Advanced Approaches to High Intensity Laser-Driven Ion Acceleration

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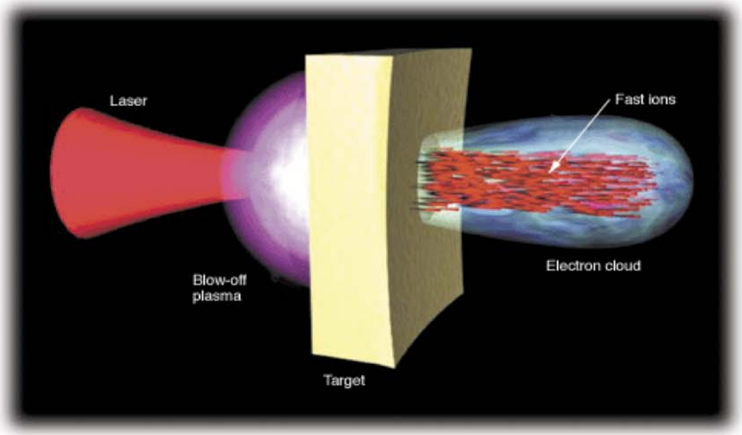
TNSA (Target Normal Sheath Acceleration)



- opaque target
- hot electrons generate quasi-static E-field (TV/m)
- ions are accelerated from the back surface (MeV/u)

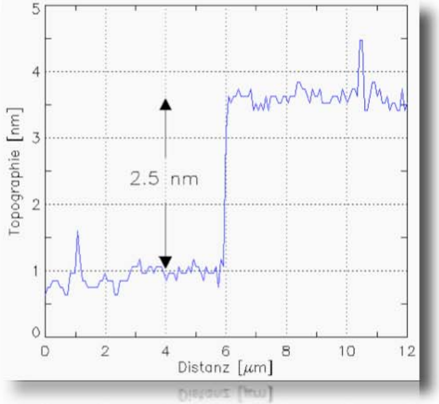
But:

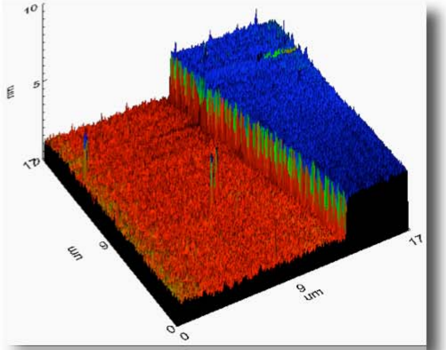
- large transverse spreading of E-field (100s of μm)
- energy transfer to electrons spatially separated from ion acc.
- stationary instead of co-propagating acceleration field
- exponential spectrum (low conversion efficiency to highest energetic ions)

Ultrathin (nm-scale) DLC foil targets

DLC is an ideally suited material

- high percentage of sp^3 bonds gives diamond-like properties
- high radiation and heat resistence
- high tensile strength





DLC foils produced at LMU

- thickness 2 nm - 60 nm
- bulk density (2.7±0.3) g/cm^3 (75 % sp^3)
- damage threshold: 10^{11} W/cm^2 @ 500 fs, 10^8 W/cm^2 @ 1.2 ns

Large-scale systems / long pulses

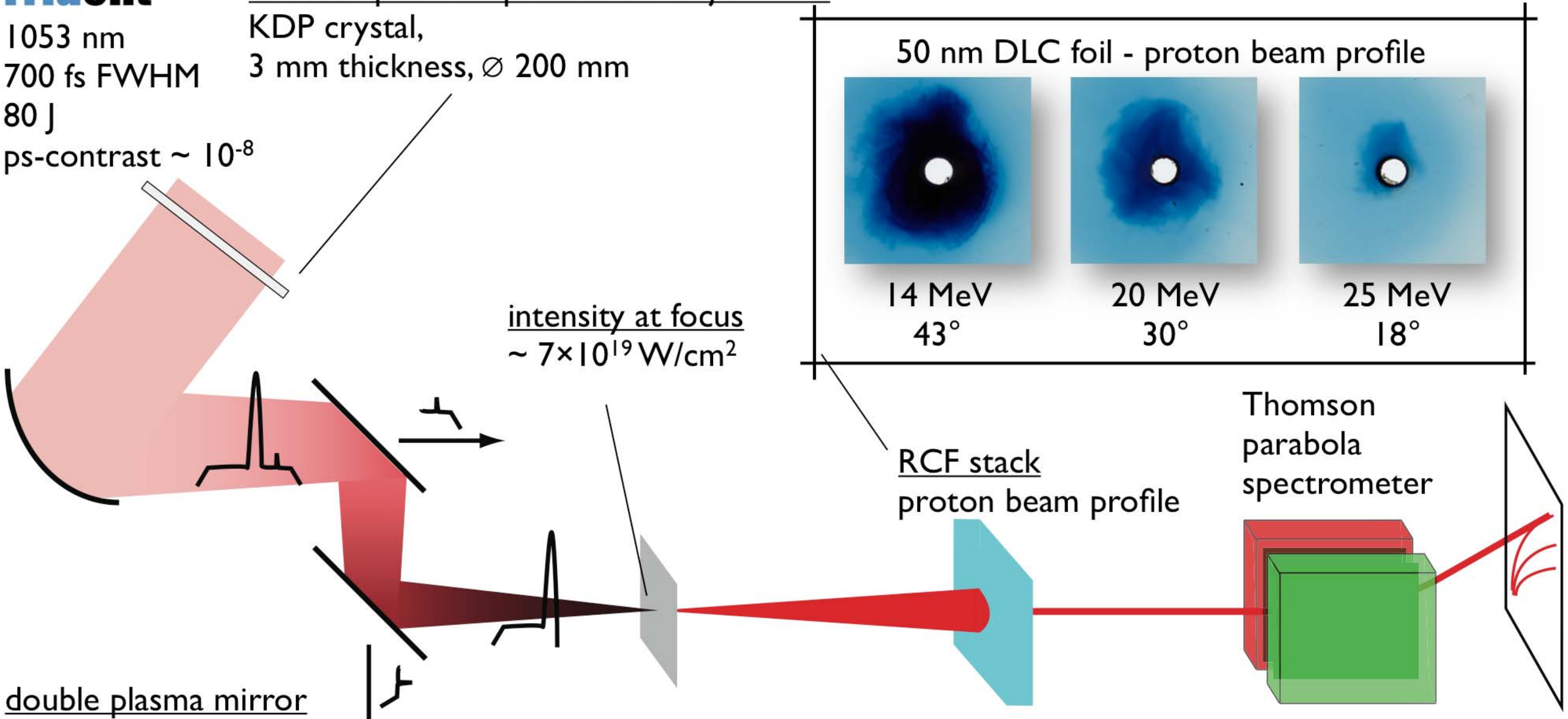
Experiments in collaboration with Los Alamos National Lab

