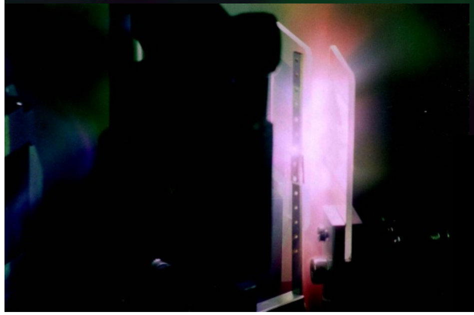
"Shooting nano-targets: The high-contrast, high-energy, arbitrary polarization Trident Shortpulse Laser at Los Alamos"

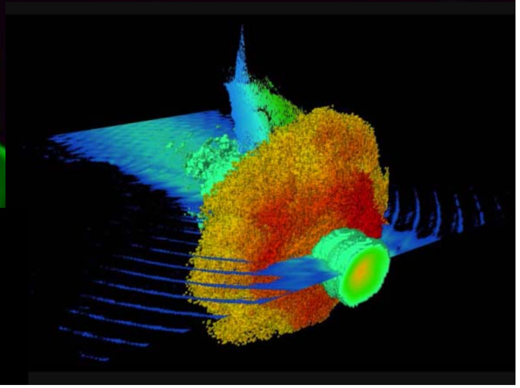
Björn Manuel Hegelich

3rd ICUIL conference

Tongli, PR China,

Oct. 27th – 31st, 2008





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Colleagues and Collaborators

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LMU München & MPQ:
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Lawrence Livermore National Laboratory:
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Support by LANL LDRD Program Office, Office of Fusion Energy Sciences, and LMU Excellent.

Outline:

- Motivation: Why nm-targets?
  - New acceleration mechanisms (BOA, RPA) – towards GeV energies
- The LANL Trident Ultrahigh Intensity Laser
  - Basis system outline
  - New, ultrahigh contrast frontend
- Laser-driven particle acceleration
  - 1st demonstration of Break-Out Afterburner Acceleration
  - 1st demonstration of e^- breakout
- Summary

Motivation:
Laser-driven Ion Acceleration

Towards GeV ion energies - new acceleration mechanisms:
BOA
RPA
...

Nanoscale targets: Pathway to a new, highly efficient acceleration mechanism?

Enhanced TNSA: Thinner targets enable higher ion energies:

1.LLNL: Enhancement of Proton Acceleration by Hot-Electron Recirculation in Thin Foils Irradiated by Ultraintense Laser Pulses. A. MacKinnon, et al., **PRL 88**, (2002)

2.LULI: Ion acceleration using high-contrast ultra-intense lasers, J. Fuchs et al., **J. Phys. IV France 133** (2006) 1151–1153

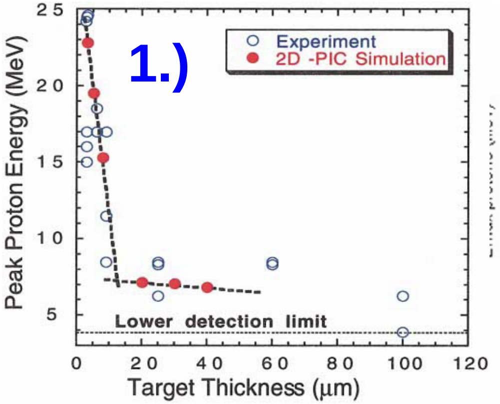
Break-Out Afterburner (BOA): Matching of laser and target parameters enables additional energy transfer via relativistic Buneman instability:

3.LANL: GeV laser ion acceleration from ultrathin targets: The laser break-out afterburner, L. Yin, et al., **Laser and Particle Beams 24** (2006), 1–8

4.LANL: Monoenergetic and GeV ion acceleration from the laser break-outafterburner using ultrathin targets, L. Yin, et al., **PoP 14**, 056706, (2007).

5.LANL: Relativistic Buneman instability in the laser breakout afterburner, B. J. Albright, et al., **PoP 14**, 094502, (2007)

1.)



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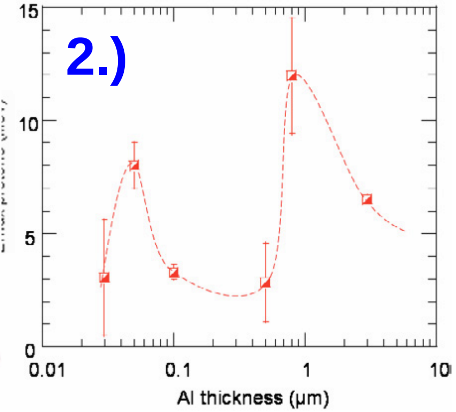

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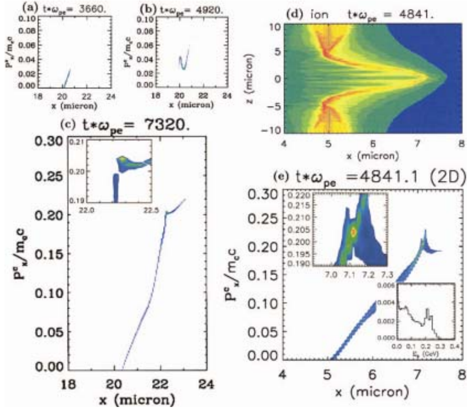

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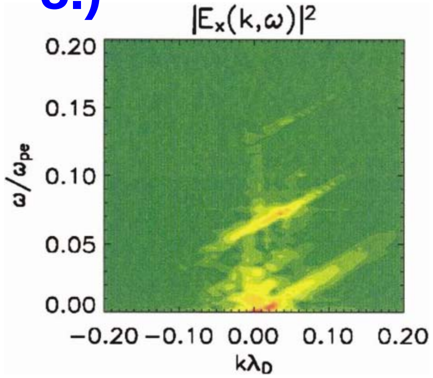
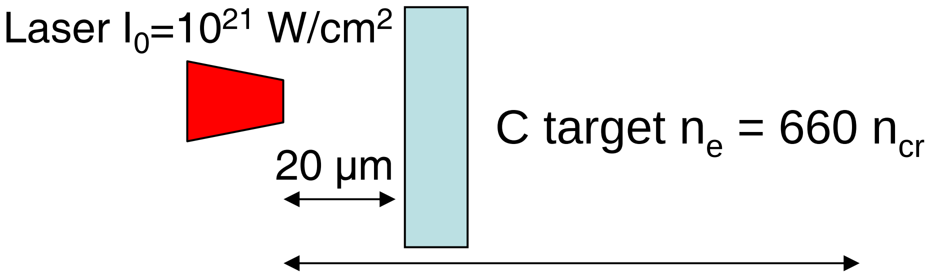
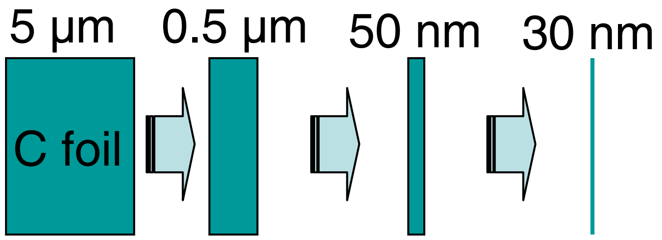


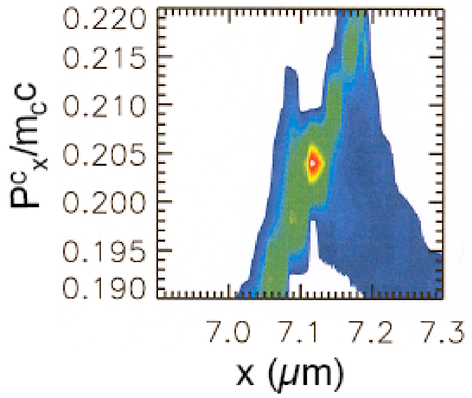
2D-VPIC: Towards GeV ions: The Break-Out Afterburner (BOA) acceleration mechanism



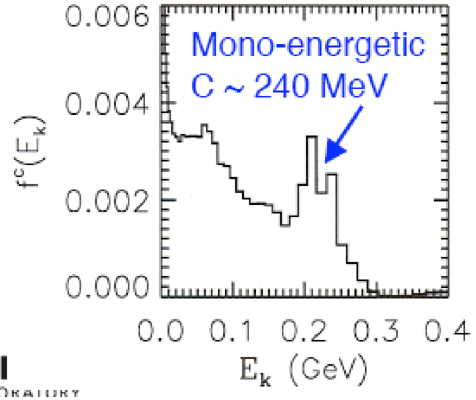


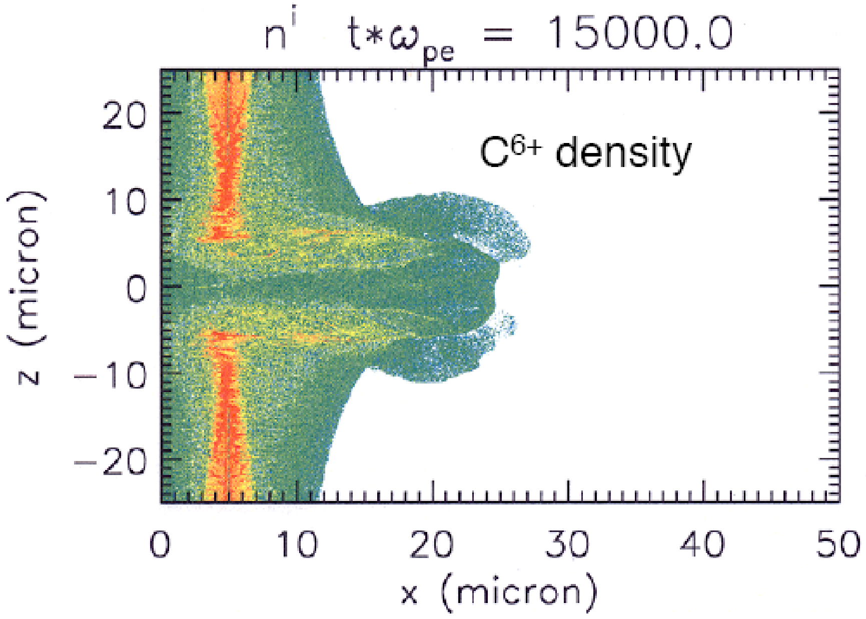
L. Yin, B. J. Albright, B. M. Hegelich, K. J. Bowersz, K. A. Flippo, T. J. T. Kwan, and J. C. Fernández, Phys. Plasmas 14, 056706, (2007).

C^{6+} momentum



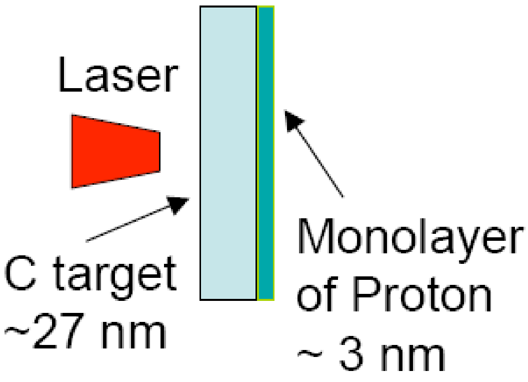
C^{6+} energy spectrum

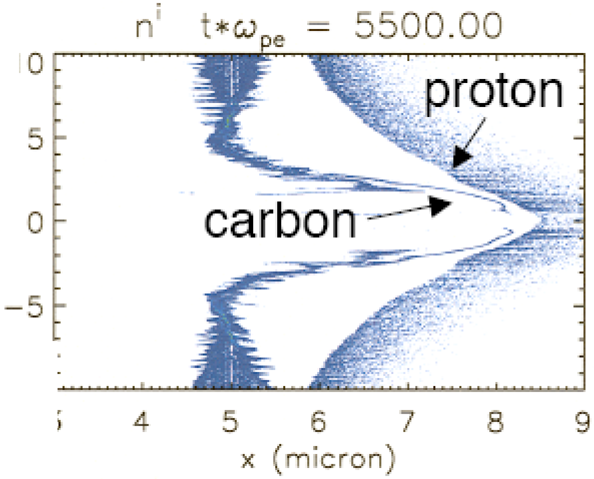


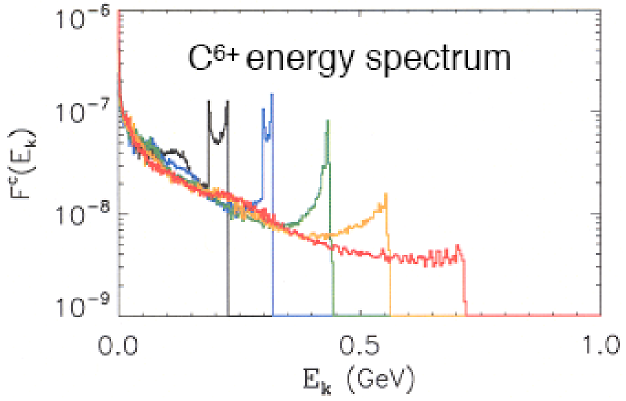


VPIC calculations: 1.2 billion cells, done on LANL ASC Lightning/Bolt supercomputer

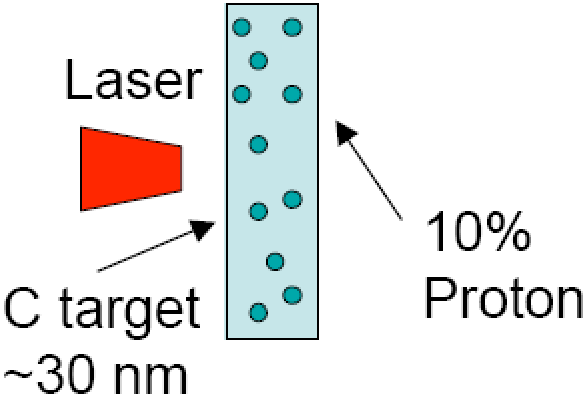
Target cleaning is not required with BOA. Protons move with carbons and gain the same velocity.

