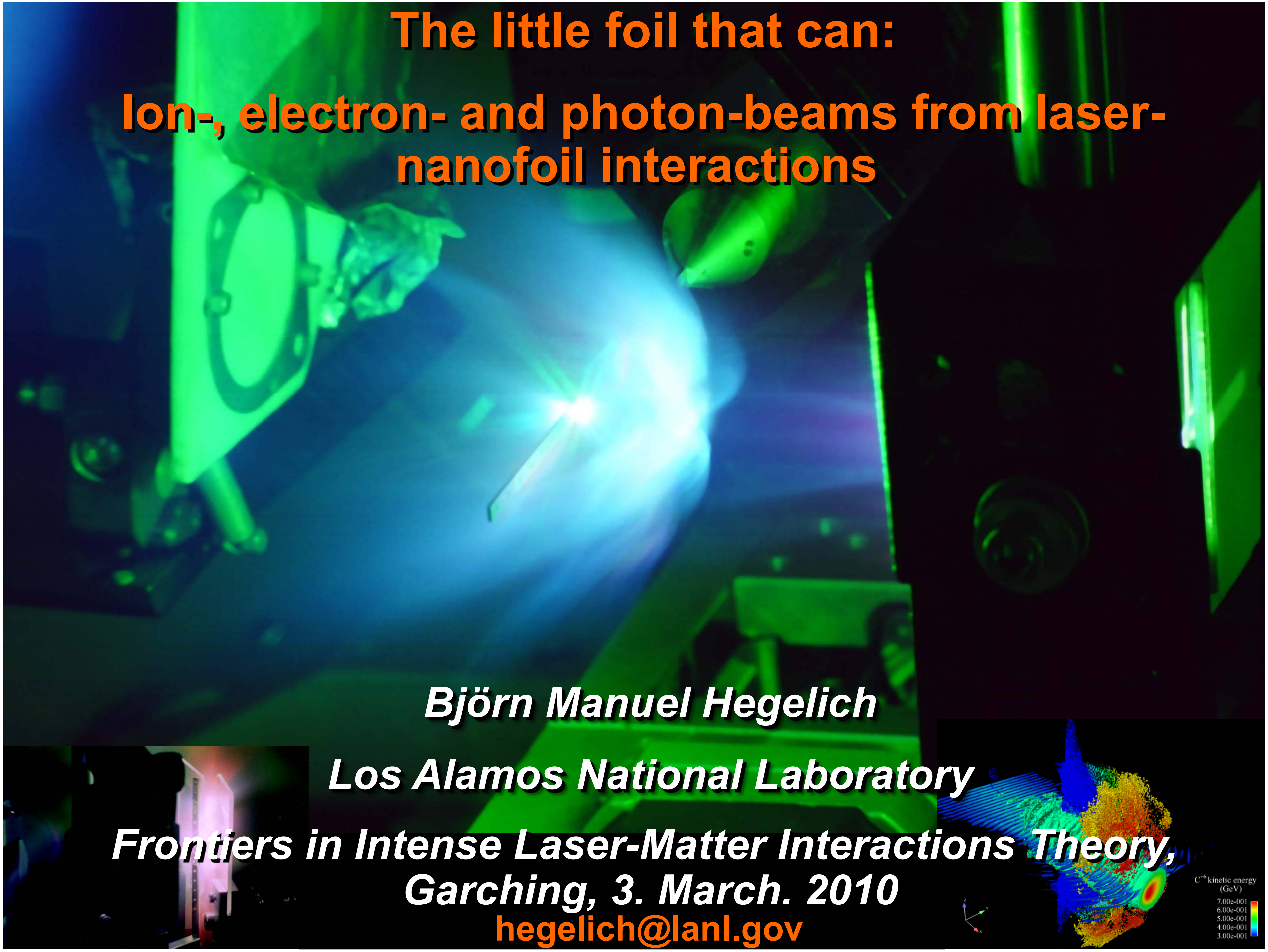

The little foil that can:

Ion-, electron- and photon-beams from laser-nanofoil interactions

Björn Manuel Hegelich

Los Alamos National Laboratory

Frontiers in Intense Laser-Matter Interactions Theory, Garching, 3. March. 2010

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

Outline

Nanofoils can be …

- … be a GeV ion source
- … do laser pulse shaping
- … be a coherent x-ray source
- Summary

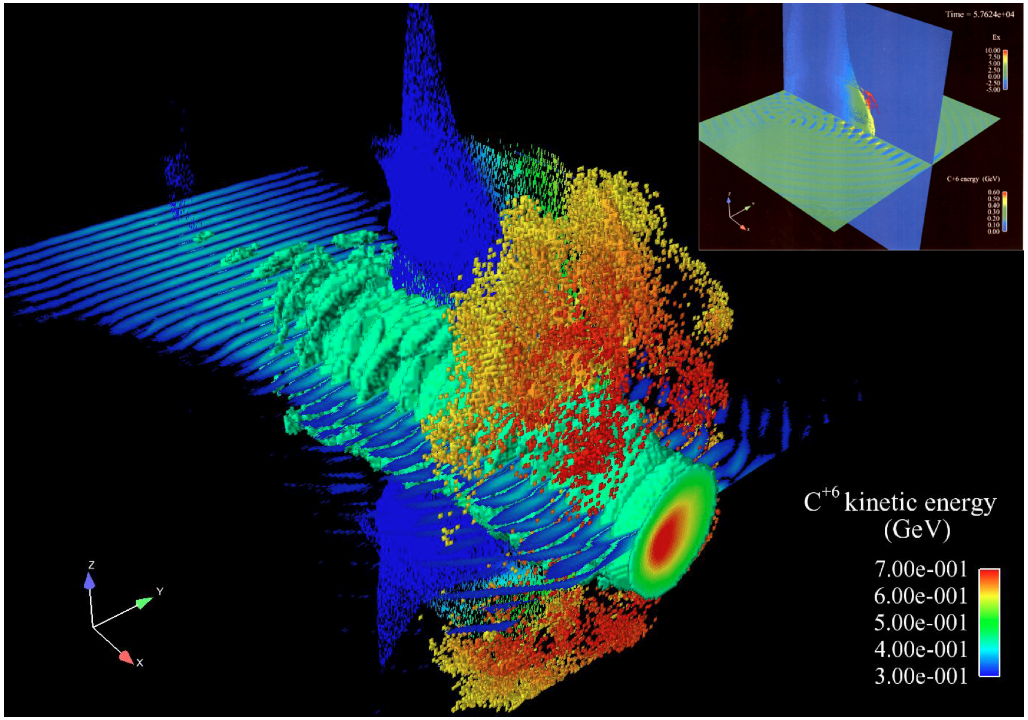
Nanotargets can …
… be an ion source

- Break-Out Afterburner (BOA) and Radiation Pressure Acceleration (RPA)
    - 0.5 GeV peak energies
    - High conversion efficiency
    - Quasi-monoenergetic ions

