ICUIL News

2024

Volume 12

The International Committee on Ultra-High Intensity Lasers

Chairman's Introduction

Professor Dino Jaroszynski
Chair of the International Committee on Ultrahigh Intensity Lasers, ICUIL

On behalf of the ICUIL Board, I would like to thank Chris Barty for his chairmanship over the last years, as well as Catherine Leblanc and Terrance Kessler for their valuable contributions as Board members. I would also like to welcome the new Board members Vincent Bagnoud, who has taken on the role of Treasurer, Jake Bromage, as Secretary, and Sylvie Jacquemot, who is now co-Chair. This new team brings invaluable experience leading ICUIL and acting on its behalf.

As described in the Newsletter, the huge growth in laser peak power and intensity is being driven by their applications. High-intensity lasers are currently among the largest instruments available, alongside accelerators and synchrotrons. The distinction between large accelerators and lasers is now blurring; laser-driven plasma accelerators have exceeded 10 GeV particle energies in a few centimetres, as recently demonstrated at the Texas Petawatt Laser Facility. At intensities of 10^{22-23} $\mathrm{Wcm^{-2}}$, delivered e.g. at the CoReLS facility, matter is fully ionised and plasma becomes non-linear due to the relativistic motion of electrons and rapid permittivity changes. At even higher intensities, when the Schwinger limit is approached, ion motion turns relativistic and quantum electrodynamic phenomena appear. Next-generation high-intensity lasers, such as the Extreme Light Infrastructure, XCELS and Vulcan 20-20, will explore this new and exciting ultra-high intensity regime, known as the intensity frontier. High energy densities are now readily achievable from high power lasers, enabling studies of astrophysical phenomena and inertial fusion, while the development of next-generation accelerators allows for radiotherapy and radio-isotope production. Applications of high-power lasers are making excellent progress as a basis for next-generation radiation sources that have unique characteristics, such as attosecond pulse duration, coherence and photon energies in the MeV range.

In a broader context, and consistent with millennia of advancement of science and technology, next-generation lasers are providing tools for researchers to increase knowledge and understanding of the immediate world and the wider universe, and to exploit this knowledge for the betterment of society which, for most, leads to growth across the nations, but also acts as a strong differentiator.

Development of new technologies and their application improves people's lives and a better quality environment leads to healthier, longer and more interesting lives. It is clear that exploitation of new technologies is having a significant impact on the world; but there are downsides – consider the changing climate due to the exploitation of carbon fuel resources. The scramble for control of natural resources is driving global politics and increasing conflicts and instabilities around the world. While the world is a better place to live in, revolutions in food production, healthcare, communications, transport and education have raised the standard of living everywhere; but it is also a more differentiated world, dividing the developed and lesser-developed countries. ICUIL is striving to support growth, while countering the differences arising from growth, by making laser technologies available to less advanced nations.

High-intensity lasers play an important part in generating knowledge and developing new technologies. This is evident not only in the inexorable growth of laser technology but also in the proliferation of facilities dedicated to the exploitation and application of lasers. One of ICUIL's goals is bring communities together by providing a forum for communication between scientists to nurture development and exploitation of high-intensity lasers. The community has formed unique global networks of advanced laser facilities, forged collaborations between scientists to exploit lasers and provide a training environment to produce the next generation of creative scientists. Examples of scientists who have used high-intensity lasers to make world-leading advances are Pierre Agostini, Ferenc Krausz and Anne L'Huillier, who were awarded the 2023 Nobel Prize in physics for developing "experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter". The ICUIL Board congratulates these major achievements.

Their advances have only been possible because of the development of lasers over the last half a century. In 2018 Gérard Mourou and Donna Strickland were awarded the Nobel Prize for the ground-breaking invention of chirped pulse amplification, which is the major advance enabling laser technology development to produce high-intensity, ultra-short optical pulses.

The ICUIL community has recognised the benefits of advancing laser technology and applying it; over the last decade the number of laser facilities has trebled. The size and complexity of facilities is driving a need for skilled staff to develop and to exploit the lasers. Training is being provided through numerous graduate programmes to develop skills in experimental and theoretical methods, and engineering techniques. Laser components are becoming very large and costly, with long delivery times, which is stimulating the development of new amplification methods e.g. by coherently combining multiple beams and creating new robust optical media based on plasma for manipulating ultra-high-intensity laser beams that can result in significant reduction of the size of optical components. Many new diagnostics, described in the Newsletter, are being developed and the community now regularly uses advanced methods such as artificial intelligence in the design and optimisation of laser experiments and data extraction.

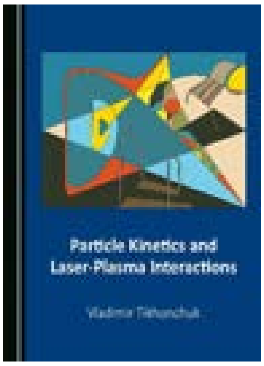
The communities represented by ICUIL are versatile; they have taken advantage of the COVID-19 pandemic to develop new ways of working, such as remotely controlled experiments, which is offering a new way of reaching out to lesser-developed areas of the world. It will allow not only uncovering talent from around the world but transferring advanced technologies to these countries, thus increasing the breadth and the depth of research undertaken around the world by the community.

ICUIL working groups have been set up to accelerate progress by sharing information, exploring opportunities for joint effort, exchanging equipment, ideas and personnel among laser laboratories world-wide. We encourage you to join one or more of these working groups; they require your participation to be successful. The working groups will help promote diversity and attract students to high-field science by promoting their education and training, their interactions with prominent scientists, and access to the facilities and exposure to new techniques and unique research tools. They will strengthen and exploit synergy with other relevant fields and techniques, notably accelerator-based free-electron lasers and medical application of lasers.

An important part of ICUIL is convening conferences. After a two year delay caused by the COVD-19 pandemic, the 9th ICUIL conference was held on Jeju Island off the South Korea coast, in 2022, chaired by Chang-Hee Nam and Chris Barty. The conference, dedicated to ultra-high-intensity lasers and their applications, was a great success, attracting a record number of participants – 166 from people at all career stages from 22 countries – in spite of the pandemic. The next 10th ICUIL conference will be held on September 9-13 this year at the El Cozumeleño Beach Resort on the beautiful Cozumel Island off the Mexican coast. It will be chaired by Eric Rosas (Mexican Photonics Cluster, Mexico), Christian Schubert (Universidad Michoacana de San Nicolas de Hidalgo, Mexico) and Tsuneyuki Ozaki (INRS, Canada).

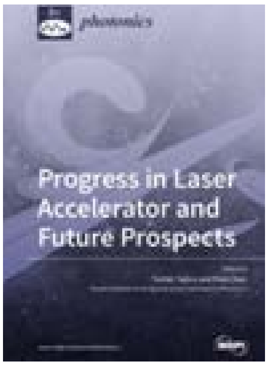
This conference series is a good example of ICUIL's outreach efforts to promote development of high-intensity lasers in less developed countries, which is broadening the community's reach and scope. We thank all Conference Chairs for their valuable contributions to the community and encourage you all to attend the 10th ICUIL Conference.

In the Book Stores



V. Tikhonchuk recently published
“Particle Kinetics and Laser-Plasma Interactions”
(Cambridge Scholars Publishing, ISBN: 1-5275-5254-3)

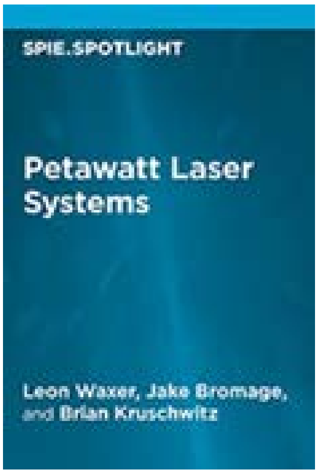
The book provides a comprehensive introduction to the physics of the interaction of intense laser pulses with high-temperature plasmas motivated by applications in high-energy-density physics and inertial confinement fusion. It combines the presentation of basic elements of the kinetics of charged particles in plasma and properties of electromagnetic waves with up-to-date developments related to nonlinear laser-plasma interactions, plasma heating, particle acceleration, excitation and mitigation of parametric instabilities.



T. Tajima and P. S. Chen edited a Photonics special issue
“Progress in Laser Accelerator and Future Prospects”
published by MDP Books (ISBN 978-3-0365-7472-1)

Among the 15 papers, E. Barraza-Valdez *et al*. explore numerically the near-critical density regime for laser beat-wave acceleration while D.E. Roa *et al*. describe the possibility to drive laser wakefield acceleration with fiber lasers for endoscopic cancer therapy. Both papers are co-authored by the recipients of the 2018 Nobel Prize in Physics.

https://www.mdpi.com/journal/photonics/special_issues/Laser_Accelerator#info



L. Waxer, J. Bromage, and B. Kruschwitz recently published
"Petawatt Laser Systems"
(SPIE Press)

This work introduces the reader to the science and technology underpinning petawatt laser systems with a goal of providing an appreciation of the substantial technological advances required to achieve today's state-of-the-art, high-intensity laser performance. Intended for the non-specialist with a general knowledge of lasers, topics include a brief introduction to ultrashort laser pulse generation, broadband laser amplifiers with an emphasis on approaches that scale to large apertures, design considerations for chirped pulse amplification systems, methods for optimizing and characterizing on-target peak powers and intensities, current limitations to state-of-the-art petawatt lasers, and prospects for future systems.

https://spie.org/publications/books/spotlights

ICUIL Prizes Announcement

IUPAP ICUIL Early Career Scientist Prize

The IUPAP ICUIL Early Career Scientist Prize is recognizing outstanding contributions made by scientists at early stages of their careers in the field of Ultra-high Intensity Laser Science & Technology. The recipients must be no more than 8 years past the award of their PhDs on 1 September 2024 (excluding career interruptions).

The awardee will be asked to give a talk at the next ICUIL conference (September 9–13, 2024, Cozumel, Mexico) and to write an article for the ICUIL newsletter.

Nominations should be sent before March 29th, 2024, to the ICUIL chair (d.a.jaroszynski@strath.ac.uk) with the following email subject " IUPAP ICUIL Early Career Scientist Prize: nomination for *Name-of-Nominee*".

The nominations should include a 3-page description of the work of the Early Career Scientist, clearly mentioning key achievements and up to 5 major publications (with DOI and citation numbers) in support of the nomination, a CV with a full list of publications and up to 3 reference letters, combined in a single pdf file. A short citation (no more than 350 characters) must also be proposed. Nominators are asked to include a statement saying that, to the best of their knowledge, the nominee meets the commonly held standards of professional ethics and scientific integrity. Self-nominations will not be accepted.

The ICUIL Board strongly encourages diversity of nominations, particularly in terms of gender and other under-represented groups and geographical regions.

IUPAP ICUIL Yoshiaki Kato Award
for outstanding contributions in ultra-high intensity laser S&T

This Award is established in honour of Prof. Yoshiaki Kato, who was the first chair of the IUPAP Working Group: International Committee on Ultrahigh Intensity Lasers (ICUIL).

It is presented for research achievements, which have either shaped the world of ultra-high intensity laser science and technology, or have demonstrated the potential to do so in the near future. The development of new technologies, novel applications of existing ones will be considered in the determination of the award.

The awardee will be asked to give a lecture at the next ICUIL conference (September 9–13, 2024, Cozumel, Mexico) and to write an article for the ICUIL newsletter.

Nominations should be sent before March 29th, 2024, to the ICUIL chair (d.a.jaroszynski@strath.ac.uk) with the following email subject "ICUIL Yoshiaki Kato: nomination for *Name-of-Nominee*".

The nominations should include a 3-page description of the scientific achievements of the nominee and how they have influenced the field of ultra-high intensity laser science and technology, a short citation (no more than 350 characters), the 5 major publications and the most significant qualifications and honours of the nominee, plus 3 letters of support, combined in a single pdf file. Self-nominations will not be accepted. ICUIL Board members cannot be nominated.

Report on the ICUIL 2022 Conference

Chang Hee Nam
Center for Relativistic Laser Science (CoReLS);
Institute for Basic Science & Gwangju Institute of Science and Technology (Korea)

Due to the COVID-19 pandemic, ICUIL 2020, initially scheduled to be held on Jeju Island in South Korea early September 2020, was postponed by 2 years. The 9th International Conference on Ultrahigh Intensity Lasers (ICUIL 2022) was thus held on September 18–23, 2022 on Jeju Island, Korea. The two conference chairs were C. H. Nam and Chris Barty (UC Irvine, USA).

