Volumetric Interaction of Ultra-Intense Laser Pulses with Over-Dense Targets

ICUIL '10, Watkins Glen, NY, Sept. 28

Presented by:

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Los Alamos
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NNSA

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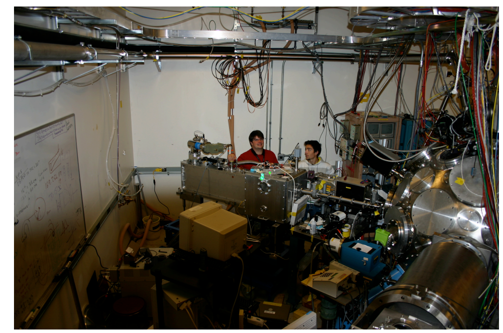
Support by LANL LDRD Program Office, Office of Fusion Energy Sciences, Domestic Nuclear Detection Office and LMU Excellent.

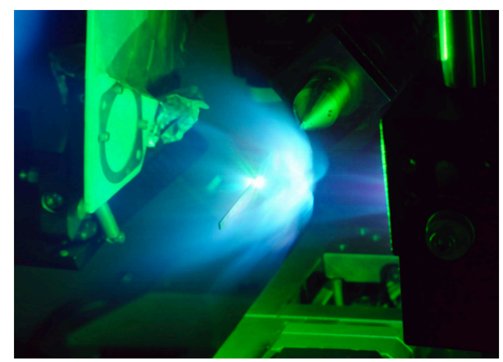
Outline

1. The Trident Laser
2. Relativistic Overdense Interactions
   1. Ion acceleration (BOA)
   2. Electron acceleration
   3. High Harmonic generation
3. Physics model & simulations
4. Relativistic pulse shaping
5. Proton acceleration
6. Outlook - towards extreme intensities

The Los Alamos Trident Laser Facility

200 TW, 100J, 500fs, 1 shot/h shortpulse + 2x 500J, 1ns longpulse beams





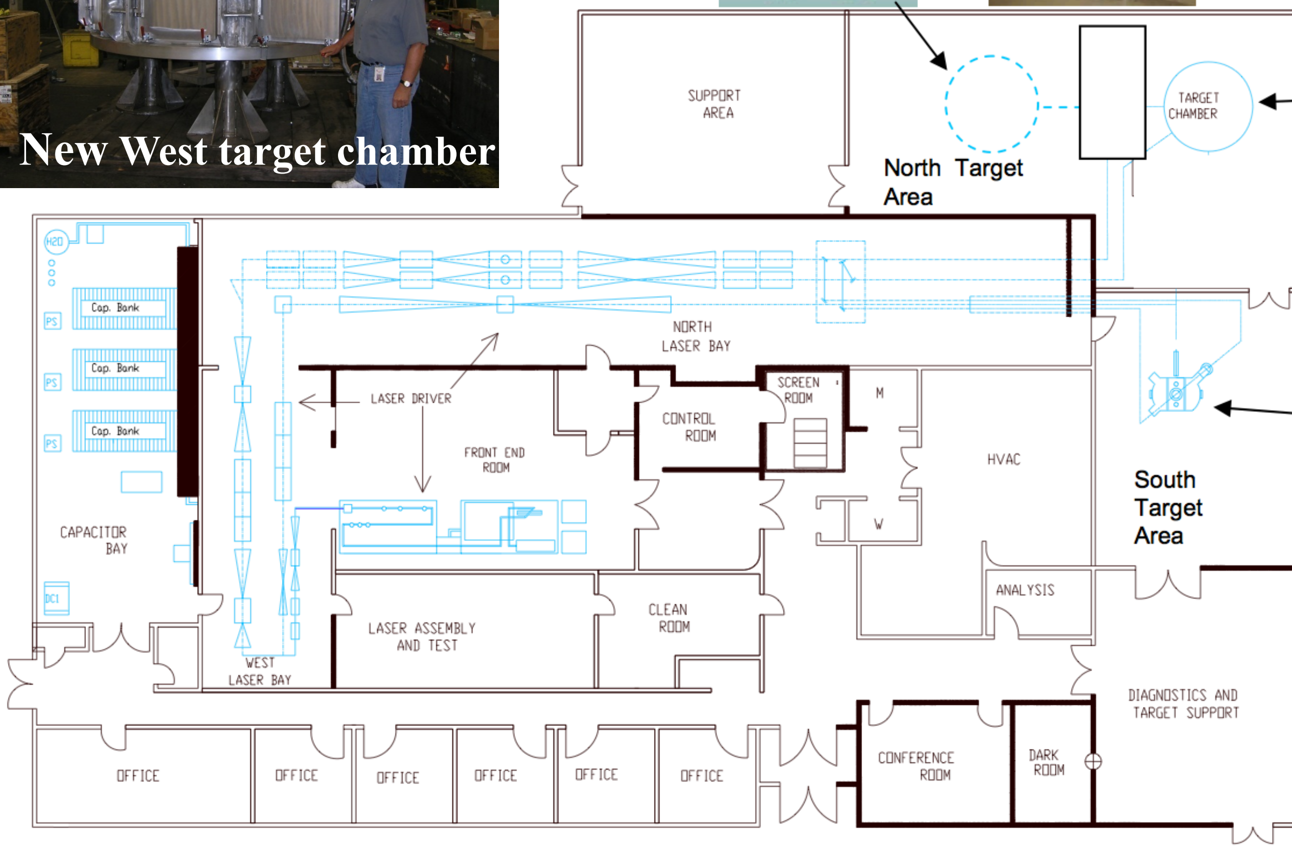
3 beamlines, 3 target areas:

A + B: 100ps – 6µs, 80-1000J (532nm), temp. pulse shaping

High Intensity C-Beam:

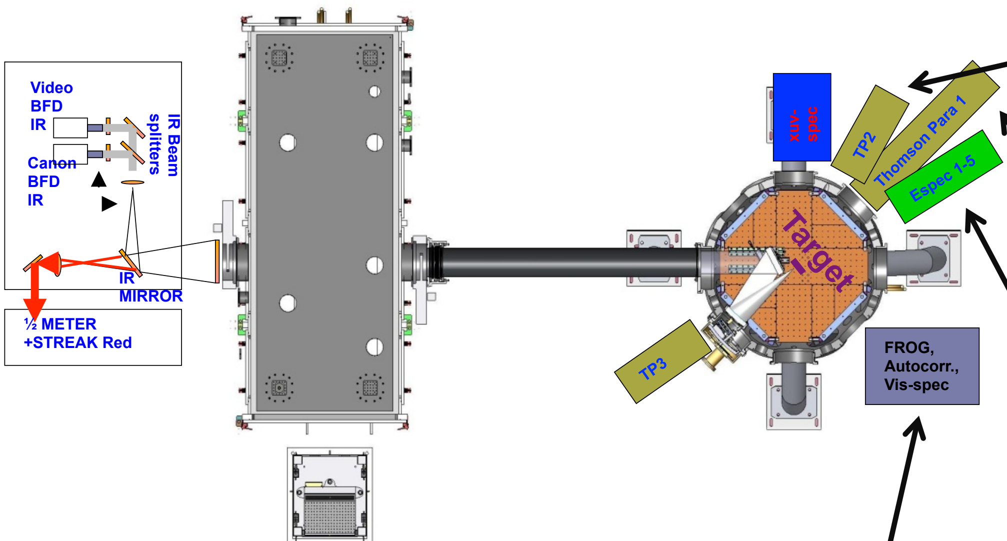
- typical performance (>90% of shots): <600fs, >80J, >130 TW (1054nm), >50% E in DL spot,
- best performance: 460fs, 111J, 241 TW
- F/3 OAP: I_{peak}= 5 x 10^{20} W/cm^2, I_{ave}= 2 x 10^{20} W/cm^2
- F/8 OAP: I_{peak}= 2 x 10^{20} W/cm^2, I_{ave}= 8 x 10^{19} W/cm^2
- Rep. rate: 1 shot / 45 min.
- Contrast: 10^{-12} @ 500ps, 10^{-9}@ 50ps, 10^{-7} @ 5ps, 10^{-4} @ 2ps

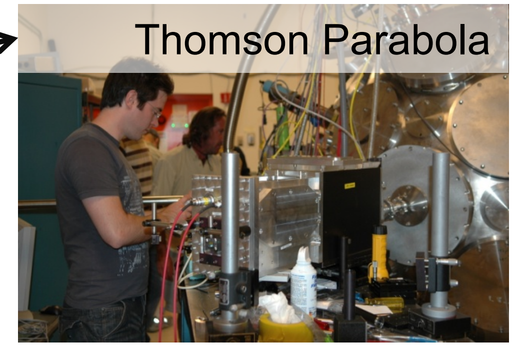
Trident layout:
Shortpulse Frontend lab, main laser bay, cap. bay, laser control room, 2 Target bays, diagnostics & target setup lab, clean room , conference room, dark room, scanner room, offices, storage

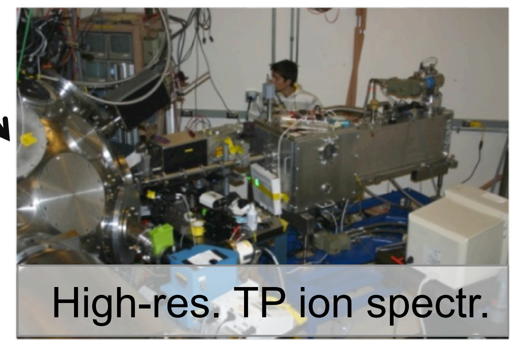


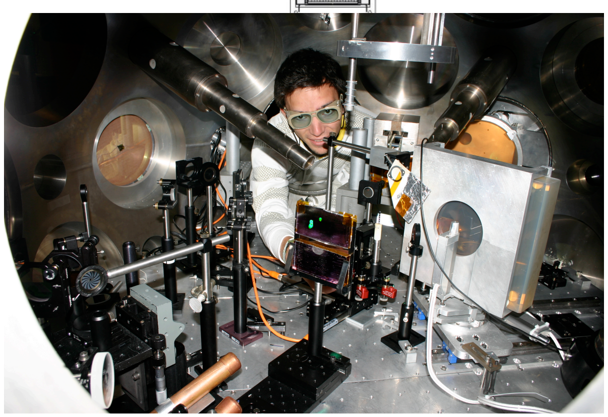
Typical Experimental Setup & Diagnostics:

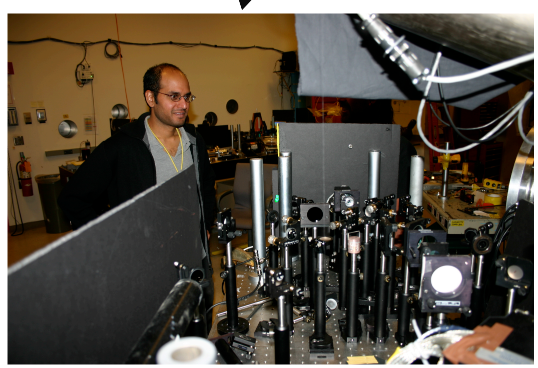
LANL and LMU have developed diagnostic and experimental techniques to investigate the transparent overdense regime

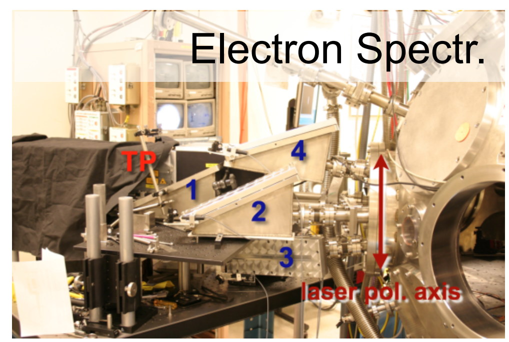






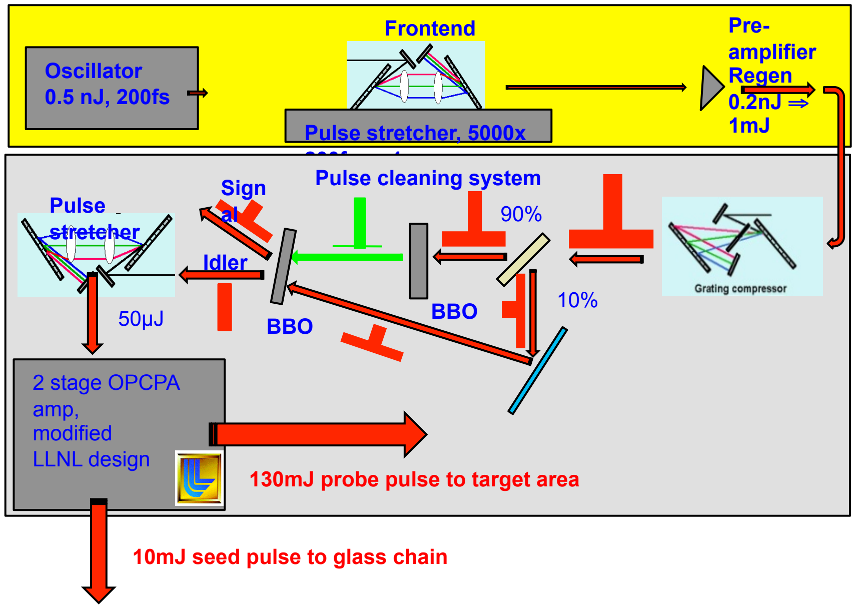




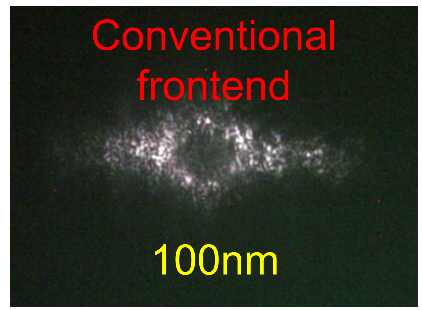


Nonlinear pulse cleaning

Short Pulse Optical Parametric Amplification (SPOPA)[1] enhances the contrast and enables overdense interaction with nanotargets down to 3nm



Full energy backscatter images[2]:



1st implementation of SPOPA (Sept. 08) + subsequent improvements:

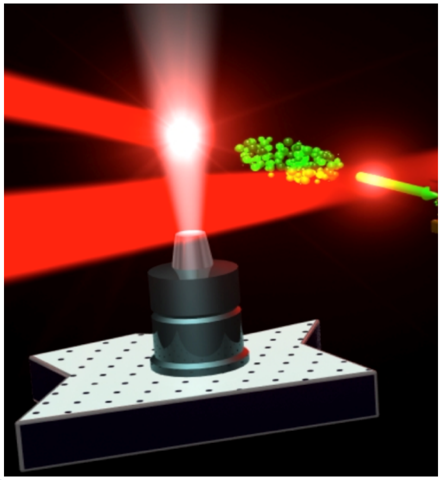
- 100mJ in, 10mJ out
- Contrast: 10^{-12} @ 0.5ns & <10^{-7} @ 5ps

[1]R. Shah et al., Opt. Lett. 34, 15 (2009), 2273
[2]D.C. Gautier et al., RSI 79, 10F547 (2008)

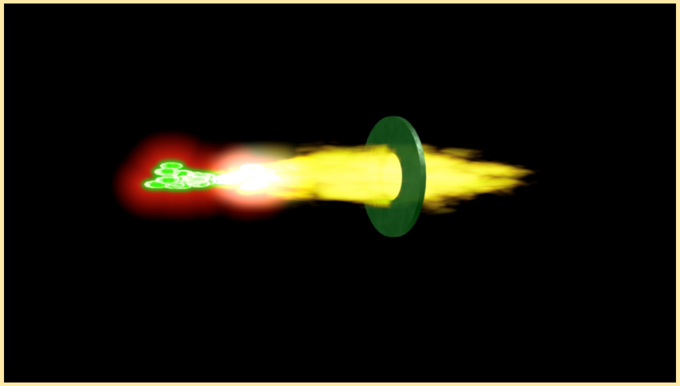
LANL pioneered a new paradigm in relativistic laser-matter interaction: VOLUMTRIC INTERACTION WITH AN OVERDENSE TARGET

Underdense targets

- **Gas jets, capillaries,…**
- Electron acceleration, gas harmonics
- DLA, wakefield, bubble
- **Low density**
- **High coupling**



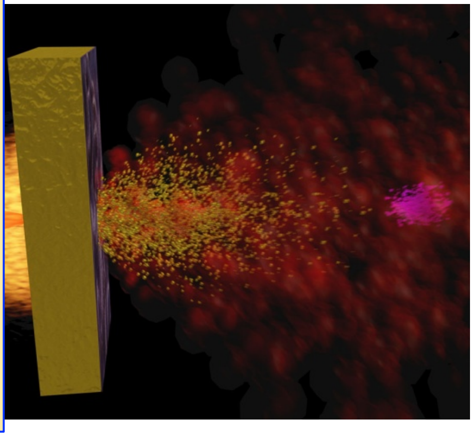
Relativistically transperent, overdense targets



- **Nanometer foils, aerogels, solid hydrogen,…**
- Ion acceleration, electron acceleration, transmitted surface harmonics
- BOA, RPA, PSA, ROM, REM
- **High density**
- **High coupling**

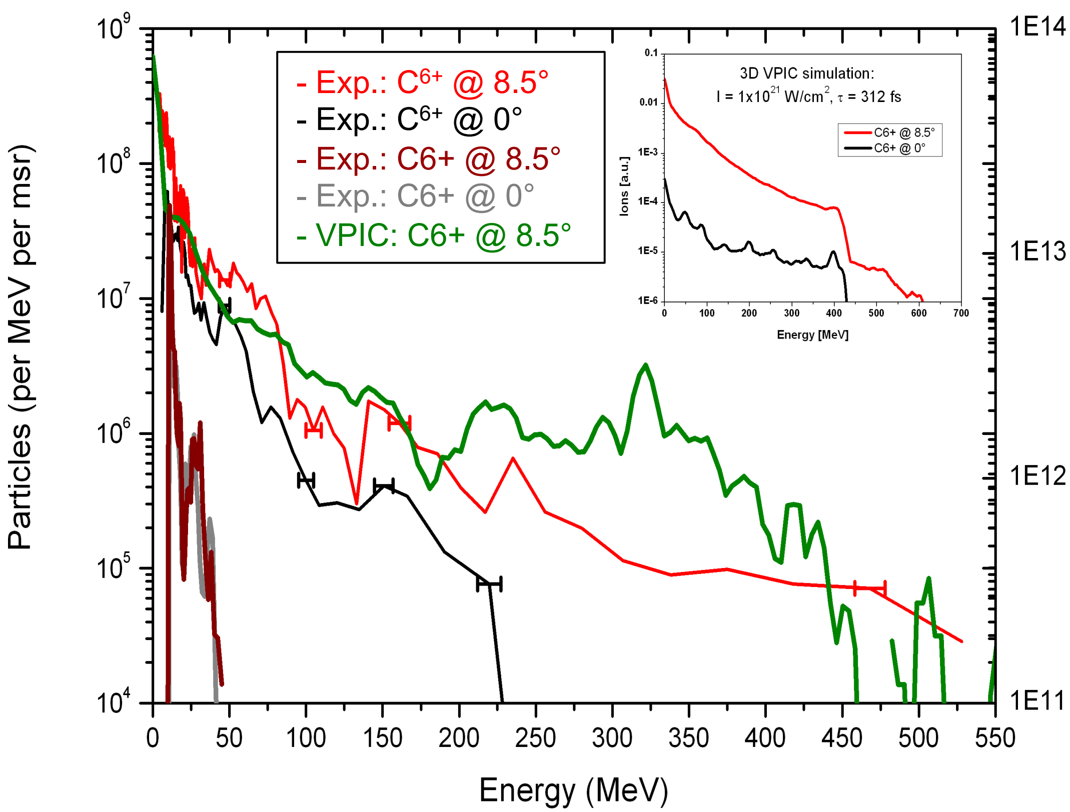
Classically over-dense targets

- **~ Micron-thick foils, cones,…**
- Proton & ion acceleration, K_{α}, …
- TNSA, preplasma interaction
- **High density**
- **Low coupling**



First BOA experiments show >0.5 GeV C ions

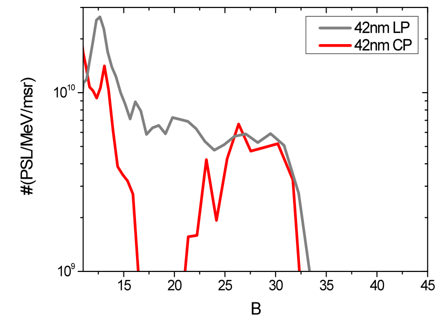
58nm DLC foil, I_{peak}= 5x10^{20} W/cm^2, I_{ave} = 2x10^{20} W/cm^2, 540fs laser pulse,