Laser – Nanotarget Interaction:

Targets 30nm, 58nm Diamond-Like Carbon foils @ 821 n_{cr}

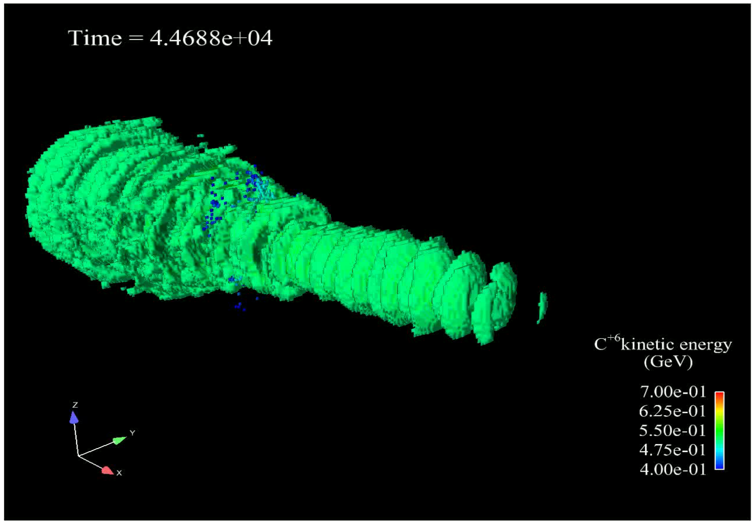
Lin. Pol.

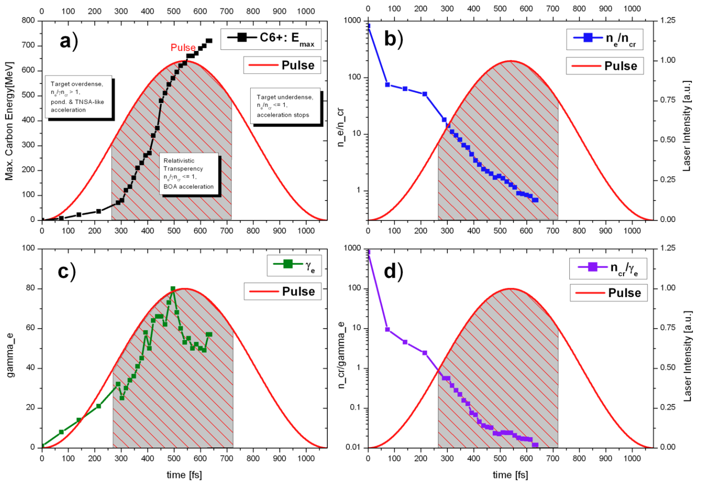


3D-VPIC simulation of a 10^{21} W/cm^2, 304 fs, laser pulse interacting with a 30nm DLC foil

Parameters of BOA phase:

- Duration: ~500fs
- Spatial extend: ~15 μm





2D-VPIC simulation: 10^{21} W/cm^2, 540 fs, laser interacting with a 58nm DLC foil

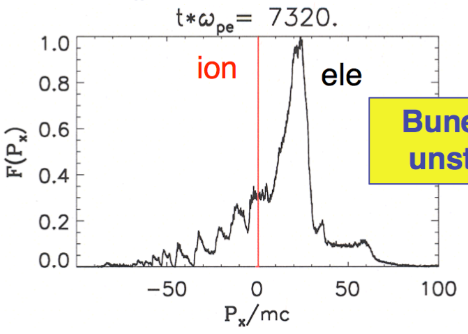
Energy transfer: laser ➔ electrons ➔ ions

Dispersion relation consistent with rel. Buneman instability

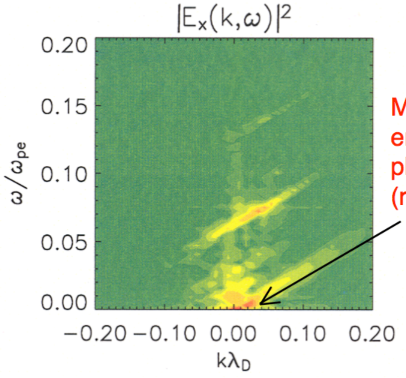
Parameters of BOA phase:
- Duration: ~500fs
- Spatial extend: ~15 μm

Parameters of instability:
- Growth rate: 1.7 fs
- Phase speed: 0.1 c
- Spatial extend: ~50-500 nm

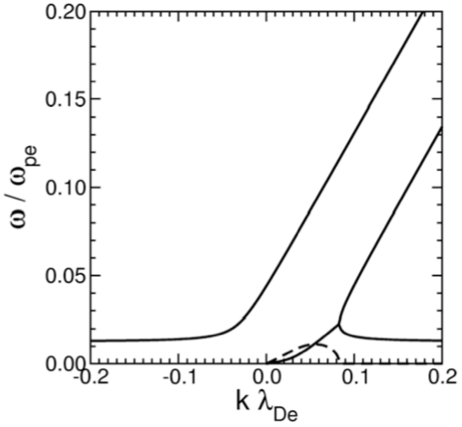
Electron distribution function at peak of E_x field & bulk of C ions