Since its inception in 2004, the ICUIL conference has served as the representative venue for reporting the research progress and communicating among researchers in the area of ultrahigh intensity laser science and technology. Through the ICUIL conferences in the past one and a half decades, we have witnessed the increase of laser intensity by more than several orders of magnitude, reaching an extreme intensity of about 10^{23} W/cm^2, and the corresponding expansion in the applications of ultrahigh intensity lasers from relativistic laser plasma interactions to strong-field quantum electrodynamics. At ICUIL 2022, in addition to the continued progress in the field, we had the opportunity to hear about new research results produced with multi-PW lasers around the world, of which proliferation was witnessed at ICUIL 2018 held in Lindau, Germany. Moreover, we celebrated the recent public recognition of our research area, marked by the 2018 Nobel Physics Prize given to Gerard Mourou (the first chair of ICUIL) and Donna Strickland for their invention of chirped pulse amplification, the very basis of our research on ultrahigh intensity lasers. In this sense, ICUIL 2022 was a festive venue to hear the special lecture, entitled "Extreme Light for the Benefit of Science and Society," by Prof. Mourou, and furthermore the community shared the emergence of pioneering science characterized by unprecedented physical parameters.

The conference programme included a range of topics in three categories: (1) Ultrahigh intensity lasers: design and performance, (2) Novel technologies for ultrahigh intensity lasers, and (3) Applications of ultrahigh intensity lasers. In addition to the special lecture, two keynote talks, 18 invited talks and 52 contributed oral talks were organized in a single session, along with 58 poster presentations.

The total number of participants was 166 from 22 countries, including 7 online participants, among whom 115 were from abroad: 28 from Germany, 27 from France, 15 from the USA, 9 from Hungary, 7 from India, 6 each from Czech Republic and UK, 4 each from Italy and Japan, 3 each from Canada, Portugal and Russia, 2 each from Iran and Israel, 1 each from Brazil, Egypt, Finland, Greece, Liberia, Romania and the Ukraine. Besides, 15 companies joined the exhibition showing their new products.

ICUIL 2024 Announcement

Eric Rosas
Clúster Mexicano de Fotónica, A. C. (Mexico)

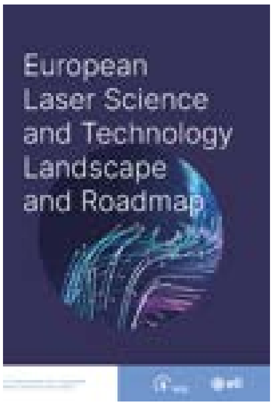
The 10th International Conference on Ultrahigh Intensity Lasers (ICUIL 2024) will take place on the island of Cozumel, Mexico from Sept. 9th to 13th 2024. Cozumel is a quiet island in the Caribbean Sea, off the eastern coast of Mexico's Yucatán Peninsula.

As with past ICUIL conferences, ICUIL 2024 will serve as the representative venue for reporting research progress and exchanging ideas among researchers in the area of ultrahigh-intensity laser science and technology. The event is exceptionally timely, with the recent recognition of our research field, marked by the 2023 Nobel Prize in Physics, awarded to Prof. Anne L'Huillier, Prof. Ferenc Krausz and Prof. Pierre Agostini for their studies in high-order harmonic generation and attosecond pulses.

ICUIL 2024 will also be the first of its series to be held in Latin America, recognizing the significant interest of many researchers in the region. Like the explosive advances we have seen in Europe, Asia and North America, we hope that ICUIL 2024 will serve as a catalyst for similar expansion in ICUIL research in Latin America through promoting international collaborations.

European Laser Science and Technology Landscape and Roadmap

Sylvie Jacquemot[1]*, Allen Weeks*[2]*, Jens Biegert*[3]
[1]*Laserlab-Europe Project Coordinator*
[2]*ELI ERIC Director General & IMPULSE Project Coordinator*
[3]*Laserlab-Europe AISBL Executive Director*



Laserlab-Europe and the Extreme Light Infrastructure (ELI ERIC) have joined forces to analyse the current laser-based science landscape in Europe. The analysis aims to assess the European laser community to provide a better understanding of the services offered to users by Research Infrastructures (RIs) operating laser sources as well as the user needs and requirements.

Across Europe, there is a wide distribution of laser RIs hosted by some 23 countries, including 11 'Widening countries'. These very diverse facilities – ranging from microscopy stations to highly accessible national instruments, to ESFRI landmarks – each offer unique, high-quality services and expertise, and help serve a broad user community extending beyond the European borders. They also contribute to a coherent, staged laser ecosystem, coordinated by Laserlab-Europe and ELI ERIC.

The consolidated report gives an overview of the complex landscape of laser RIs in Europe, identifies complementarities and efforts to be aligned, and defines high-level objectives. The factual and up-to-date information provided will support discussions – with the European Commission and with national agencies – about sustainable funding for RIs. It will prove valuable to decision-makers, stakeholders and the wider laser RI community in ensuring the growth and sustainability of this critical field.

RI services and user community needs

The RI survey revealed that the European laser landscape is extremely diverse in terms of the services offered to users, and is not restricted to laser photon providers. The services range from primary laser sources to secondary sources – covering a wide range of radiation wavelengths – and include a variety of laser-based instruments and techniques.

A strong collaborative component exists alongside this access to tools and techniques. The majority of the RIs offer the support and expertise of their local technical and scientific teams, meeting the needs of almost 90 percent of users surveyed. In addition, many RIs offer additional support services, which are greatly appreciated by users. For example, around half of the RIs offer mechanical workshops, one-third offer biology/cell culture laboratories (up to bio-sample management and handling) or target laboratories, and one-fifth offer cryogenics. These additional features should be duly advertised, as they may be specific to the European laser RI community and they may encourage new users to apply for access.

Collaboration and support from technical and scientific teams are essential and highly valued by the user community. The impact of laser-based instruments is broad, and crosses a large number of sectors, including energy, health, space, environment, manufacturing, food production and processing as well as cultural heritage. For an in-depth analysis of the various sectors, please download the landscape and roadmap document.

Need to establish a sustainable European laser RI ecosystem

The survey results suggest a need to establish a sustainable European laser RI ecosystem, offering improved access to facilities and increased collaboration. The challenges in standardisation, coordination and funding need to be addressed to ensure the sustainability and global competitiveness of the resulting ecosystem.

The report makes several recommendations to address these challenges, including:

- establishing a common strategy for laser RIs in Europe to better align efforts, enhance complementarities and increase synergies
- encouraging standardisation and interoperability of laser RIs to improve efficiency, facilitate user mobility and ensure data compatibility
- securing long-term and sustainable funding for laser RIs to ensure their stability, growth and competitiveness
- enhancing coordination between laser RIs and user communities, to gain a better understanding of user needs and requirements, and to better align the development of laser RIs with user demands.

To download the Landscape Analysis, please visit: https://www.laserlab-europe.eu/news-and-press/european-laser-science-and-technology-landscape-and-roadmap.pdf

New Facilities at the Central Laser Facility to support science, technology, innovation and industry

Cristina Hernandez-Gomez
Head of "High Power Lasers" Division, Central Laser Facility, STFC Rutherford Appleton Laboratory (England)

There are three exciting projects taking place at the Central Laser Facility, located in the Harwell Campus in Oxfordshire (UK): EPAC, HiLUX and Vulcan 20-20.

EPAC

The Extreme Photonics Applications Centre (EPAC), under construction at the Harwell Campus in Oxfordshire (UK), will comprise a 1 PW laser operating at 10 Hz, with two dedicated experimental areas, housed in a stand-alone building. EPAC will bring together academic and industrial communities in a diverse programme of fundamental and applied research.

EPAC will use diode-pumped solid-state laser (DPSSL) technology developed by the CLF. To achieve the required high peak power and repetition rate, the laser system will comprise a Front End using Optical Parametric Chirped Pulse Amplification (OPCPA), and a main Ti:sapphire amplifier pumped by the DPSSL system.

The building construction phase of the EPAC was completed in May 2022, and the laser systems are currently being installed. All work is expected to be completed in 2025 with Experimental Area 1 (EA 1) becoming fully operational in 2026, capable of exploiting the applications of laser-driven plasma accelerators at 10 Hz.

HiLUX

HiLUX is a £17.2M project to upgrade the Ultra and Artemis facilities at the CLF. This upgrade of the CLF's existing open-access laser spectroscopy and dynamics facilities, based in the Research Complex at Harwell (RCaH), will extend the range of techniques for 'ultrafast dynamics' – changes and processes on timescales of femtoseconds to picoseconds. These spectroscopic techniques essentially use the absorption or scattering of light to cover the electromagnetic spectrum from the deep infrared (giving information

EPAC Experimental Area 1 hall photograph and artist impression with beamline installed on molecular vibrations) to the extreme ultra-violet (electron motion) and soft x-ray (atomic positions).

The project began in April 2023 and has already seen significant change within the Ultra facility, as the original Ultra laser system has been decommissioned and the labs have been cleared ready for renovation. The project is due to be completed in March 2027, with the full suite of capabilities available at this time; in the interim, new experiments will be made available to the user communities as they are commissioned.

VULCAN 20-20

The Vulcan 20-20 project is a major upgrade to the existing Vulcan facility at the CLF, to drive new scientific research in High Energy Density and Extreme Field Science. With this latest upgrade, Vulcan will deliver 20 petawatts in a single beam using the OPCPA technique. Vulcan is currently a multi-beam facility, and this upgrade will also increase the energy of the long pulse beams by a factor of ten such that the total energy output is up to 20 kJ – hence Vulcan 20-20 (20 PW-20 kJ). The upgraded facility will have a new large experimental area, and the existing Target Area Petawatt (TAP) will also be refurbished. The project began in July 2023, and the first activity will involve decommissioning the existing Vulcan facility to enable construction of the building extension. Vulcan 20-20 is expected to be operational in 2029.

The Apollon Laser Facility Upgrade to the Multi-PW Level

Dimitrios N. Papadopoulos
Laboratoire pour l'Utilisation des Lasers Intenses (France)

The recent commissioning of the last amplification stage of the Apollon laser system allowed the generation of 140 Joules/minute. Compression of the pulses to <24 fs with an energy of about 90 Joules, at the output of the compressor, corresponds to >3.7 PW of actual peak power capacity of the Apollon laser. The first experimental campaign at about 2 PW using solid targets has been realized and the facility is preparing for the first international call of experimental proposals at the multi-PW level.

The Apollon laser facility (Orme des Merisiers, Saclay, France), aims to be among the first multi-PW installations in the world devoted to the study of high intensity laser matter interaction at unprecedented regimes and peak intensities above 5×10^{22} W/cm^2. The final goal of the Apollon laser is the generation of 10 PW peak power pulses corresponding to an energy of 150 J and 15 fs duration at a repetition rate of 1 shot/minute [1, 2]. The architecture of the Apollon laser is hybrid, combining a high contrast OPCPA based Front End [3] followed by 5 Ti:sapphire multipass amplifiers allowing to reach up to 300 J before compression. Apollon provides up to four beam lines (10 PW, 1 PW, 10 TW, uncompressed beam), all generated by the same beam after the last amplifier with the possibility to be combined on the target under different geometries and synchronization configurations. The Apollon facility offers two experimental areas (fig. 1): 1) The Short Focus Area (SFA), where tight focusing (F#2.5) on solid targets and ion acceleration is the principal objective; 2) The Long Focus Area (LFA), where mostly gas targets and electron acceleration experiments are realized. The Apollon facility is open to the international research community since 2020 with ~15 experimental campaigns already realized with the 1 PW beamline of the system. The recent commissioning of the last amplifier of the laser (at this phase, with only a part of the final pump energy) allowed the operation of the system to the 3.7 PW peak power level and the realization of the first experimental demonstrations with multi-PW pulses.