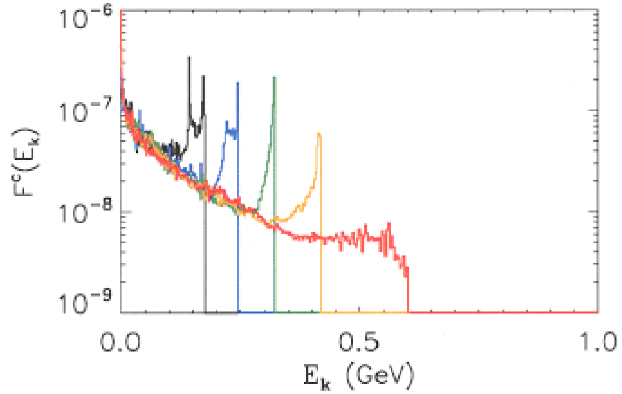






142, 155, 170, 187, 220 fs

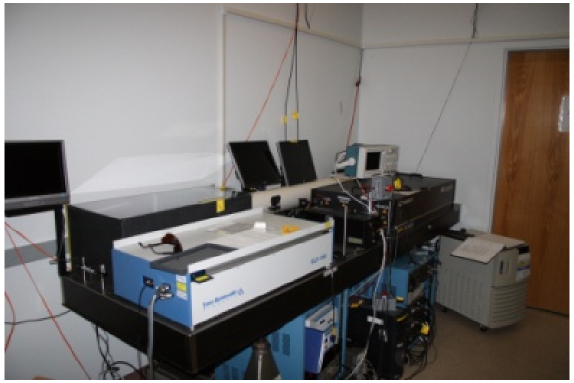




142, 155, 170, 187, 220 fs

The Trident laser facility at Los Alamos

The Los Alamos Trident Laser Facility:



3 beamlines, 3 target areas:

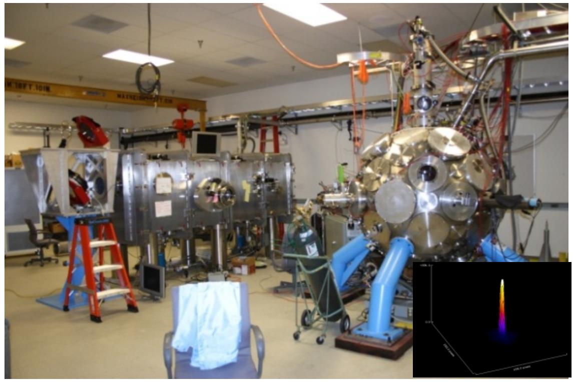
A + B: 100ps – 6µs, 80-1000J (532nm)

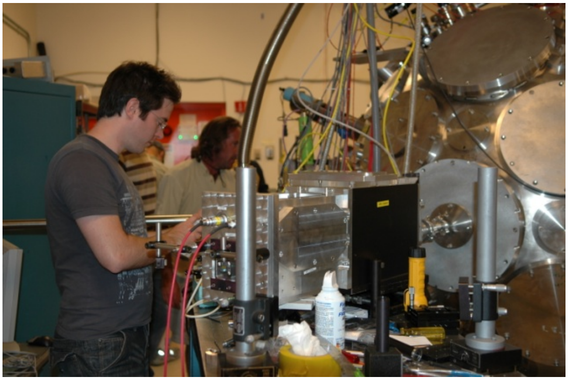
Full temporal pulse shaping

C-Beam: 500fs, 125J, 250 TW (1054nm)

Intensity: 5×10^{20} W/cm^2

- Rep. rate: 1 shot / 45 min.
- AODF (spectral control), adaptive optics
- Complete suite of laser diagnostics on each shot (Energy, pulse length, pre-pulse, spectrum, far field, near field)
- Contrast: Old frontend: ~10^{-7}
  New frontend: < 5×10^{-10} (prepulse)
  < 2×10^{-12} (pedestal)





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Trident

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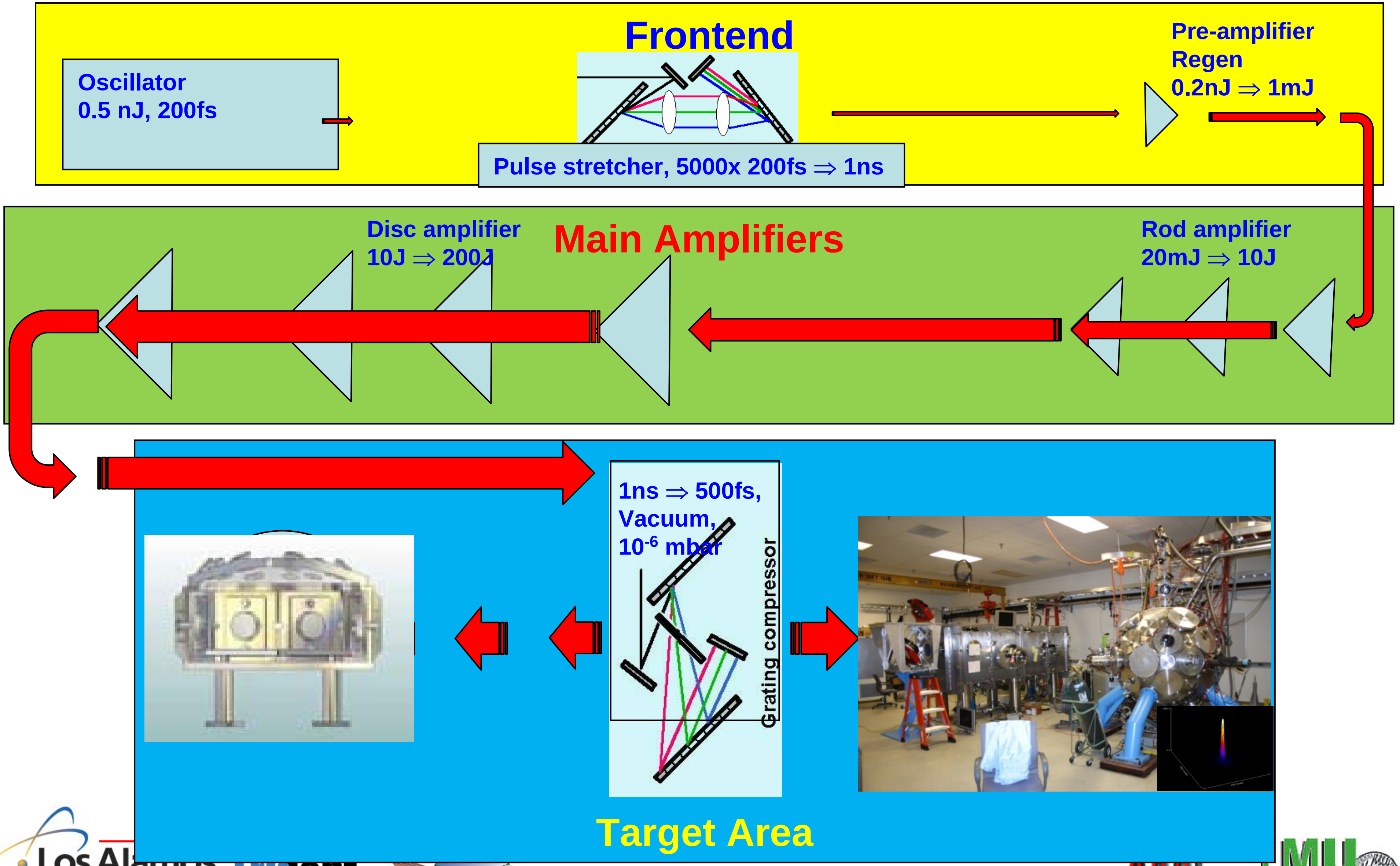
Trident system layout



Frontend

Oscillator
0.5 nJ, 200fs

Pulse stretcher, 5000x 200fs ⇒ 1ns

Pre-amplifier
Regen
0.2nJ ⇒ 1mJ

Main Amplifiers

Disc amplifier
10J ⇒ 200J

Rod amplifier
20mJ ⇒ 10J

Target Area

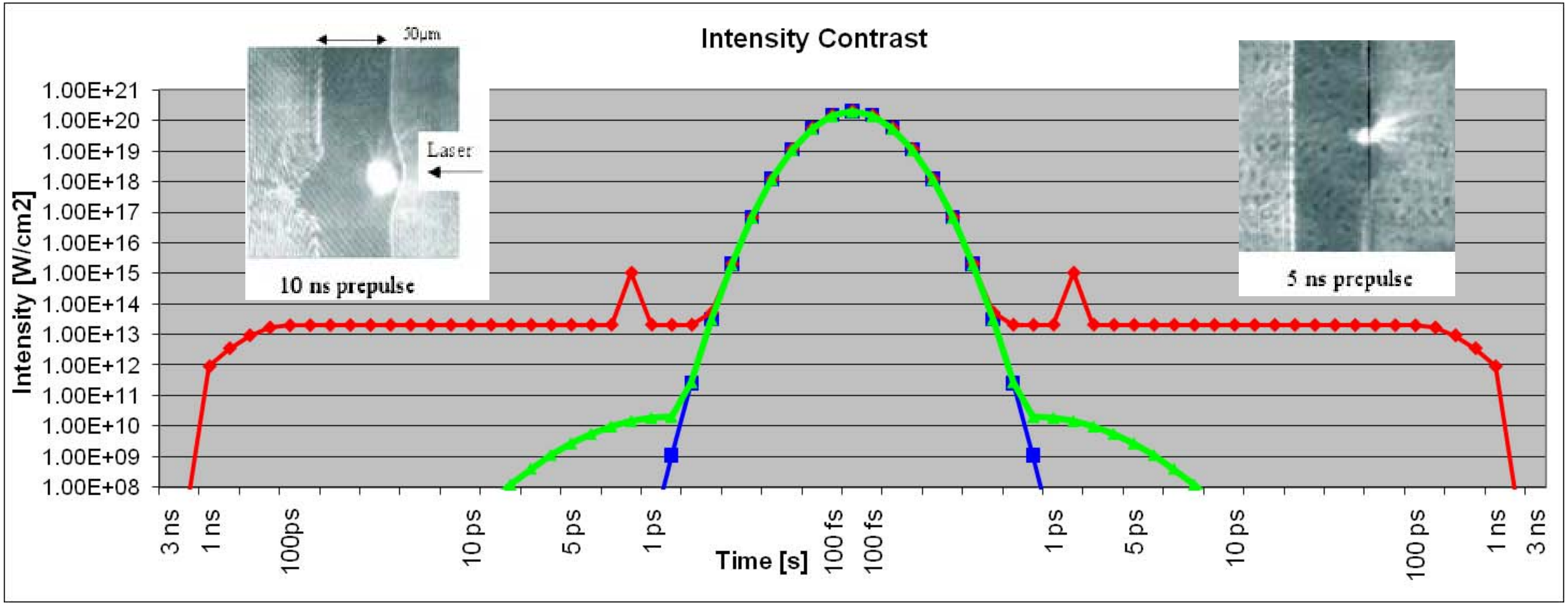
1ns ⇒ 500fs,
Vacuum,
10^{-6} mbar

High-contrast ($<10^{-10}$ @ 5ps) is needed to shoot ~40nm targets without shot breakout before the main pulse:

Starting point:

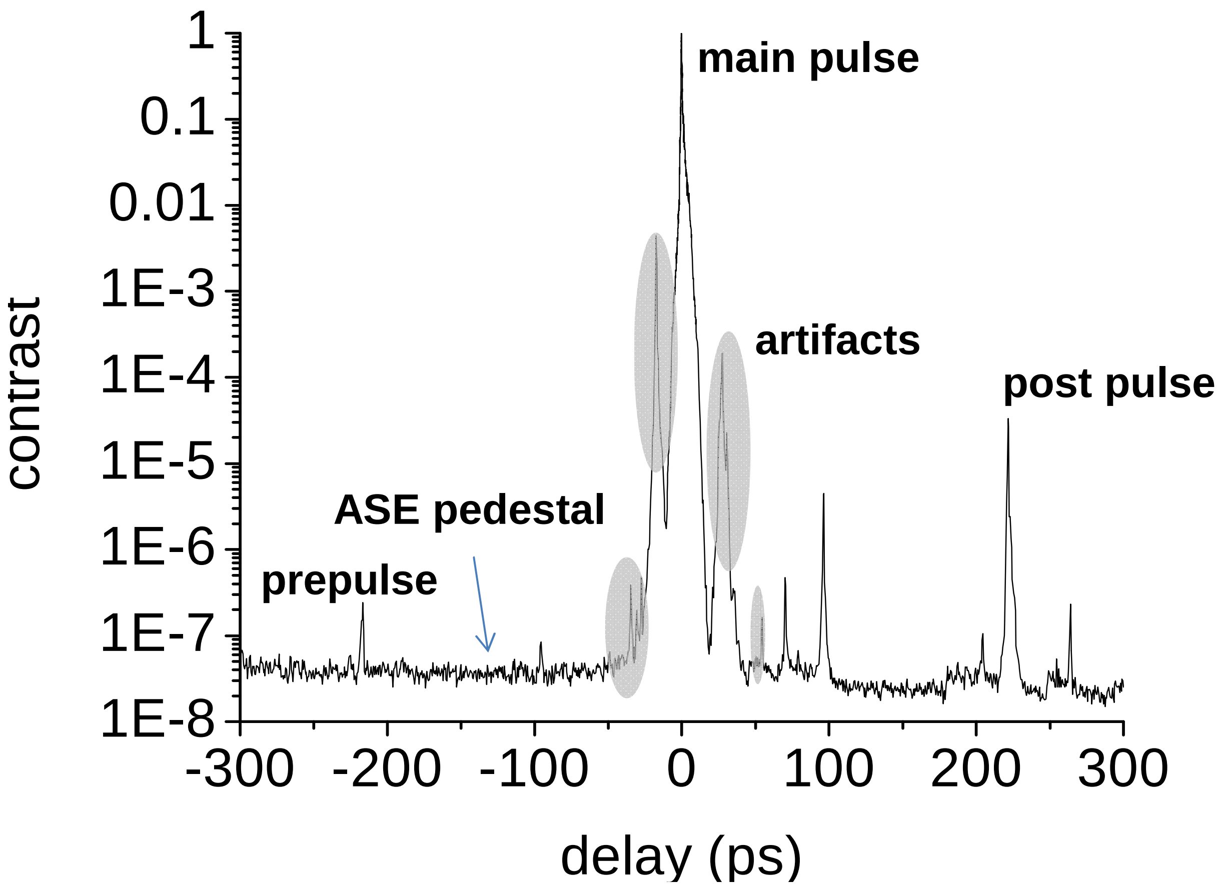
- Current contrast: $<10^{-7}$ @ 1ns
- V_s~7 nm/ps ⇒ 40nm/5.7ps

Goals:
Intensity contrast of $<10^{-10}$ @ 5ps on target



Energetic ions generated by laser pulses: A detailed study on target properties
M. Roth, T.E. Cowan, J. C. Gauthier, M. Allen, P. Audebert, A. Blazevic, J. Fuchs, M. Geissel, M. Hegelich, S. Karsch, J. Meyer-ter Vehn, A. Pukhov, T. Schlegel,
PRST – AB, Vol. 5, 061301, 2002

Trident Pulse Contrast with old frontend



ASE at 10^{-7} from amplified fluorescence

Postpulses (often ignored) can create prepulses

On target goal: 10^{-10}
Will increase …

Few shot measurement work described in EJPD submission

There are two classes of Contrast Enhancement Techniques:

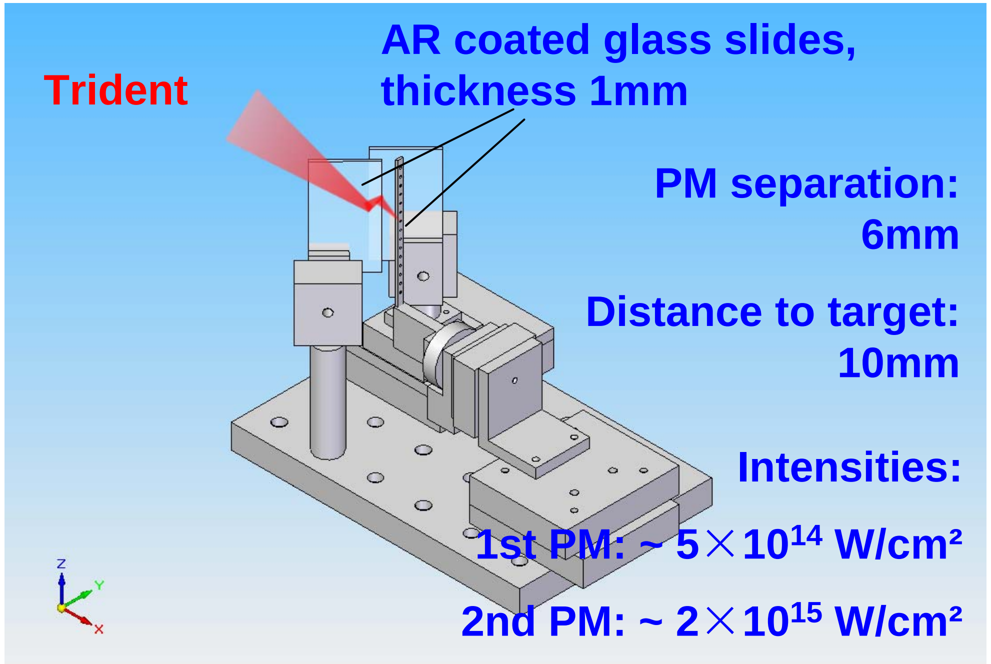
After the main amplifiers:

- 2nd harmonic generation
- Plasma mirrors
- Relatively easy implementation
- Pulse shaping capabilities?
- But: high losses of energy

Before the main amplifiers:

- Saturable absorbers
- XPW
- SPOPA
- …
- Energy losses are recouped
- Gain after cleaning re-introduces bad contrast

High Contrast: Double plasma mirror setup: successfully shot 50, 30,10nm DLC targets



Trident

AR coated glass slides, thickness 1mm

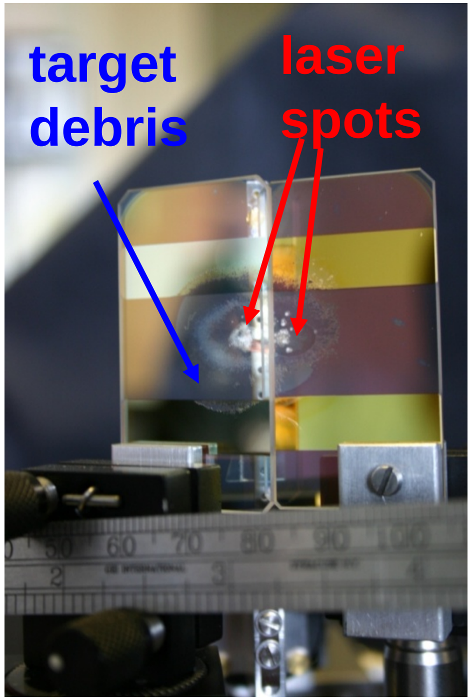
PM separation: 6mm

Distance to target: 10mm

Intensities:

1st PM: ~ 5×10^{14} W/cm²

2nd PM: ~ 2×10^{15} W/cm²

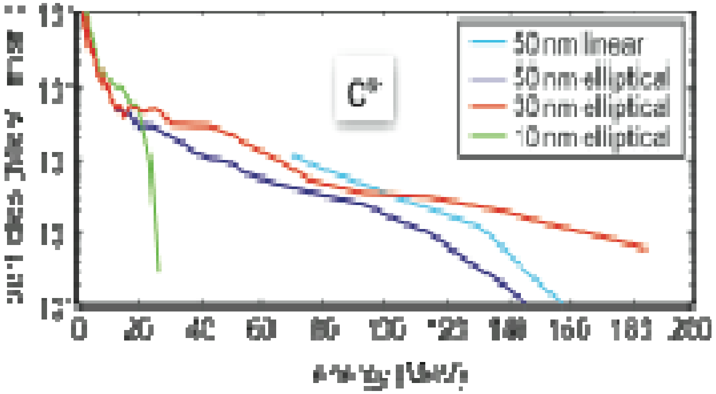


Energy in: 80J

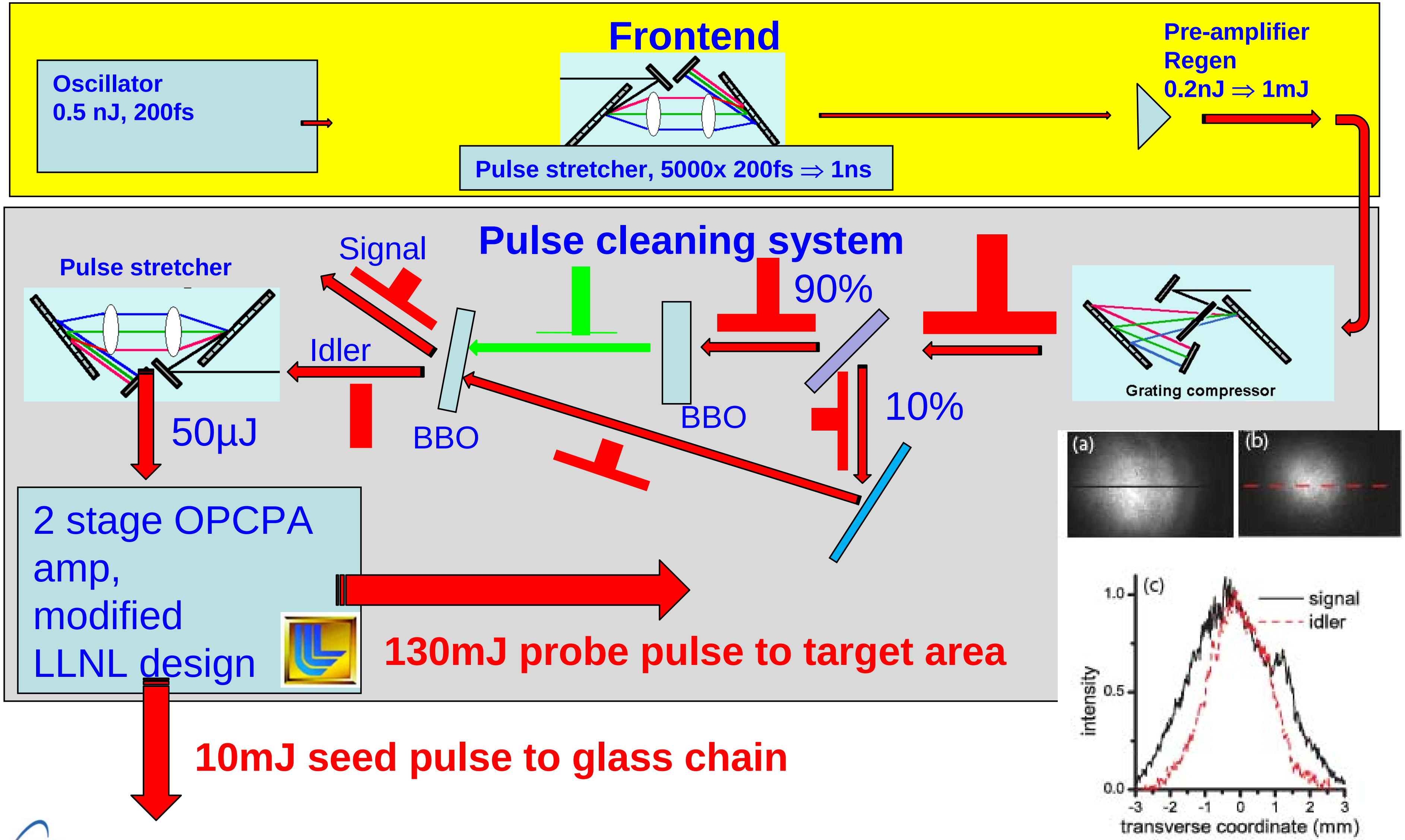
Energy out: 45 J

Pulse duration: 600 fs

Intensity: ~ 7×10^{19} W/cm²



New Trident frontend with pulse cleaning



Frontend

Oscillator
0.5 nJ, 200fs

Pulse stretcher, 5000x 200fs ⇒ 1ns

Pre-amplifier
Regen
0.2nJ ⇒ 1mJ

Pulse cleaning system

Pulse stretcher

Signal

Idler

90%

10%

BBO

BBO

50µJ

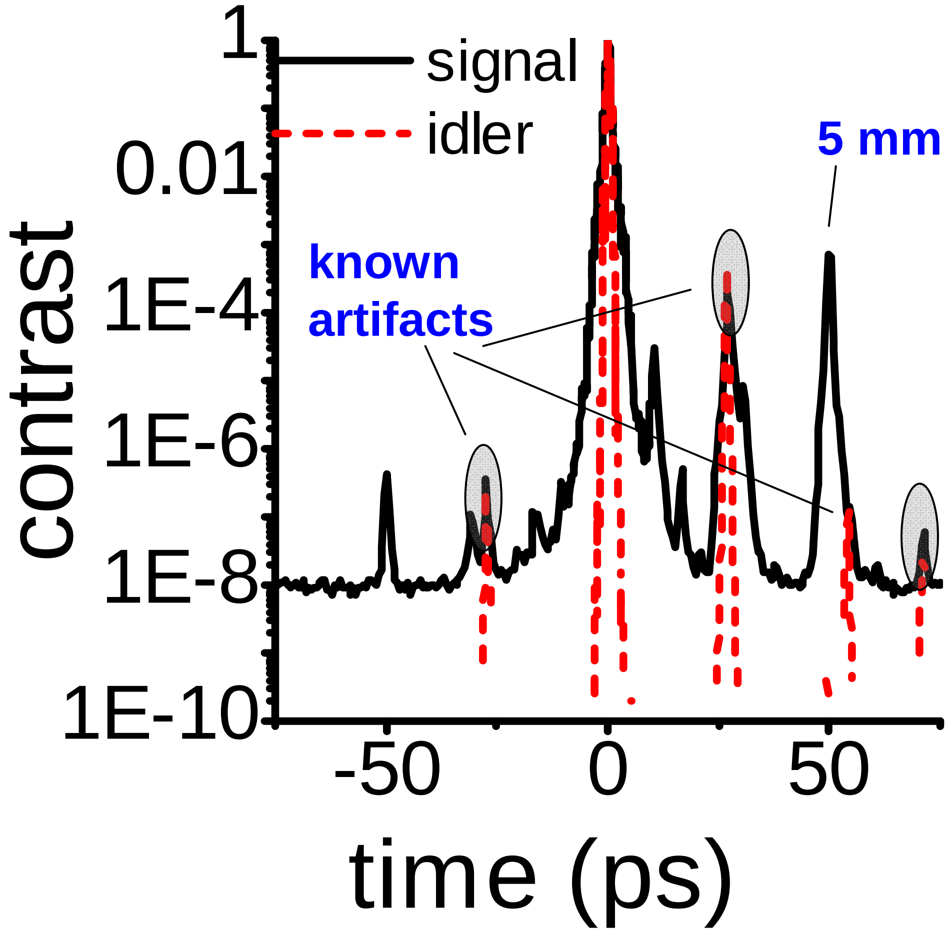
Grating compressor

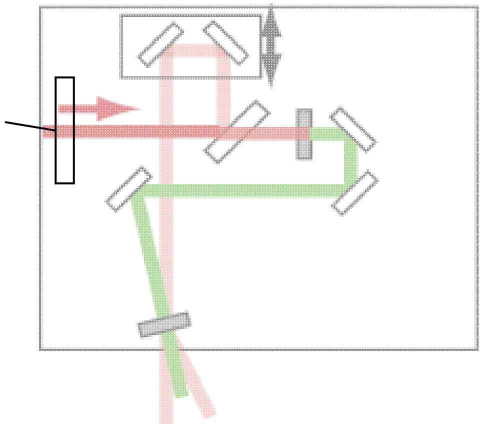
2 stage OPCPA
amp,
modified
LLNL design

130mJ probe pulse to target area

10mJ seed pulse to glass chain

Trident Pulse Contrast with new frontend: Contrast measurement shows cubic cleaning



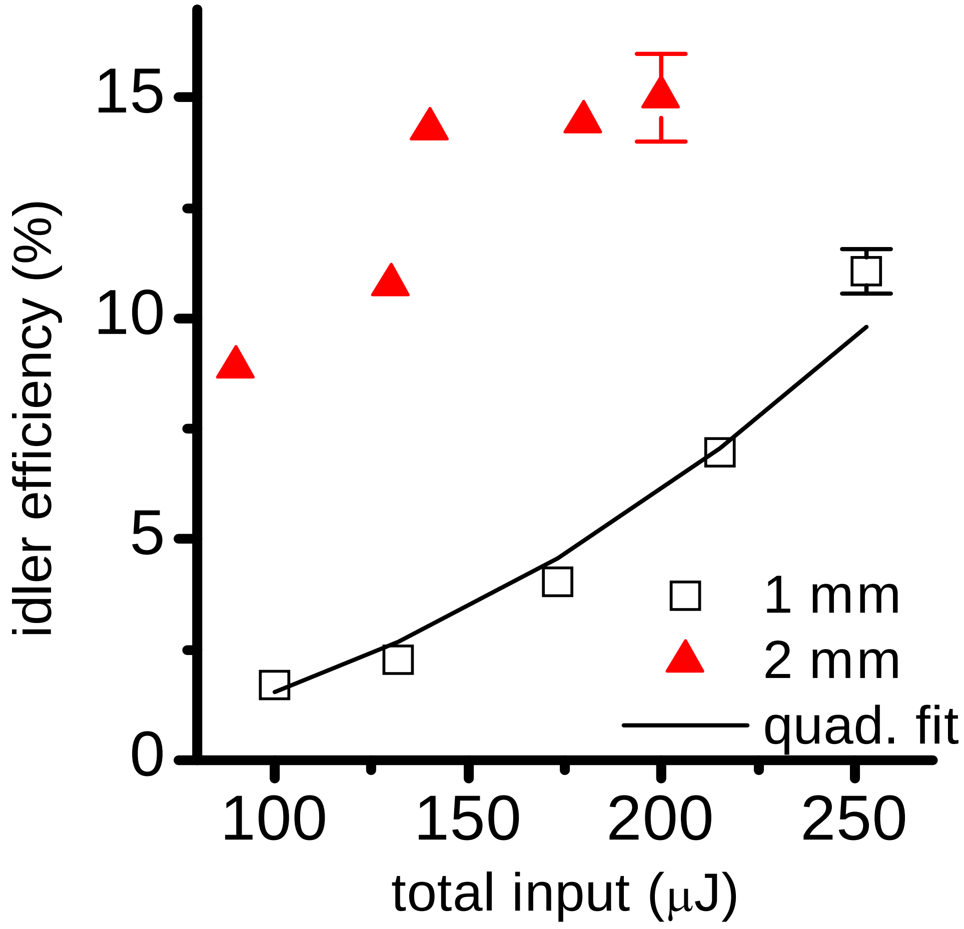


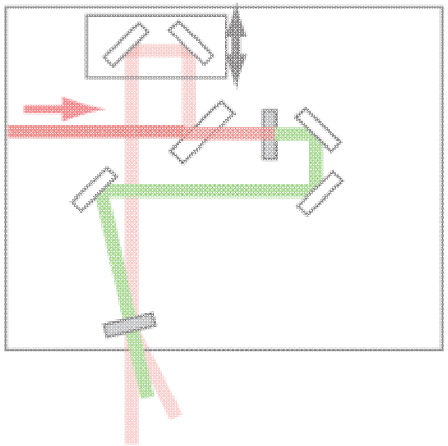
Etalon 1st order cubed

Measurement artifacts form after cleanup, in correlator (Del Mar Photonics)

ASE below 10^{-10} limit (scatter contribution estimated at 10^{-18})

Unsaturated Efficiency Shows Cubic Relation; Maximum Efficiency 15%





For 1 mm, max gain around 2 so low gain cubic dependence applies

Cubic process yields 3x degradation in stability

Saturated case obtain 1:1 shot-shot-stability

Summary Pulse Cleaning: Temporal Pulse Cleaning with Low Gain OPA

Demonstrated low gain OPA approach for cubic pulse cleaning. Use of $\chi^{(2)}$ process avoids B integral.

15% efficiency with 250 μJ, 500 fs pulses. Spectral width and spatial quality preserved with near field implementation.[1]

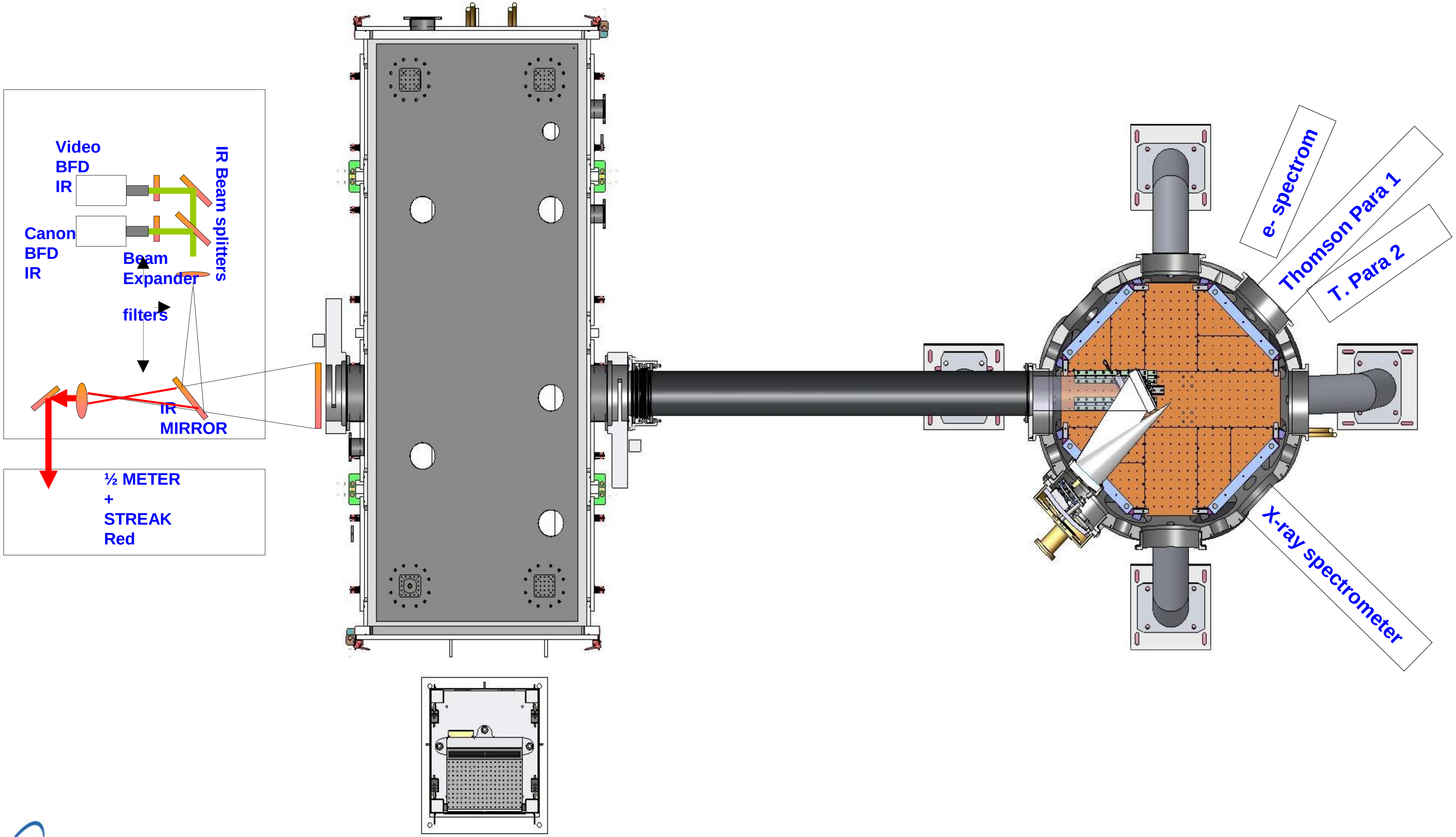
Pulse tilting could extend application to larger apertures and shorter pulses.