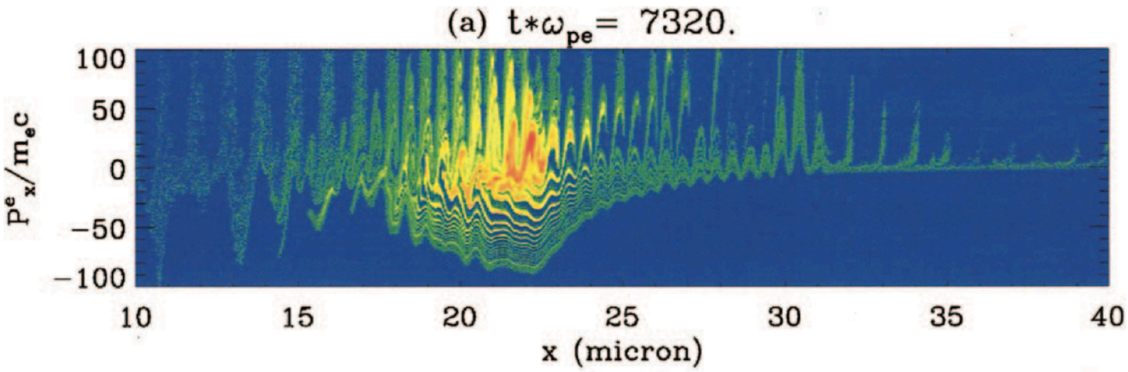


Buneman unstable



Max spectral energy at low phase speed (resonant with ions)



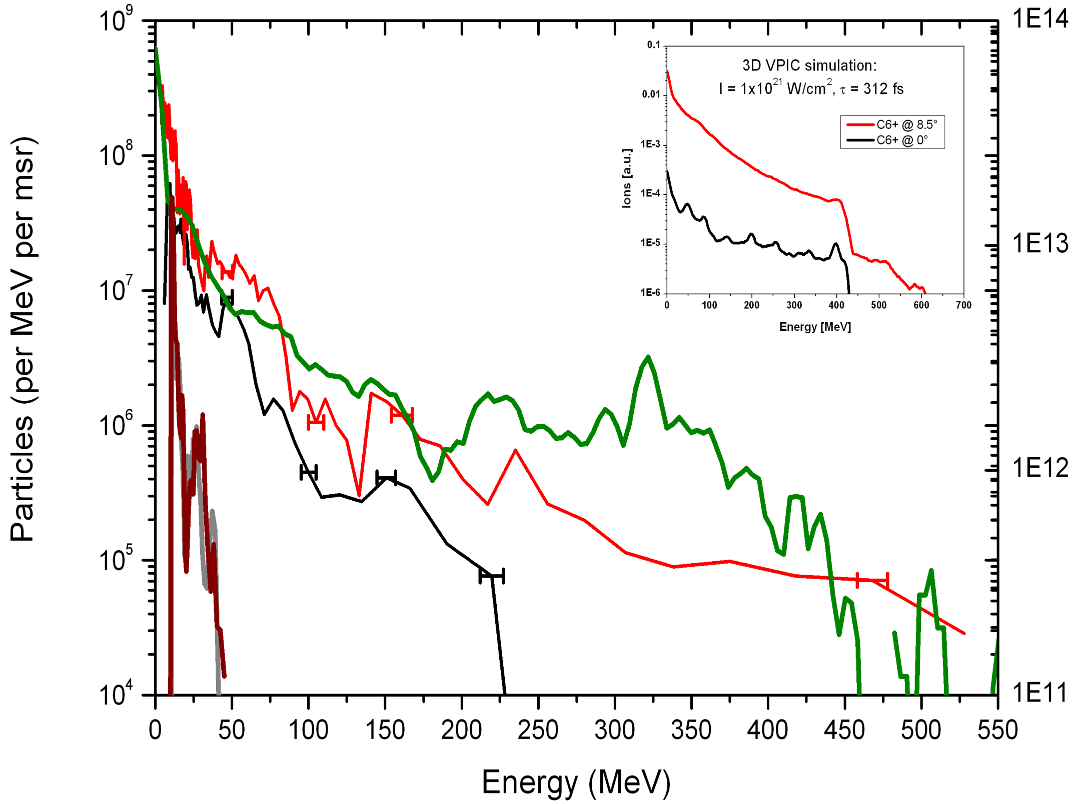


Each half-cycle of the laser launches high-γ electron bunch
⇒many independent occurences of instability

BOA: Comparing Experiment & Sim.

58nm DLC foil, Ipeak= $5x10^{20}$ W/cm², I_{ave} = $2x10^{20}$ W/cm², t=540fs,

Lin. Pol.



- Simulations agrees with measured spectra (energy, number, angular distribution)
- Protons have same velocity as Carbon
- Spectra retain mono-energetic remnant from adiabatic phase

Theory: reduced model for max. ion energy

Yan, Tajima, Hegelich, Appl. Phys. B. (2009) in press, (arXiv:0904.1466)

↕ Lin. Pol.

$E_{sum} = E_{max,i} + E_{max,BOA}$

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

$$\bar{E}_0(t_1) = m_e c^2 \int_0^{t_1} (\sqrt{T(t')a^2(t')+1}-1)\frac{dt'}{t_1}$$