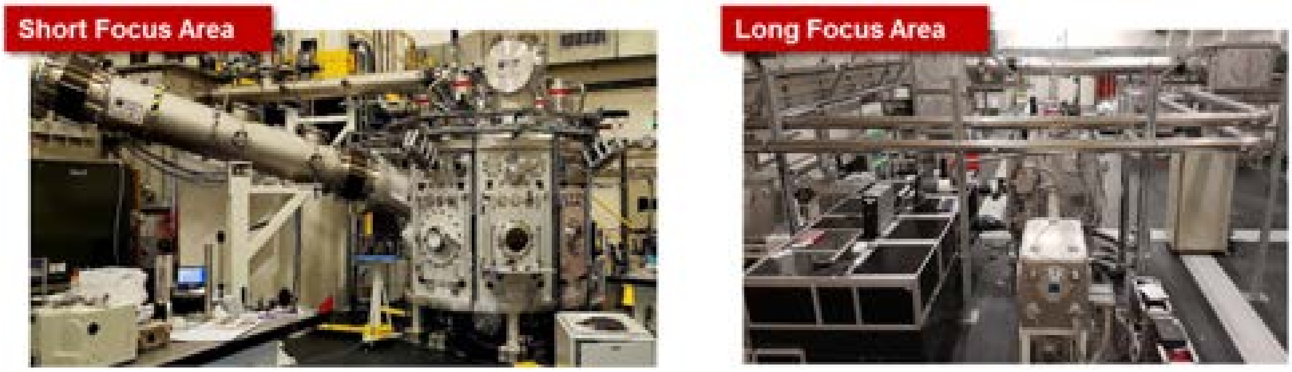


Fig. 1. General view of the two experimental areas of the Apollon facility. The SFA area is already fully operational for both beam lines, the 1 PW and the 10 PW one, with the interaction chamber and part of the beam transport systems of both lines shown in this picture (left). The LFA area is fully operational for the 1 PW beam line (the interaction chamber and part of the beam line transport are shown on the foreground of this picture), while the 10 PW beam line is in construction phase (background of the image) (right)

For the needs of the initial operational phase, at the 1 PW peak power level of the Apollon facility, a period of about 2 years, the last amplification stage of Apollon (5 stages in total) has been by-passed, limiting the maximum energy capacity of the laser at about 30 J (before compression). During this time, the construction and optimization of this amplifier has been progressively realized. Recently, for 270 Joules of pump energy delivered on the 196 mm diameter TiSa crystal of the amplifier we obtained >140 Joules every minute in a beam of 140 mm diameter. A typical fluence distribution of the near field of the amplified beam is shown in fig. 2 (left-top) presenting a flat-top repartition and a good homogeneity over the full aperture. The amplifier has been extensively tested regarding its short and mid-term stability characteristics showing typically < 5% PtV energy fluctuation (fig. 2, center-top) over a complete day of operation (300 shots, over 5 hours). The pointing and wavefront stability has been also measured to be about 7 µrad PtV, and 70 ± 10% Strehl ratio fluctuations, respectively, over 30 full energy shots. The amplified beam has been expanded by an off-axis parabolic telescope to 400 mm diameter and then compressed in the 10 PW beamline compressor (fig. 2, left-bottom). The pulse duration of the compressed pulse has been measured to < 24 fs based on a Wizzler device (fig. 2, right-bottom). Based on the transmission of the compressor, measured to ~70%, and the beam transport between the amplifier's output and the compressor (~92%), we estimate the maximum energy of the compressed pulses at >90 Joules corresponding to >3.7 PW peak power capacity. The compressed beam has been sent to the SFA area, where focusing by an off-axis parabola of 1 m focal distance (F#2.5) resulted in a focal spot with typically 55% Strehl ratio, after careful optimization of the wavefront (fig. 2, right-top). Based on the measured total laser chain transmission efficiency (between the amplifier and the target) of ~55%, the on-target maximum intensity can be, therefore, estimated to be $>10^{22}$ W/cm^2. Further measurements are scheduled to enable a precise estimate of the intensity capacity of Apollon, based on spectrally resolved on-target wavefront acquisitions, taking into account residual spatiotemporal coupling effects.

The first commissioning experiments using the multi-PW beam have been recently realized in the SFA area with the goal of proton acceleration and X-ray radiation generation using thin metallic foils as targets. The use of a non-optimized and uncoated protection thin film of the focusing parabola (against target debris) resulted in the limitation of the actual energy on the target to about 45 Joules and, therefore, an effective peak power around 2 PW. The obtained results (in preparation for publication) of >50 MeV maximum proton energy, agree well with the simulations and constitute a first step in understanding and further fine optimization of the laser itself towards even higher proton energies to be made in the near future. A dedicated temporal contrast measurement campaign and integration of an optimized double plasma mirror setup are scheduled during 2024.

During next year, a number of upgrades is scheduled for the laser system and the Apollon facility in general. The first one is to increase the pump energy of the last amplifier to at least 600 Joules, to allow amplification to >250 Joules (beginning of 2024). The commissioning

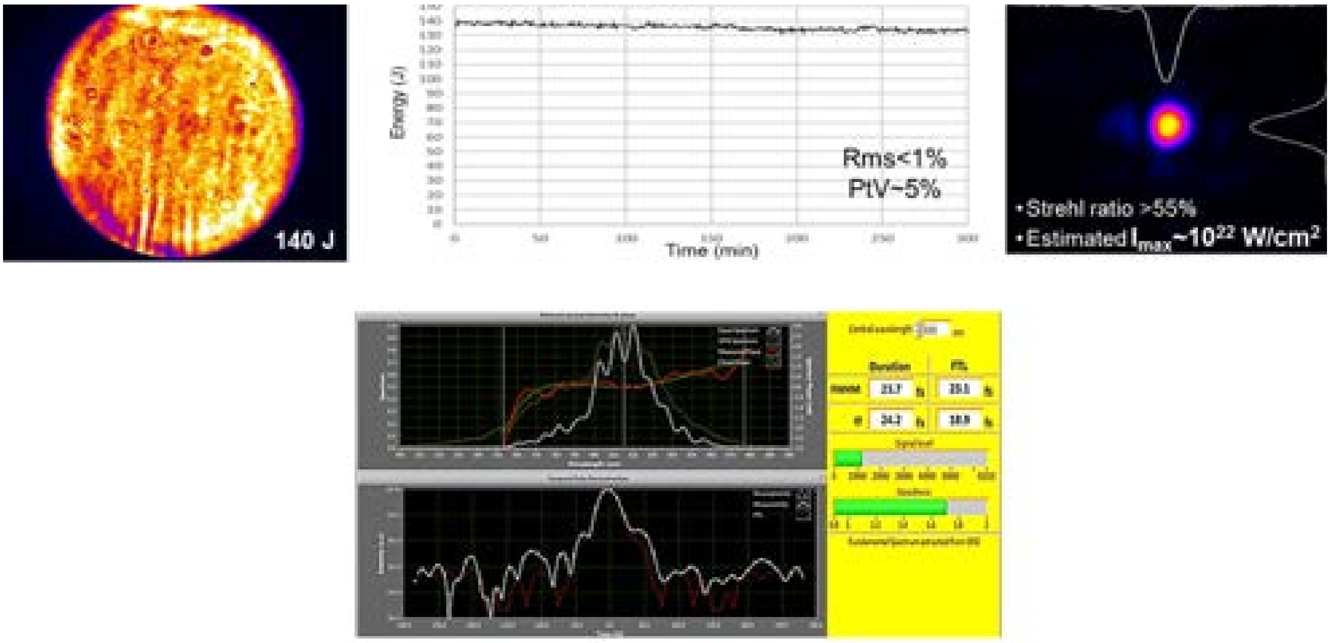


Fig. 2. Near-field energy distribution of the multi-PW beam (left-top). Typical energy stability of the last amplifier over 300 shots (5 hours) (center-top). Typical focal spot quality obtained in the SFA area (right-top). General view of the inside of the 10 PW compressor of Apollon laser (left-bottom). Wizzler measurement of the compressed pulses at the output of the 10 PW compression showing a pulse duration of 23.7 fs (for 23.1 fs Fourier transform limited duration)

of the LFA and first experiments with gas targets at the multi-PW level will follow, while the international opening of the facility to external users at the 7–8 PW level is scheduled for early 2025. Final optimization of the pulse duration of Apollon will result in the 10 PW operation during the same year.

References

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2. J.-P. Zou *et al.*, "Design and current progress of the Apollon 10 PW project", High Power Laser Sci. Eng. **3**, e2 (2015)

3. L. Ranc *et al.*, "Improvement in the temporal contrast in the tens of ps range of the multi-PW Apollon laser front-end", Opt. Lett. **45**, 4599 (2020)

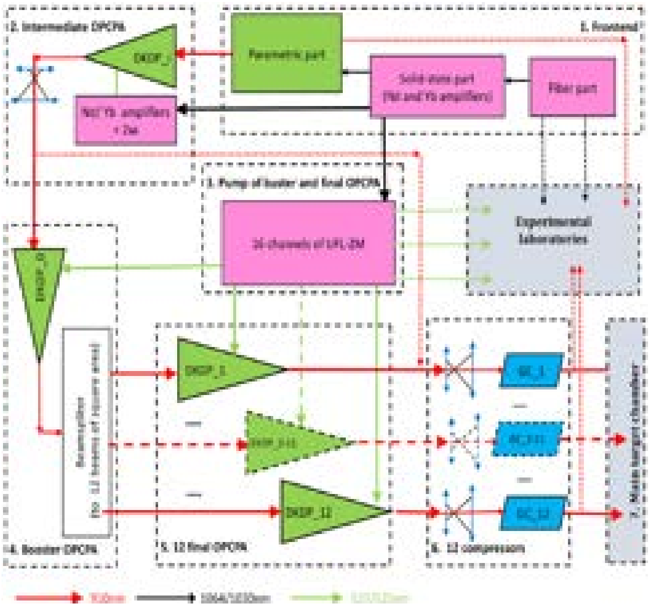
4. D. N. Papadopoulos *et al.*, "First commissioning results of the Apollon laser on the 1 PW beam line", in *CLEO Science & Innovations* (2019)

5. K. Burdonov *et al.*, "Characterization and performance of the Apollon short-focal-area facility following its commissioning at 1 PW level", Matter Radiat. Extrem. **6**, 64402 (2021)

Exawatt Center for Extreme Light Studies (XCELS)

The XCELS (eXawatt Center for Extreme Light Studies) project aims to create a large scientific infrastructure based on lasers with a giant peak power. The project relies on the significant progress achieved in the last decade. The planned infrastructure will incorporate a unique light source with a pulse power of 600 PW using OPCPA in large-aperture DKDP crystals. The interaction of such laser radiation with matter represents a completely new fundamental physics. The direct study of the space-time structure of vacuum and other unknown phenomena at the frontier of high-energy physics and the physics of superstrong fields will be challenged. Expected applications will include the development of compact particle accelerators, the generation of ultrashort pulses of hard X-ray and gamma radiation for material science, enabling probing material samples with unprecedented spatial and temporal resolution, the development of new radiation and particle sources, etc.

See detailed description of the XCELS laser and scientific case in E. Khazanov et al., "eXawatt Center for Extreme Light Studies", High Power Laser Sci. Eng. **11**, e78 (2023)



General diagram of the XCELS laser. DKDP_i: nonlinear crystal in intermediate OPCPA; DKDP_0: nonlinear crystal in booster OPCPA; DKDP_1-12: nonlinear crystals in final OPCPAs; GC: grating compressors

Compression of Femtosecond Laser Pulses Using Self-phase Modulation

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The International Union of Pure and Applied Physics (IUPAP)

1. Introduction

From the advent of lasers to the present day, one of the main goals of research in this field has been to obtain the shortest possible laser pulses. The pulse duration at the output of femtosecond lasers is usually close to the Fourier limit and can be shortened by increasing the spectrum width. For this, self-phase modulation (SPM) during pulse propagation in a medium with cubic (Kerr) nonlinearity is used. The index of refraction n of such a medium depends on intensity as

$$n = n_0 + n_2 I, \qquad (1)$$

where n_0 is the linear index of refraction and n_2 is the nonlinear index of refraction. It can be seen from (1) that the pulse in this case passes through a medium with a time-varying refractive index, since $I=I(t)$. This leads to self-phase modulation (SPM) and, consequently, to broadening of the emission spectrum:

$$\omega_{inst}(t) \equiv \partial\Phi/\partial t = \omega_0 - k_0 z \partial n/\partial t , \qquad (2)$$

where ω_{inst} is the instantaneous frequency, ω_0 is the centre frequency, $k_0 = \omega_0/c$, $\Phi = \omega_0 t - k_0 z n$ is the phase, z is the coordinate, and c is the speed of light. In addition to spectral broadening, all frequency components of the spectrum must be in phase. This is readily attained, as near the pulse maximum, ω_{inst} depends on frequency linearly, while the phase of the spectrum quadratically (fig. 1). This method of nonlinear compression of laser pulses is usually called post-compression. In application to high-power lasers, the term Thin Film Compression (TFC) or the Compression after Compressor Approach (CafCA) is also used.

We can formulate four fundamental problems that limit the scaling of input and output pulses: large-scale self-focusing (LSSF) characterised by critical power P_{cr} and length L_{cr}, small-scale self-focusing (SSSF) determined by the B-integral $B=k_0 L n_2 I$, optical breakdown that occurs at the intensity higher than $I_{br}=P_{br}/A$, A being the aperture, and spatial inhomogeneity of the SPM. The influence of these restrictions on the power scaling at post-compression significantly depends on the geometry of beam propagation in a nonlinear medium (fig. 1). We will consider a waveguide (secs. 2–4) and free (sec. 5) propagation. Results of more than 150 experimental studies are presented in fig. 2 in historical development and in figs. 3, 4 on the plane of the parameters.

2. Single mode fibre (SMF)

The simplest waveguide is a single-mode fibre (SMF), in which the field is retained due to either total internal reflection (SMF-TIR) or cladding microstructuring – the so-called photonic crystal fibres (SMF-PCF). Their important feature is minimal energy loss, as well as compactness and practically unlimited length, which makes fibres indispensable for low-power lasers. At the same time, a very small aperture of single-mode fibres is also their main disadvantage: LSSF and optical breakdown limit power scaling. In SMF-TIR, the input power P_{in} is strictly limited to P_{cr} of about 4 MW.

