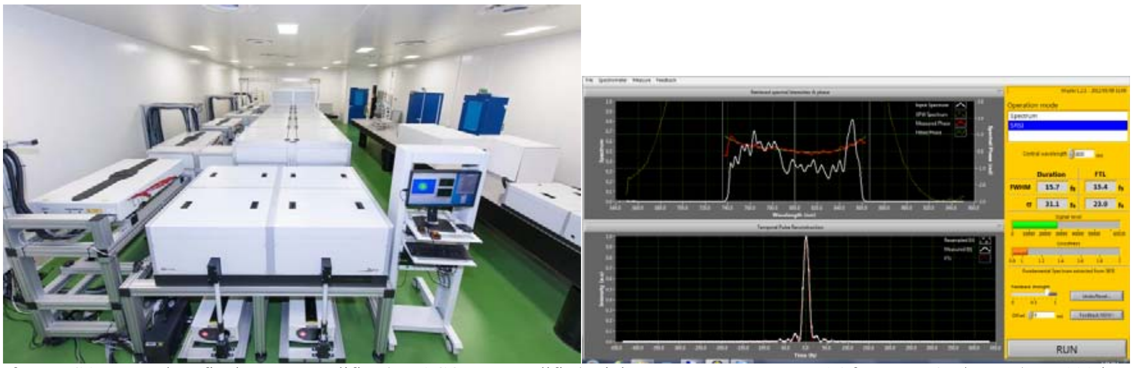
During the past years, the growing interest for research areas such as the creation of short scale length high density plasmas from solid target [1], has driven the development of high energy, high peak power laser systems. High filed Physics, in particular, laser-driven electron and ions acceleration, now requires laser intensities greater than 1022 W/cm^2 on target [2]. The expectations for the Laser system characteristics have grown with the increase of the output energy (>30 J). Therefore, the laser community takes now a great care on the topic of spatial and temporal qualities of the delivered beams.
For more than a decade, Amplitude Technologies is one the major actor in the development of these High Energy Ultra-fast lasers.
In this communication, we report the development of the latest generation of compact ultra-intense laser systems with unprecedented capabilities at this energy level: compressed pulse energy > 4J, Pulse duration as short as 16 fs and high temporal contrast ASE < 10-12, leading to peak powers greater than 250 TW at 5 Hz.
We will also describe the high performances obtained on the last PetaWatt laser manufactured (VEGA laser source at CLPU facility and DRACO in HZDR Dresden). We will emphasize the high level of performances on the laser/optical specifications point of view, but also on the Men Machine Interface (MMI) aspects (supervision, control-command, automated safeties) and finally on the complete characterization of the laser pulse/beam (spatial and temporal real-time diagnostics, metrology…).



Left: PULSAR PW-class final power amplifier (DRACO PW amplifier), right: WIZZLER measure: 16 fs FTL at 4 J / 5 Hz (JETI100 laser)

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Contrast Enhancements to the Orion Short Pulse Beamlines Using Picosecond OPA and Frequency Doubling

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The Orion laser [1] has been operating since April 2013 as a facility for performing high energy density plasma physics experiments. Orion has 10 nanosecond beamlines each producing 500 J at 351 nm and two chirped pulse amplification (CPA) beamlines each generating 500 J in 0.5 ps.

The Orion CPA beamlines consist of a mode locked Ti:sapphire oscillator generating 160 fs pulses centered at 1054 nm. These are stretched to 6ns then amplified to ~100 mJ by a 3 stage lithium tri-borate (LBO) optical parametric amplifier (OPA) [2]. The beam is amplified by a series of Nd:glass amplifiers of increasing aperture then compressed to ~500fs using a pair of gold diffraction gratings and focused to target using an F#3 off axis parabola.

In common with other facilities of its class the main laser pulse is lead by a pre-pulse/pedestal of ~3 ns duration at ~$10^{7\text{-}8}$ of the intensity of the main pulse. This pedestal is due to parametric florescence from the nanosecond OPA and its intensity scales with the signal to noise ratio at the first stage of the OPA. The pedestal is intense enough to generate pre-heating in the target which makes some experiments impossible to realize. To mitigate this Orion has the ability to frequency double one the CPA beamines post compression at reduced aperture providing a 100 J, 527 nm beam with a contrast of 10^{14} [3]. In order to enhance the contrast in the first harmonic we have installed a short pulse (picosecond) optical parametric amplifier (SPOPA) in the front end of the system. The SPOPA increases the nanosecond contrast to >10^{10} without the energy losses associated with frequency doubling at reduced aperture. It is also possible to run the SPOPA in conjunction with the frequency doubling system to enhance the contrast to an estimated 10^{18} which is well beyond our current measurement capabilities.

Picosecond optical parametric amplifiers of similar designs to that presented here are used on OMEGA EP [4], Vulcan [5] and PHELIX [6]. Our system is inserted into the Orion CPA beamlines between the oscillator and nanosecond stretchers. A series of Pockels cells and polarisers select two separate pulses, one is stretched to a few picoseconds using a folded Martinez stretcher which is designed to match the stretcher and compressor used on the main beamlines. The other pulse seeds a linear regenerative amplifier which uses a diode pumped Nd:YLF amplifier module from Northrop Grumman to produce 1 mJ,~ 4 ps pulses at 10 Hz. The output of the regenerative amplifier frequency doubled using a 10mm thick LBO crystal achieving ~50% conversion efficiency.

The pump and signal pulses are combined in an LBO optical parametric amplifier to generate stable 30uJ pulses with a Gaussian spatial profile. The spectral output of the OPA is maintained by controlling the duration and beam size of the signal pulse such that it matches the pump beam and the OPA begins to saturate. This flattens the spectrum aiding the temporal fill of the nanosecond OPA and aids energy stability.