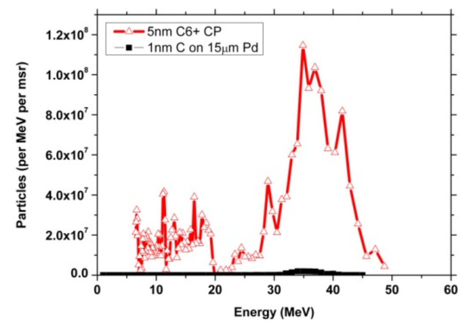
- Simulations agree with measured C spectra (energy, number, angular distribution)
- Protons & C have same Max. velocity
- Spectra retain mono-energetic remnants from adiabatic phase

We can affect the ion energy spectrum by varying polarization, focal spot size and intensity

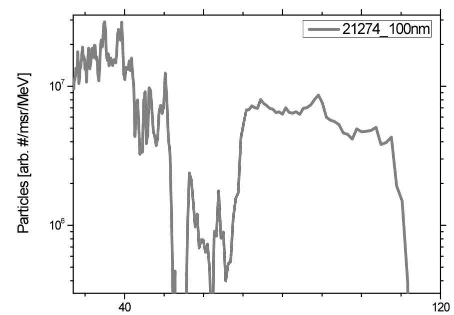
- Switching polarization from linear to circular:
  - mono-energetic protons @ 30 MeV



  - ~10-100x efficiency increase for mono-energetic carbon @ 40 MeV over prev. best [Hegelich et al., Nature 2006]



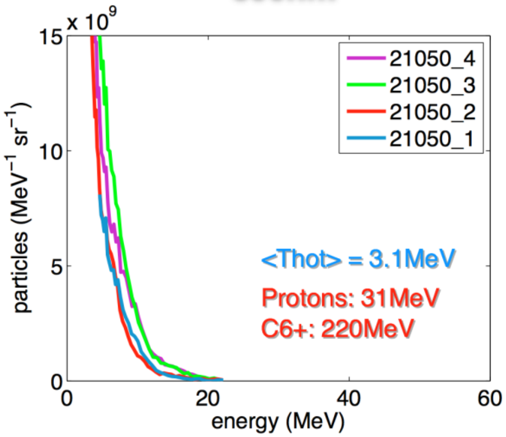
- Increasing focal radius and length:
  - 3x higher energy for mono-energetic carbon @ 100 MeV



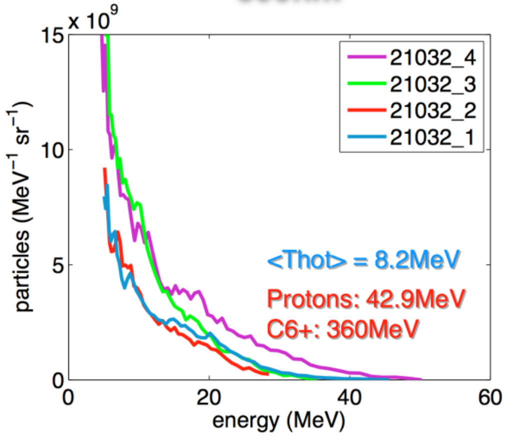
D. Jung, Monday

Electron temperature rises with decreasing foil thickness until spectra become mono-energetic for thinnest targets.

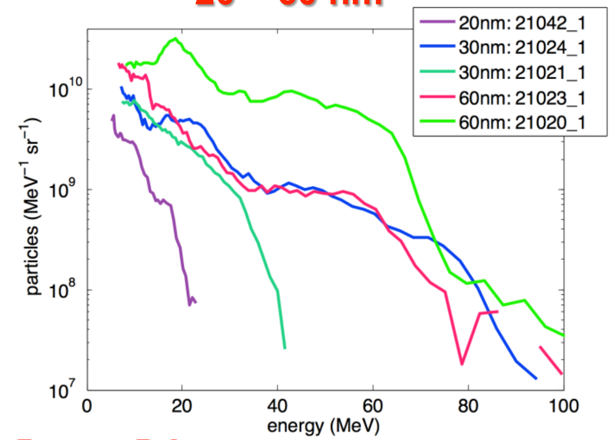
600nm



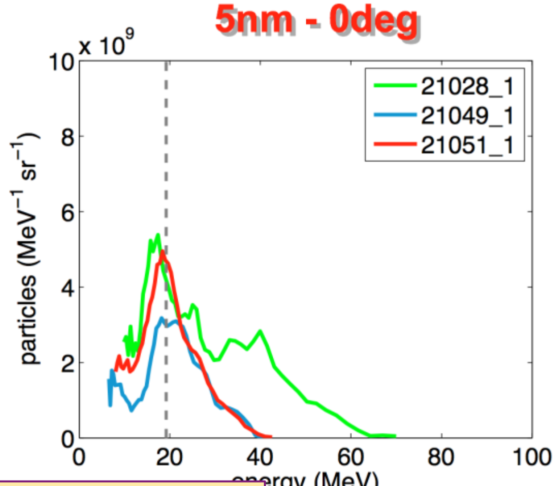
300nm



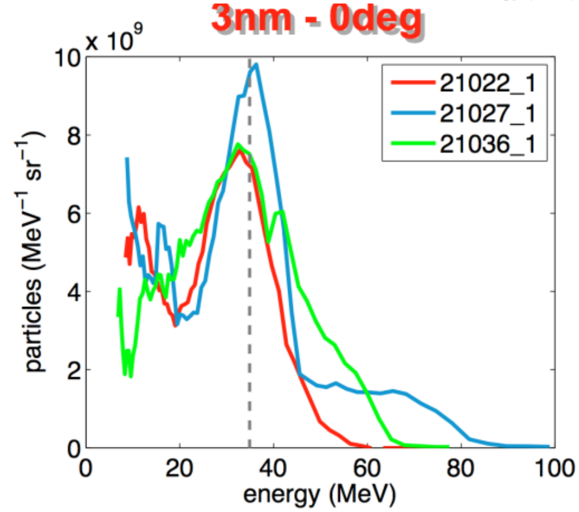
20 – 60 nm



5nm - 0deg



3nm - 0deg

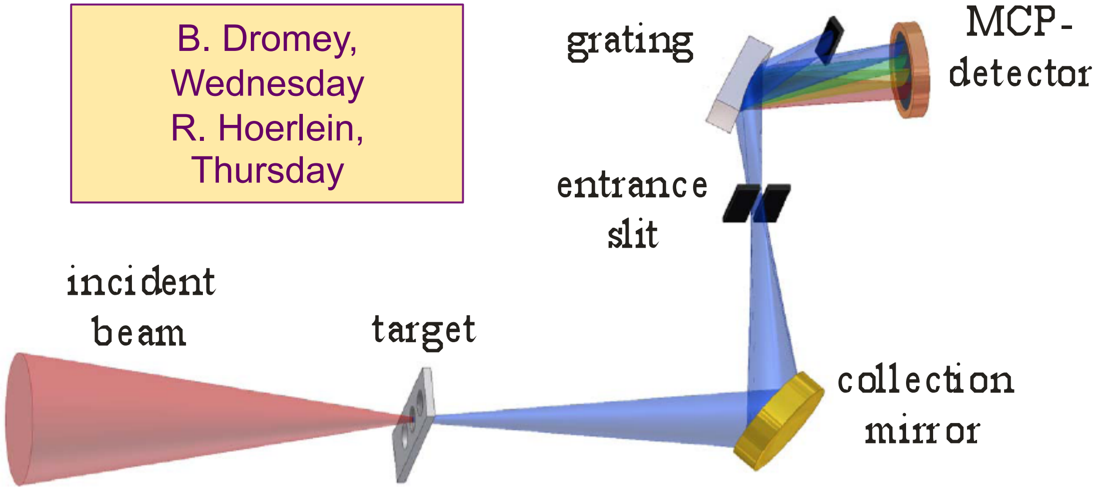


D. Kiefer, Monday

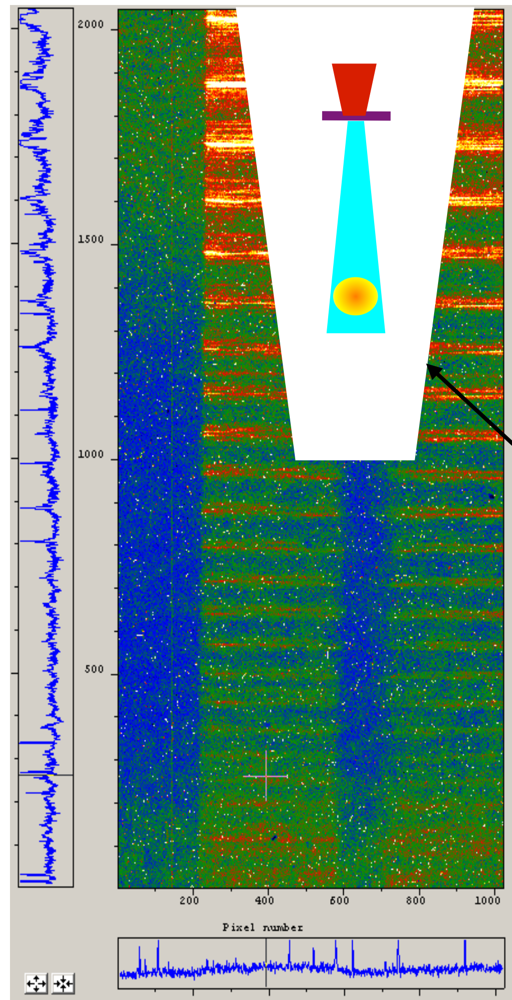
Kiefer, et al., Eur. Jour. Phys. D (2009)

Nanotargets enable forward directed coherent x-rays via Relativistic Oscil. Mirror High Harmonic Gen. (ROM-HHG)

B. Dromey, Wednesday
R. Hoerlein, Thursday



- Surface HH reach higher photon energies than gas HH
- ROM HH are a way of extending present probing with HH in material science to higher energies on MaRIE
- With the right driver, HH enables probing even of WDM, ICF plasma, ...