Significant progress has been associated with the SMP-PCF invented in 1996. The size of the fundamental mode in the SMF-PCF was increased, while the single-mode regime was retained. This in itself did not result in significant power scaling, since the main limitation, P_{cr}, does not depend on aperture. This limitation was overcome by using hollow-core SMF-PCFs, in which P_{cr} is much higher, as light propagates mainly in gas, the P_{cr} of which is several orders of magnitude higher than that for fused silica. Thus, optical breakdown limits the power. The threshold breakdown power P_{br} in hollow-core SMF-PCFs is higher due to a higher (compared to silica) gas breakdown threshold and a large mode size.

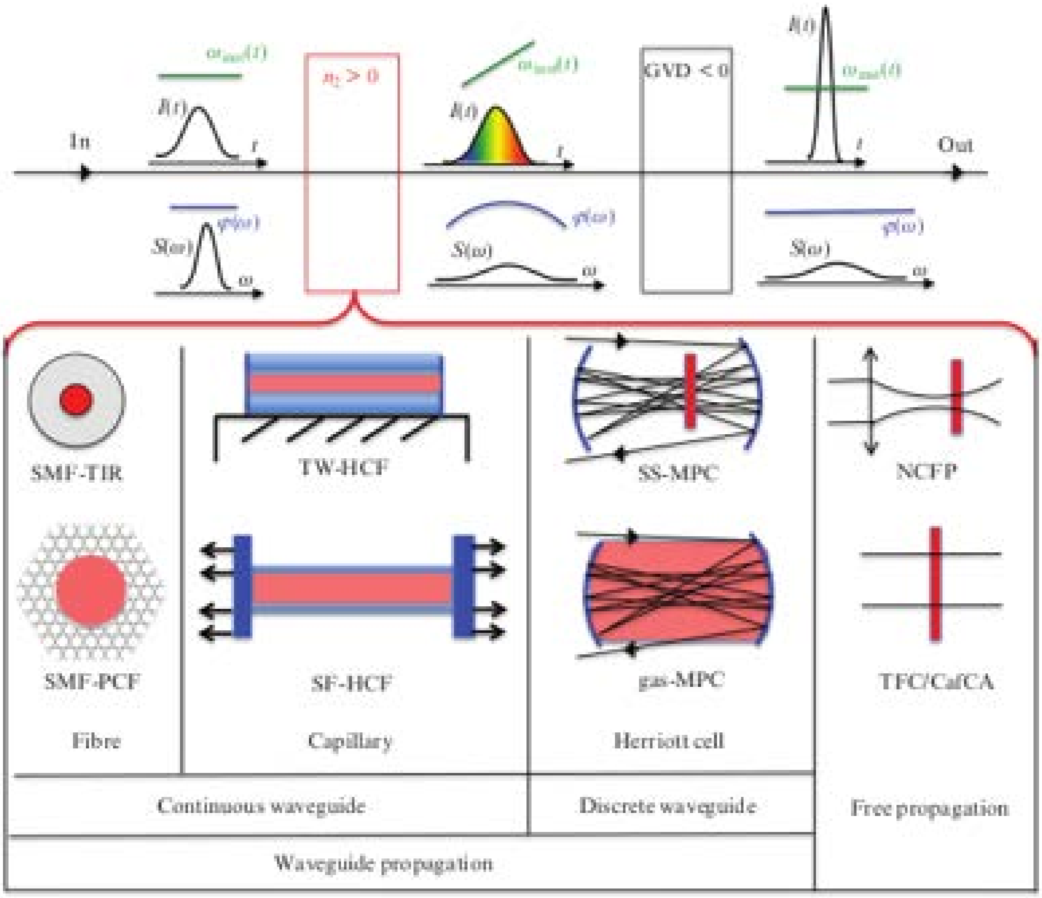

Fig. 1. Principle of post-compression and variants of nonlinear medium geometry

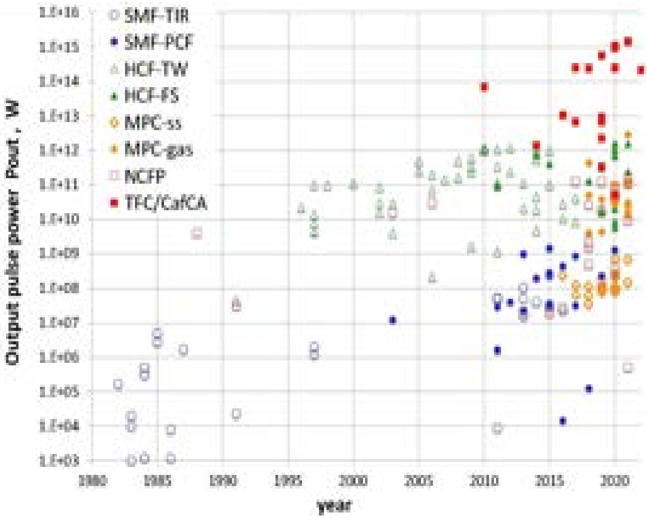

Fig. 2. History of post-compression. Experimental results

3. Capillaries (HCF)

The input power P_{in} may be significantly increased using, instead of single-mode fibres, gas-filled capillaries i.e. hollow-core fibres (HCF). The characteristic feature of a capillary is its multimode nature and the fact that the grazing angles of incidence on the walls of the capillary, rather than the total internal reflection, prevent the beam from transverse spreading. As a result, the energy transmission of HCF is typically less than 50%. The HCF advantages are a large aperture (up to 1 mm) and the use of gas as a nonlinear medium. A large aperture and a high gas breakdown threshold increase P_{br}, while a small n_2 in gases increases P_{cr}.

The length of conventional rigid thick-walled hollow core fibres (HCF-TW) does not exceed 1 m, since it is impossible to ensure the required quality of the inner wall for longer lengths. The fact is that losses are significant, even with minimal bends (deformations) of the capillary. Stretched flexible thin-walled hollow core fibres (HCF-SF) can have a significantly longer length. The idea is that capillaries with thin walls (tens of microns) are flexible, which allows them to be stretched by applying opposite forces to both ends. As a result, the hollow core becomes straight, like a guitar string. Thus, the capillaries have radically shifted the power limits (P_{cr} and P_{br}) up to tens of GW (figs. 2–4).

4. Discrete waveguides – multipass cells (MPC)

Continuous waveguides – fibres or capillaries – may be replaced by discrete ones. The beam propagates in free space, and diffraction is compensated for by periodically located lenses or mirrors, with waists in between. In practice, discrete waveguides may be organised using a compact Herriott cell, which consists of two spherical mirrors with an aperture much larger than the beam aperture. Such devices are called multipass cells (MPCs), through which the radiation passes dozens of times. Solid-state plates (MPC-ss), usually located near the waist, and a gas filling the entire cell (MPC-gas) are used as nonlinear media. In both cases, the SPM remains small per pass but accumulates over many passes.

There are two qualitative differences between MPC-gas and MPC-ss. First, the nonlinear medium occupies the entire propagation region i.e., the length of the medium is much longer than the length of the waist: $L >> kw^2$. It was shown that under two conditions – the B-integral << 1 and $(P/P_{cr})^2 << 1$ – the Gaussian beam (TEM_{00} mode) is resistant to self-focusing. Namely, during the propagation to the focal plane, part of the energy of the TEM_{00} mode is transferred to the TEM_{01} mode, but after the focal plane the direction of the energy flow changes, and all the energy from the TEM_{01} mode returns to the TEM_{00} mode. It is interesting to note the power of 2 in the second condition ($(P/P_{cr})^2 << 1$), which allows us to approach the critical power of up to $P = 0.5P_{cr}$. Secondly, the transition from a solid-state nonlinear medium to a gas medium enables a substantial increase in P_{cr} and, hence, in P_{in} and P_{out}. Thus, in MPC the power is limited by the value of P_{cr}. In MPC-ss, the nonlinear medium is thin and can be shorter than L_{cr}, which allows $P_{in} > P_{cr}$. In MPC-gas, P_{in} must be strictly less than P_{cr}, but the value of P_{cr} is much larger due to the low value of n_2 in gases (figs. 2–4).

5. Free propagation

An alternative to waveguides is a bulk solid-state nonlinear element in which a laser beam propagates freely. For a solid-state nonlinear medium, the case $P_{in} < P_{cr}$ is of little interest because of a small value of P_{cr}. Therefore, the only possibility is to use thin nonlinear plates with length $L < L_{cr}$. To avoid breakdown at a high radiation power, a large enough beam diameter is required, from 1 to 10 cm or more for multiterawatt and petawatt power. Thus, the geometry of the nonlinear medium radically changes from a long cylinder to a thin disk. Paradoxically as it is, the increase in power completely solves the problem of large-scale self-focusing. The point is that the focusing length L_{cr} at $P_{in} >> P_{cr}$ decreases as $(P_{in})^{-1/2}$ but grows as the square of the diameter i.e., at a given intensity L_{cr} increases (rather than decreases) in proportion to $(P_{in})^{1/2}$. In other words, LSSF can be neglected. As compared to the waveguide propagation, free propagation has three drawbacks.

First, spectral broadening inhomogeneous over the cross section leads to inhomogeneous pulse compression. In particular, at the beam periphery, where the intensity is much lower than along the axis, the compression

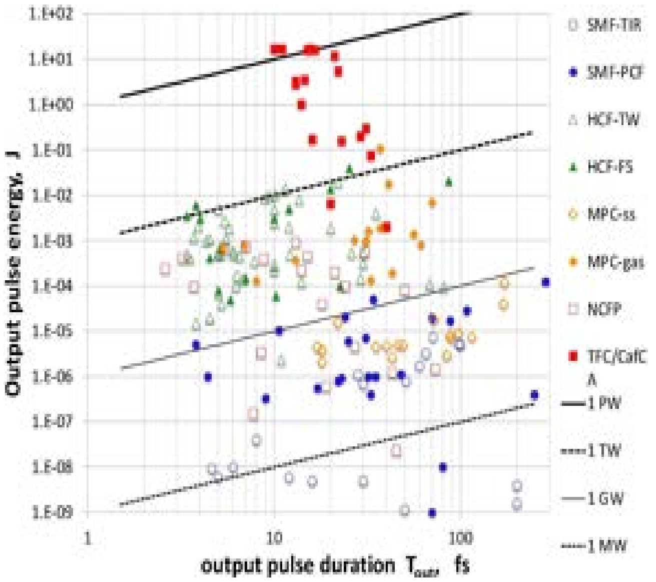

Fig. 3. Experimental results:
output pulse duration – output pulse energy plane

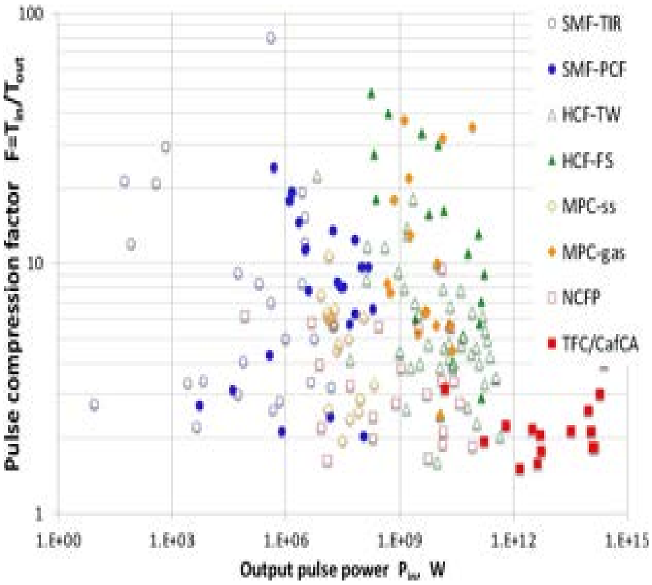

Fig. 4. Experimental results:
output pulse power – pulse compression factor plane

effect almost disappears. For relatively small beam diameters, the nonlinear phase incursion can be made more uniform by resorting to noncollinear free propagation (NCFP). For collinear propagation (TFC/CafCA), this problem can be solved using a nonlinear element in the form of a negative lens, in which L varies over the beam cross section. In addition, the estimates show that, compared to a flat-top beam, for a super-Gaussian beam with exponent m, the compressed pulse power P_{out} at large B decreases by a factor of $2^{1/m}$ i.e., for $m = 1$ (Gaussian beam), P_{out} decreases two times, and for $m = 4$, only 1.08 times.

Second, the inhomogeneity of the spatial phase leads to nonlinear distortions of the wavefront. This degrades the quality of beam focusing. If we neglect the dispersion, the phase distribution will be proportional to the B-integral. Analysis shows that, to minimize aberrations, there is no need to obtain large values of m, $m = 2$ and the Strehl number $S > 0.8$ at $B < 5$ are quite sufficient i.e., aberrations will lead to an intensity decrease in focus by no more than 20%. At large B values, an adaptive mirror should be used.