www.attoworld.de

Trident

1053 nm
700 fs FWHM
80 J
ps-contrast ~ 10^{-8}

λ/4 waveplate for polarisation adjustment
KDP crystal,
3 mm thickness, ∅ 200 mm



50 nm DLC foil - proton beam profile

14 MeV
43°

20 MeV
30°

25 MeV
18°

intensity at focus
~ 7×10^{19} W/cm^2

RCF stack
proton beam profile

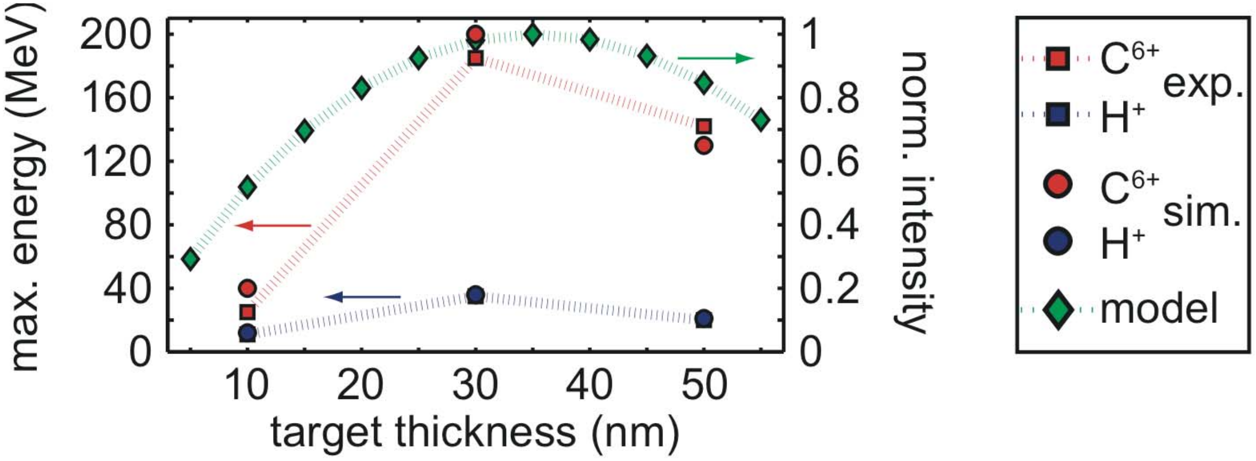
Thomson
parabola
spectrometer

CR39 /
image plates

double plasma mirror
reflectivity$_{tot}$ ~ 50 - 60%
40 - 50 J energy throughput
resulting ps-contrast ~ 10^{-12}

ultrathin foil targets
diamond-like carbon (DLC) foils
50% sp3, high mechanical stability, radiation hardness
10 - 50 nm thickness
∅ 1 mm

185 MeV carbon ions



- t_1: $n_e / (n_{cr}\ \gamma) \sim 1$, target becomes relativistically transparent
- short period of strong ion acceleration until t_2: $n_e / n_{cr} \sim 1$
- 10 nm foil: acceleration terminated before peak intensity is reached

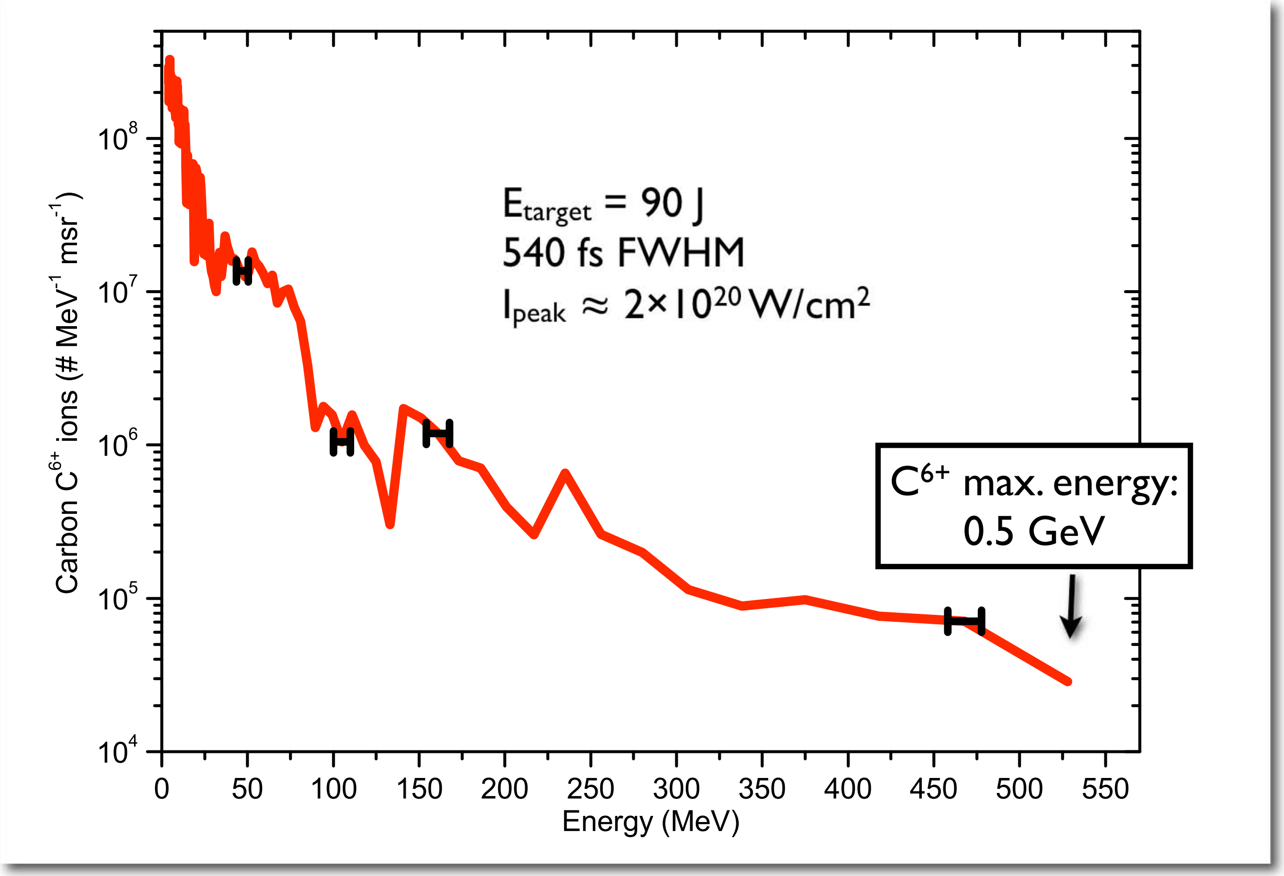
relativistic transparency regime / BOA:
highest ion energies generated for max. I (t_1)