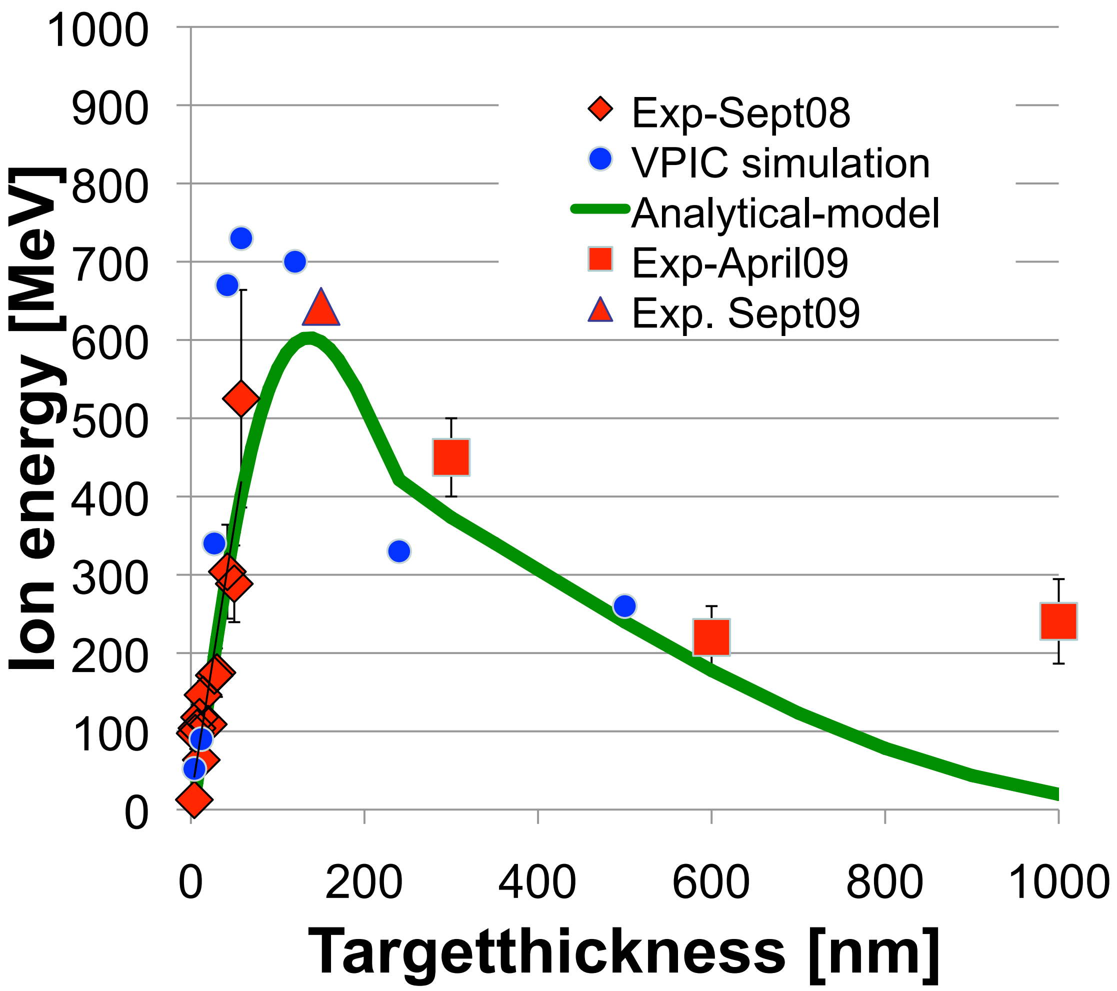
$$\varepsilon_{\max,i,BOA} = (2\alpha+1)Q\bar{E}_0((1+\omega(t_2-t_1))^{1/2\alpha+1}-1)$$

t_1 : $n_e/\gamma n_{cr} \sim 1$

$$t_1 = \left(\frac{M}{m}\frac{3N^2d^2}{q_i\omega_0^2c^2a_0^3}\right)^{1/4} = \left(\frac{12}{q_i\pi^2}\frac{M}{m}\frac{N^2d^2}{a_0^3}\frac{\tau^2}{c^2}\right)^{1/4}$$

$t_2 = t_1 + \Delta t$: $n_e/n_{cr} \sim 1$

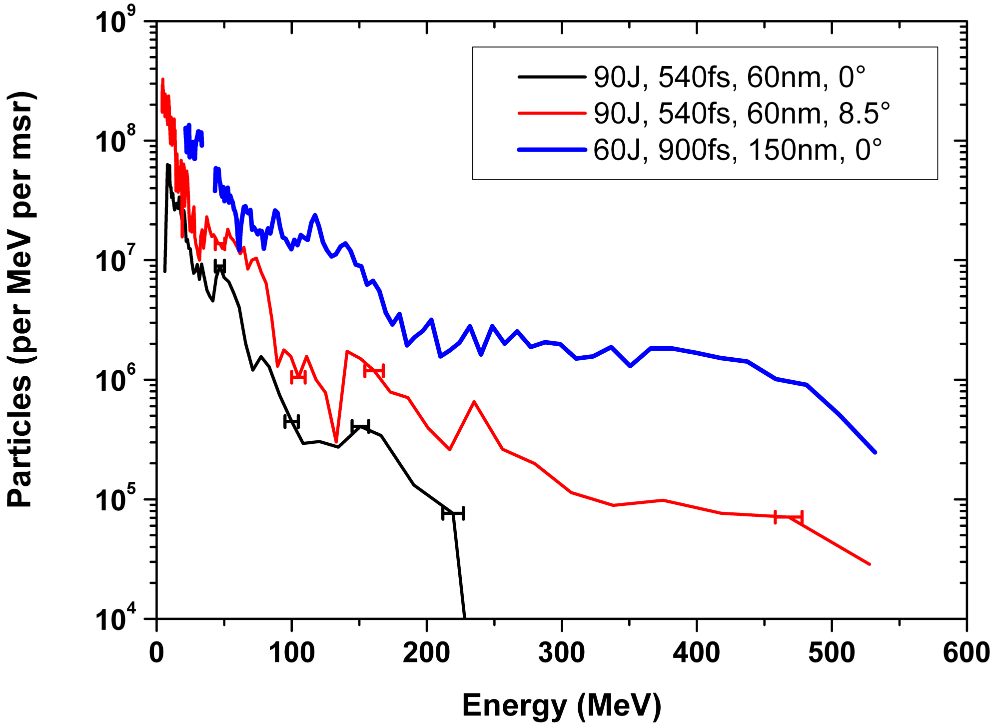
$$\Delta t = \frac{x_2-x_1}{C_{s,\max}}\frac{1}{\sin(\omega t_1)} = \frac{x_1(\gamma^{1/3}-1)}{C_s}\frac{1}{\sin(\omega t_1)} = \frac{Nd(\gamma^{1/3}-1)}{\gamma C_s}\frac{1}{\sin(\omega t_1)}$$



BOA: Ongoing Opt. of laser-target param.

150nm DLC foil, Ipeak= 2.5×10^{20} W/cm^2, $I_{ave} = 8 \times 10^{19}$ W/cm

Lin. Pol.