[1] **Rahul Shah *et. al.* to be submitted to Optics Letters (2008)**

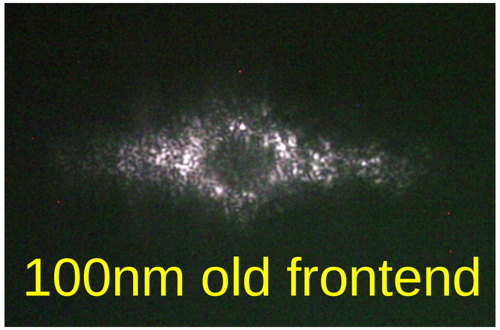
Experimental Realization of nanoscale target interactions:

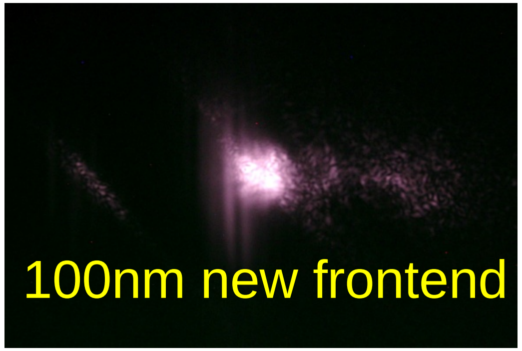
First experiments at the Los Alamos Trident Laser

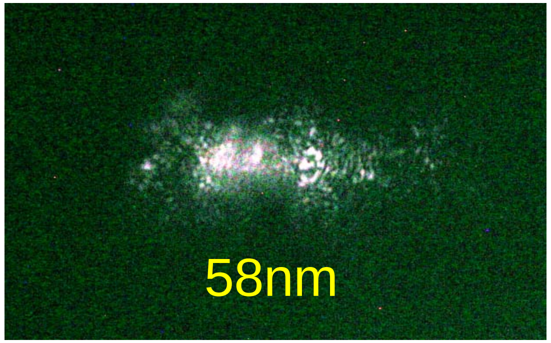
Experimental Setup: F/3 OAP, 2 Thomson parabola ion spectr., e-spectr., Full-Aperture Backscatter (FABS), x-ray spectrom.

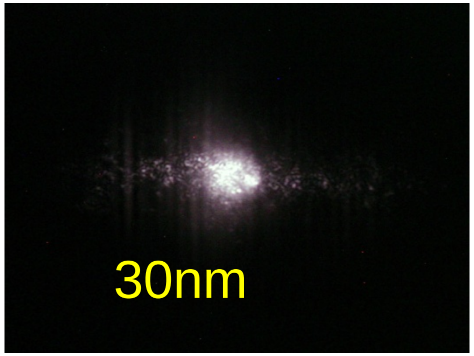


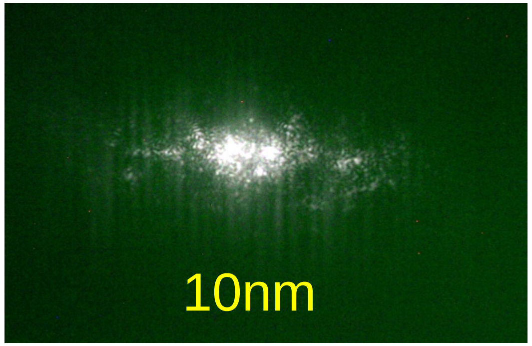
Contrast Measurement: Target condition at shot by FABS

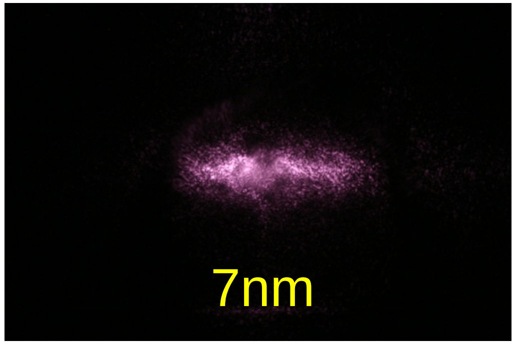

100nm old frontend

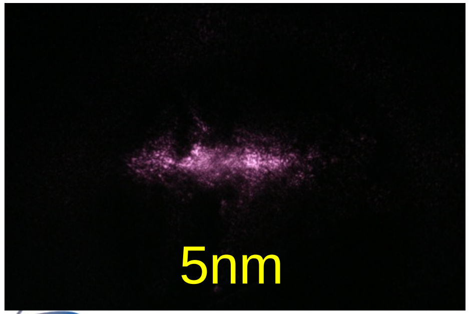

100nm new frontend

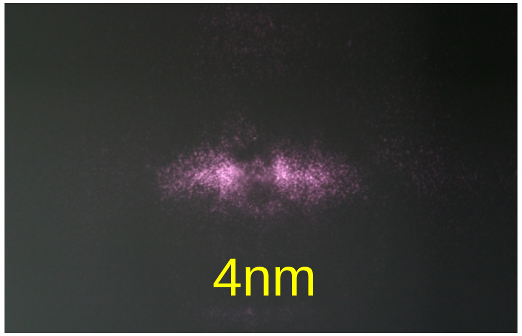

58nm

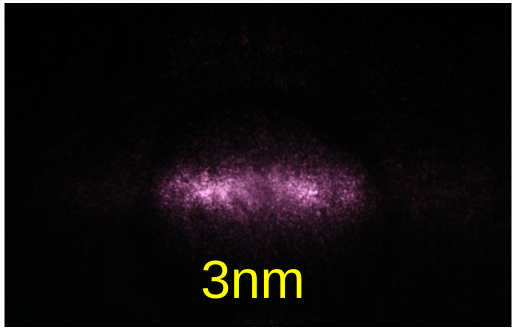

30nm


10nm


7nm


5nm

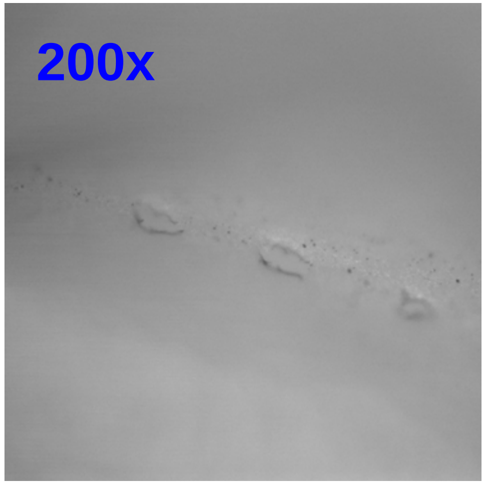

4nm

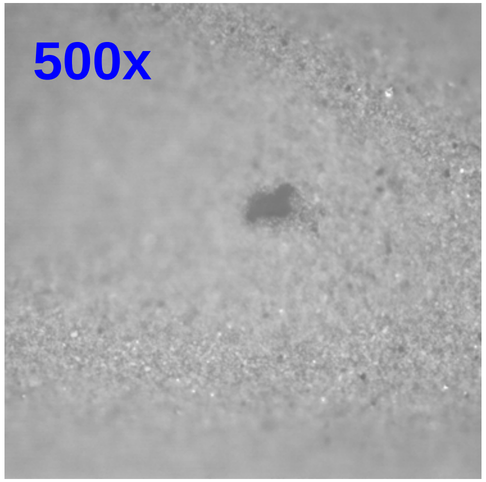

3nm

Contrast Measurement: Damage Threshold

We measured the target damage threshold for 500fs pulses (prepulse) and 1.2ns pulses (pedestal). The measurement was done in-situ in the original shooting position and low energy pulses were propagated through the full chain from the frontends.

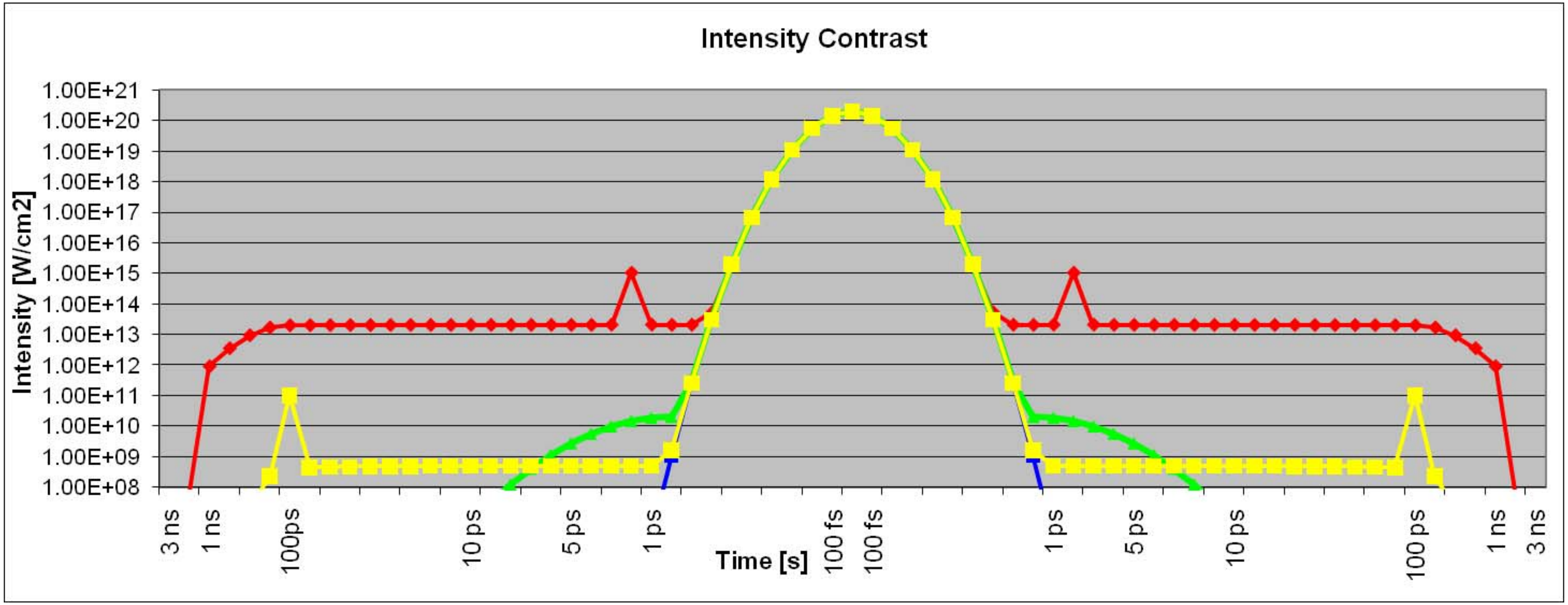
500 fs pulse: severe damage (~50 µm) @ 10^{11} W/cm², 100nJ
$\Rightarrow$ Contrast (I_{pp} / I_{ave}) < 5×10^{-10}
1.2 ns pulse: ~50 µm damage @ 5×10^{8} W/cm², 1000nJ
~20 µm damage @ 10^{8} W/cm², 200nJ
$\Rightarrow$ Contrast (I_{ped} / I_{ave}) < 2×10^{-12}





Achieved contrast improvement almost 2 orders of magnitude better than design value ($<10^{-10}$ @ 5ps):

Short Prepulses ⇒ Contrast (I_{pp} / I_{ave}) $< 5 \times 10^{-10}$
Pedestal ⇒ Contrast (I_{ped} / I_{ave}) $< 2 \times 10^{-12}$



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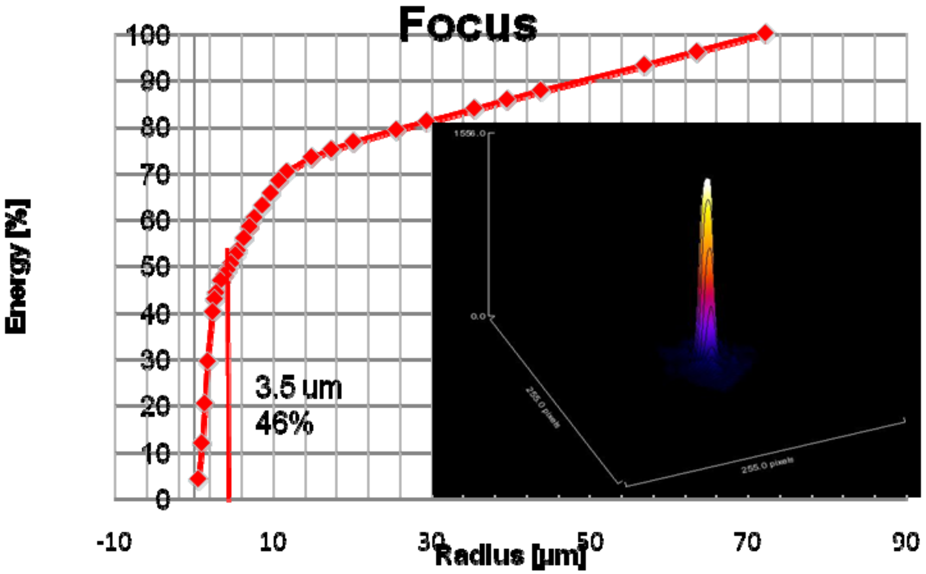
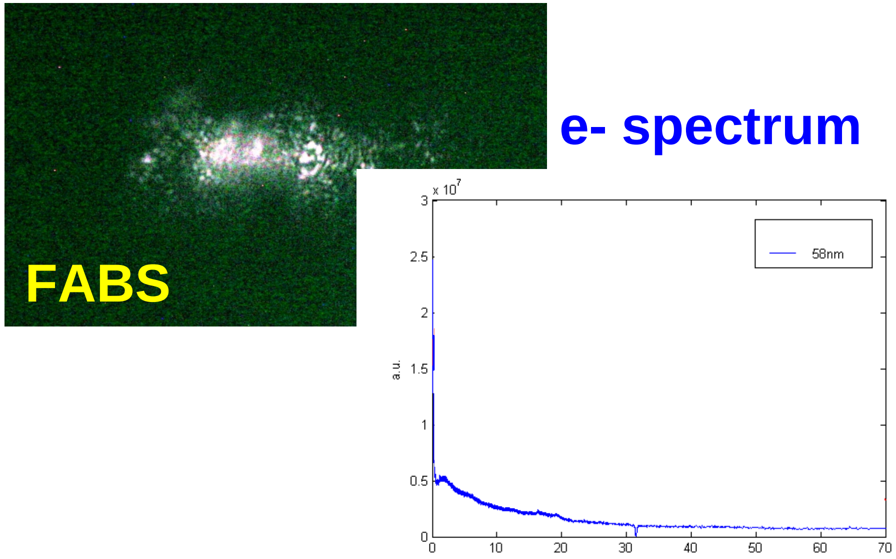
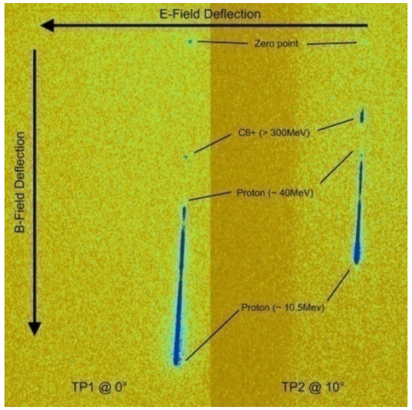
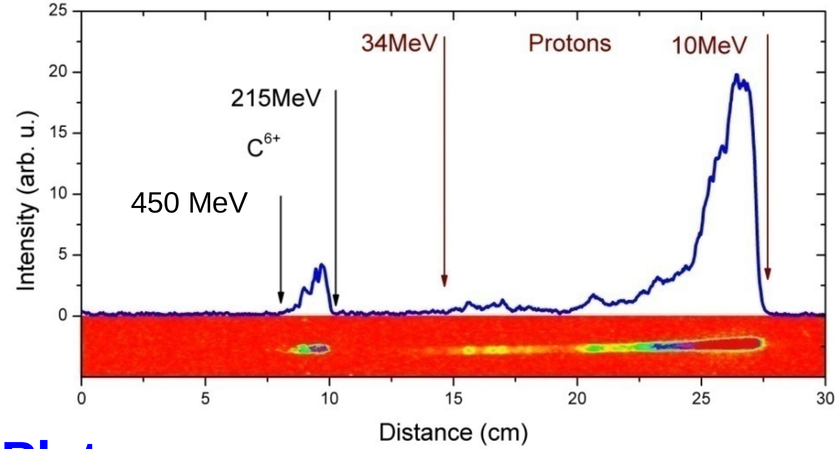
Break-Out Afterburner: Shot #20570, 58nm DLC foil, E_{laser} = 112.7J, E_{target} = 90.1J, t=540fs, $I_{peak} = 6.5\times10^{20}$ W/cm², $I_{ave} = 2\times10^{20}$ W/cm²