A. Henig et al., *Enhanced Laser-Driven Ion Acceleration in the Relativistic Transparency Regime*, PRL **103**, 045002 (2009)

Increasing the energy to 0.5 GeV

new OPA-based frontend resulting in high contrast on target *without* plasma mirrors, increased peak intensity of $I_{peak} \approx 2\times10^{20}$ W/cm^2

optimum thickness increases as expected, highest ion energies at 58 nm:



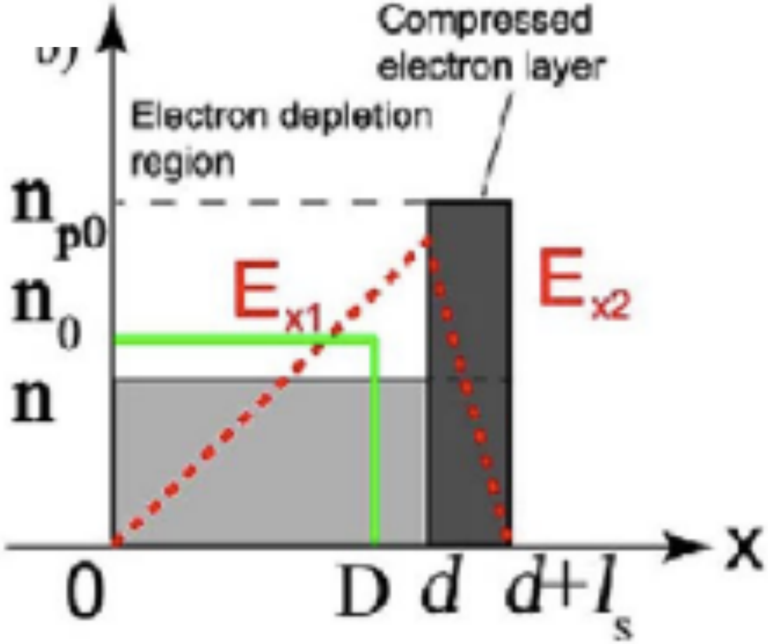
Radiation Pressure Acceleration (RPA)

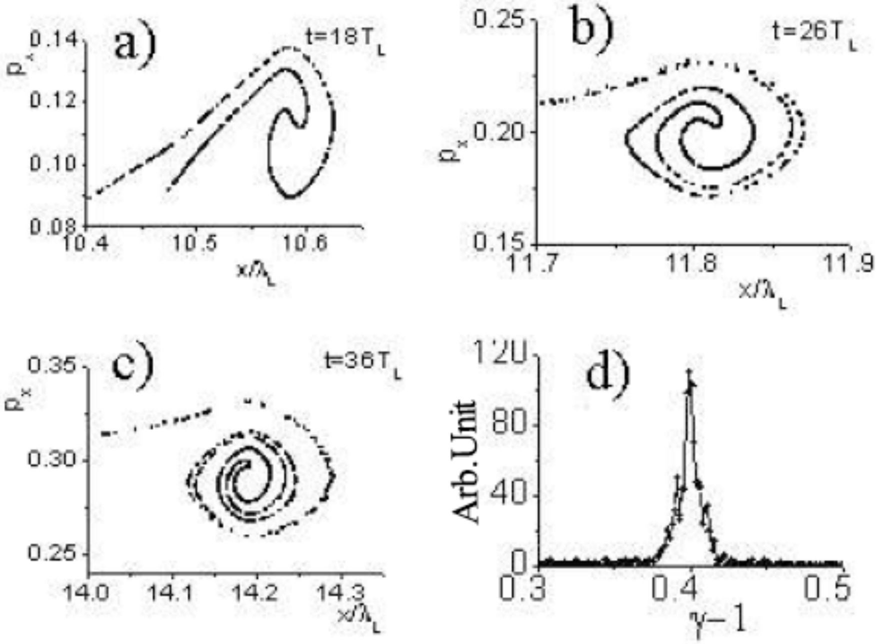
optimum condition: $\boxed{\sigma_{opt} / n_{cr} \lambda = (I/I_1)^{1/2}}$ $I_1 = 1.368 \times 10^{18}\,\mathrm{W/cm^2} \times (\mu\mathrm{m}/\lambda)^2$