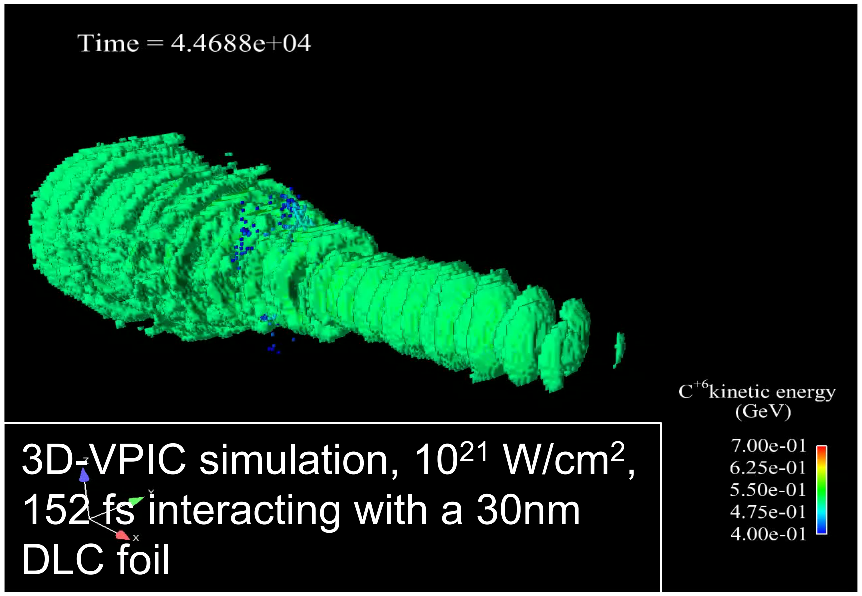


23rd harmonic

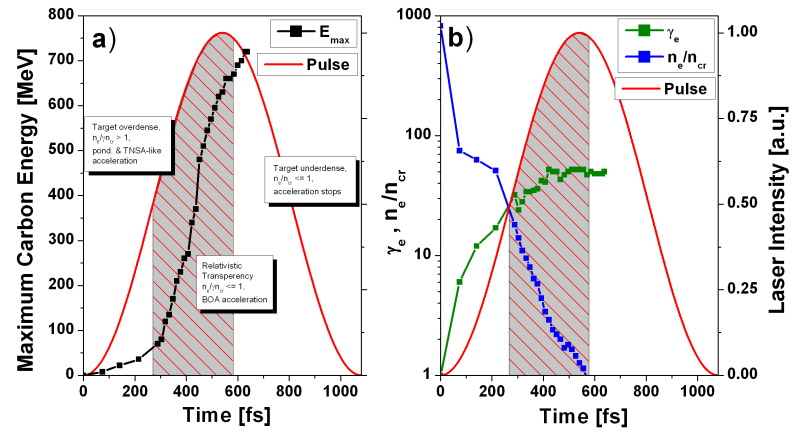
Cutoff from n_{crit} profile

50th harmonic

Break-Out Afterburner (BOA) acceleration in the relativistic transperency regime



3D-VPIC simulation, 10^{21} W/cm^2, 152 fs interacting with a 30nm DLC foil



2D-VPIC simulation: 5x10^{20} W/cm^2, 540 fs, laser interacting with a 58nm DLC foil

From simulations and model we expect to observe:

- *increased maximum ion energy compared to the TNSA*
- *an angular symmetry break for the fastest ions*
- *the same maximum velocities for protons and carbon ions at optimal BOA conditions*
- *optimal target thickness for a given set of laser parameters*

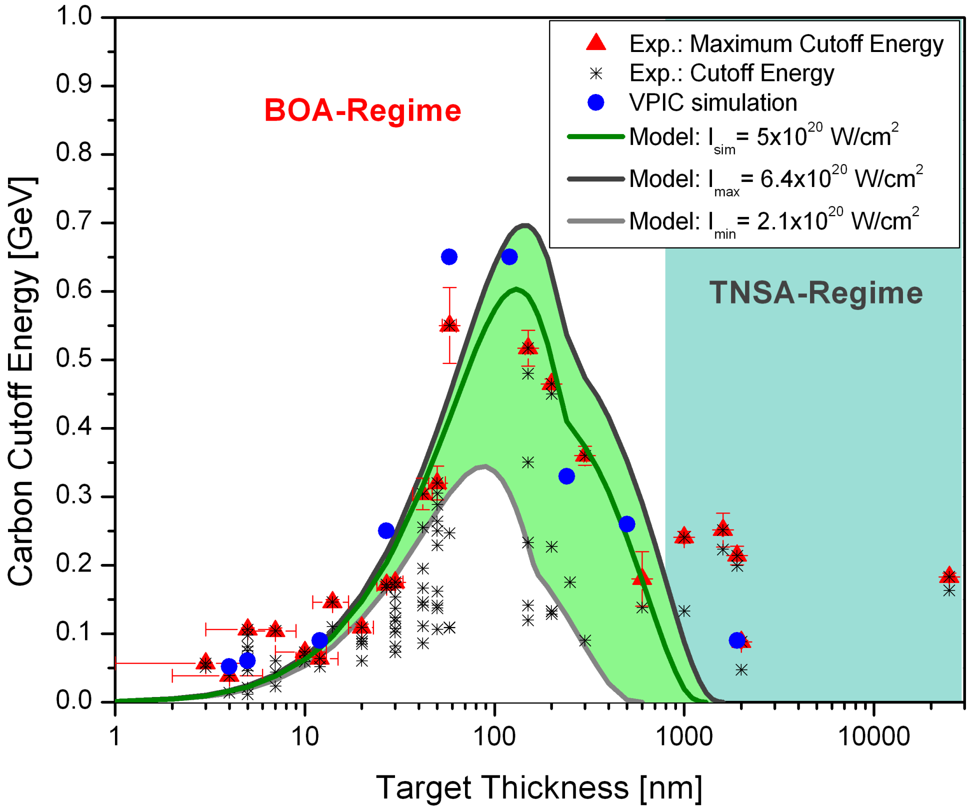
[1]L. Yin, et al., Laser and Particle Beams 24 (2006), 1–8

[2]L. Yin, et al., Phys. Plasmas 14, 056706, (2007).

[3]B. J. Albright, et al., Phys. Plasmas 14, 094502 (2007)

[4]Henig, A., et al., Phys. Rev. Lett. 103, 045002 (2009)

We have developed a simple analytical model for BOA predicting maximum ion energies from laser & target parameters



The model calculates:

- t_1 & t_2 based on a 1D (t_1) and 3D (t_2) isotropic expansion
- maximum ion energy gain due to the electrostatic potential between the ions and the coherently moving, non-thermal electrons

$$\varepsilon_{\max,i,BOA} = (2\alpha+1)Q\bar{E}_0((1+\omega(t_2-t_1))^{1/2\alpha+1}-1)$$

α ~ 3, electron coherence parameter

Yan, Tajima, Hegelich, et al., Appl. Phys. B (2010) 98:711-721

On-shot laser diagnostics

are essential to interpreting the data taken by target diagnostics and to understand the underlying physics

"Conventional" laser diagnostics (incoming pulse):
- energy
- 2^{nd} oder autocorrelation (pulse length)
- pre-pulse diodes
- spectrum
- far field
- near field

Additions:

Incoming Pulse:
- 3^{rd} order cross correlation
- Pulse shape (FROG)

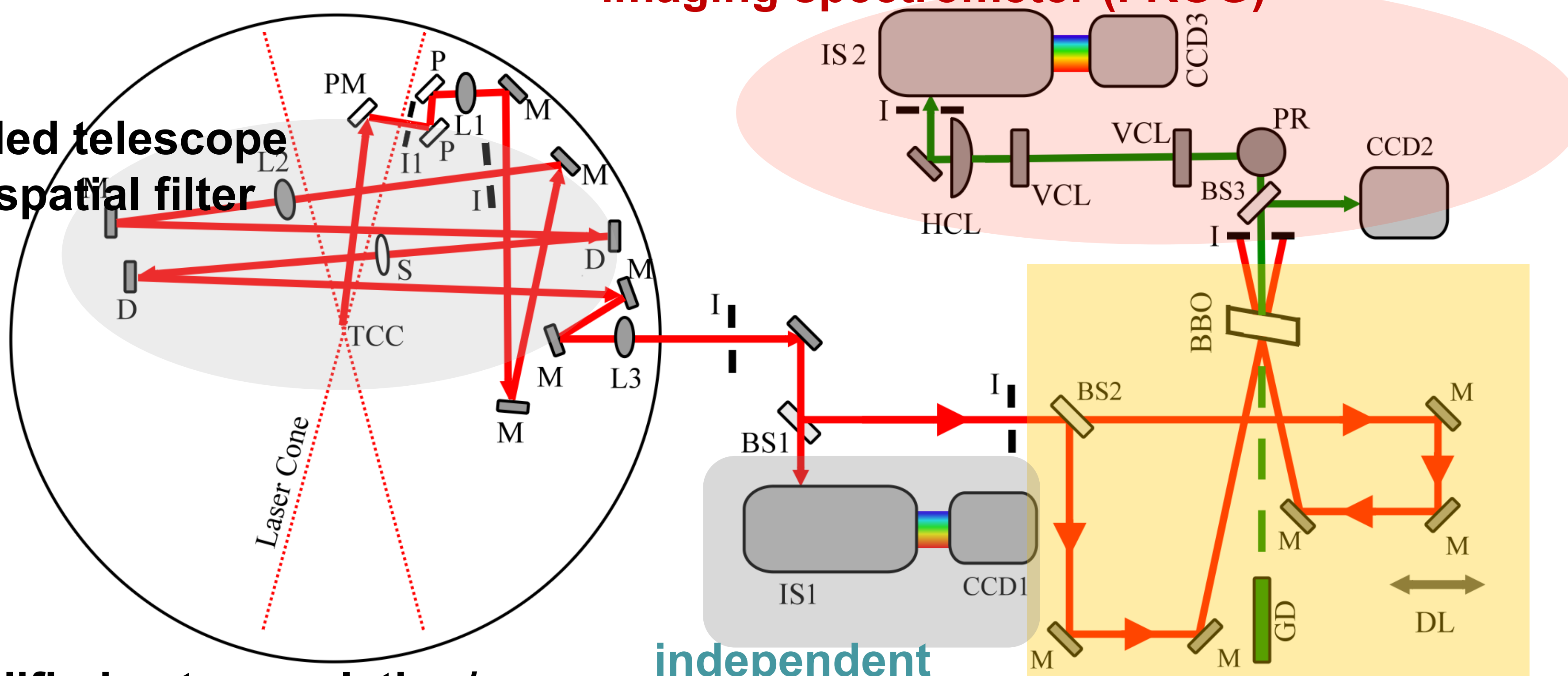
Transmitted Pulse:
- energy
- 2^{nd} oder autocorrelation
- Spectrum
- 3^{rd} order cross correlation
- Pulse shape (FROG)