With the nanosecond OPA being seeded with nanojoule pulses from the modelocked oscillator, Orion achieves a contrast of ~$10^{7\text{-}8}$. Installing the SPOPA has introduced additional passive losses to the system reducing the contrast by over an order of magnitude. When the SPOPA is activated (and the gain from the nanosecond OPA is reduced to compensate for the higher energy seed pulse) the contrast is enhanced giving a contrast of >10^{10}.

The contrast of Orion operating with the output frequency doubled has been measured at 10^{14} when seeded using nanojoule pulses. When the picosecond OPA is used in conjunction with frequency doubling we achieve an estimated contrast of ~10^{18}. By using these contrast enhancement techniques either independently or simultaneously Orion can be used to produce high energy laser pulses over a wide contrast range.

Friday Session 3

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Generation of Intense Carrier-Envelope Phase Stabilized Pulses in the Single-Cycle Regime Using a Single d-Scan System

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Due to their well-defined electric field, multi-GW-level sub-1.5 cycle CEP stabilized laser pulses are extremely attractive for strong field physics applications. However, the generation and characterization of such pulses is a nontrivial task. Bandwidths reaching or exceeding one octave, as well as extremely short pulse durations, create additional challenges for the characterization setup that must be carefully addressed in its design and construction. So far, measurement of sub-1.5 cycle pulses has usually been performed by attosecond streaking (e.g. 3.3 fs in [1], or 2.1 fs using a multi-channel chirped mirror field synthesizer [2]), SEA-F-SPIDER (e.g. 3.5 fs in [3]), 2DSi (3.8 fs in [4]) or FROG (3.8 fs in [5]). Attosecond streaking, despite fully characterizing the electric field of the pulse in the streaking target plane, requires a complex vacuum setup and long measurement times. SEA-F-SPIDER, 2DSi and FROG, being all optical measurement techniques, significantly reduce such requirements, but still require interferometric beamsplitting, recombination and precise alignment and delay of multiple broadband beams.

Here we demonstrate that the dispersion-scan (d-scan) technique [6], whose setup consists only in a variable dispersion line and a spectrally-resolved nonlinear optical process in a single-beam, in-line configuration, can be extended to the sub-1.5 cycle regime using a single-channel hollow fiber compressor. Additionally, for octave spanning spectra, the d-scan setup doubles as an f-2f interferometer, allowing us to monitor and stabilize the CEP jitter of the pulses directly at the output of the hollow fiber compressor. We coupled 33 fs, 400 μJ pulses at 1 kHz from a femtosecond amplifier into a 250 μm core, 1 m long hollow fiber filled with Argon at 1 atm. The output beam of the fiber was sent to a d-scan setup composed of a pair of motorized BK7 glass wedges and ultra-broadband chirped mirrors (Ultrafast Innovations GmbH). The retrieval algorithm, described in detail in [6], compensates for limitations in SHG/SFG bandwidth, allowing the retrieval of a spectral phase spanning approximately one octave, corresponding to a pulse as short as 3.2 fs at a wavelength of 722 nm, i.e., 1.4 cycles, with an energy of 160 μJ [7]. Due to the spectral overlap of the SHG/SFG signal and the fundamental spectrum at 450-480nm, we also observe clear f-2f fringes, allowing the measurement of the CEP from the same d-scan setup. Using this signal for feedback and one d-scan wedge as the feedback element we attained a CEP jitter of 140 mrad over more than 100 minutes. This unprecedentedly simple and reliable approach provides reproducible CEP-stabilized pulses in the single-cycle regime for applications such as CEP-sensitive spectroscopy and isolated attosecond pulse generation.

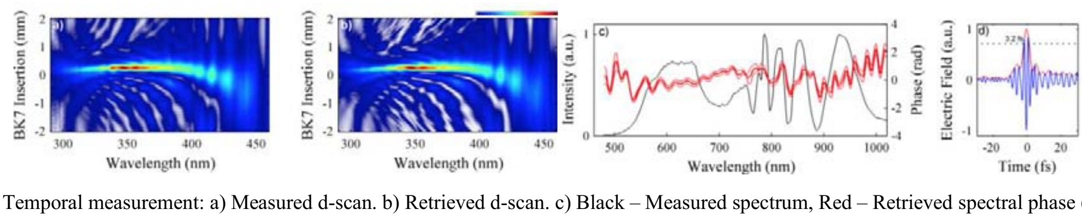

Fig. 1. Temporal measurement: a) Measured d-scan. b) Retrieved d-scan. c) Black – Measured spectrum, Red – Retrieved spectral phase (thick line – average of 5 retrievals. Thin lines – standard deviation of 5 retrievals). d) Electric field of shortest pulse (3.2 fs/1.4 cycle intensity FWHM).

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The Nexawatt Laser: Concepts for an Exawatt and Beyond Using NIF

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The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) is the world's highest energy laser. While NIF was designed as a nanosecond, few hundred TW peak power UV laser system, its 192 laser beams are capable of producing of order 5 mega-joules of infrared laser energy and have an architecture that is compatible with sub-picosecond pulse generation. This presentation will review novel concepts that would leverage the existing NIF infrastructure to produce exawatt and beyond peak power laser pulses.


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OKAMOTO optics
Aperture Optical Sciences
Amplitude Technologies
ATOS
LASER SCIENCE
PHASICS
SILIOS Technologies
SCHOTT glass made of ideas
NORTHROP GRUMMAN
CRISTAL LASER

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