formation of compressed,
highly dense electron layer

→

characteristic loops
in ion phase space





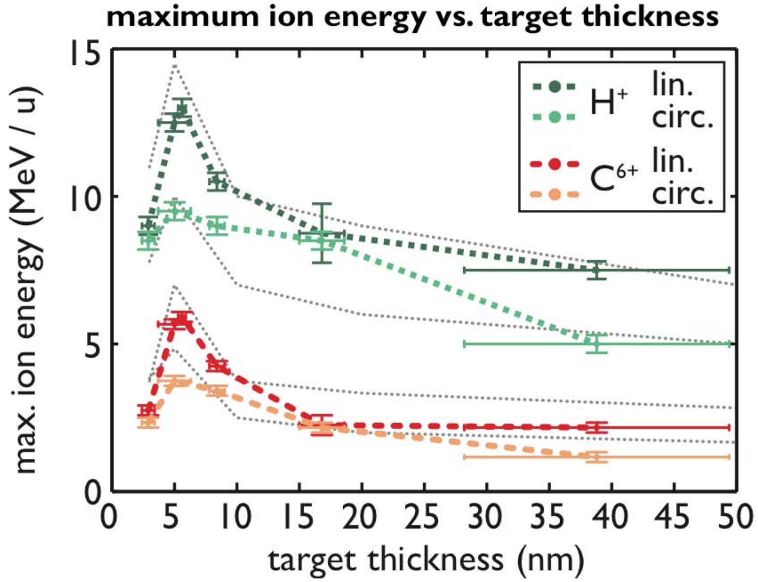
by X. Q. Yan

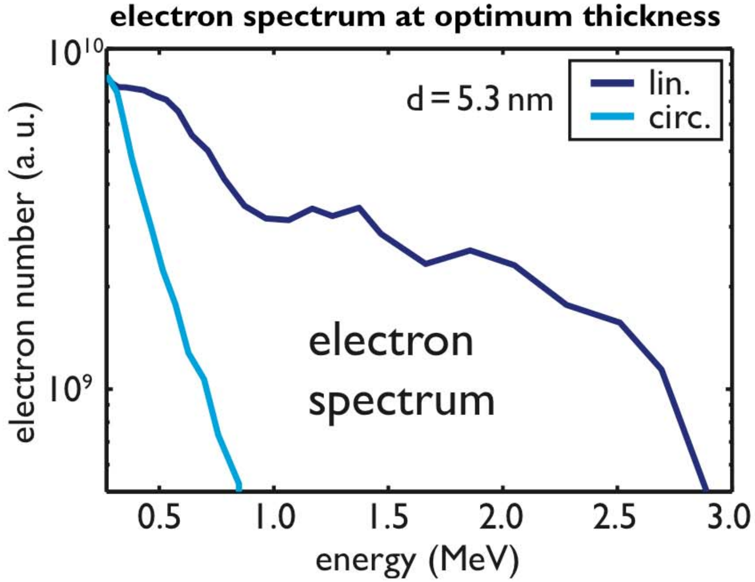
key to success: suppression of electron heating

First comparative experimental study

Experiments in collaboration with MBI Berlin

10 Hz Ti:sapph system, 45 fs FWHM, 0.7 J on target after DPM (contrast ~ 10^{-12}) focussed to peak intensity of 5×10^{19} W/cm^2





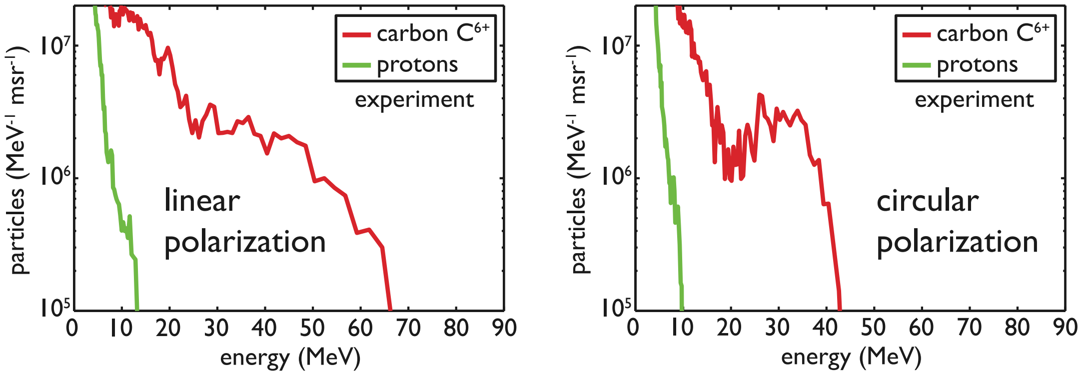
optimum thickness d = 5.3 nm consistent with condition $\sigma_{opt} / n_{cr} \lambda = (I/I_1)^{1/2}$

circular polarization results in significant reduction of electron heating

A. Henig et al., *Radiation pressure acceleration of ion beams driven by circularly polarized laser pulses*, PRL **103**, 245003 (2009)

Distinct peak in C^{6+} spectrum

measured proton
and C^{6+} spectra



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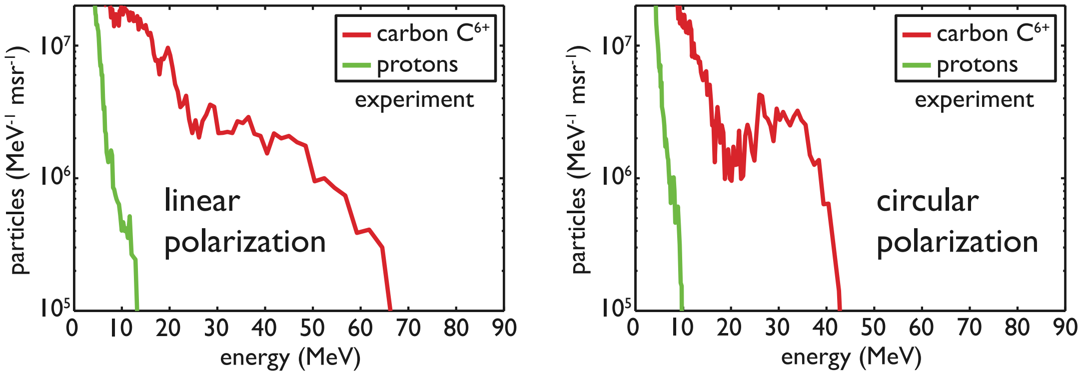
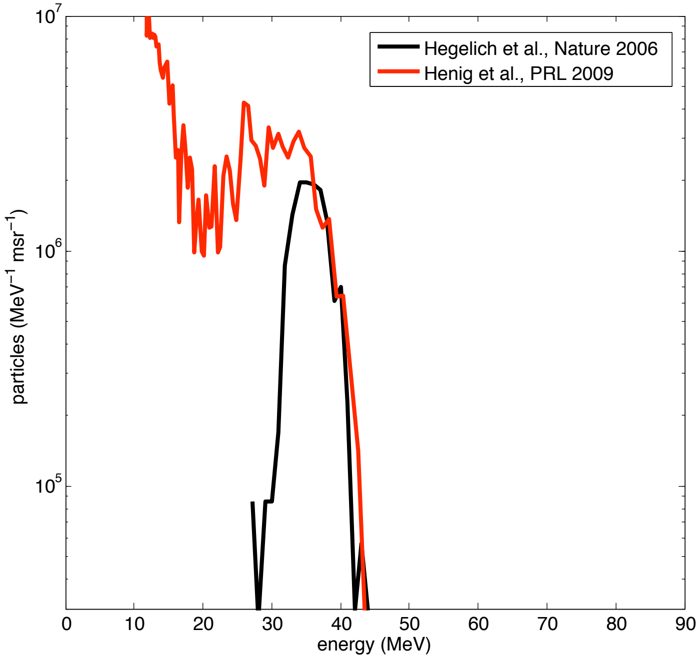


comparison with TNSA, Hegelich *et al.*, Nature **439**, 441 (2006):