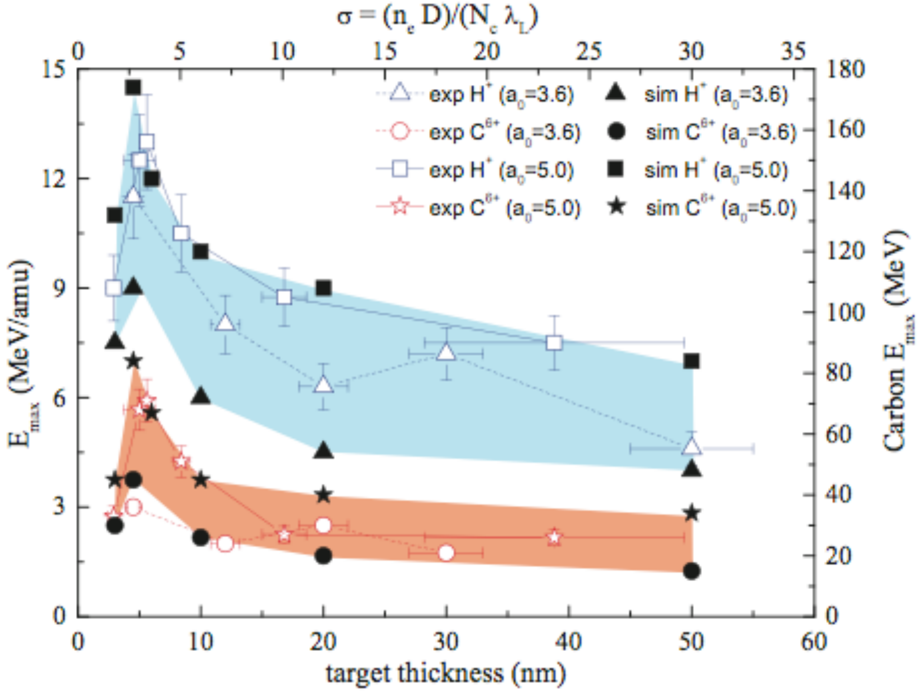
- Further contrast improvement on 5-10ps scale: cloaser to ideal pulse shape
- Target thickness obtimized to laser parameters
- 2x improvement of energy @ same angle
- 2 orders of magnitude higher efficiency

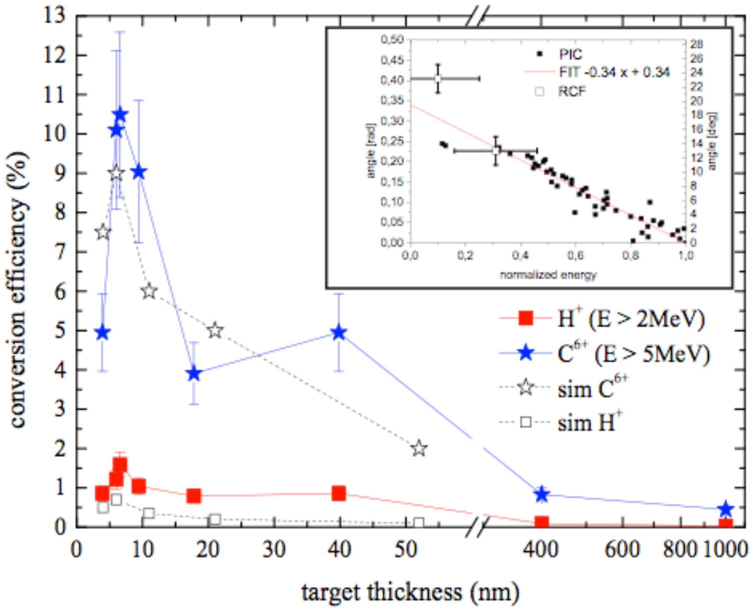
Enhanced Efficiency and Energy from nm-targets: Steinke et al., AP B (2010)

Lin. Pol.

Emax (Proton): 14 MeV
Emax (Carbon): 80 MeV

CE (Proton): 2%
CE (Carbon): 11%





- 10Hz Ti:Sapphire laser system: 700 mJ, 45 fs, 3 x 10^{19} W/cm²
- double plasma mirror for contrast enhancement
- DLC-foils of thickness 50nm down to sub-5nm (shot at normal incidence)

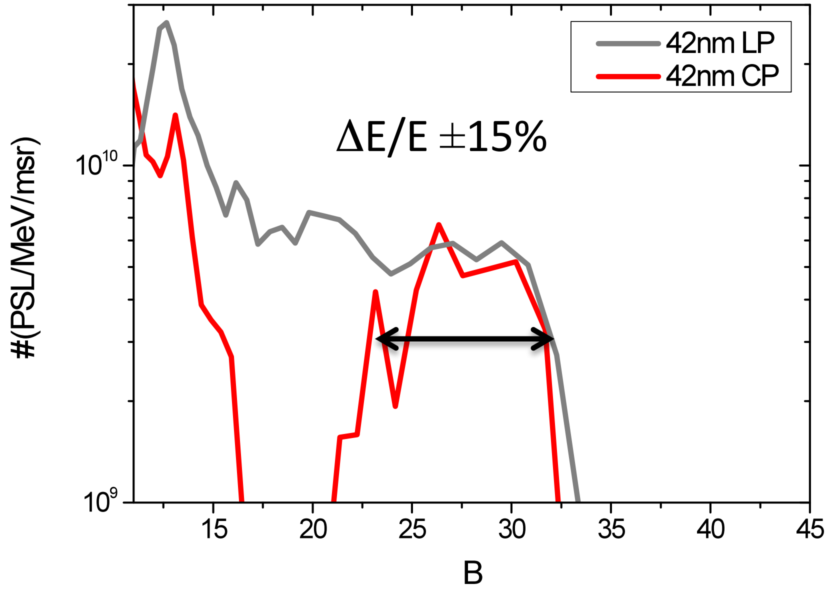
Experiments @ MBI Berlin:
A. Henig, Habs, M. Hegelich, R. Hörlein, D. Kiefer, D. Jung, X. Yan, D. (LMU)
S. Steinke, T. Sokollik, M. Schnürer, P. Nickles, W. Sandner (MBI)