Third, until recently it was believed that effective compression during collimated propagation is impossible due to SSSF. SSSF leads to beam splitting into a large number (on the order of P_{in}/P_{cr}) of filaments, resulting in optical breakdown. The instability increment is determined by the B-integral; it was argued that at $B > 2$–3 the beam inevitably splits into filaments. At $B = 3$, the power can be enhanced only by a factor of 2.5. This argument, which is valid for nanosecond pulses, was erroneously transferred to femtosecond pulses and, unfortunately, continues to be repeated, even in the recent reviews. It was demonstrated back in 2012 that, in high-power femtosecond lasers, SSSF can be effectively suppressed by beam self-filtering during propagation in free space, which served as a stimulus for experiments with collimated propagation (figs. 2–4).

6. Conclusion

As is clear from fig. 2, HCF-SF, MPC-gas and TFC/CafCA are currently the most dynamically developing variants, promising for the further progress in the near future. From the viewpoint of super-high-power lasers, TFC/CafCA is the best option for pulse compression. It is worth noting that, although this is the cheapest and simplest technology, it has virtually no power limit. The most relevant areas for further TFC/CafCA research are the following:

1. Despite the experimental confirmation of SSSF suppression at B up to 19, there is still no complete understanding of all the related mechanisms.

2. The study of the beam focusing quality, with the help of adaptive mirrors among others, is at its very beginning and, despite the encouraging results, requires further theoretical and experimental studies.

3. The range of pulse durations (see figs. 3–4) mastered with the help of TFC/CafCA is relatively narrow: $T_{in} \leq 126$ fs, $T_{out} \geq 10$ fs. The advancement to durations of one field cycle, opening up new opportunities for petawatt lasers, and the compression of picosecond pulses, which will make it possible to significantly increase both the compression factor T_{in}/T_{out} and the output power P_{out}, are highly promising.

4. Search for new nonlinear media (polymer, glass, crystal) is needed, which will improve the compression parameters.

A more detailed information about post-compression can be found in the reviews [1–6].

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Recent Achievements with the 4-PW Laser at CoReLS

Record-breaking laser intensity

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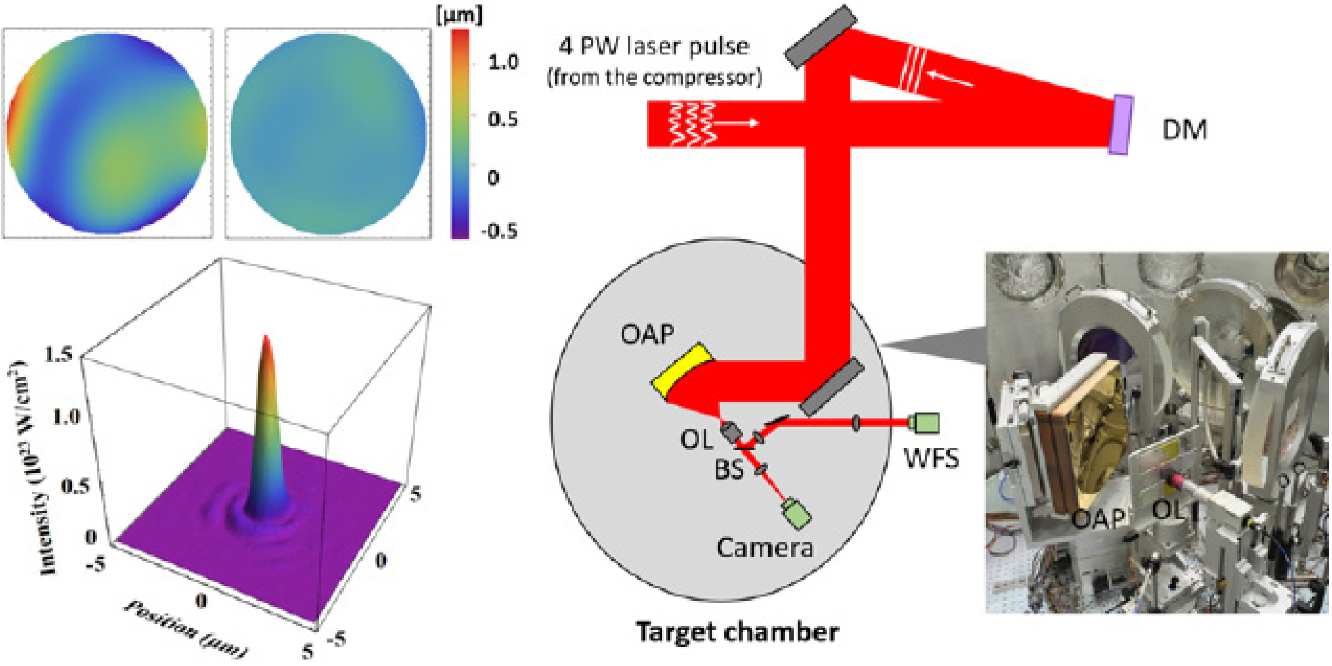
With the 4 PW laser developed at the Center for Relativistic Laser Science (CoReLS) in 2016 we recently realized the unprecedented laser intensity of 1.1×10^{23} W/cm^2. After the demonstration of 10^{22} W/cm^2 at the University of Michigan two decades back, this set a new laser intensity record. This kind of laser intensity has been desired for the exploration of novel physical phenomena in strong field quantum electrodynamics (QED).

In order to achieve such a laser intensity, the wavefront correction and the diffraction-limited tight focusing of the PW laser are quite critical. For the wavefront correction, two deformable mirrors (DMs) have been employed in the beam line. The first DM, installed after the final amplifier, compensated for the wavefront distortion accumulated through a series of amplifiers. The second DM, installed after the pulse compressor, corrected additional aberrations induced in the large aperture optics of the pulse compressor, the beam delivery line and the target area. In the target chamber, the wavefront-corrected PW laser beam was tightly focused with an f /1.1 off-axis parabolic mirror (f = 300 mm) shown in the figure, together with the measured



Top left: Measured wavefront maps before and after the wavefront correction. An almost flat wavefront was obtained after the wavefront correction. Bottom left: 3D image of the focal spot profile for the measured highest intensity of 1.4×10^{23} W/cm^2. Right: Layout of the experimental setup and the photo of the target chamber with a gold-coated OAP. DM – deformable mirror; WFS – wavefront sensors; OAP – f/1.1 off-axis parabolic mirror; OL – objective lens; and BS – beam splitter wavefronts and the 3D focal spot image. The focal spot image in the figure shows the case of the highest laser intensity measured, presenting a spot size of 1.1 µm (FWHM) and the corresponding peak intensity was 1.4×10^{23} W/cm^2. This result was published in Optica.

This ultrahigh intensity laser will open new frontiers in high field science, especially strong field QED that has been dealt with mainly by theoreticians. At CoReLS we are applying the ultrahigh-intensity laser to the demonstration of nonlinear Compton scattering between a laser wakefield accelerated GeV electron beam and an ultrahigh intensity laser beam to examine a strong field QED process in the nonlinear regime, in which one electron collides simultaneously with several hundred laser photons, generating gamma-ray photons with energy well above 100 MeV. Our work will pave the path to examine extreme astrophysical phenomena in laboratory.

Non-destructive imaging using laser-driven betatron gamma-rays

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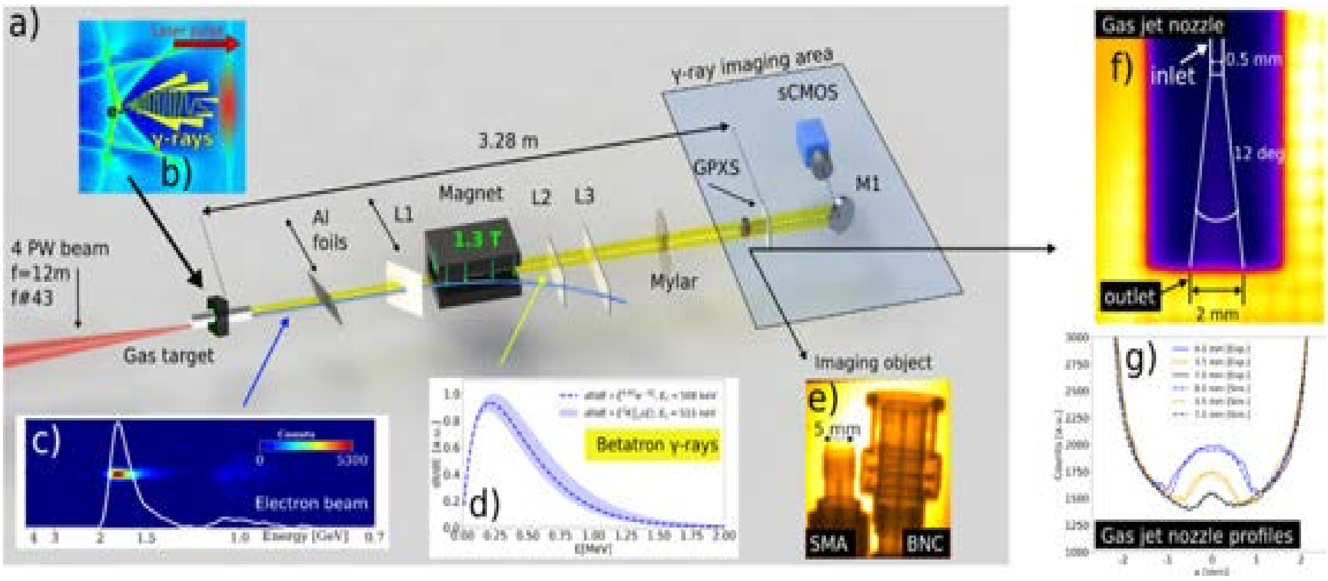
Center for Relativistic Laser Science (South Korea)

At CoReLS gamma-ray imaging has been investigated using the betatron radiation emitted during laser wakefield electron acceleration. The 4PW laser has been utilized to generate multi-GeV electron beams. Concurrently, these electron beams emit a significant amount of gamma-rays via betatron radiation.

The synchrotron-like betatron radiation covers a wide energy spectrum with a critical energy of 515 keV, extending beyond 1 MeV. The high energy, combined with a large photon count ($\approx10^9$) and low divergence (≈10 mrad), makes the source ideal for applications such as non-destructive imaging. Consequently, we have used this source to produce radiographs of centimeter-scale structures, such as circuits, metallic cable connectors, and gas jet nozzles. Our experiments have demonstrated that using betatron radiation, we can examine the internal structure of metallic targets with a resolution as low as 38.5 µm per pixel. Thanks to the high photon flux, radiographs can be obtained with a single laser shot. As an example, we successfully imaged a gas nozzle, determining its internal dimensions, outlet geometry, and nozzle opening angle. These experimental results were validated by GEANT4 simulations.

The unique properties of this source make it well-suited for non-destructive inspection in applications like soldering, crack detection, and additive manufacturing. Beyond industrial applications, the combination of high energy, ultrashort pulse duration, and low divergence also makes this source a valuable tool for probing extreme densities, such as those encountered in inertial confinement fusion.

This research has been published in the European Physical Journal A [C. I. Hojbota *et al.,* “High-energy betatron source driven by a 4-PW laser with applications to non-destructive imaging”, Eur. Phys. J. A 59, 247 (2023)].



Experimental setup and results: setup for LWFA and radiographic imaging (a); electrons, oscillating during LWFA, emit betatron gamma-rays (b); electron beam spectrum (c) and the betatron radiation spectrum (d); in a single shot, radiographs of an SMA and BNC connector can be obtained (e); gamma-ray image of a gas jet nozzle (f) and its sectional profiles at different heights (g). The experimental profiles (solid lines) show good agreement with GEANT4 simulations (dashed lines) revealing the internal diameter of the inlet and outlet

Installation and Characterization of Plasma Mirror System at J-KAREN-P Facility

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In recent years, with the development of high-power laser technology, many laser systems have been constructed all over the world [1]. At the KPSI of QST, Japan, the upgrade of the J-KAREN laser system and experimental area was completed in 2018 [2]. In addition, in 2021 we installed a plasma mirror (PM) system to improve temporal contrast further for J-KAREN-P (1 PW, 0.1 Hz). The PM is one of the most powerful tools for the suppression of pre-pulse which interferes with the interaction between ultra-intense laser pulses and the target [3]. Here, we will briefly introduce the PM system installed in our facility and its performance [4].