Hegelich et al. (TNSA):
20 J laser pulse energy

Henig et al. (RPA):
0.7 J laser pulse energy



40 times increased
conversion efficiency

Distinct peak in C^{6+} spectrum

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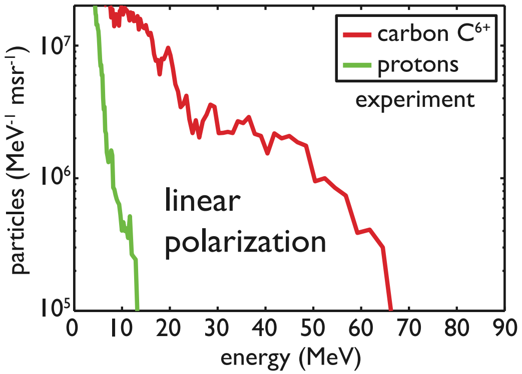
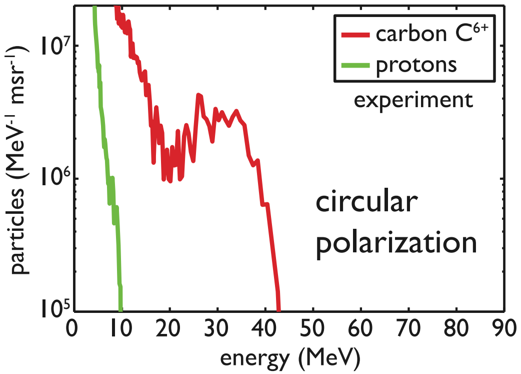
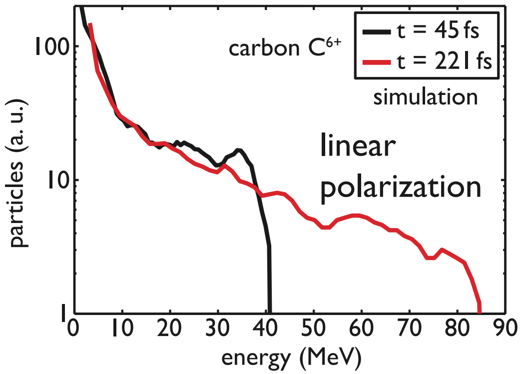
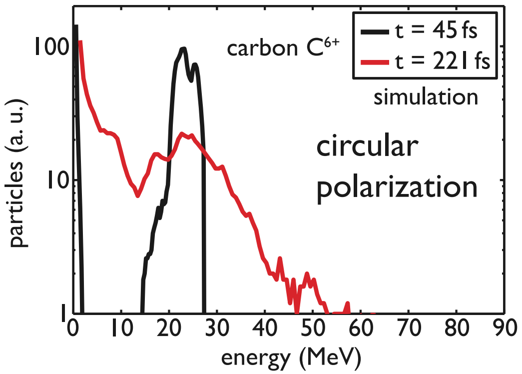