Thomson parabolas:





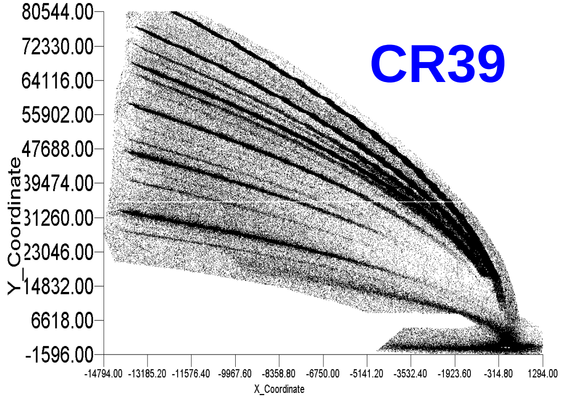
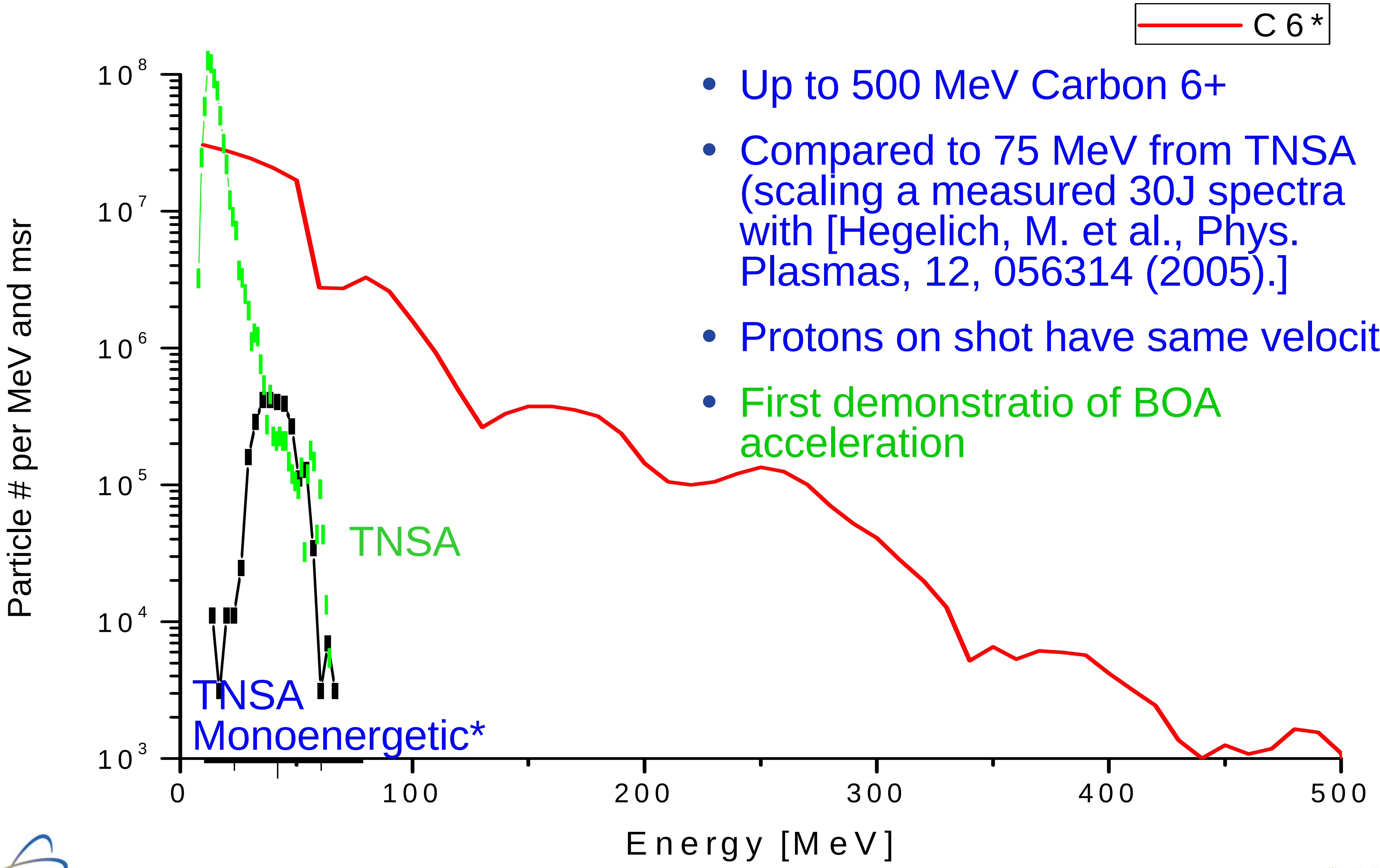


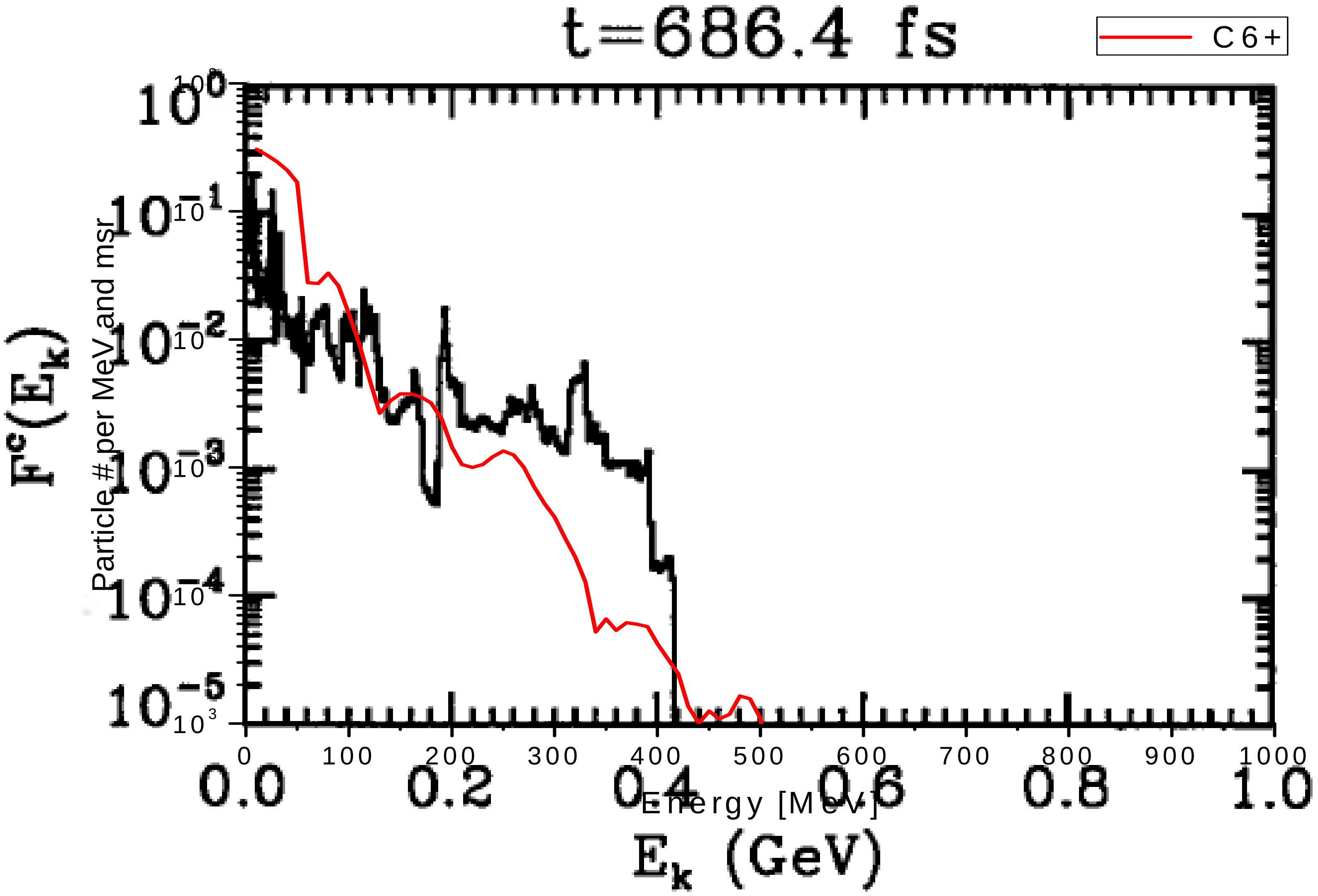
Image Plates

Break-Out Afterburner: Shot #20570, 58nm DLC foil, E_{laser} = 112.7J, E_{target} = 90.1J, t=540fs, I = $2x10^{20}$ W/cm²

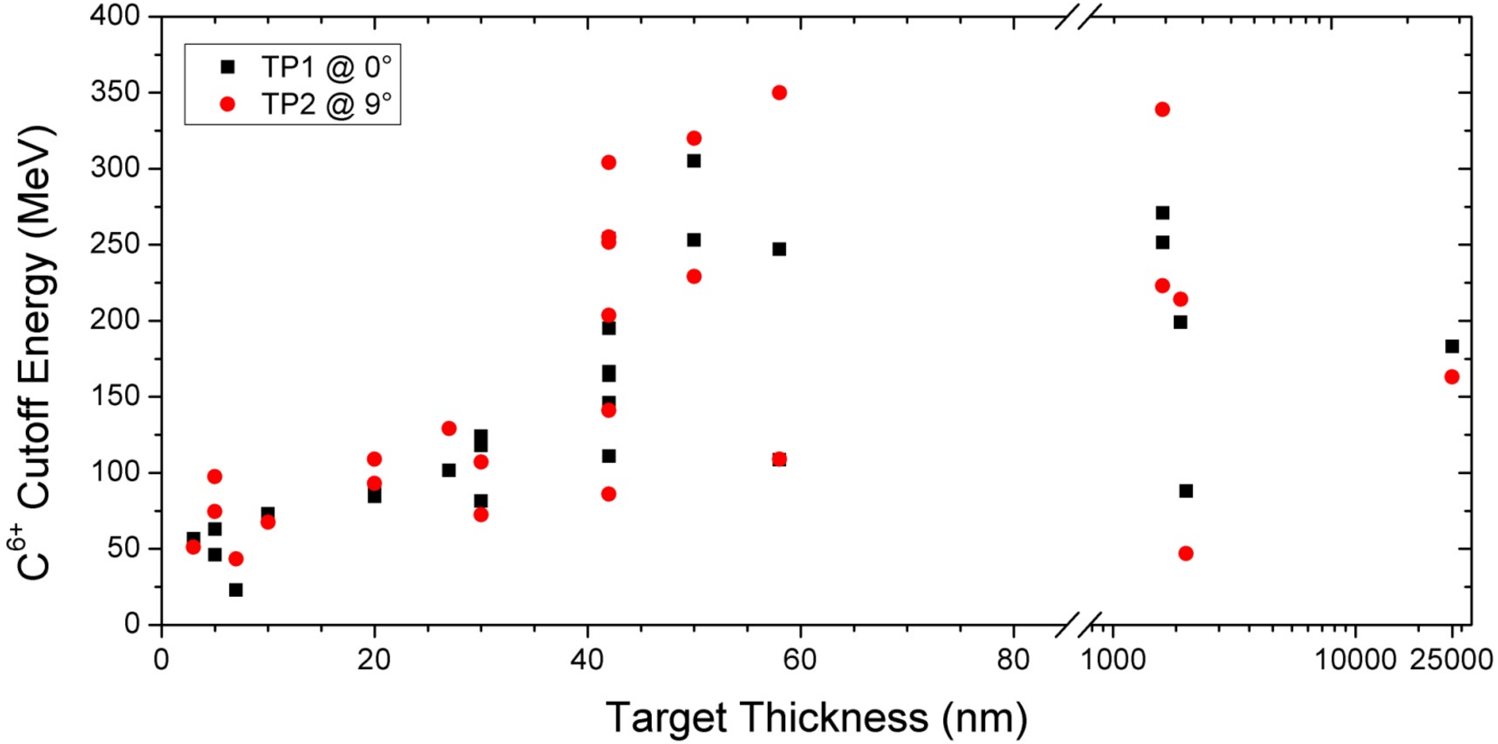


- Up to 500 MeV Carbon 6+
- Compared to 75 MeV from TNSA (scaling a measured 30J spectra with [Hegelich, M. et al., Phys. Plasmas, 12, 056314 (2005).]
- Protons on shot have same velocity
- First demonstratio of BOA acceleration

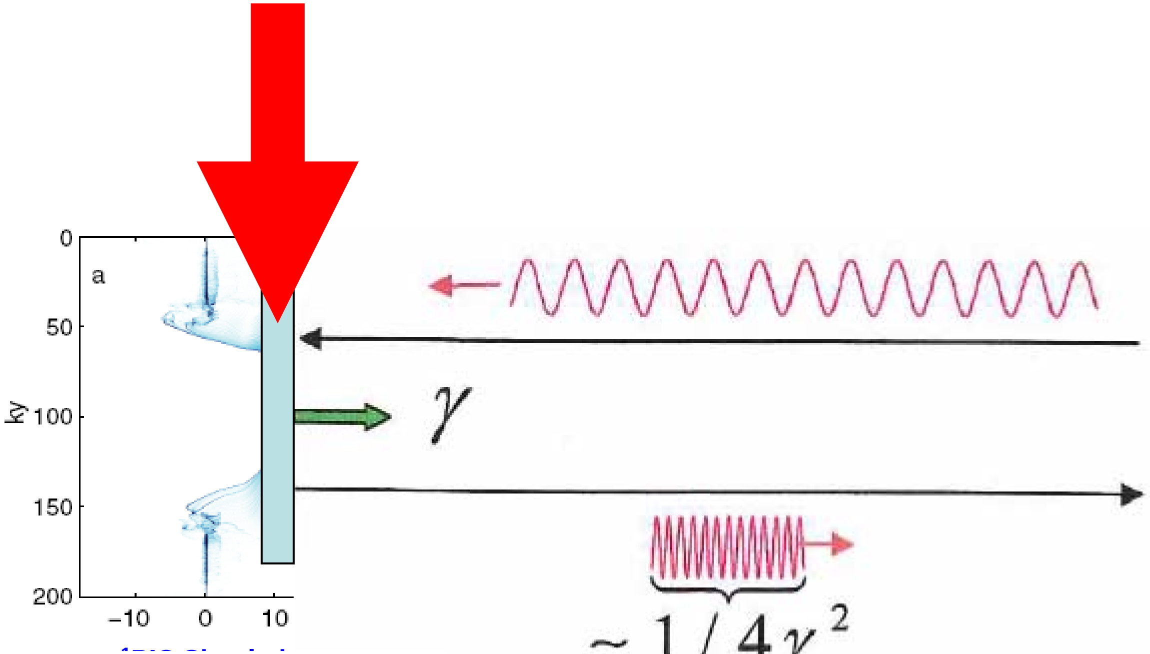
Comparison with 1D VPIC simulation shows good qualitative agreement. 2D & 3D currently running.