The J-KAREN-P laser is a double-CPA Ti:sapphire laser system with the OPCPA pre-amplifier. As shown in fig. 1, the PM system is installed after the final compressor and before the target chamber for Off-Axis Parabolic (OAP) of F/1.3 to F/3. The size of the vacuum chamber of the PM system is 2.1 m×2.7 m× ×2.3 m. The internal components consist of two periscope pairs, two OAP mirrors, and a PM substrate (fig. 1). In this installation, as a first step, the setup uses a "single" plasma mirror, but we plan to use a "double" plasma mirror in the future. The OAP has a focal length of 2 m (F/8) and a wavefront accuracy of $\lambda/10$ (P-V). The size of the PM substrate is 400×70×30 mm, and the laser is incident on the mirror with S polarization at an incident angle of 16 degrees. The substrate can withstand about 3000 shots without replacement. The reflectance of the anti-reflective (AR) coating on PM substrate is <0.1% at 770–830 nm.

The maximum reflectivity of PM was 85% at a fluence of roughly 100 kJ/cm^2. In addition, there was no significant difference between near-field image with and without PM. Temporal contrast was measured using a third-order cross-correlator (SEQUOIA, Amplitude Technologies). The result of temporal contrast with and without the PM system is shown in fig. 2. From –13 ps to several hundred fs, the contrast was improved by about a factor of 1000. The measured results are in good agreement with this estimate considering the AR coat (<0.1%). The inset in fig. 2 shows the pulse duration which was measured using a self-referencing spectral interferometer (WIZZLER, Fastlite). The duration of Full Width Half Maximum was ~46 fs. There was no significant difference in the pulse width between the conditions with and without PM.

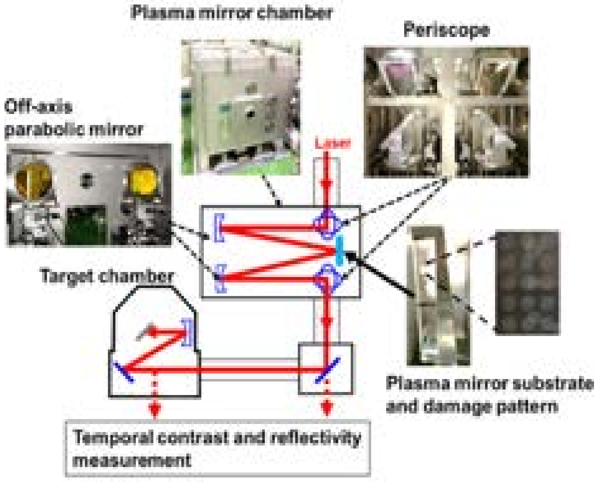

Fig. 1. Plasma mirror system at J-KAREN-P

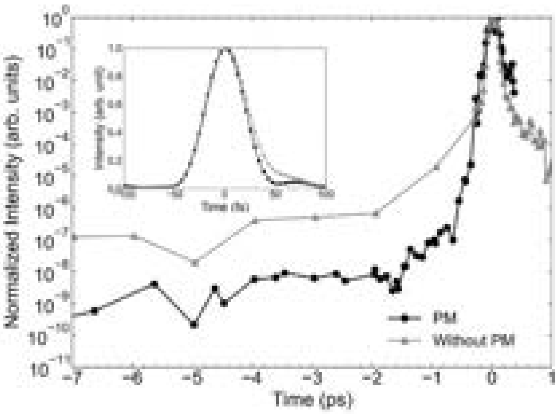

Fig. 2. Temporal contrast
with and without a single plasma mirror

In recent ultra-intense laser facilities, PMs are the techniques to dramatically improve the temporal contrast and are often used in experiments such as laser ion acceleration and high-order harmonic generation. We briefly introduced the plasma mirror system installed in KPSI and its performance. We are conducting experiments (e.g. ion acceleration) using the contrast-enhanced laser system and a large-aperture deformable mirror after the compressor. Following this, we will upgrade to a double PM to further improve the laser quality.

Acknowledgement

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EPIC in India

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The Extreme Photonics Innovation Centre (EPIC) is a joint UK-India innovation initiative aimed at developing technology for next-generation accelerators using lasers. Funded by the UK Research and Innovation (UKRI), this £4 million centre jointly established between UK's Central Laser Facility (CLF) and the Tata Institute of Fundamental Research (TIFR) is housed in laboratories set up at TIFR Hyderabad. EPIC is led by Rajeev Pattathil of CLF, UK and M. Krishnamurthy and G. Ravindra Kumar of TIFR, India.

This centre will serve as a research and innovation hub for high-power laser technology, attracting a pool of Indian talent to help establish a critical mass of high-tech workforce. This will pave the way for industry and academia to work together to advance laser science and technology.

EPIC is working collaboratively with 6 dedicated teams across India and UK to develop the much needed ancillary technologies for high repetition rate laser-driven accelerators, which primarily include target positioning systems, particle and radiation detectors, key opto-mechanics, vacuum systems and EMP-resistant drive systems, control system solutions, and high volume data analysis including CT.

EPIC inauguration event at TIFR-Hyderabad, September 2019. From Left to Right – M. Krishnamurthy (TIFR-H Dean at the time, Centre Director since 01/2024) V. Chandrasekhar (TIFR-H Centre Director till 12/2023), Mustansir Barma (TIFR Ex-Director) Sandip Trivedi (TIFR-Director at that time), Srikumar Banarjee (Ex- AEC and DAE chairman; TIFR academic council member at that time, now deseased), John Collier (Director, CLF, RAL, UK), Andrew Fleming (British Deputy High Commissioner Hyderabad)

EPIC's technologies will be used to develop laser-driven accelerator applications that will have a significant economic and societal impact. Particle and x-ray beams will be used in the joint UK-India plan to revolutionise a wide range of fields, from industrial non-destructive testing to bio-medical imaging, with enhanced scan speeds without sacrificing performance, high-resolution dynamic captures, and large and dense objects. This revolutionary accelerator technology has the potential to usher in a paradigm shift in industrial inspection, imaging for advanced manufacturing, and biomedical optics. EPIC will bring together world leading expertise in lasers, accelerator science and technology, target manufacturing, engineering, and diagnostics.

Compact Free-electron Lasers Based on a Laser Wake Field Accelerator

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Laser wakefield acceleration (LWFA) of electrons driven by ultrafast intense lasers is very attractive for the development of compact and low-cost electron accelerators and novel radiation sources due to their ultra-high acceleration gradient.

Free-electron lasers (FELs) are the best way to produce high-brightness coherent radiation sources in the X-ray range, which can be used to detect the internal dynamic structure of matter, study the interaction of light with atoms, molecules and condensed matter and promote the development of condensed matter physics, chemistry, structural biology, medicine, materials, energy and environment, among other disciplines. However, the large scale of the devices limits their popularization. The development of miniaturized and low-cost XFELs is very important for the application expansion and technology change. In recent years, significant progress has been made in LWFA, but there

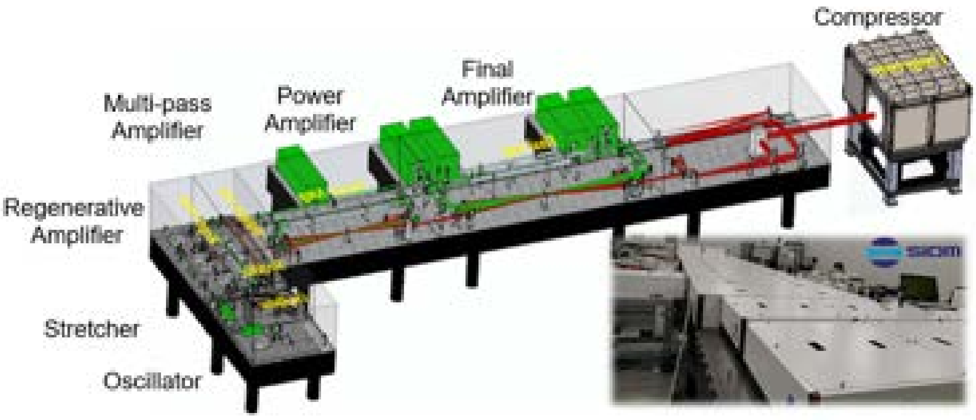

Fig. 1. The 200-TW Ti:sapphire laser system at SIOM

are still many problems and challenges for driving table-top FELs due to the insufficient quality and stability of the electron beam.

In order to achieve the scientific goal of compact X-ray FELs, the research team from SIOM pushed this research for a decade with the spirit of "10 years for sword". They completed the entire optimization from driving lasers to LWFA and to FEL.

They upgraded the 200 TW/1 Hz laser facility shown in fig. 1. The fluctuation of pulse energy and beam pointing for consecutive 5400 pulses in 90 min are as low as 0.55% and 1.5 μrad, respectively. The focal spot obtained by an f/30 off-axis parabolic mirror is 54×52 μm at $1/e^2$, which is very close to the diffraction limit. The energy inside this diameter is 58.4%, with an effective peak intensity of 6.2×10^{18} W/cm^2 [1].

They focused on improving the quality and stability of laser-driven electron beams. A special plasma density distribution was designed to optimize the injection process and the acceleration process of the electron beam, so that the comprehensive quality of the electron beam (including energy spread, emittance and charge) could be improved. By designing a structured gas density profile between the dual-stage gas jets to manipulate electron seeding and energy chirp reversal for compressing the energy spread, they experimentally produced high-brightness high-energy electron beams from a cascaded LWFA with peak energies of ~600 MeV, 0.4%–1.2% rms energy spread, ~30 pC charge [2]. A simple, efficient scheme was developed to obtain near-GeV electron beams with energy spreads of a few per-mille level in a single-stage LWFA. Longitudinal plasma density was tailored to control relativistic laser-beam evolution, resulting in injection, dechirping, and a quasi-phase-stable acceleration. With this scheme, electron beams with peak energies of 780–840 MeV, rms energy spreads of 2.4–4.1‰, and charges of 8.5–23.6 pC were experimentally obtained [3]. Such high-quality electron beams would boost the development of compact x-ray FELs.

By controlling and optimizing the phase space evolution of the electron beam, the smooth transfer of the electron beam from plasma to vacuum was realized, and the beamline was designed to realize the long distance transport of the electron beam and effectively coupling them into the undulators. As shown in fig. 2, the total beamline had a length of 12 m from the gas target to the X-ray spectrometer. The accelerated electron beam was focused by a group of three quadrupoles consisting of a pair of permanent quadrupoles and an electromagnetic

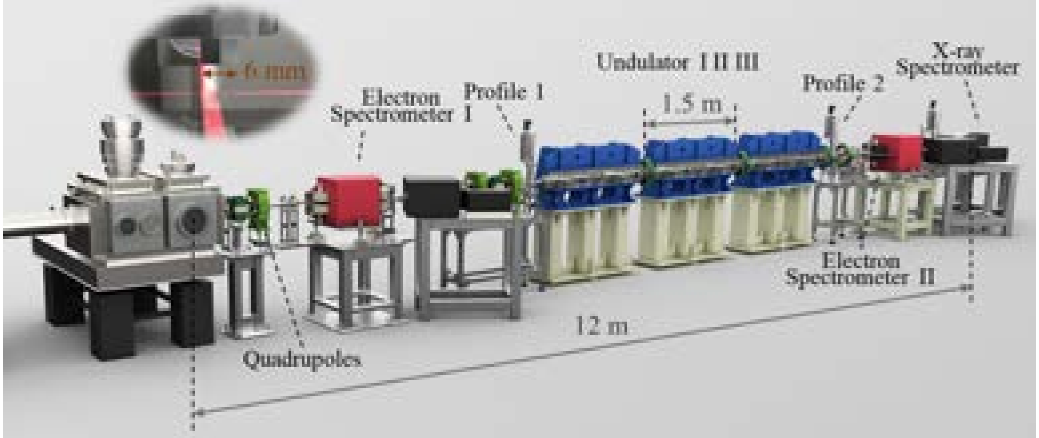

Fig. 2. Schematic layout of the table-top FELs based on LWFA at SIOM

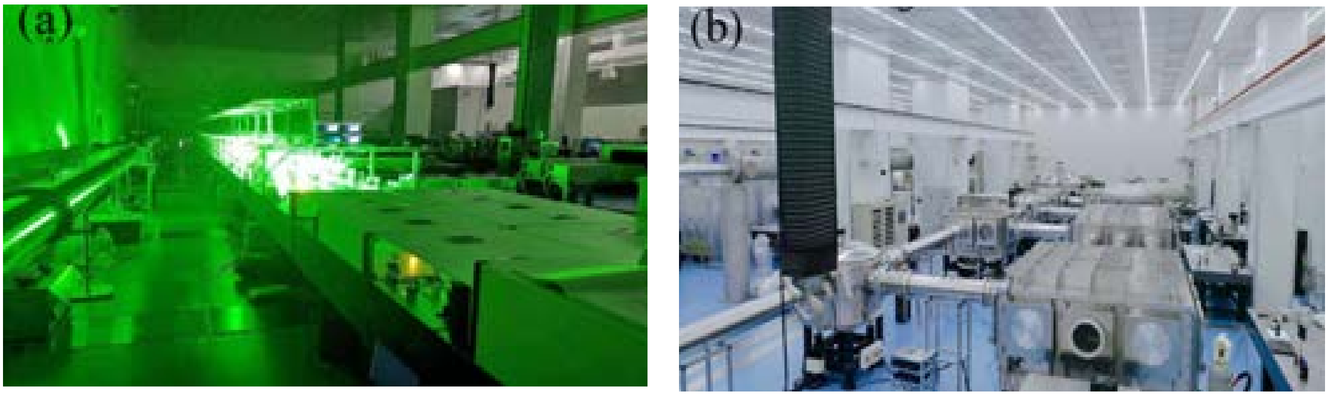

Fig. 3. Shanghai Superintense Ultrafast Laser Facility (SULF). 1 PW/0.1 Hz laser (a); Ultra-fast chemistry and macromolecular dynamics research platform (b)

quadrupole, which ensured an effective focusing for handling the initial divergence. Then, the electron beam was adjusted by an additional pair of electromagnetic quadrupoles to retain ~20-µm sizes throughout the undulator. The radiation beamline contained three 1.5-m-long undulators, which was sufficient for FEL operation in the saturation regime. For the first time, the team experimentally observed radiation in the extreme ultraviolet (EUV) range, with a center wavelength of 27 nanometers and a single energy pulse up to 150 nanojoules. It was proved that the energy gain in the last undulator was up to 100-fold due to orbit kick and spontaneous radiation calibration. This was the first realization of the spontaneous emission amplification based on LWFA [4].