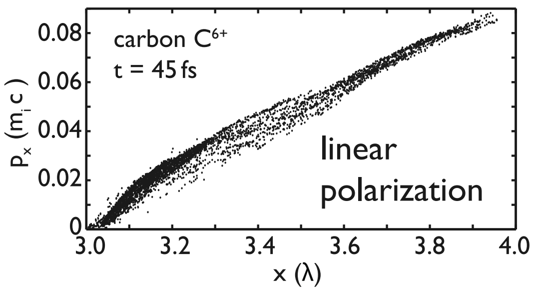
<u>2D PIC results for C^{6+}</u>

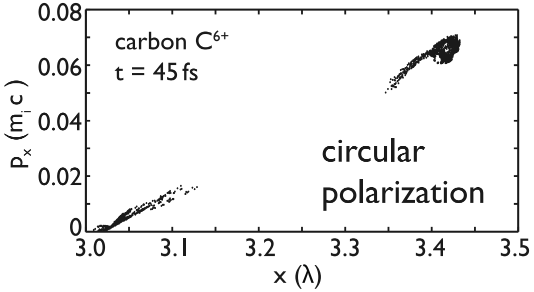
C^{6+} spectrum at
different times





C^{6+} phase space

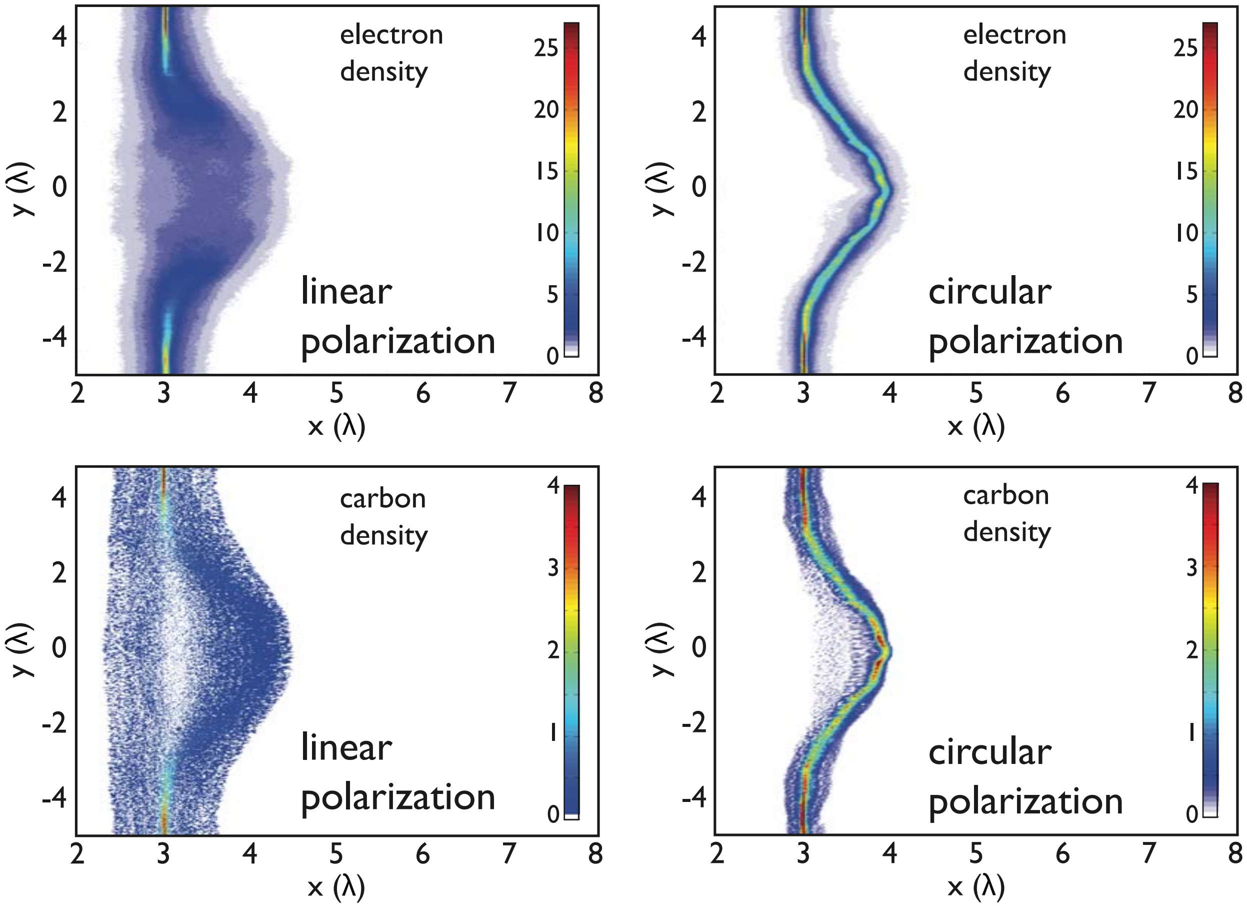




Evolution of particle densities

linear polarization

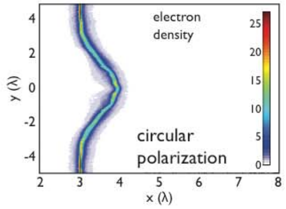
circular polarization



strong expansion driven by hot electrons

ballistic acceleration of whole focal volume

Keeping the spectrum mono-energetic



Gaussian focal spot causes foil to bend

↓

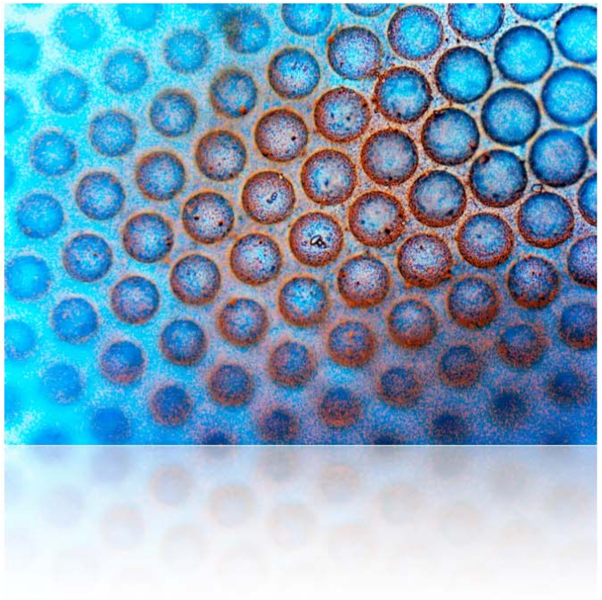
Strong electron heating sets in due to oblique incidence on walls

↓

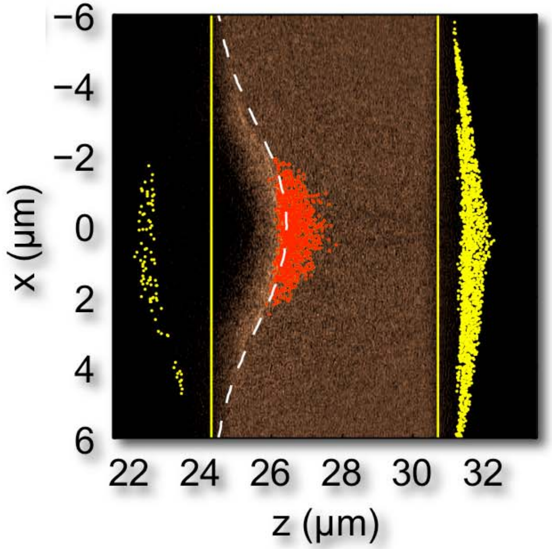
Rapid foil expansion / termination of RPA

Potential solutions:

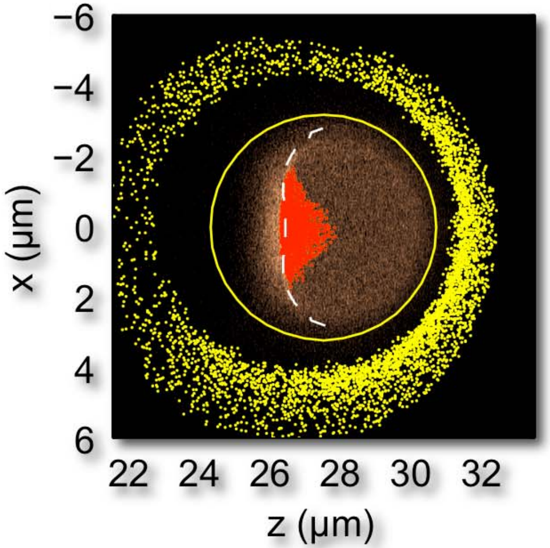
- increased focal spot size
- higher laser intensities
- pre-curved targets



Mass-limited targets / microspheres



- collimated ion beam from back surface (TNSA)
- divergent ion beam from front surface



- TNSA ions now accelerated into 4π
- highly directed ion beam from front surface