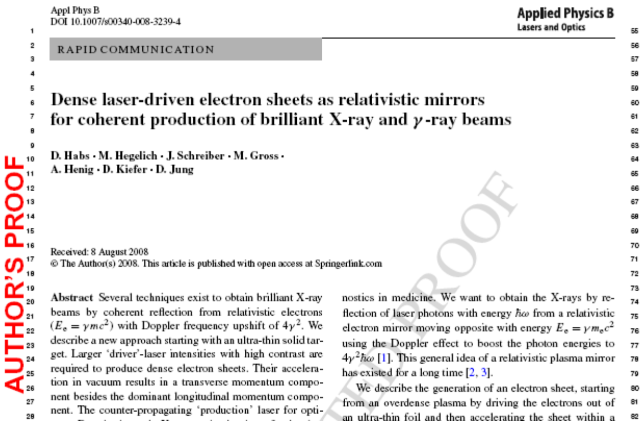


BOA mechanism is reproducable: Incomplete summary of C6+ cutoff energies for different targets



Relativistic Coherent Electron Mirror





Appl Phys B
DOI 10.1007/s00340-008-3239-4

Applied Physics B
Lasers and Optics

RAPID COMMUNICATION

Dense laser-driven electron sheets as relativistic mirrors for coherent production of brilliant X-ray and γ-ray beams

D. Habs · M. Hegelich · J. Schreiber · M. Gross ·
A. Henig · D. Kiefer · D. Jung

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Abstract Several techniques exist to obtain brilliant X-ray beams by coherent reflection from relativistic electrons ($E_e = \gamma mc^2$) with Doppler frequency upshift of $4\gamma^2$. We describe a new approach starting with an ultra-thin solid target. Larger 'driver'-laser intensities with high contrast are required to produce dense electron sheets. Their acceleration in vacuum results in a transverse momentum component besides the dominant longitudinal momentum component. The counter-propagating 'production' laser for opti-

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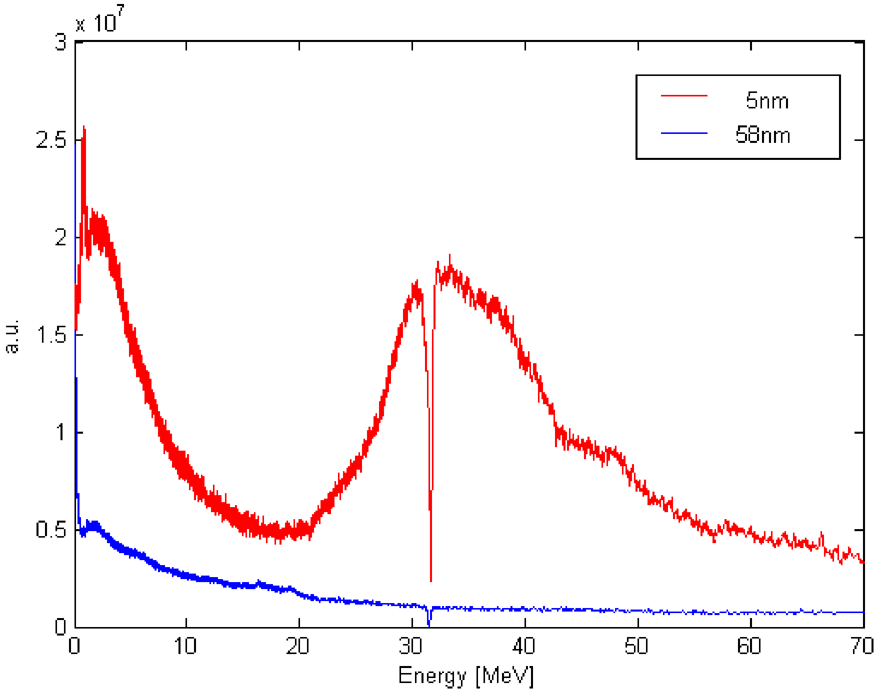
We describe the generation of an electron sheet, starting from an overdense plasma by driving the electrons out of an ultra-thin foil and then accelerating the sheet within a

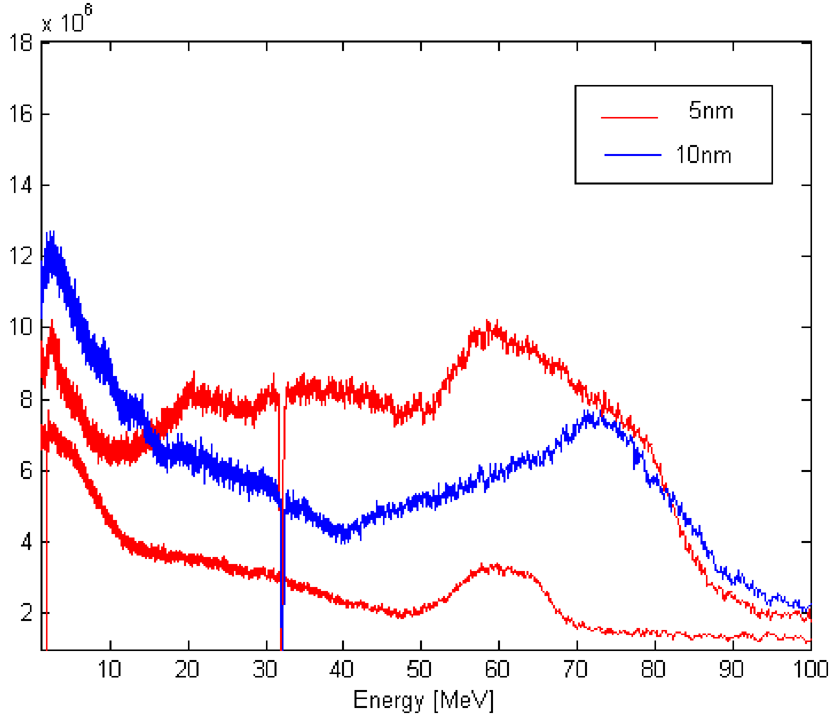
[1] A. Einstein, Annalen der Physik 17, 891 (1905)

[2] Victor V. Kulagin, et a. PRL 99, 124801 (2007)

[3] D. Habs, M. Hegelich et al., APB (2008)

Electrons – linear polarization



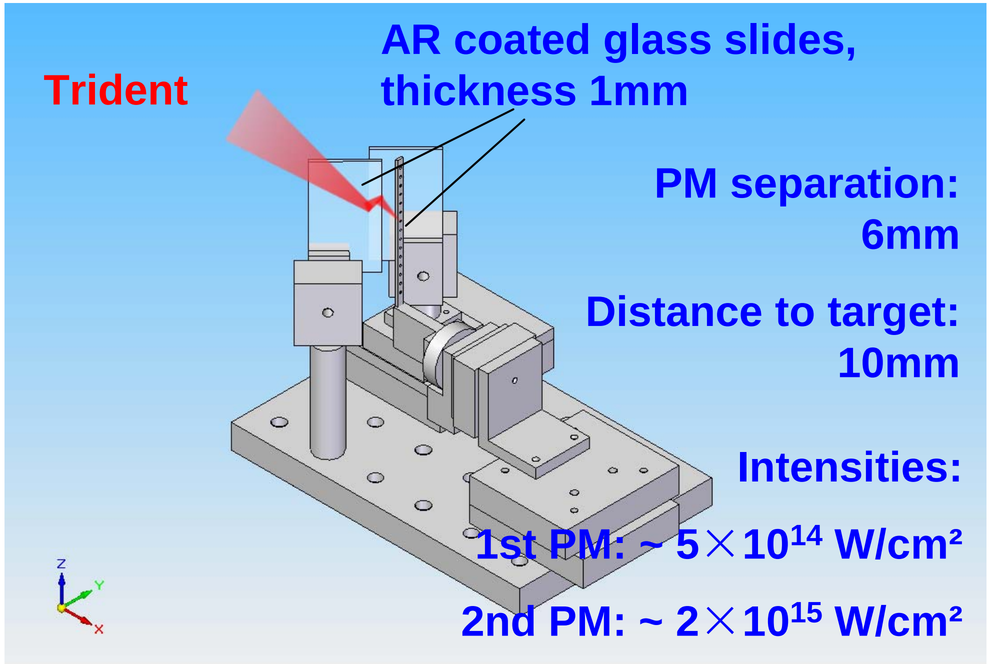


Summary

- A number of new particle acceleration mechanisms require nm-scale targets
- Nm-scale targets require ultraclean pulses
- Successful production, mounting and use of up to 3nm thin, free standing (~mm) diamond targets
- Successful design and implementation of pulse cleaning based on shortpulse optical parametric amplification in a operating PW-class experimental facility.
- First observation of BOA with carbon energies >400 MeV, promising for applications like IFI and hadron therapy
- First observation of e- break-out at very thin targets, potential for relativistic mirrors and compact coherent x-ray and gamma sources.

Thank you for your attention!

High Contrast: Double plasma mirror setup: successfully shot 50, 30,10nm DLC targets



Trident

AR coated glass slides, thickness 1mm

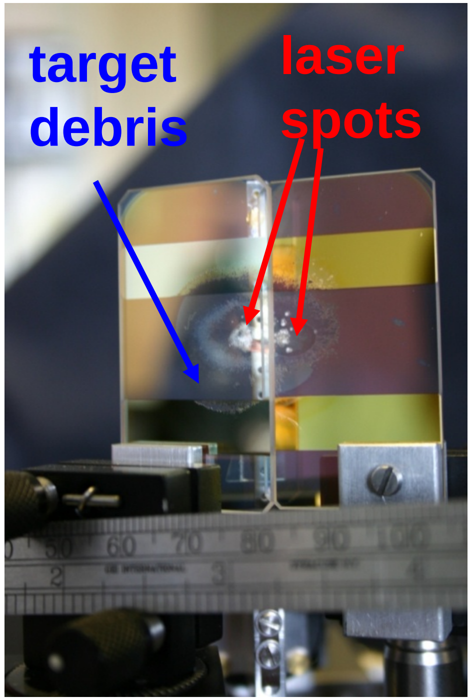
PM separation: 6mm

Distance to target: 10mm

Intensities:

1st PM: ~ 5×10^{14} W/cm²

2nd PM: ~ 2×10^{15} W/cm²

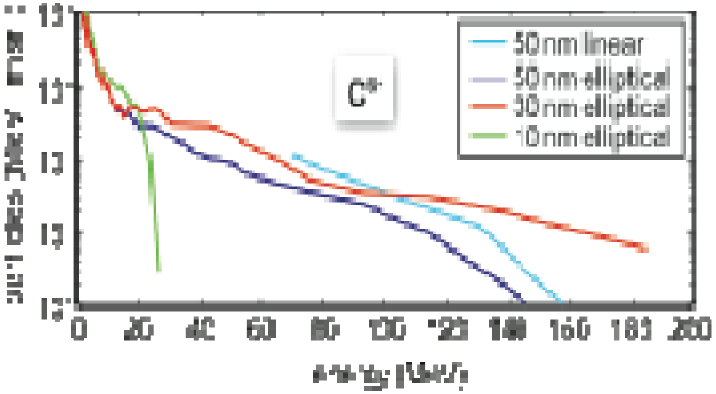


Energy in: 80J

Energy out: 45 J

Pulse duration: 600 fs

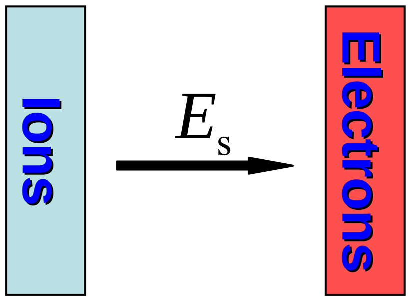
Intensity: ~ 7×10^{19} W/cm²



nm-foil acceleration

“Electron blow off”: $Nk_L d < a_0 \quad (E_s < E_L)$

J. Meyer-ter-Vehn,
Hui-Chun Wu



Ions

E_s

Electrons

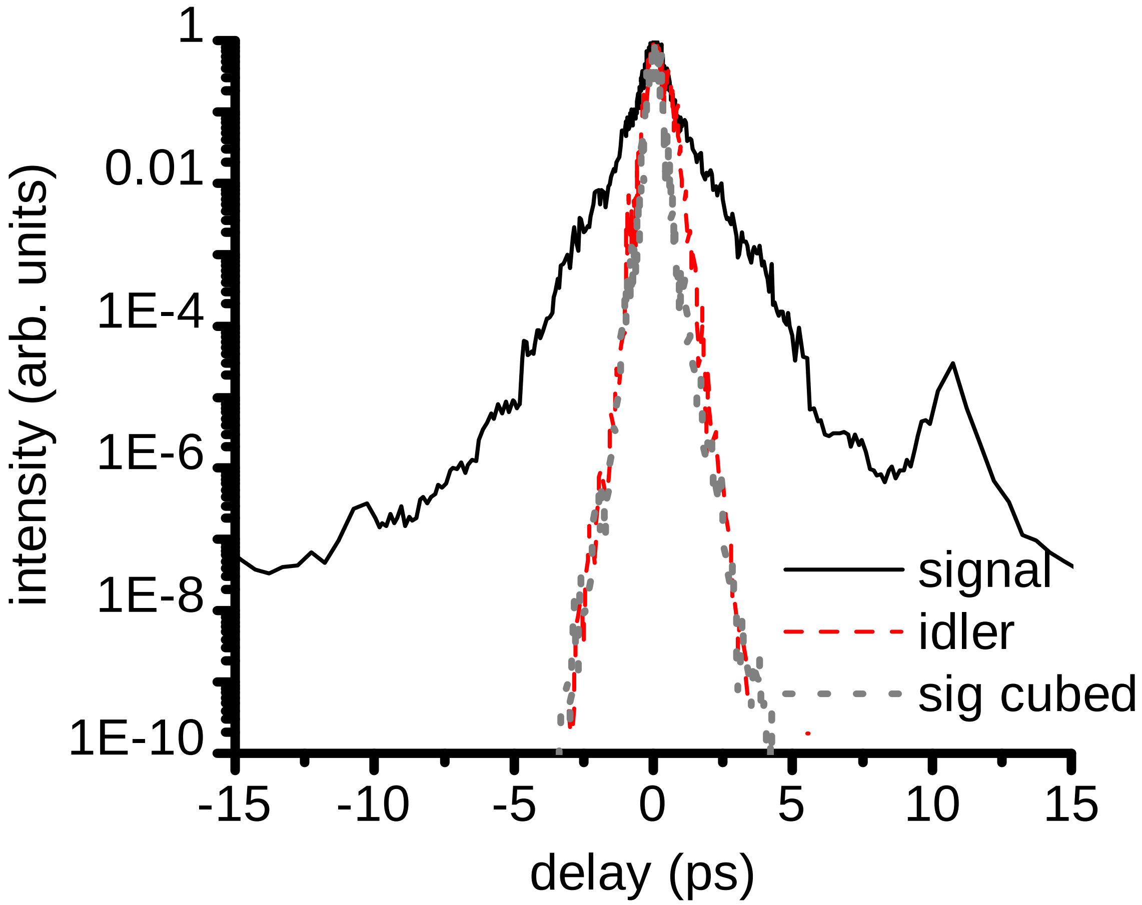
Trident Experiment (Sept ‘08):

3nm DLC foil: $Nk_L d = 660 \frac{2\pi}{1054\text{nm}} 3\text{nm} \cong 12$

$I = 3\text{x}10^{20} W/cm^2 \qquad => a_0 \cong 15$

Skin depth: $l_{skin} \cong 6\text{nm}$

Contrast measurement shows cubic cleaning



Cubic fit works fairly well

Do not see temporal shortening (either due to saturation or mismatch in group velocities (GVM) estimated at ~200 fs)