Reflected Pulse:
- backscatter image @1ω
- backscatter image @ 3ω
- spectrum
- energy
- 3^{rd} order
- FROG

Experimental setup for pulse-shape measurement

imaging spectrometer (FROG)

folded telescope w./ spatial filter



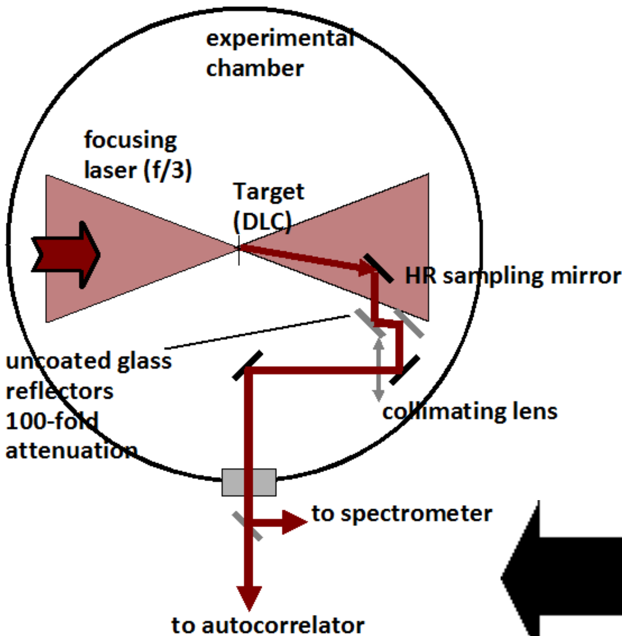
independent spectrometer

autocorrelator

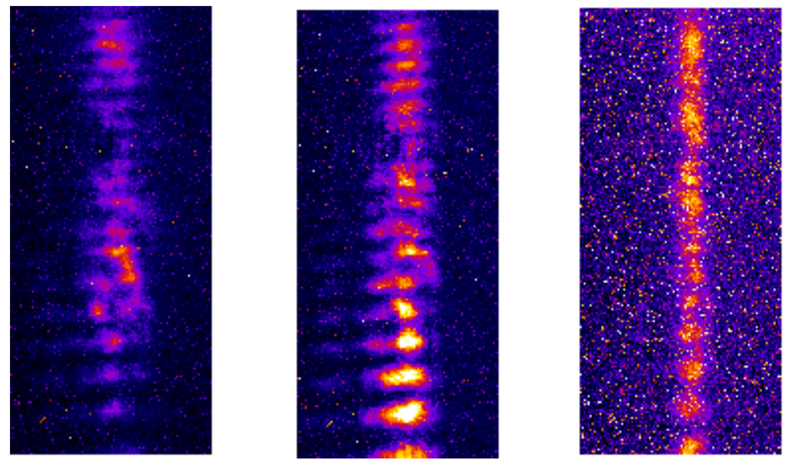
Modified autocorrelation/ spectrum setup to include telescope imaging and imaging spectrometer for FROG

S. Palaniyappan, et al., Rev. Sci. Instrum. 81, 1 (2010)

We have demonstrated relativistic transparency by measuring the pulse shortening of the transmitted pulses

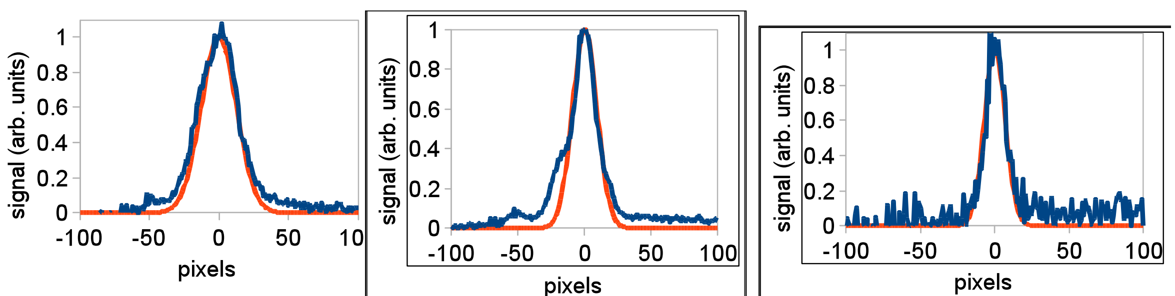


5 nm DLC | 17 nm | 20 nm



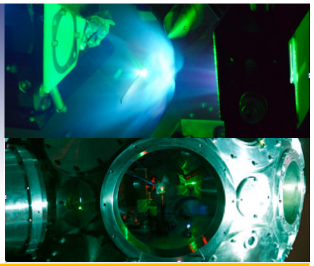
THICKER FOILS
Signal weakens to below detection at 300 nm

THINNER FOILS no change

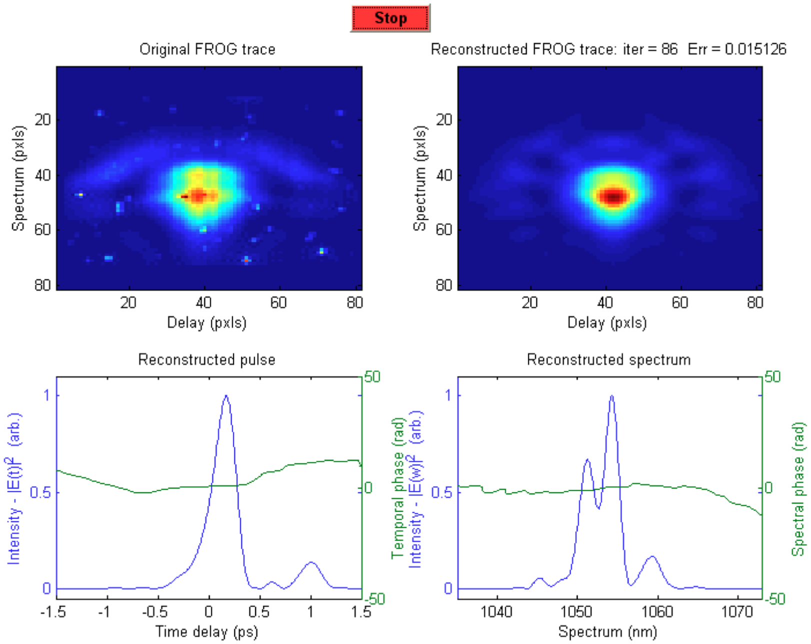


FWHM (pixels)	36	20	12
Duration (fs)	585	321	195

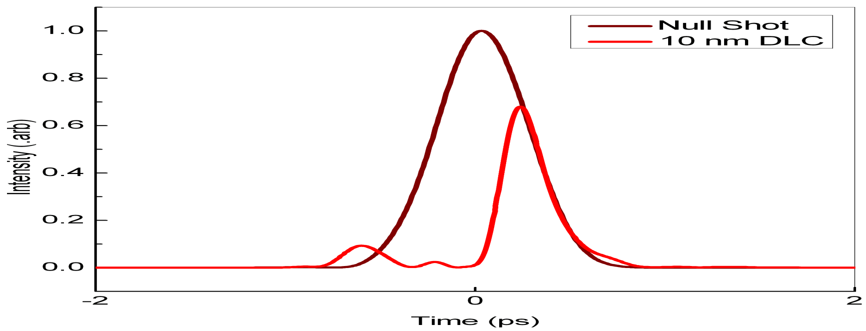
We can utilize relativistic transparency to do laser pulse shaping (steepening) beyond its Fourier limit



- Trident has ~3nm bandwidth and is thus limited to ~500 fs FWHM pulse durations and rise times



- Single shot FROG setup measures 100 fs rise time and 200 fs duration



R. Shah, Thursday

Time Dependent Electron Density From Temporal Phase

$$\phi(t) = \frac{2\pi}{\lambda} \int_0^{x_f} n_{ref}(x,t)\,dx$$

$$n_{ref}(t) = \sqrt{1 - \frac{n_e(x)}{\gamma(t)\, n_c}}$$

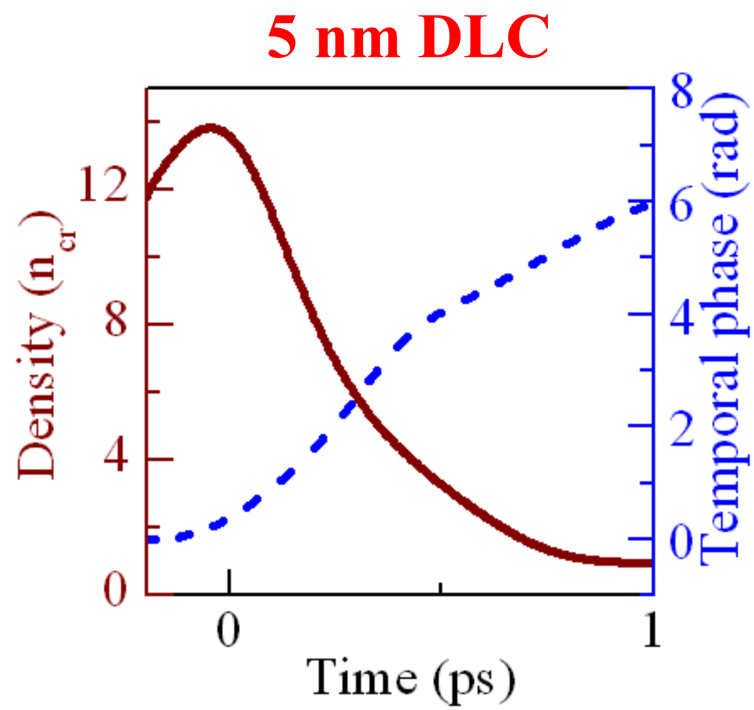
Assuming $n_e(x) = n_e$ and

1 - D target expansion

$$\phi(t) = \frac{2\pi}{\lambda} n_{ref}(t) L$$

$$n_e(t) = \frac{-\frac{\alpha}{\gamma(t)} + \sqrt{\frac{\alpha^2}{\gamma(t)^2} + 4\phi'\alpha}}{2\phi'}$$