A. Henig et al., *Laser-driven shock acceleration of ion beams from spherical mass-limited targets*, PRL **102**, 095002 (2009)

Conclusions and Outlook

- First experiment showing the correlation of relativistic transparency enabled laser penetration and enhanced ion energies using nm-scale DLC foils and a DPM-setup at TRIDENT
- World record 0.5 GeV carbon ions generated at upgraded TRIDENT
- First experimental demonstration of radiation pressure acceleration (RPA) to become the dominant ion acceleration mechanism when using nm-thin foil targets and circular polarization
- Highly promising route towards intrinsically mono-energetic, dense ion beams at large conversion efficiencies
- For the moment, keeping the monochromaticity by suppressing electron heating over extended times remains a demanding challenge

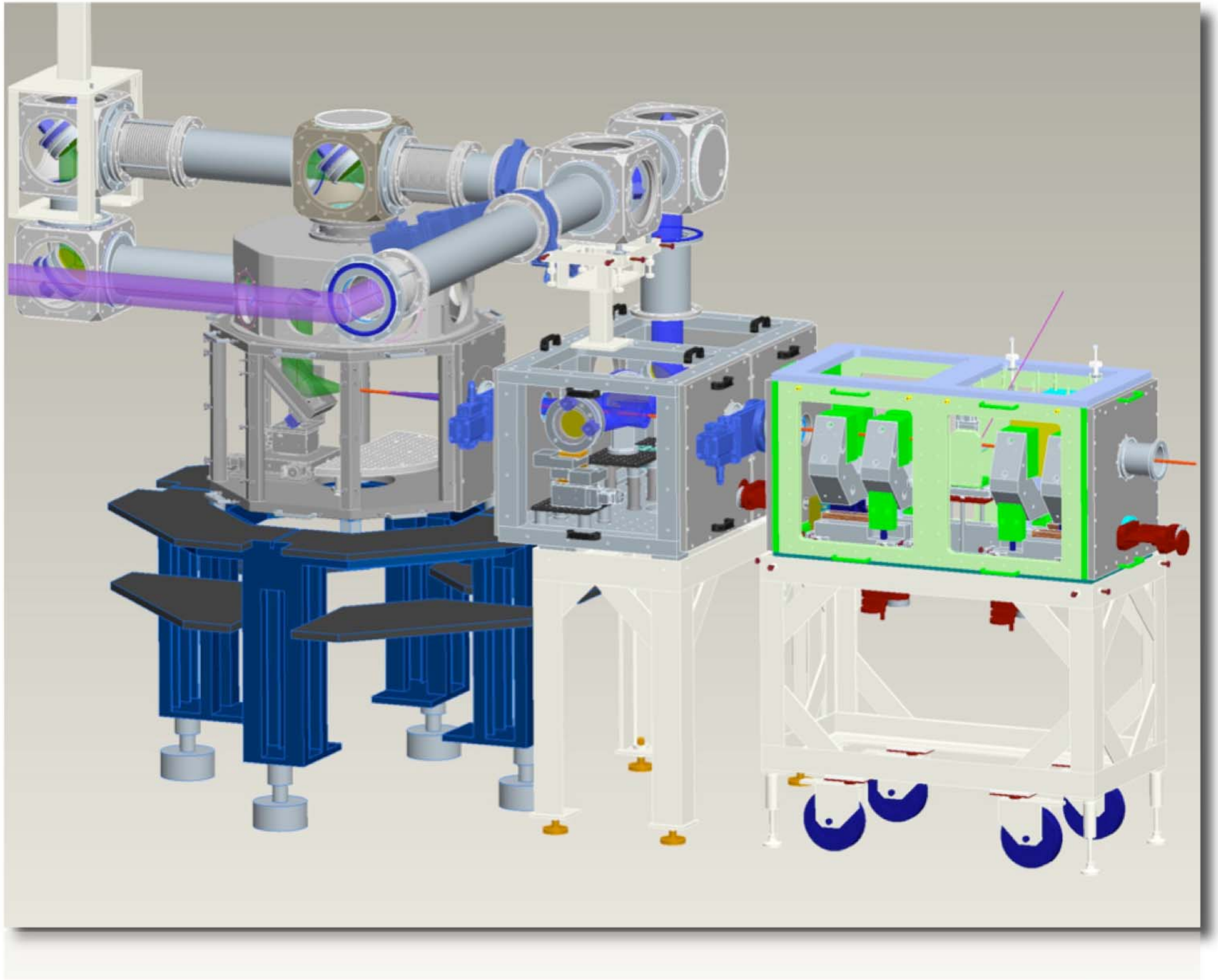
Related Publications

A. Henig et al., *Radiation pressure acceleration of ion beams driven by circularly polarized laser pulses*, PRL **103**, 245003 (2009)