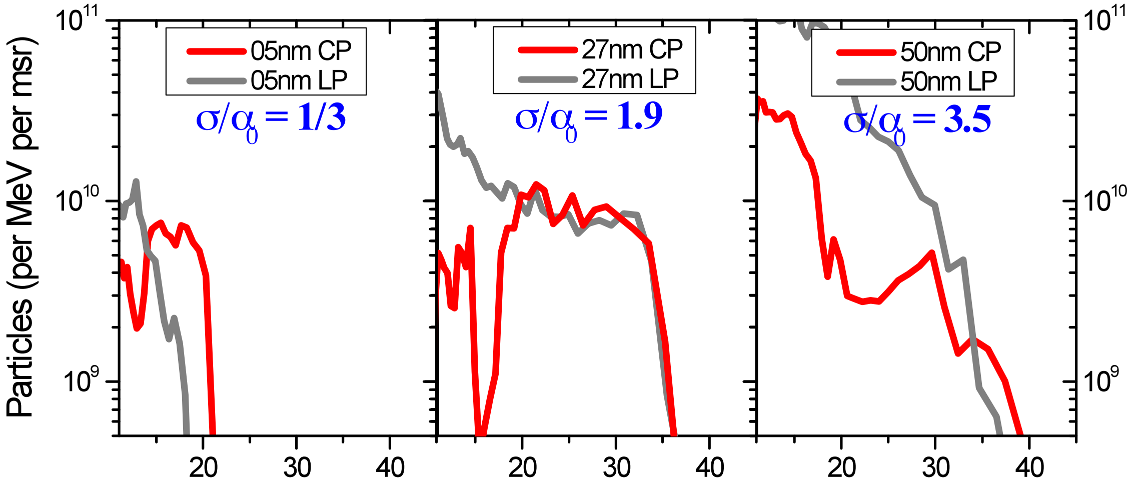
Proton data from experiment using CP

Protons

σ Scan from 3 to 50 (a_0=12)

- Equals thickness of 3nm to 60nm
- For $^1/_3 \lesssim {}^\sigma/_{a_0} \lesssim 3$ we see monoenergetic proton beams with CP, otherwise exponential spectra
- First experimental generation of monoenergetic proton beams with circular polarized light showing signatures of light pressure acceleration (RPA/PSA)
- Monoenergetic spectra measured 1.2m behind the target; beam quasi-neurtrality indicated by theory

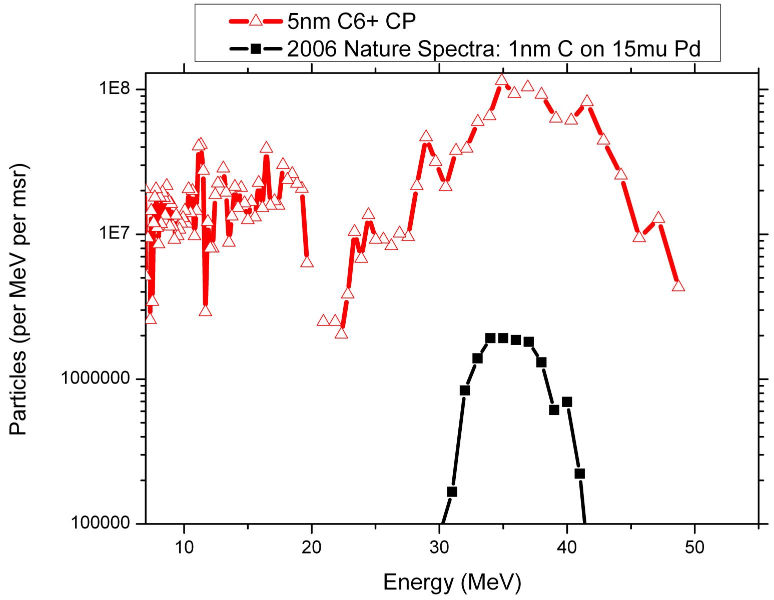


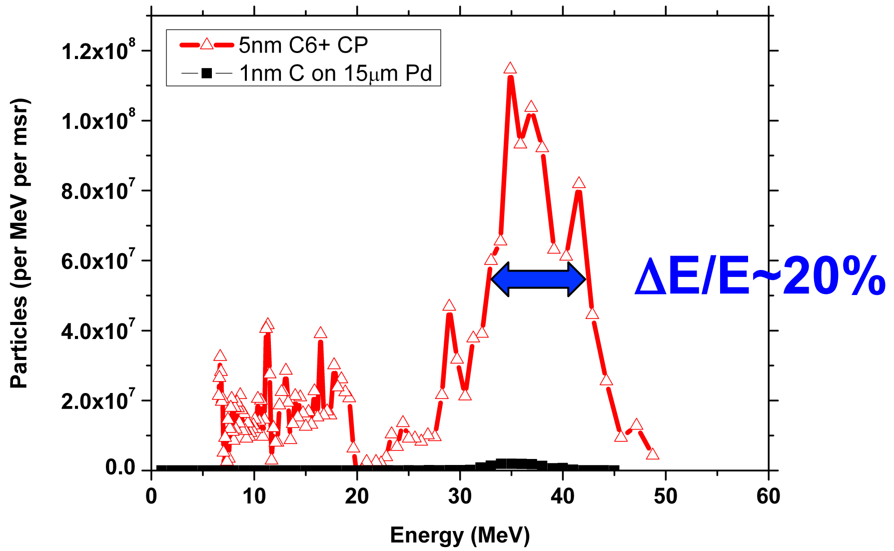


Trident: Carbon Acceleration w Circ. Pol.

typical pulse parameter: 80J, 550fs, 3 × 10^{20} W/cm^2, contrast < 10^{-11} @ 50ps

Circ. Pol.



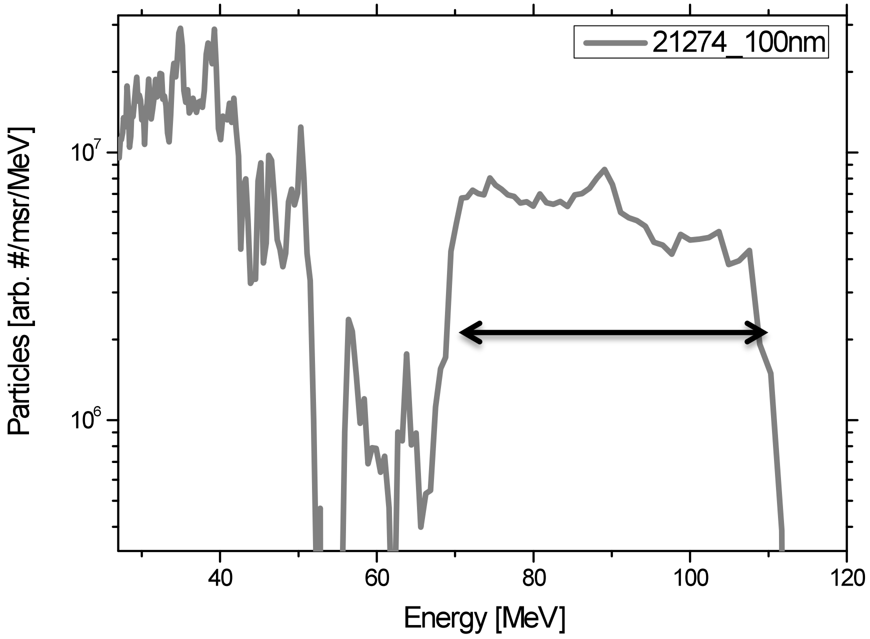


Almost 2 orders of magnitude more particles into peak than in the 2006 Nature experiment.