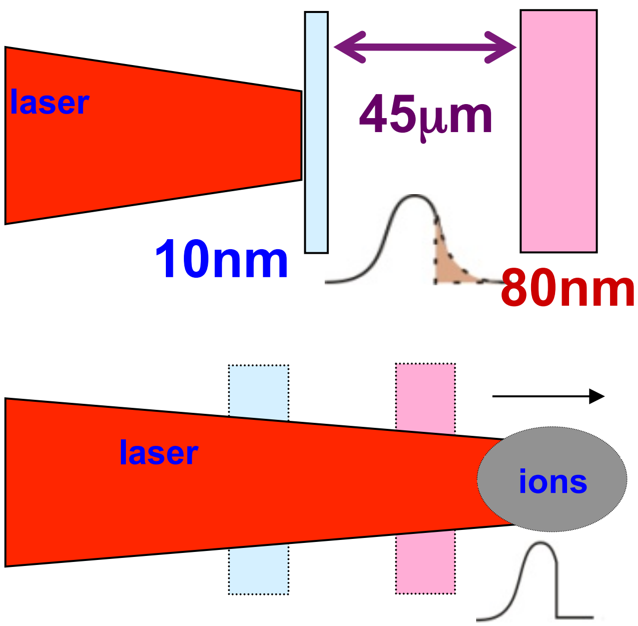
Where $\alpha = n_{e0} L_0$ and $\phi' = \left(\frac{\lambda}{2\pi}\phi\right)^2$

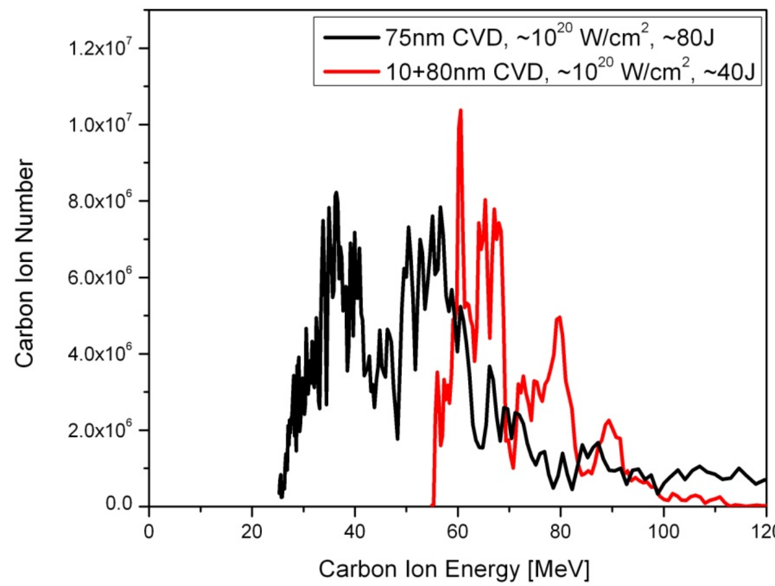


- **FROG gives relative phase**
- **Absolute phase is fixed by assuming zero phase when transparency happens**

Double-target proof-of-principle experiments on nanotarget shaped pulses shows effects of shorter rise-time.

- **Double nano-targets enable sharp temporal interactions even with glass lasers**





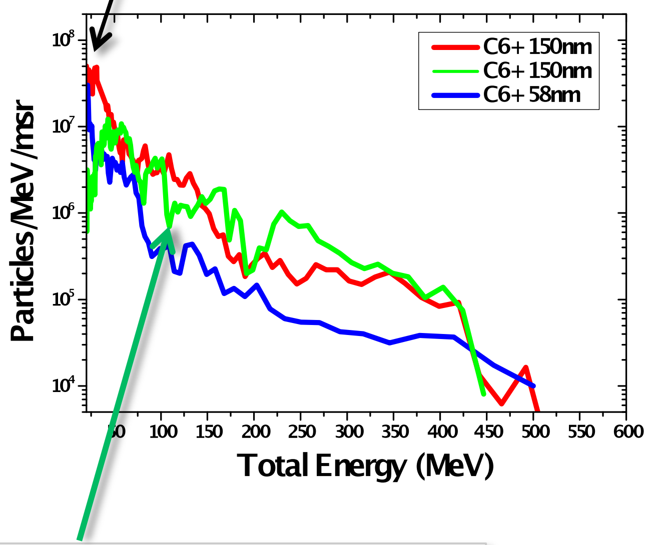
- **1st non-optimized test shows ion-spectral modification & improvement**

Overcoming TNSA limitations with relativistic laser plasma interaction (BOA[1,2,3,4,5]):

We measured laser accelerated protons up to 66MeV and carbon C^{6+} ions up to 42MeV/amu

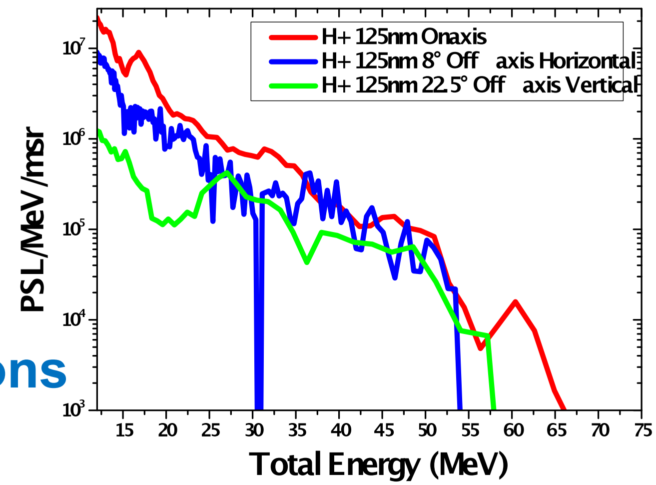
(Previous: H^{+}:60MeV, C^{6+} 5MeV/amu)

Spectrometer low energy cutoff (ranges from 5MeV to 18MeV)



Carbon C^{6+}

Protons



600nJ at 22.5° in $5x10^{-5}$msr
→ $CE_{20\text{-}300MeV}$ ~8%

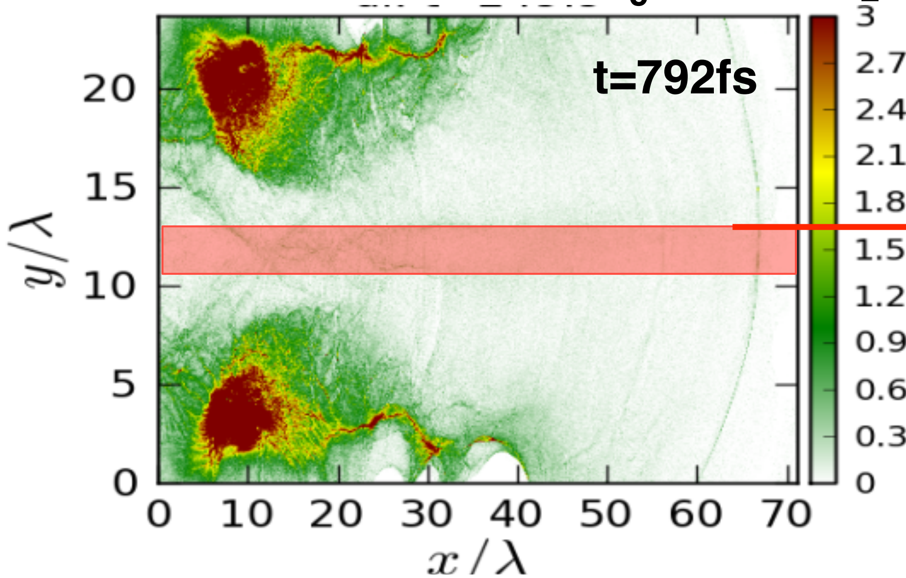
[1] *L. Yin, et al., Laser and Particle Beams 24 (2006), 1–8*
[2] *L. Yin, et al., Phys. Plasmas 14, 056706, (2007).*
[3] *B. J. Albright, et al., Phys. Plasmas 14, 094502 (2007)*
[4] *A. Henig, et al., Phys. Rev. Lett. 103, 045002 (2009)*
[5] ***B. M. Hegelich, et al., submitted to Nature Physics (2010)***

Cyrogenic hydrogen target leads to higher energy and efficiency than CH_2

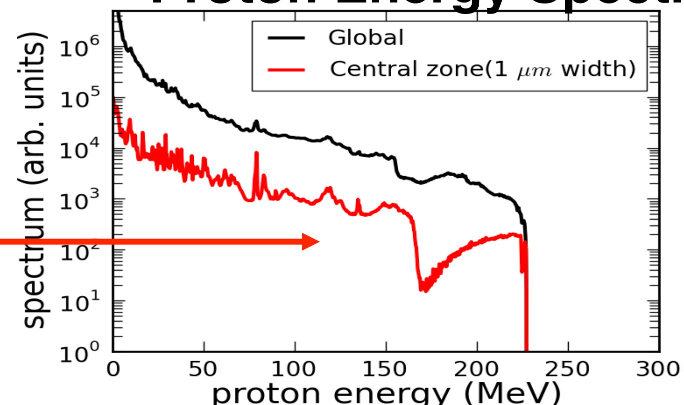
Cyrogenic hydrogen target at (0.07g/cm^3), n_e=42.6 n_{cr}

Target Thickness l	400 nm	1000 nm	1500nm	2500 nm
H^+ E_{max}	145 MeV	205 MeV	230MeV	190 MeV