Error in fit potentially due to variation in compression between measurements

Spectral Convolution Results from Temporal Cubing

Spectral smoothing

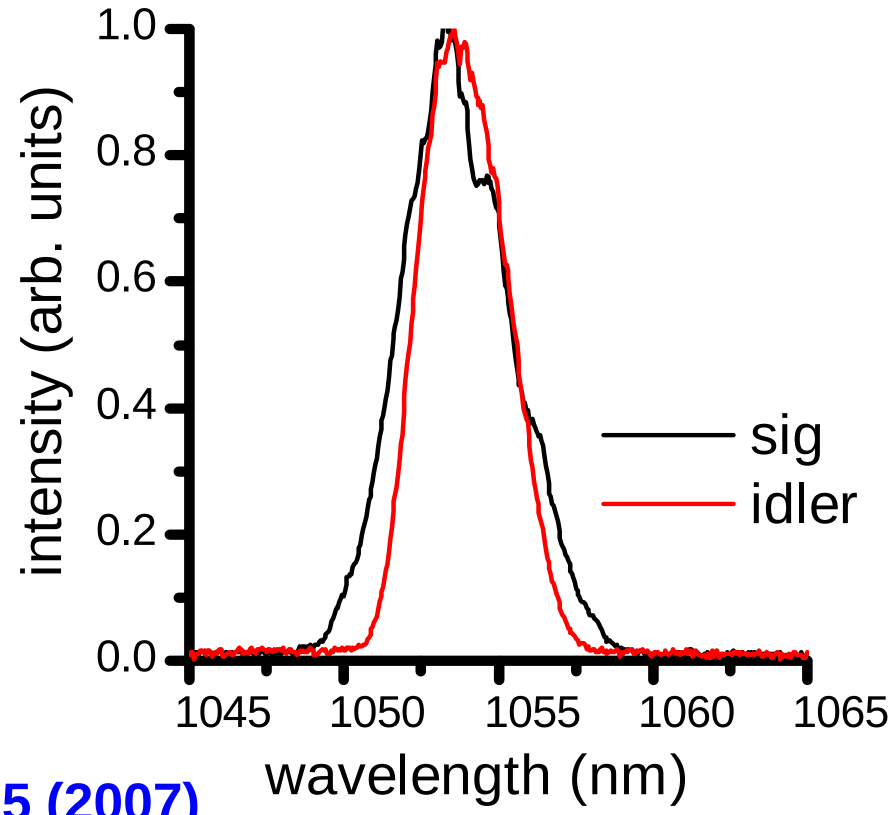
$$P_{idler}(t) \propto E_{signal}(t) \times E_{signal}(t) \times E_{signal}{}^{*}(t)$$

$$P_{idler}(\omega) \propto E_{signal}(\omega) * E_{signal}{}^{*}(\omega) * E_{signal}(\omega)$$

Time multiplication corresponds to spectral convolution—smoothing

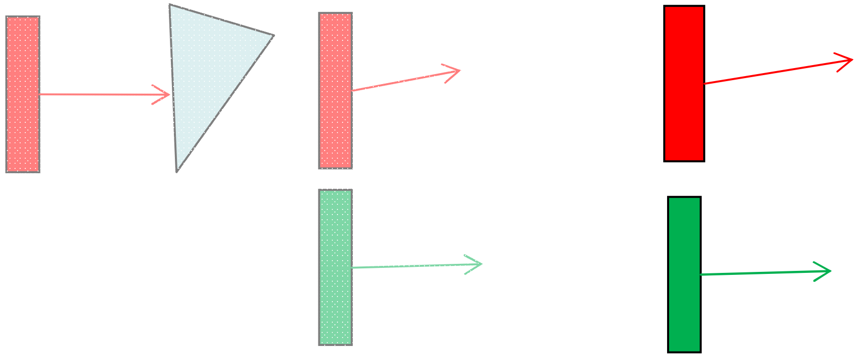
Saturation or GVM could eliminate bandwidth gains; Some bandwidth loss (12%) brings closer to transform limit

With chirped pulses see BW loss because duration shortens but temporal phase (chirp) unchanged[1]



[1] Julien *et. al..* Appl. Phys. B:. 87: 595 (2007)

Pulse tilt could scale to shorter pulses and larger apertures

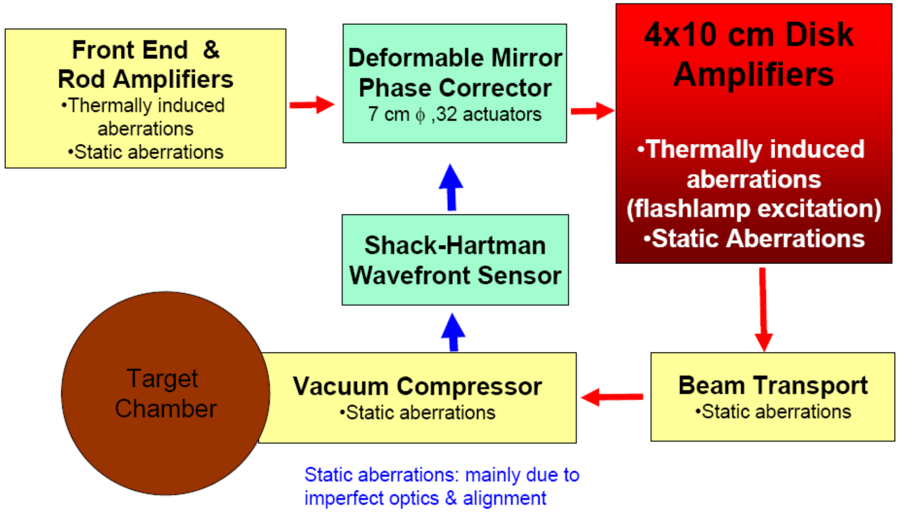


Using a prism, one can tilt the pulse so as to match velocities in propagation direction.

This also provides tilt for separation of degenerate signal and idler without compromising overlap over full aperture (problem for Φ > few mm with 500 fs pulse)[1]

[1] E. J. Divall and I. N. Ross, Opt. Lett. 29: 2273 (2004)

An adaptive optic system was designed to compensate for both static and thermal aberrations



Front End & Rod Amplifiers
- Thermally induced aberrations
- Static aberrations

Deformable Mirror Phase Corrector
7 cm ϕ ,32 actuators

4x10 cm Disk Amplifiers
- Thermally induced aberrations (flashlamp excitation)
- Static Aberrations

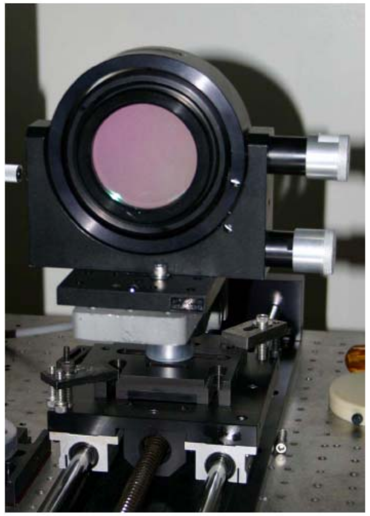
Shack-Hartman Wavefront Sensor

Beam Transport
- Static aberrations

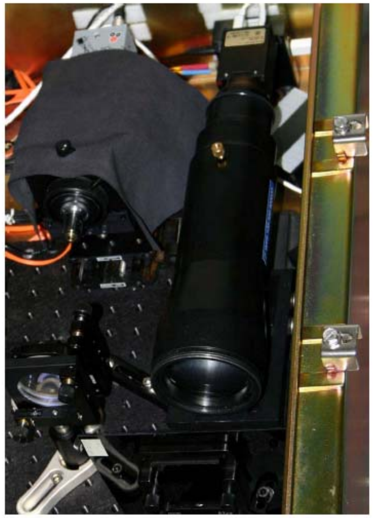
Vacuum Compressor
- Static aberrations

Target Chamber

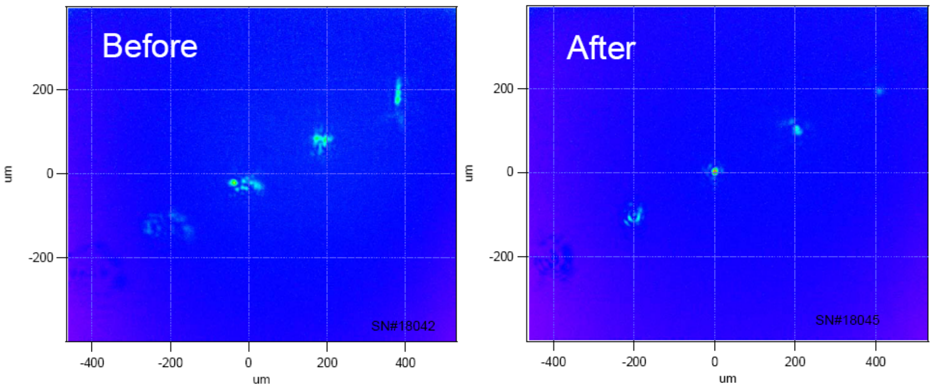
Static aberrations: mainly due to imperfect optics & alignment



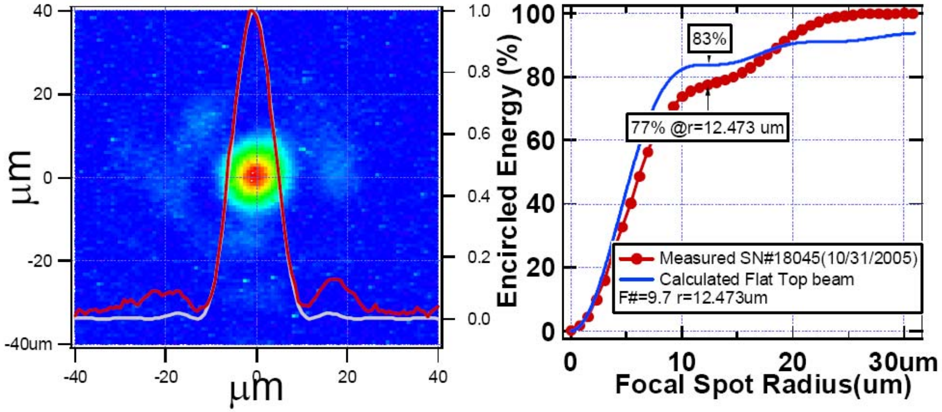
72mm - 32 actuator deformable mirror



Shack Hartman sensor



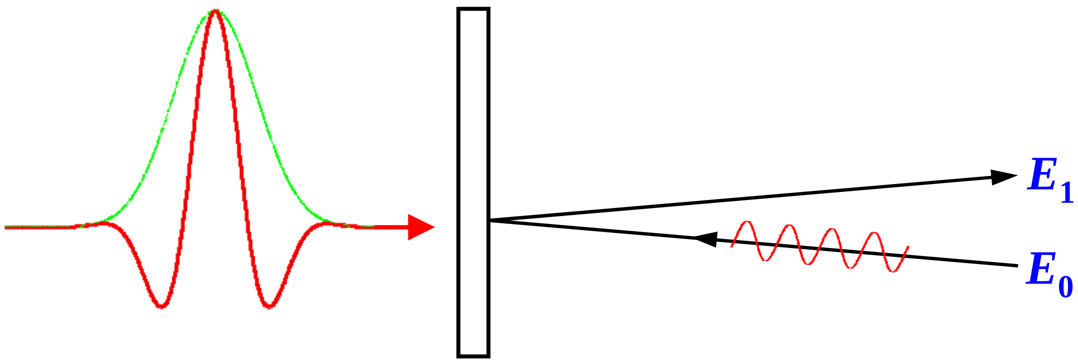
All the rod amplifiers and 4-10 cm disk amplifiers were fired.

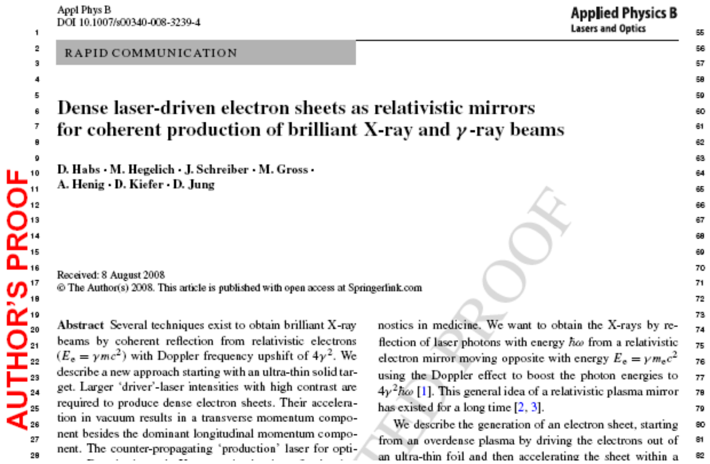


Measured equivalent focal spot size indicates 77% of total energy in 7.7 µ m with F/#3 parabola

Intense 50keV X-rays

for medical applications





Appl Phys B
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Applied Physics B
Lasers and Optics

RAPID COMMUNICATION

Dense laser-driven electron sheets as relativistic mirrors for coherent production of brilliant X-ray and γ-ray beams

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A. Henig · D. Kiefer · D. Jung

AUTHOR'S PROOF

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Abstract Several techniques exist to obtain brilliant X-ray beams by coherent reflection from relativistic electrons ($E_e = \gamma mc^2$) with Doppler frequency upshift of $4\gamma^2$. We describe a new approach starting with an ultra-thin solid target. Larger 'driver'-laser intensities with high contrast are required to produce dense electron sheets. Their acceleration in vacuum results in a transverse momentum component besides the dominant longitudinal momentum component. The counter-propagating 'production' laser for opti-

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We describe the generation of an electron sheet, starting from an overdense plasma by driving the electrons out of an ultra-thin foil and then accelerating the sheet within a

Electrons accelerated

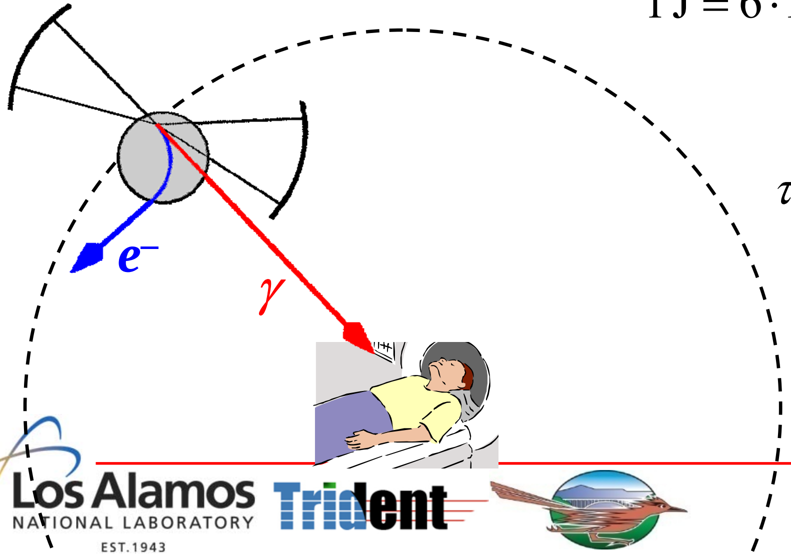
at $\gamma \approx 110 \ (\hat{=} 60\,\text{MeV})$

Compton reflexion

$$E_1 = 4\gamma^2 \cdot E_0 \qquad (E_0 = 1\,\text{eV} \rightarrow E_1 = 50\,\text{keV})$$

Reflectivity $R \propto \frac{1}{\gamma^4}$

$$1\,\text{J} \,\hat{=}\, 6 \cdot 10^{18}\ \text{Photons} \xrightarrow{R=10^{-7}} \approx 10^{11}\ \text{Photons}$$



$$\tau_0 = 30\,\text{fs} \rightarrow \tau_1 = \frac{30\,\text{fs}}{4 \cdot (100)^2} \approx 1\,\text{as}$$

Compact X-ray source, monochromatic, brilliant.