Approximately 20% energy spread with far from optimal laser parameters.

Main results from F/8 OAP and LP

$\Delta E/E$ ±20% @90MeV



- 1/10th of intensity due to increased spot size ~20 µm decreased a_0=~3
- linear instead of circular polarization

- mono-energetic feature at 90MeV
- increased energy spread of $\Delta E/E$~40%

- Mono-energetic feature is reproducable with all thicknesses from 5nm to 100nm

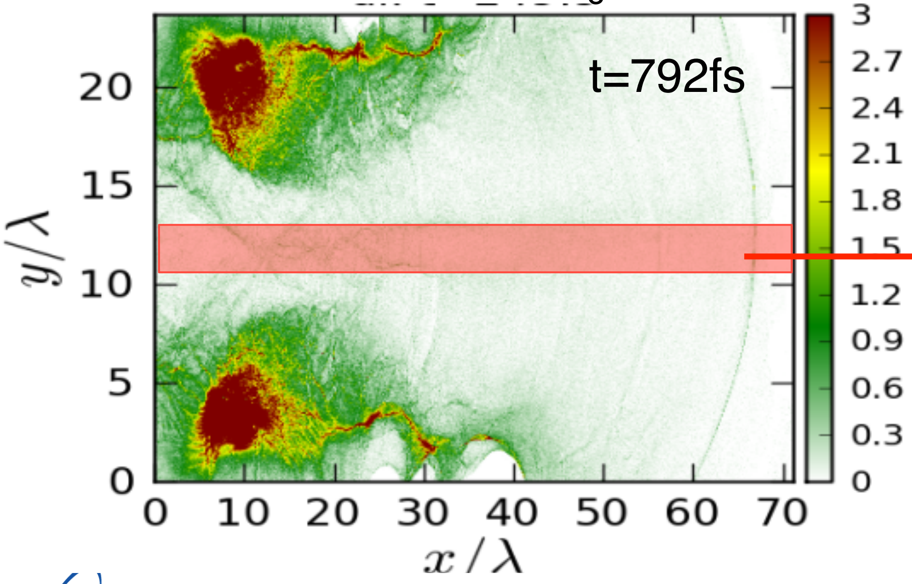
H target

Cyrogenic hydrogen target leads to higher energy and efficiency than CH_2

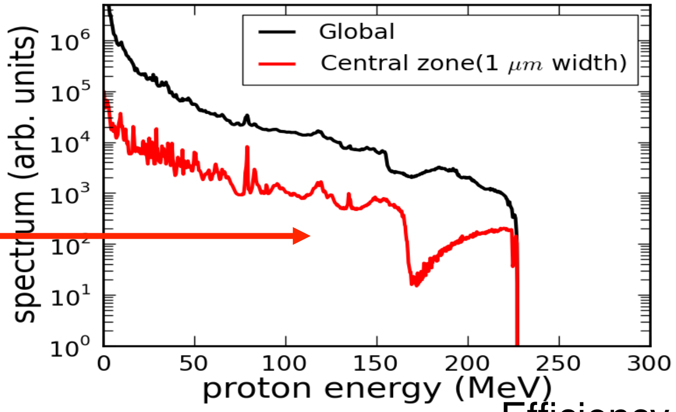
Cyrogenic hydrogen target at (0.07g/cm^3), n_e=42.6 n_{cr}

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%	6.5x10^{10}
>50MeV	2.2%	1.9x10^{11}
>10MeV	4.2%	9.7x10^{11}

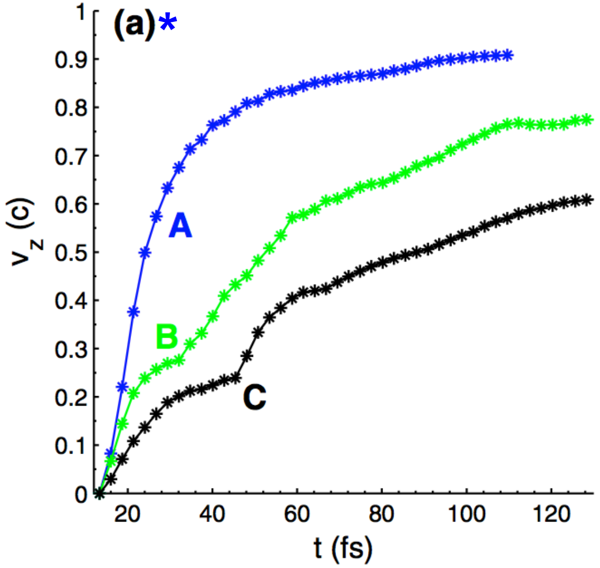
Monoenergetic protons with energy up to GeV can be obtained using higher intensity laser

*Qiao et al. (PRL 2009):