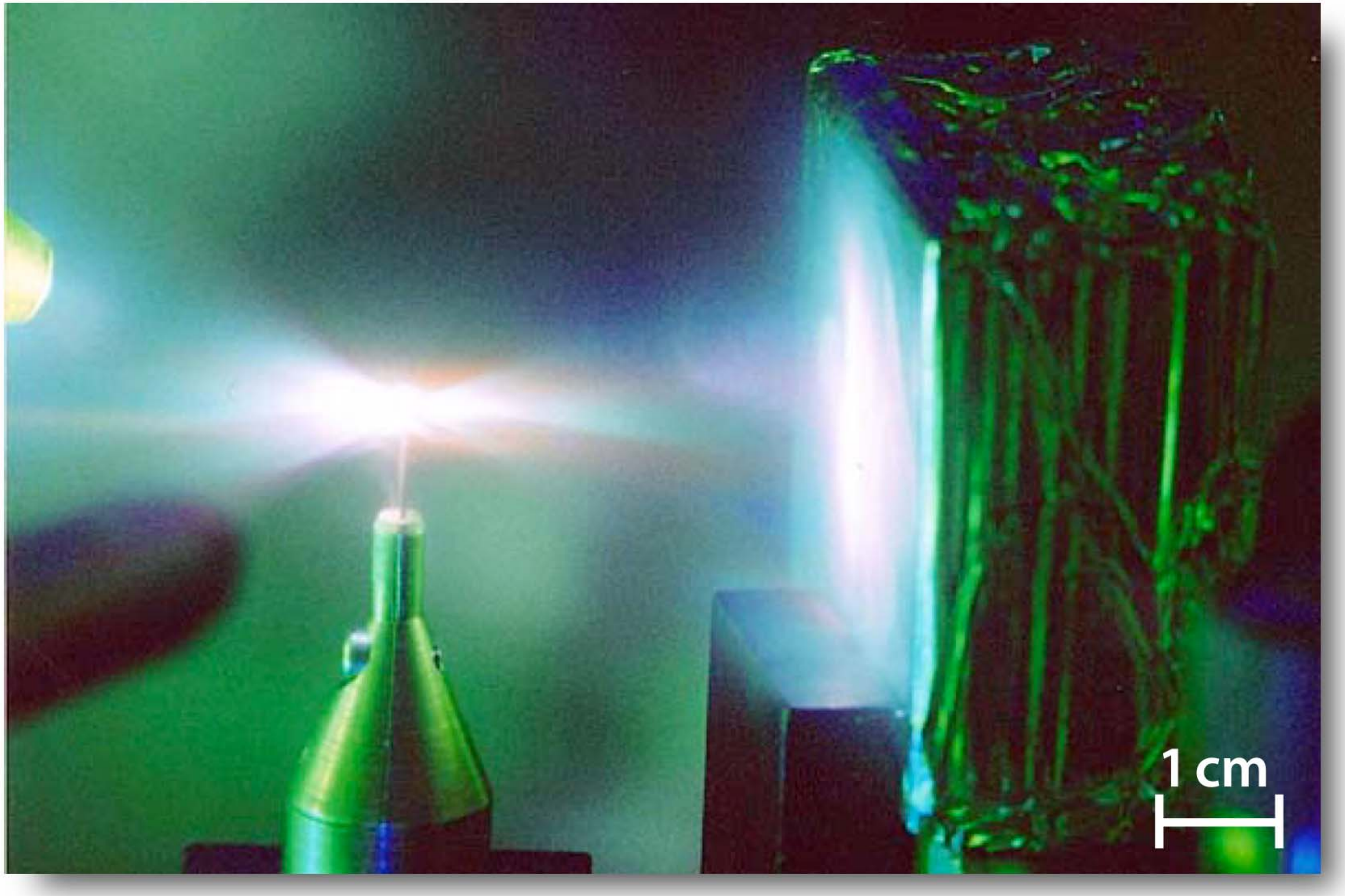
A. Henig et al., *Enhanced Laser-Driven Ion Acceleration in the Relativistic Transparency Regime*, PRL **103**, 045002 (2009)

A. Henig et al., *Laser-driven shock acceleration of ion beams from spherical mass-limited targets*, PRL **102**, 095002 (2009)

Biomedical beam line at MPQ

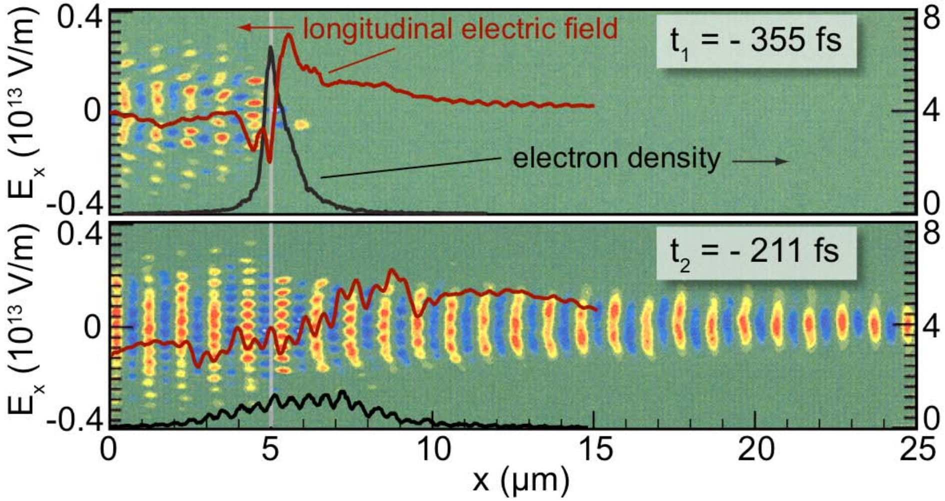


0.5 GeV C^{6+} within microns



PIC simulations (LANL code VPIC)

Simulation of 10 nm foil case



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- short period of strong ion acceleration until t_2: n_e / n_{cr} ~ 1
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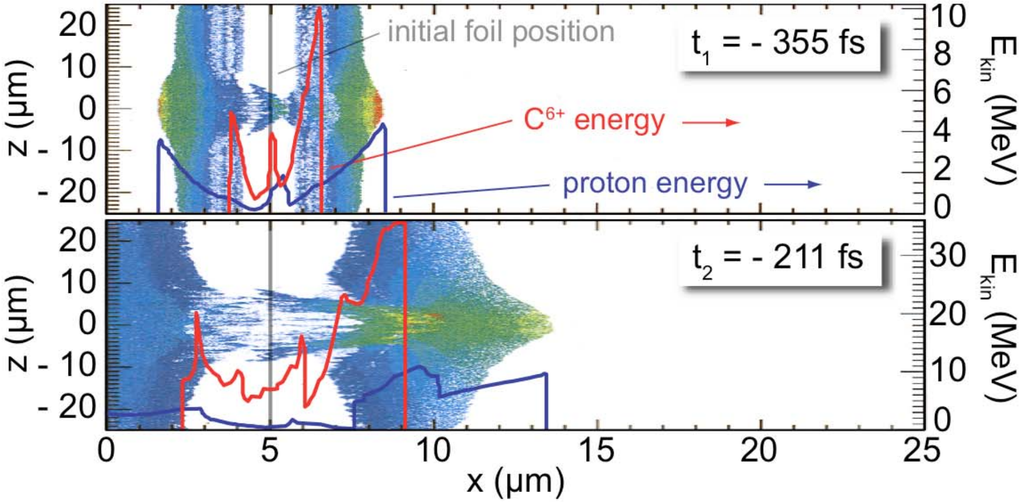

- penetrating laser pulse imposes asymmetry on acceleration
- in contrast to low-intensity irradiation of nm-foils

A. Andreev et al.,
Phys. Rev. Lett. **101**, 155002 (2008)