The research team agrees that much work still needs to be done to make plasma-based FELs a reality, citing optimisation of energy spread as well as improving current and emittance as notable challenges. They will focus on the enhancement of the output power, the photon energy and the stability of such devices. An important part of the ultra-fast chemistry and macromolecular dynamics research platform in the SULF laser facility in Shanghai is shown in fig. 3.

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High-intensity Laser-driven Probes on the Omega Laser Facility

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Laboratory for Laser Energetics, University of Rochester (USA)

The Omega Laser Facility houses the OMEGA 60 [1] and OMEGA EP [2] laser systems (fig. 1). EP consists of four Nd:glass beam lines capable of delivering up to 6.5 kJ in 10 ns at the third harmonic (351 nm), achieving maximum power with 1.25 kJ in 1 ns. Two of the beams may be diverted to a CPA (chirped pulse amplification) system, each delivering up to 2.6 kJ in 100 ps at the fundamental (1053 nm), achieving maximum power with 700 J in 0.7 ps. The CPA beams can be focused to a spot containing 80% of the laser energy within a diameter < 18 µm. The beams can be delivered either to the EP target chamber perpendicular to one another (backlighter and sidelighter), or to the OMEGA 60 target chamber along a single path in joint-shot operation. The EP CPA beams can be used to generate short pulses of energetic protons, x-rays, relativistic electrons, or THz radiation for probing ICF (inertial confinement fusion) and basic high energy density physics experiments, as described below.

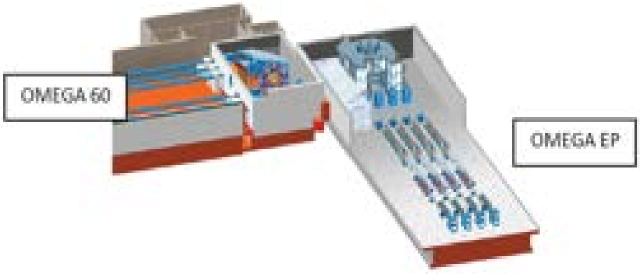

Fig. 1. Layout of the Omega Laser Facility

Proton Probing

Proton probing with EP CPA beams relies on the acceleration of protons from contaminants on the back surface of metal foils by the fast electrons emitted at relativistic laser intensities. The first experiments established that x-rays emitted from the experiments being probed damaged the foils, leading to the development of a protective "proton tube" (fig. 2). The proton foil can still be damaged by the laser-induced blast wave, limiting the probing delay to ~4 ns for multi-kJ experiments.

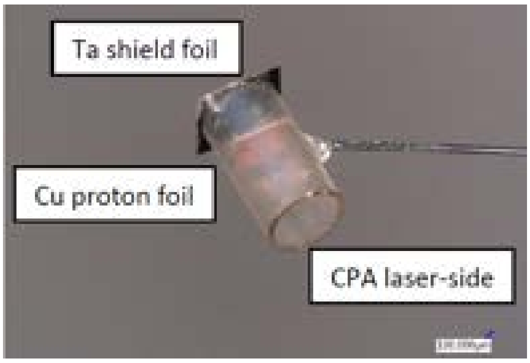

Fig. 2. Photograph of a proton tube used in EP experiments. The extent of the tube behind the Cu foil varies. For oblique incidence the foil is placed near the entrance

The protons are detected by an RCF (radiochromic film) stack. The proton energies achieved depend on the experimental setup. With the current maximum power on EP of 500 J in 0.7 ps, clear proton images can be obtained up to 40 MeV. For experiments using high-mass targets, disposable debris shields are required for the EP parabolas, limiting the energy to 50 J, which can provide clear proton images up to 15 MeV; similar performance is obtained using EP on OMEGA 60. Sample data from planar foil experiments on EP are shown in fig. 3. Results from similar experiments looking specifically at the Rayleigh-Taylor instability have been published [3, 4].

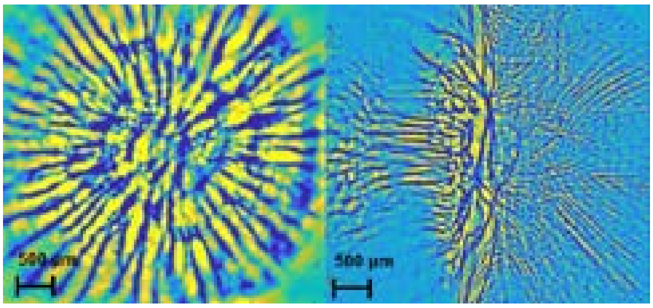

Fig. 3. Sample proton radiographs of a 20-µm thick polystyrene foil irradiated by two, overlapped 2 ns, 2 kJ beams with 750 µm DPPs probed from the front (left) and side (right) at 2.3 ns with 18 MeV protons. The long-pulses are incident from the left in the side-on image. Similar filamentary structures are observed in spherical implosions on OMEGA 60. The EP experiments are being used to understand their physical nature

X-ray backlighting

X-ray backlighting is a powerful technique to observe the flow of cold and dense material in laser experiments, which typically does not emit enough radiation to be recorded directly. Direct-drive cryogenic deuterium–tritium (DT) implosions [5] are very challenging experiments to backlight because of the low opacity of the DT shell, the high shell velocity, the small size of the stagnating shell, and the very bright self-emission of the hot core. A backlighter system driven by ~20-ps short pulses from EP using a crystal imaging system with a Si He_α emission at 1.865 keV was developed [6, 7] to overcome these challenges (fig. 4). The high laser pulse energy of ~1.5 kJ provided by EP was essential to obtain good photon statistics.

An aspherically shaped quartz crystal with a radius of curvature of 500 mm, cut along the 1011 planes for a 2d spacing of 0.6687 nm, was used at a Bragg angle of 83.9°. The spectral bandwidth of the crystal imager is ~10 eV, which matches the typical line-width of the resonance line from the backlighter. The 500-µm square backlighter was placed at a distance of 5 mm from the implosion target. A fast target insertion system inserts the backlighter target within 100 ms after the cryogenic shroud has been removed. Collimators are used to suppress background from Compton scattering and fluorescence from structures in the target chamber. To reduce the impact of the self-emission from the hot core, an x-ray framing camera with an exposure time of ~40 ps is used as the detector. The framing camera is triggered by an electro-optical trigger system with a jitter of < 2-ps RMS. Experiments with resolution grids show an ~15-µm, 10% to 90% edge response for the crystal-imaging system. The monochromatic backlighter makes it possible to achieve similar brightness within the narrow spectral acceptance range of the imager to the hot core emission using much less laser energy

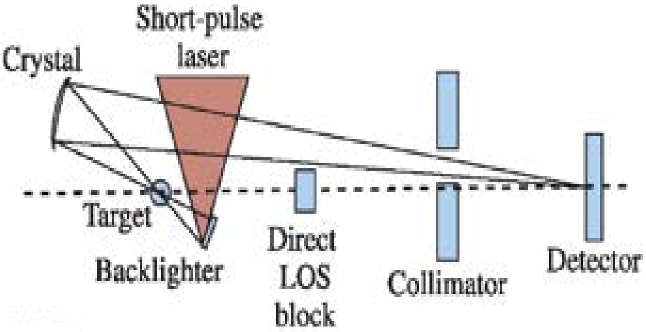

Fig. 4. Schematic of the spherical-crystal-imager backlighting setup (not to scale). The short-pulse laser illuminates the backlighter behind the primary target, which is irradiated by 60 beams from the OMEGA laser (not shown). A direct line-of-sight (LOS) block and collimators (only one shown) protect the detector from background

in the backlighter than the implosion. The cryogenic targets used in these experiments had an outer radius of ~450 µm, with a 12-µm-thick ablator of deuterated plastic (CD) encasing a 60-µm-thick cryogenic DT ice layer. The targets were imploded with total energy of ~24 kJ and a carefully prescribed pulse shape to achieve high densities in the compressed DT shell.

A sample image is shown in fig. 5. The dashed white line indicates the original diameter, and the white line at the bottom of the image shows the location of the target stalk. The image is clipped at the top because of a misalignment caused by repeatability issues in the crystal insertion mechanism. The absorption from the dense compressed shell is seen in the image as a ring-like feature around an emission feature from the hot core of the implosion.

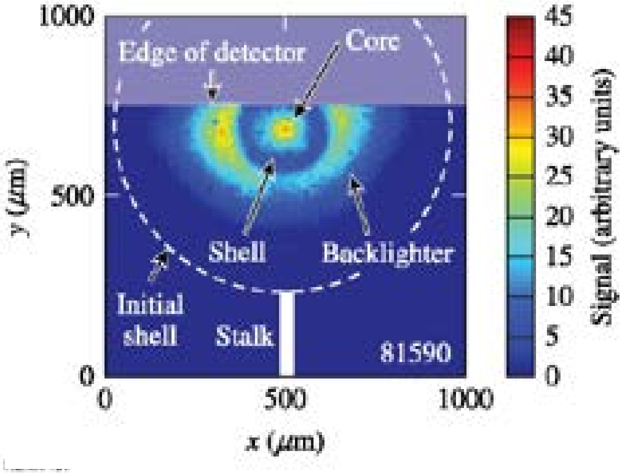

Fig. 5. Time-gated image of backlit DT cryogenic implosion with an exposure time of ~40 ps. The initial radius and the location of the stalk are shown for comparison. From [9]

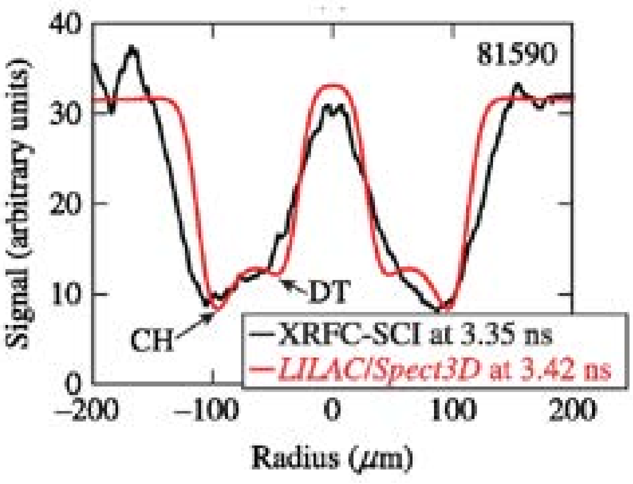

Fig. 6. Corrected horizontal lineout of the data shown in fig. 5 compared to 1-D LILAC hydrodynamic simulations, which are post processed with a radiation transport code Spect3D. From [9]

Figure 6 shows the backlighter shape corrected horizontal lineout of the radiograph of fig. 5 compared to Spect3D post-processed, 1-D LILAC simulations [8]. The backlighter intensity was adjusted to match the observed ratio of backlighter relative to the level of self-emission of the core. The simulated line-out matches the experiment quite closely in both size and magnitude of the absorption. The most noticeable difference between experiment and simulation is that the slopes at the interface between shell and core and at the outside of the shell are significantly steeper in the simulation. More analysis of the data obtained backlighting cryogenic DT implosions on OMEGA can be found in ref. [9]. Work is in progress to achieve higher spatial resolution and lower photon energies ~1 keV.