Proton density n/n_c at time t_2



Proton Energy Spectrum

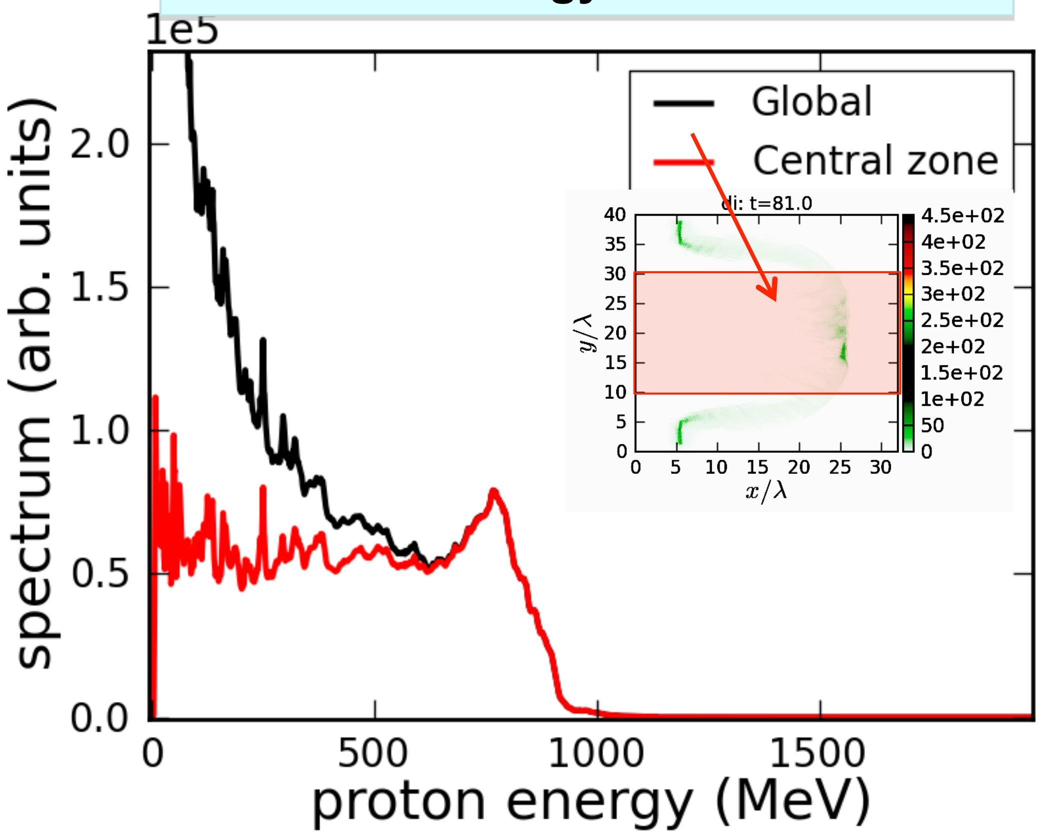


Efficiency

	$\eta_E(H^+)$*	# (H^+)*
>100MeV	1.1%	6.5×10^{10}
>50MeV	2.2%	1.9×10^{11}
>10MeV	4.2%	9.7×10^{11}

Extreme Intensity Short Pulse Laser (>10^{22} W/cm^2) enables higher conversion efficiencies & higher energies

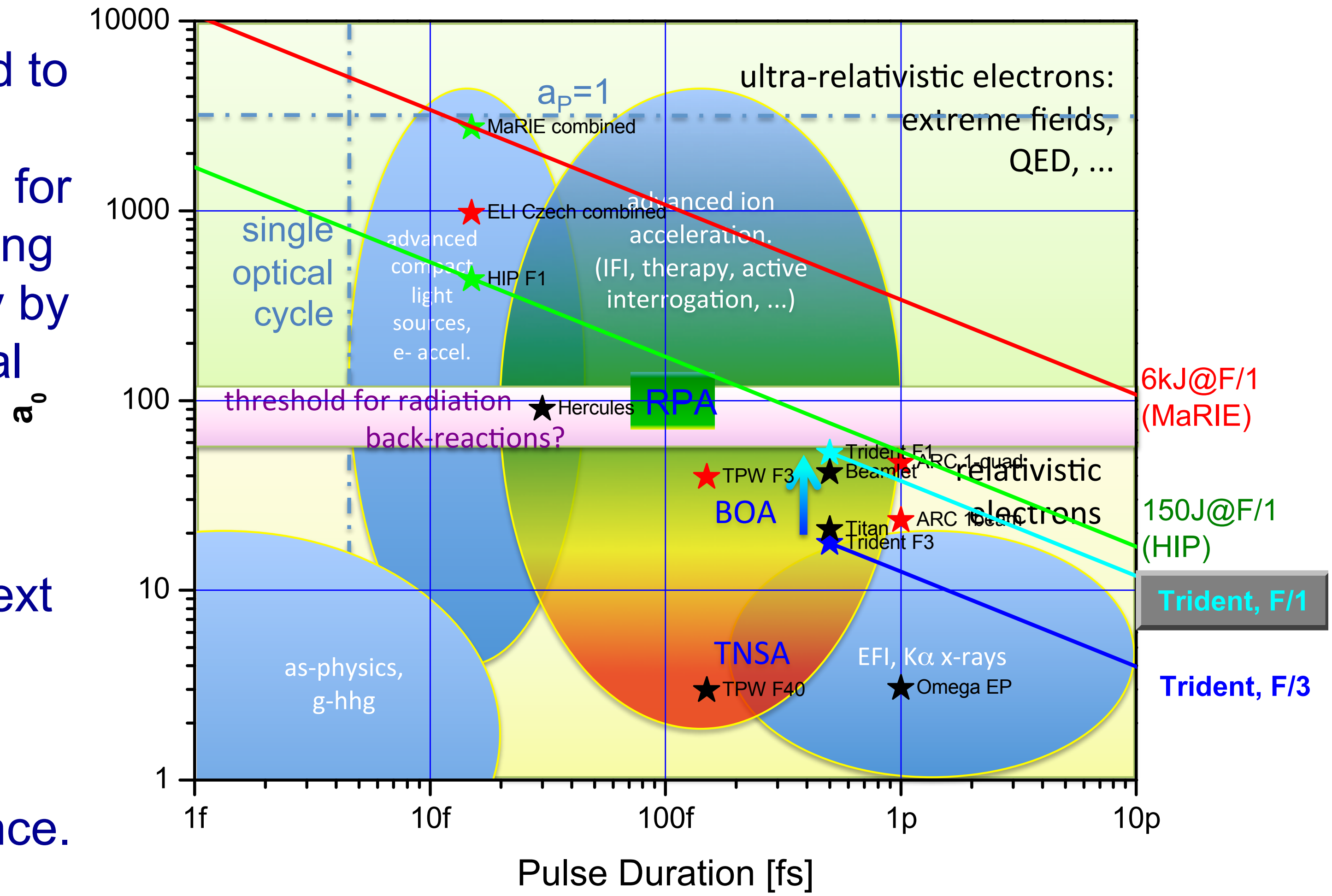
19% of laser energy goes into 6×10^{12} forward directed protons with energy >500 MeV



- **Simulation parameters from Qiao et al. (PRL 2009):**
  - **Peak intensity: 1.89×10^{22} W/cm^2**
  - **Circular polarized, super-Gaussian in space, Gaussian in time, 38 fs width**
  - **1 micron thick Proton target (n_e = 30 n_{cr})**

Unexplored physics at Extreme Intensties; Europe has build a community to tackle these problems the US has not done so, yet.

- We were invited to submit a LDRD reserve proposal for FY11 on increasing Tridents intensity by reducing the focal spot size.
- Trident 10 PW upgrade is the next logical step.
- Rich field of unexplored science.



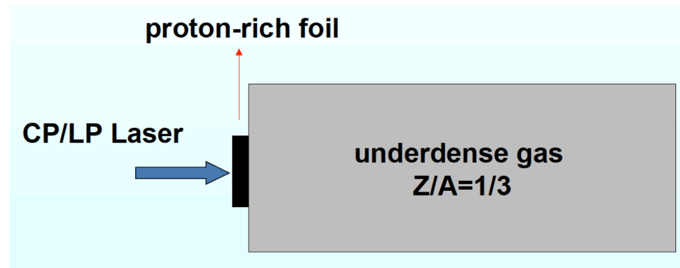
End-point-performance laser-ion accelerators require high *average* power & high *peak* power

1st stage requires high peak intensity to reach relativistic ions

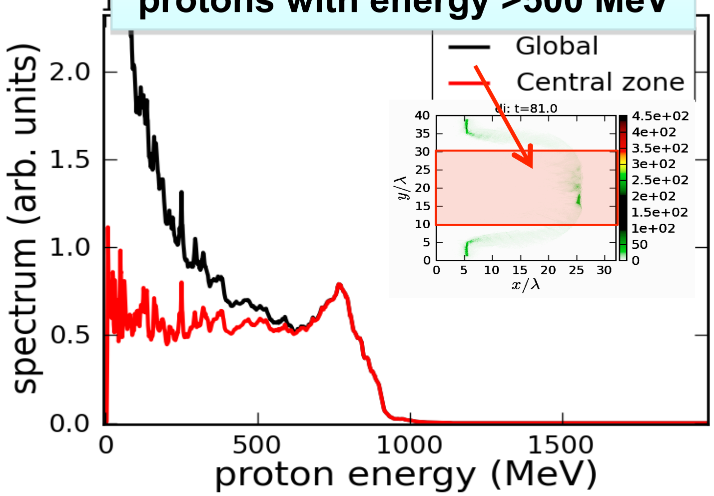
- **Peak intensity: 2×10^{22} W/cm^2**
- **τ ~ 30fs, 300J, 10PW**

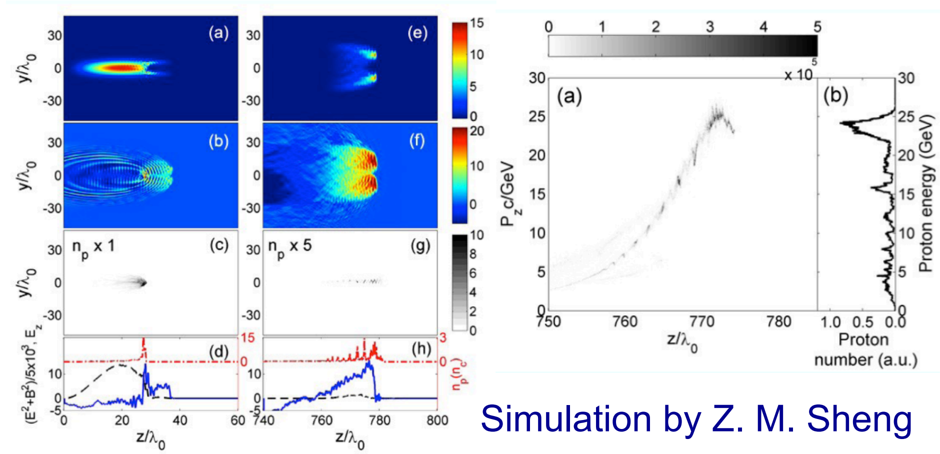
2 stage laser accelertor:
25 GeV/amu

Double-stage laser acceleration:
BOA – wakefield (200PW)