A detour into virtual space: Theory, simulations and massively parallel computers

Simulation and computer experiments
can show the way

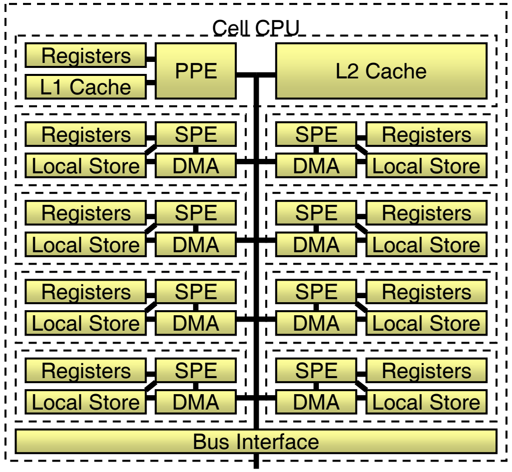
For full 3d simulations we encounter a problem: The speed of light is too slow for modern codes/computers.

- Consider a node with 3.0 GHz CPUs and 4 GB of ECC DRAM:
- The characteristic time for a signal to propagate around the memory chips, considering only the speed of light:

$$\tau_{\text{round}} \sim \frac{4n_{\text{eff}}}{c}\sqrt{\left(\frac{0.15\,\mu\text{m}^2}{1\,\text{cell}}\right)\left(\frac{9\,\text{cells}}{1\,\text{ECC byte}}\right)\left(\frac{2^{30}\,\text{bytes}}{1\,\text{GB}}\right)4\,\text{GB}} \sim 3\,\text{ns}$$

- This is already ~9 CPU clocks; enough time for ~36 single precision floating point operations (ideal case)
- Achieving high performance requires minimizing latency, bandwidth and computation, in roughly that order
- Often faster to recalculate a value locally then to retrieve it from memory.

- LANL’s new supercomputer “Roadrunner” will consist 13,000 IBM Cell CPU (same processor as Sony PlayStation 3). Each CPU contains one general purpose core (“PPE”) and eight high performance specialized 4-vector SIMD cores (“SPE”)
- Each SPE can only directly access *256KB* of high performance memory specific to it.
- **Projected performance is >2 PFlops.**



The VPIC code is optimized for the cell cpu and was recently ported onto first Roadrunner prototype unit.

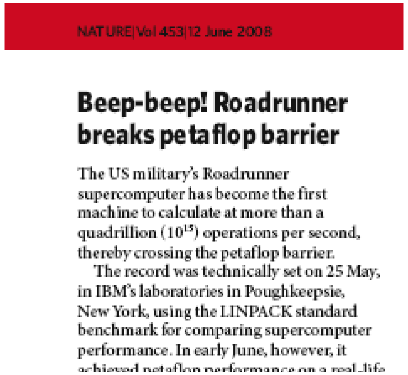

LANLSCIENCE

Roadrunner.
A new era
of computing
is here.

- Presently, VPIC performs at ~173 million cold particles advanced per second per 3.2 GHz IBM Cell CPU For comparison, VPIC runs at ~12.6 million cold PA/s on a single core 2.2 GHz AMD Opteron CPU.

- On full Roadrunner, a sustained rate up to ~2.25 trillion cold PA/s can be achieved in particle dominated simulations (~0.556 petaflop sustained performance with current code, ~2 Pflops with further optimization).

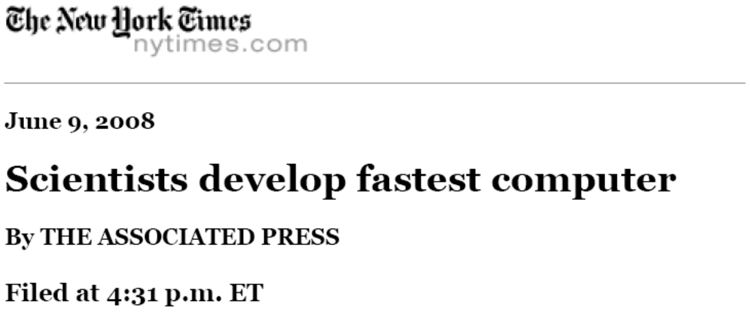
- **VPIC on Roadrunner:**
  10^{12} particles, 10^{9} cells, 10^{6} time steps will take ~10 days of actual runtime.


NATURE|Vol 453|12 June 2008

Beep-beep! Roadrunner breaks petaflop barrier

The US military's Roadrunner supercomputer has become the first machine to calculate at more than a quadrillion (10^{15}) operations per second, thereby crossing the petaflop barrier.

The record was technically set on 25 May, in IBM's laboratories in Poughkeepsie, New York, using the LINPACK standard benchmark for comparing supercomputer performance. In early June, however, it achieved petaflop performance on a real-life


The New York Times
nytimes.com

June 9, 2008

Scientists develop fastest computer

By THE ASSOCIATED PRESS

Filed at 4:31 p.m. ET

Circular Polarization: Pathway to a new, highly efficient acceleration mechanism?

Radiation Pressure Acceleration with ultraintense lasers has been suggested as an effective ion acceleration mechanism at very high intensities (10^{23}-10^{24} W/cm^2):

1.JAERI, Japan: Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime. T. Esirkepov, et al., PRL, 92 (2004)

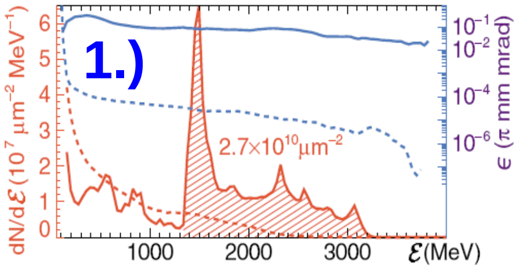
Circular Polarization enables Radiation Pressure Acceleration (RPA) or Phase Stable Acceleration (PSA) at todays intensities (~10^{20}-10^{21} W/cm^2):

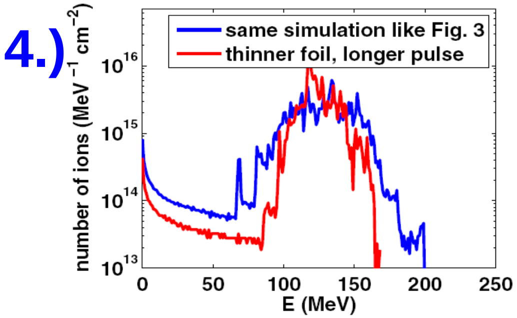
2.SIOM, China: Efficient GeV ion generation by ultraintense circularly polarized laser pulse. Xiaomei Zhang, et al., **PoP 14**, 123108 (2007)

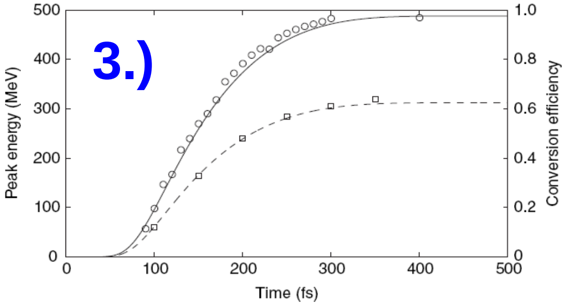
3. RAL, UK: Radiation pressure acceleration of thin foils with circularly polarized laser pulses, A. P. L. Robinson, et al., **New Journal of Physics 10**, 013021 (2008)

4. Czech Tech. Univ.: Monoenergetic ion beams from ultrathin foils irradiated by ultrahigh-contrast circularly polarized laser pulses, O. Klimo, et al., **PRST-AB 11**, 031301 (2008)

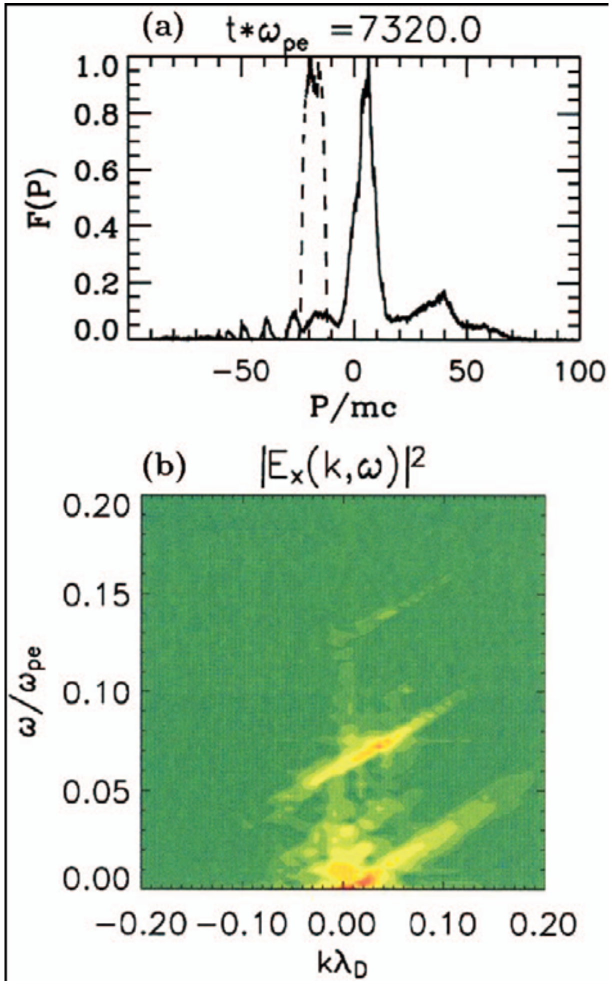
5. Peking Univ., China: Generating High-Current Monoenergetic Proton Beams by a Circularly Polarized Laser Pulse in the Phase-Stable Acceleration Regime, X.Q. Yan et al., **PRL 100**, 135003 (2008)







Origin of the co-moving accelerating electric field: BOA creates a relativistic Buneman instability.



Buneman (2-stream) instability occurs when ion and electron velocity differ by more than the ion-acoustic speed $c_s = (k_B(T_i\text{-}T_e)/m_i)^{1/2}$

- **Here: ions ~ 0.01 c, electrons ~ c ✓**

⇒ creates plasma waves (charge separation) that resonate with the ions and accelerate them.

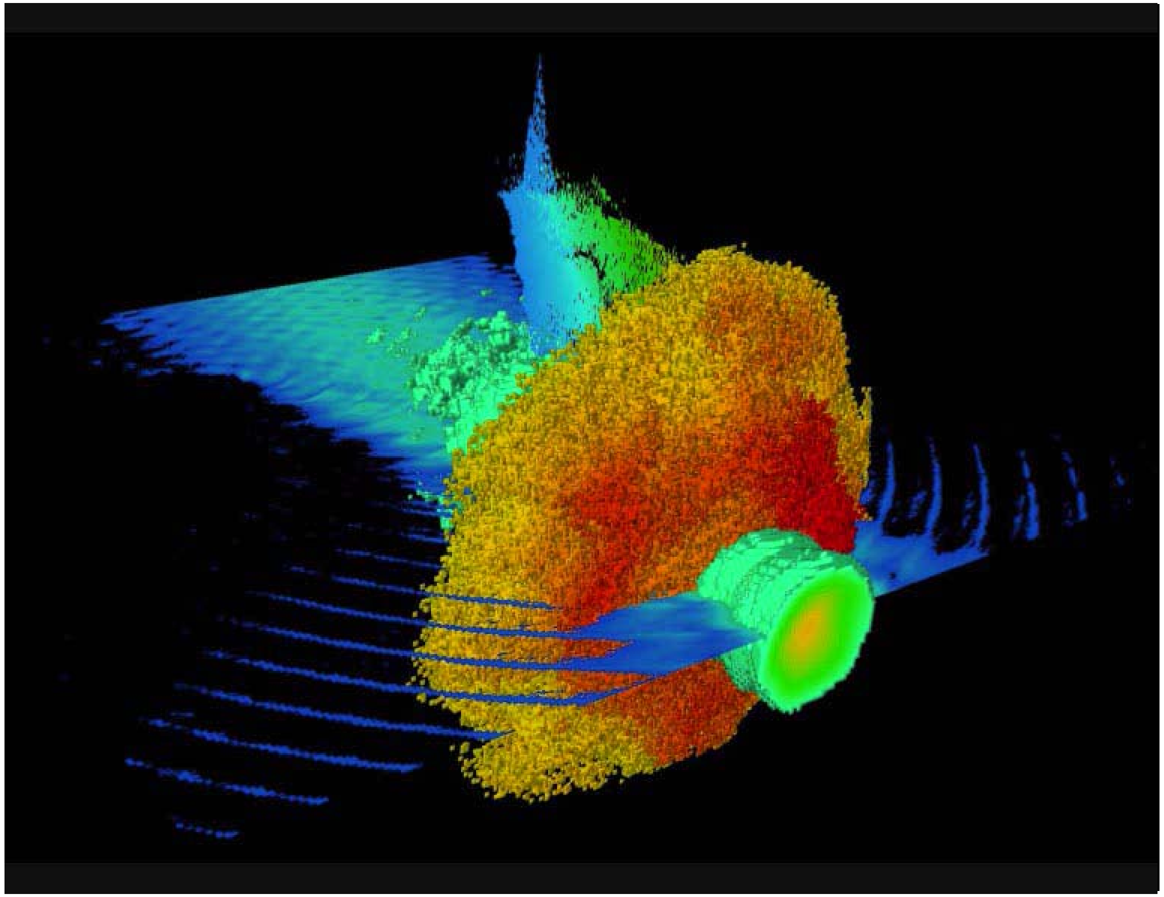
⇒ electrons loose energy to ions and get re-accelerated by the laser.

3D VPIC: simulation of the RPA mechanism shows higher-dimensional effects

Circular polarization, 30nm C and $I_0=10^{21}$ W/cm^2 & 312 fs pulse

Our largest simulation to date on ion acceleration (run on Roadrunner base system):

- Physical domain 25x25x20 μm w. solid target density
  14×10^9 cells, 21 x 10^9 particles, 4096 processors
- Contrasting with sim. size at the time of the proposal:
  0.5×10^9 cells, 2.2×10^9 particles, 510 processors
- 3D visualization using EnSight server-of-servers mode enables viewing, analysis of very large (multiple-TB) data sets.



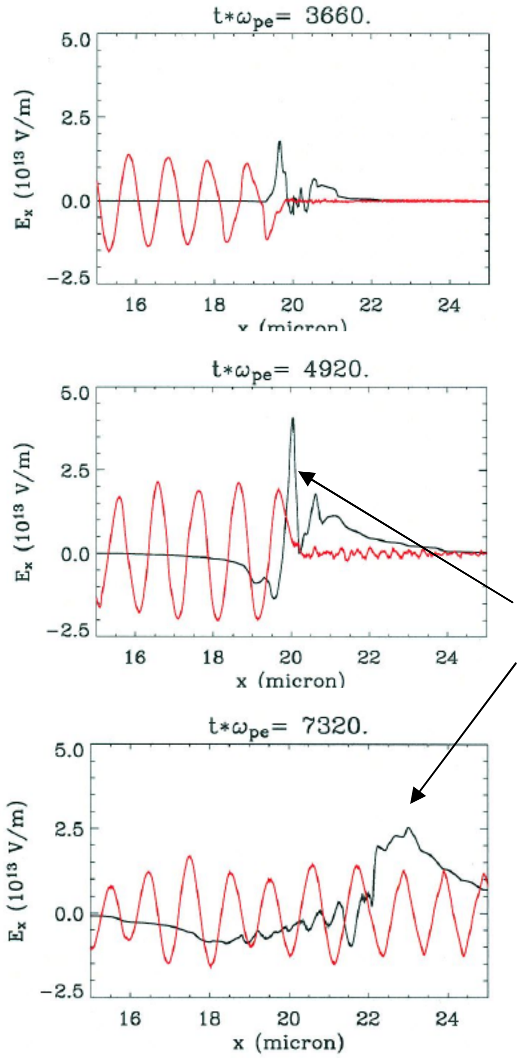
The Break-Out Afterburner (BOA) Mechanism

The Laser Break-Out Afterburner (BOA) ion acceleration mechanism

- Standard TNSA: Only a small fraction of the available electrons is promoted to ‘hot’ by the laser and sets up the accelerating field: $I=10^{21}$ W/cm^2
  ⇒ E ~ 8 TV/m.

- Enhanced TNSA: All electrons are promoted to ‘hot’: ⇒ E ~ 15 TV/m. Skindepth increases.

- **Break-Out Afterburner (BOA):** The laser burns through the target and reheats the electrons to higher energies (afterburner): ⇒ E ~ 30 TV/m. Electron transfer energy to ions by kinetic instability and get reheated by laser.



Trans. E-Field (laser)

Long. E-Field (accel.)

Accelerating E-Field moves with ions

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