Relativistic electrons

Relativistic electron probing using EP CPA beams relies on the acceleration of electrons to 10’s of MeV via laser-plasma acceleration (LPA) in a helium gas-jet [10]. The EP beam is apodised to increase the Rayleigh length and provide a cleaner focal spot. Apodization decreases the available beam energy at best compression to ~130 J, which is sufficient to generate µC electron beams with an average energy of ~20 MeV. The beam is then directed at either undriven radiography objects for beam characterization, or laser-driven targets (fig. 7) to probe fields in ultra-fast or dense plasmas that our proton probes cannot adequately characterize [11].

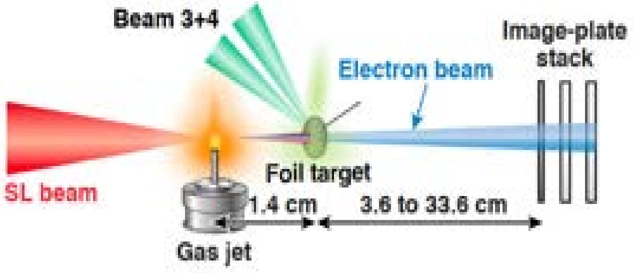

Fig. 7. Diagram of LPA relativistic electron radiography of laser-driven targets on OMEGA EP

The electrons are detected on image-plate stacks with aluminum, mylar and Teflon filters to remove low energy x-rays. More details on the experimental set-up and results from initial radiographs of static and ps-laser driven targets can be found in ref. [11]. Recent experiments have focused on ns-laser driven gold foils of relevance to indirect drive ICF [12]. A preliminary radiograph of gold, copper, and plastic foils can be seen in fig. 8. Future work will seek to provide measurements of the laser-plasma generated fields present in hohlraums and other dense, high-Z plasmas.

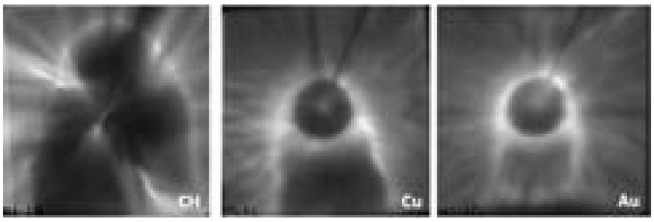

Fig. 8. Face-on relativistic electron radiographs of 1 ns, 1 kJ UV beam driven plastic, copper and gold foils. The electron beam transitioned the foil at +1 ns from the UV beam turning on

THz radiation

THz radiation provides a unique probe of matter because the frequency range is the same as that of phonon vibrations and molecular rotations [13]. THz reflection or absorption spectroscopy can ascertain chemical composition, crystal structure and DC conductivity. At high peak-powers, THz radiation is of interest as a pump not just a probe. High peak-power THz radiation typically requires ~1 ps pulses [14], which in turn create single or even half-cycle THz radiation resulting in a quasi-DC interaction with matter. Experiments on EP have generated first of a kind ~1 TW, ~1 J THz pulses [15], as shown in fig. 9.

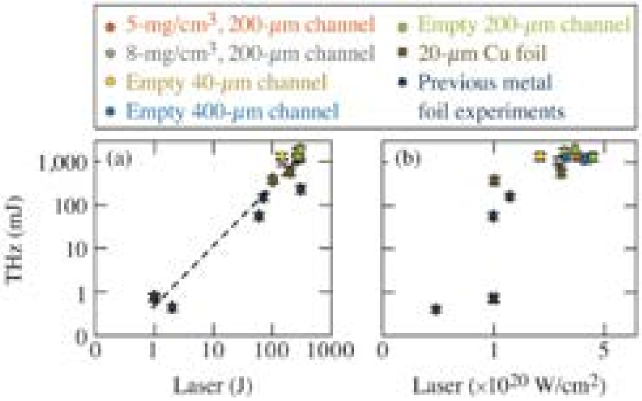

Fig. 9. THz radiation energy vs laser energy (a) and laser intensity (b) for various microchannel copper foils on OMEGA EP and foil experiments on other lasers

The EP experiments employed laser-solid interactions to generate THz radiation via coherent transition radiation (CTR) and are an order of magnitude above previously reported results [16]. Microchannel targets were found to be the most efficient radiators of THz radiation [15] and future work will seek to use these powerful THz pulses as drivers of secondary targets.

This material is based upon work supported by the Department of Energy [National Nuclear Security Administration] University of Rochester "National Inertial Confinement Fusion Program" under Award Number DE-NA0004144.

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LaserNetUS: North America's High Intensity Laser Research Network

LaserNetUS, established by the U.S. Department of Energy in 2018, has a mission to advance the frontiers of high-power laser science and applications by: supporting cutting edge research, providing students and scientists with broad access to unique facilities and enabling technologies, and fostering collaboration among researchers around the world. Users of the network have now conducted five experimental cycles, with a total of more than 70 experiments, 34 publications and 1300 registered users. The network's capabilities, spanning 10 high power laser facilities across North America, enable a broad range of science and applications, including laser-plasma experiments, high energy density science, materials science and radiation damage and High Repetition Rate laser technology. The network's users have the opportunity to gather at the LaserNetUS users' meeting, held every year in the U.S. The next call for proposals for experiments on LaserNetUS facilities is expected to be open during the November-December timeframe.

More information: https://lasernetus.org

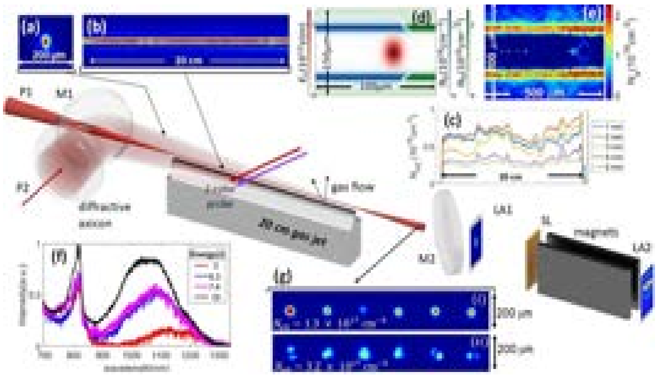
Participants of the 2023 Annual LaserNetUS Meeting attend the poster session

Experiment focus: All-Optical Multi-GeV Laser Wakefield Accelerator

Facility: ALEPH Laser, Colorado State University

Experiment PI: Howard Milchberg, University of Maryland

Using an optically formed plasma waveguide, researchers demonstrated record laser wakefield acceleration of quasi-monoenergetic electrons to 5 GeV energies. An acceleration gradient as high as 25 GeV/m was demonstrated.



All optical multi GeV laser wakefield accelerator

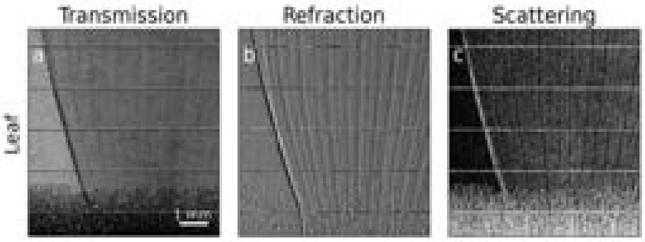
More information: B. Miao *et al.*, "Multi-GeV electron bunches from an all-optical laser wakefield accelerator", Phys. Rev. X **12**, 031038 (2022)

Experiment focus: Femtosecond multimodal imaging with a laser-driven X-ray source

Facility: Advanced Laser Light Source (ALLS), Canada

Experiment PI: Silvia Cipiccia, University College London (UCL), UK

Using betatron radiation generated by a laser-plasma accelerator at ALLS, the team has proven that absorption, refraction and scattering properties of a sample can be investigated in a single shot at the femtosecond resolution, making this technique a new powerful tool for pump-probe experiments. This is the result of a multidisciplinary collaboration between UCL, ALLS, Ghent University, Imperial College London, Central Laser Facility, Diamond Light Source, and Helmholtz-Zentrum Berlin.



Transmission, refraction, and scattering retrieved for a leaf using betatron radiation

More information: A. Doherty *et al.*, "Femtosecond multimodal imaging with a laser-driven X-ray source", Communications Physics **6**, 288 (2023)

The ZEUS Laser User Facility: First Light

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Gérard Mourou Center for Ultrafast Optical Science, University of Michigan (USA)

The Zettawatt Equivalent Ultrashort pulse laser System (ZEUS) is a National Science Foundation sponsored user facility housed at the University of Michigan [1]. When fully commissioned, ZEUS will output pulses with 75 J in 25 fs to give a maximum power of 3 petawatts. The ZEUS facility has three target areas, each with a different configuration, to perform experiments.

The ZEUS front end outputs 1.5 J in 20 fs, with a bandwidth of 90 nm at a repetition rate of 5 Hz. The first light commissioning experiments have been conducted to Target Area 3 (TA 3), achieving > 200 TW. After the compressor, the measured energy achieved was 6 J, implying a grating reflection efficiency of 62% per grating. The spectral width (e^{-2}) after amplification was 80 nm, and the intensity autocorrelation measurement was 38 fs, implying a FWHM pulse duration of 26 fs. The radial pulse delay is computed to be < 2 fs. With the use of a deformable mirror, a focal spot with a Strehl ratio of about 80% was achieved and the pointing jitter was measured to be about 1 focal spot diameter. The laser has run in a 1 Hz burst mode, with up to 20 pulses per burst, with some pulse duration lengthening at the end of the burst. TA 3 is configured with f/20 or f/40 focusing, ideal for laser wakefield acceleration (LWFA) of electron beam experiments.

During the first year of operations (FY24), the laser power will be increased to 1 PW for experiments in Target Area 1 (TA 1). TA 1 has a very long focal length optics (f/64), designed for LWFA of electrons. In the future, the laser pulse in TA 1 can be split into 2.5 PW and 0.5 PW for dual beam experiments. Then a long and short focal length configuration can be achieved for counterpropagating beam experiments. Target Area 2 (TA 2) is designed to have a short focal length configuration to achieve the highest intensities, with optional double plasma mirrors for improved intensity contrast on target. Initially the power into TA 2 will be limited to 500 TW, with a larger chamber beginning designed to allow the full 3-PW beam aperture.

ZEUS is operating as a hands-on user facility. Annual calls for proposals will be made, with proposals being selected by an external review panel. The first year has 6 outside user group experiments scheduled, 2 experiments in each target area. Typically 30 weeks of facility time per year will be offered to outside users. Further information about the ZEUS system may be found on the website: zeus.engin.umich.edu.

References

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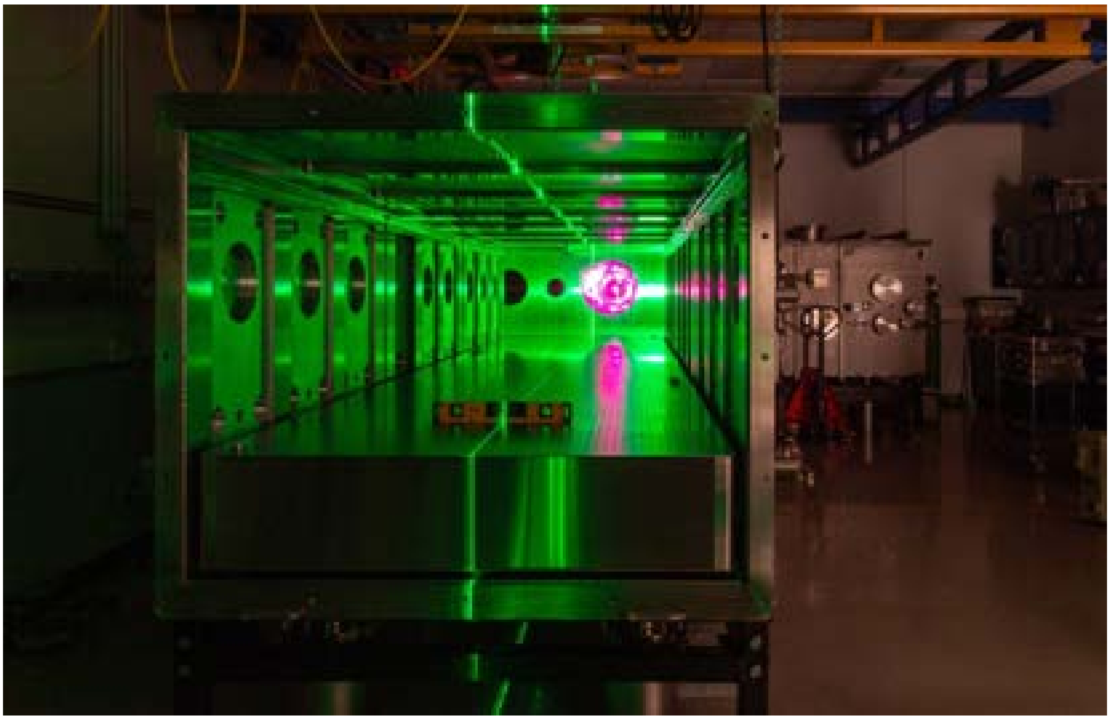

Target Area 1 vacuum chamber

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