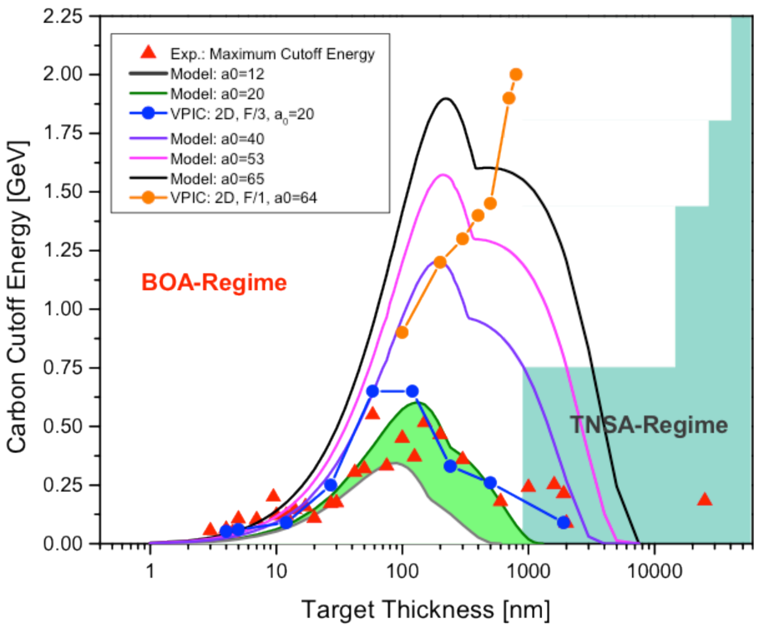
19% of laser energy goes into 6×10^{12} forward directed protons with energy >500 MeV

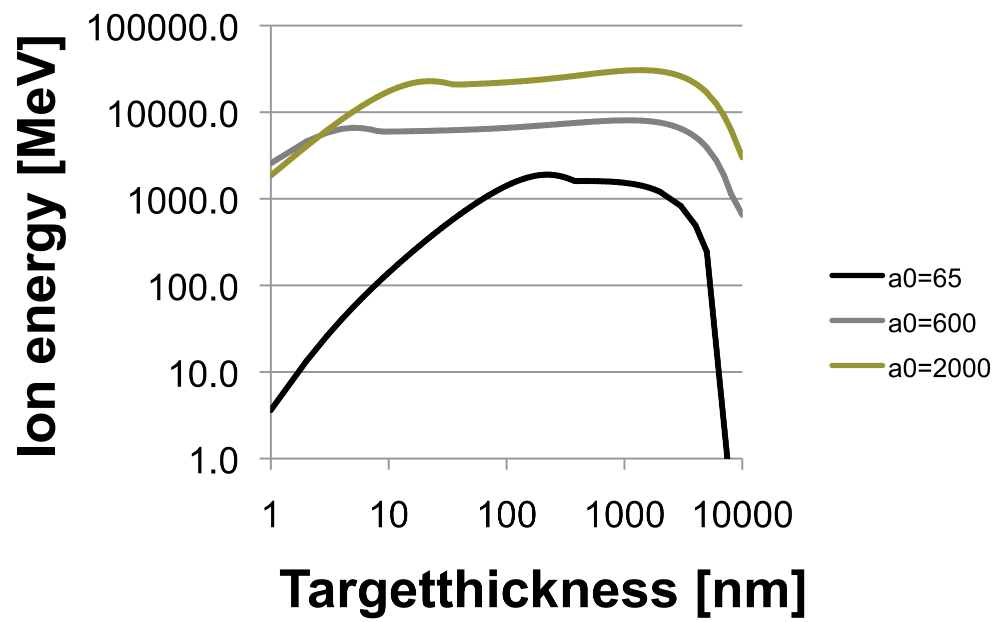




Simulation by Z. M. Sheng

Development of ion energies and optimal target thickness with increasing a_0





Recent LANL/LMU publications on nanotargets, the transparent overdense regime and its applications

1. Towards GeV laser-driven Ions: Ion Accelertion in the Break-Out Afterburner Regime
B. M. Hegelich, L. Yin, B. J. Albright, K.J. Bowers, et al., submitted to Nature Physics
2. High Harmonic Generation in the transmission of Nanometer-Scale Foil Targets Irradiated with Relativistically Intense Laser Pulses at Normal Incidence
R. Hörlein, A. Henig, S. G. Rykovanov, S. Steinke, et al., submitted to PRL
3. Improving ion spectral and spatial quality in laser foil interaction with a second foil
Chengkun Huang, B. J. Albright, L. Yin, H.-C. Wu, K. J. Bowers, B. M. Hegelich et al., submitted to PRL
4. Uniform laser-driven relativistic electron layer for coherent Thomson scattering
H.-C. Wu, J. Meyer-ter-Vehn, J. Fernandez, and B.M. Hegelich, submitted to PRL
5. Three-dimensional Dynamics of Break-out Afterburner Ion Acceleration using High-contrast Short-pulse Laser and Nano-scale Targets
L. Yin, B. J. Albright, K. J. Bowers, D. Jung, J. C. Fernandez, and B. M. Hegelich, submitted to PRL
6. Efficient ion acceleration by collective laser-driven electron dynamics with ultra-thin foil targets
S. Steinke, A. Henig, M. Schnürer, T. Sokollik, P. V. Nickles, D. Jung et al., accepted, Appl. Phys. B (2010)
7. Theory of laser ion acceleration from a foil target of nanometer thickness
X.Q. Yan, T.Tajima, M. Hegelich, L.Yin, D.Habs, Appl. Phys. B 98, 4, (2010)
8. Radiation pressure acceleration of ion beams driven by circularly polarized laser pulses
A. Henig, S. Steinke, M. Schnürer, T. Sokollik, R. Hörlein, D. Kiefer, D. Jung, et al., Phys. Rev. Lett. 103, 245003 (2009)
9. Fast ignition of inertial fusion targets by laser-driven carbon beams
J.J. Honrubia, J.C. Fernandez, M. Temporal, B.M. Hegelich, and J. Meyer-ter-Vehn, Phys. Plasmas, 16, 10 (2009)
10. Enhanced Laser-Driven Ion Acceleration in the Relativistic Transparency Regime
A. Henig, D. Kiefer, K. Markey, D. C. Gautier, K. A. Flippo, S. Letzring,, et al., Phys. Rev. Lett. 103, 045002 (2009)
11. High-temporal contrast using low-gain optical parametric amplification,
Rahul C. Shah, Randall P. Johnson, Tsutomu Shimada, et al., Opt. Lett. Vol. 34, No. 15 (2009) p2273
12. Large temporal window contrast measurement using optical parametric amplification and low-sensitivity detectors
R.C. Shah, R.P. Johnson, T. Shimada, and B.M. Hegelich, Eur. Phys. J. D (2009)
13. First observation of quasi-monoenergetic electron bunches driven out of ultra-thin diamond-like carbon (DLC) foils
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14. Progress and prospects of ion-driven fast ignition
Juan C. Fernandez, J.J. Honrubia, Brian J. Albright, Björn M. Hegelich, et al., Nucl. Fusion 49 (2009) 065004 (8pp)
15. Dense laser-driven electron sheets as relativistic mirrors for coherent production of brilliant X-ray and gamma-ray beams
Habs, D; Hegelich, M, et al., APPL PHYS B-LASERS AND OPTICS Volume: 93 Issue: 2-3 Pages: 349-354 Published: 2008
16. A novel backscatter focus diagnostic for the TRIDENT 200 TW laser
Author(s): Gautier, DC; Flippo, KA; Letzring, SA, B.M. Hegelich et al.
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17. Relativistic Buneman instability in the laser breakout afterburner
B. J. Albright, L. Yin, Kevin J. Bowers, B. M. Hegelich, et al., Phys. Plasmas, 14, 094502, (2007)
18. Monoenergetic and GeV ion acceleration from the laser break-outafterburner using ultrathin targets
L. Yin, B. J. Albright, B. M. Hegelich, et al., Phys. Plasmas 14, 056706, (2007).
19. Laser-driven ion accelerators: spectral control, monoenergetic ions and new acceleration mechanisms
K. Flippo, B. M. Hegelich, B. J. Albright, et al., Laser and Particle Beams; v.25, no.1, p.3-8
20. Theory of laser acceleration of light ion beams in ultra-intense laser-matter interaction with layered targets
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21. Advanced Lasers and Beams Applications. The ALBA Facility at LANSCE
J. Fernandez, K. Schoenberg, B. M. Hegelich, et al., LA-UR-06-7451, IPD Report 2006
22. GeV laser ion acceleration from ultrathin targets: The laser break-out afterburner
L. Yin, B. J. Albright, B. M. Hegelich, and J. C. Fernández
Laser and Particle Beams 24 (2006), 1–8
23. Mono-energetic multi-MeV/nucleon ion beams accelerated by ultrahigh intensity lasers
B. M. Hegelich, B. J. Albright, J. Cobble, R. Johnson, S. Letzring, H. Ruhl, J. Schreiber, J. C. Fernandez
Nature 439, p441 (2006).

Summary

- **LANL pioneered a new paradigm in relativistic laser-matter interaction: *volumetric interaction with an overdense target***
- **The new paradigm is enabled by two technologies:**
  We have demonstrated the production and integration of nm-scale targets and ultraclean laser pulses.
- **These enable qualitative progress in laser particle acceleration:**
  - IFI energies (500 MeV) reached with modest laser
  - IFI efficiencies (>10%) achieved: 80 MeV C^{6+} @ 11% CE with 0.7J Ti:Sa laser
  - IFI spectrum ($\Delta E<20\%$) demonstrated: at Trident with 5nm targets and circular polarization.
  - Laser-pulse shortening and pulse shaping beyond Fourier-transform limit
  - Forward directed HHG from nano-DLC targets
  - Demonstration of quasi-monoenergetic electrons and electron break-out for sub-10nm targets important first step towards Relativistic Electron Mirrors (REM)
- **To go from Proof-of-Principle to Proof-of-Performance, a dedicated program and a new generation of lasers is required.**