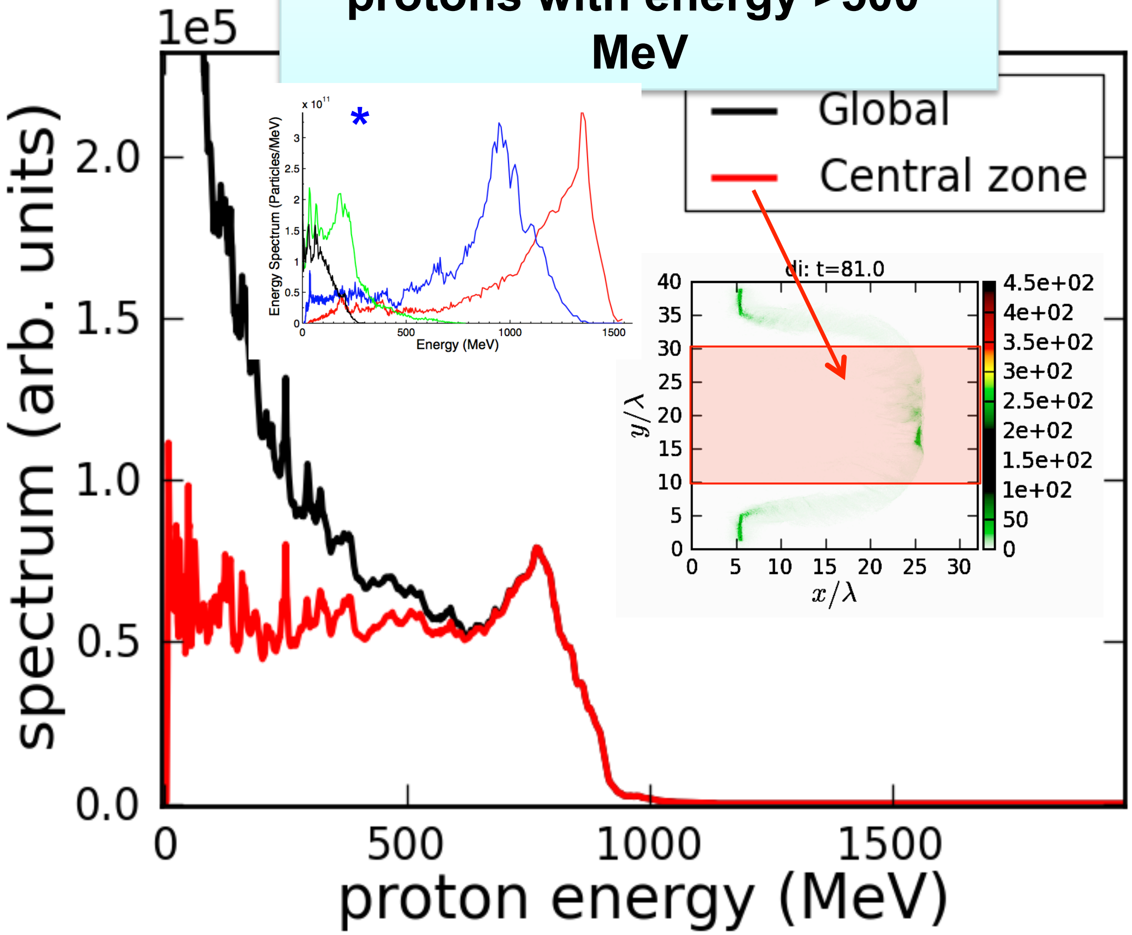
⇒ **Peak intensity: 1.89x10^{22} W/cm^2,** Circ. Pol., 4th order super-Gaussian in space (r=10μm,) Gaussian in time (t=38 fs)

⇒ E_{laser} ~ 3.5 kJ

- Target: solid H, 1μm (n_e=30 n_{cr})



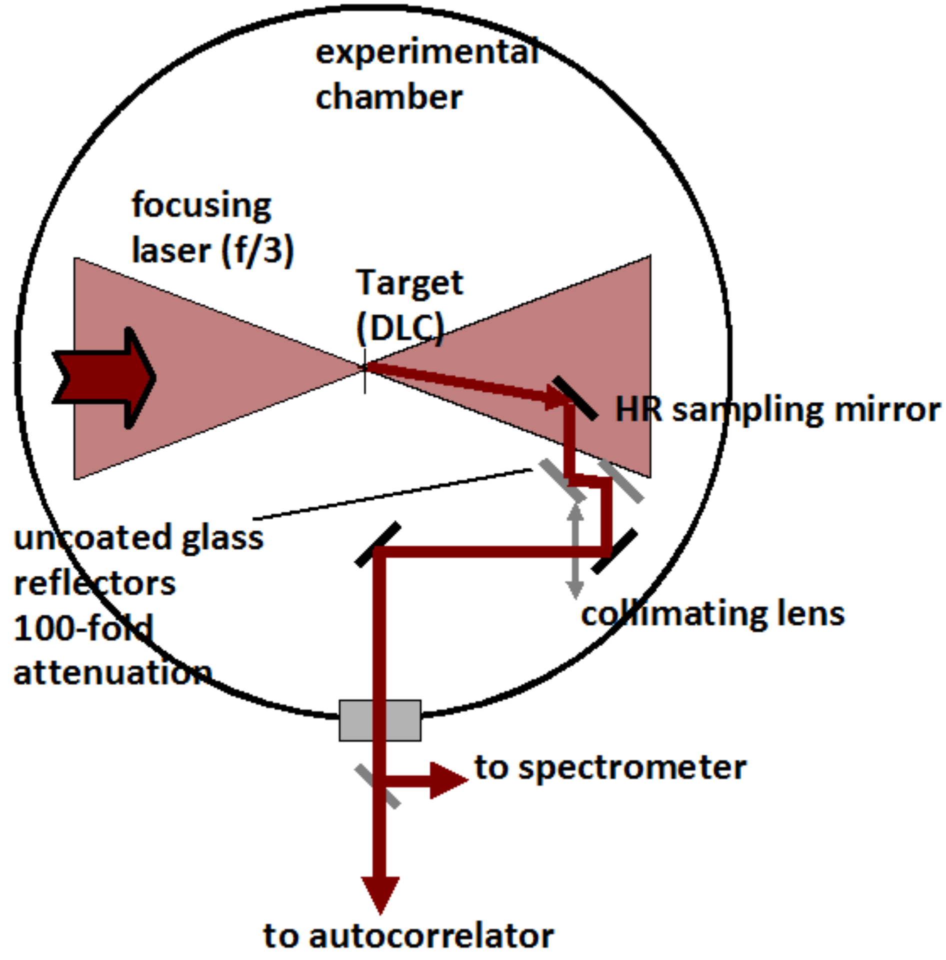
19% of laser energy goes into 6x10^{12} forward directed protons with energy >500 MeV



Nanotargets can… … Perform laser pulse shaping

- Pulse shortening – 2nd order autocorrelation measurements
- Pulse shaping – simulations and diagnostic development

Experimental Setup

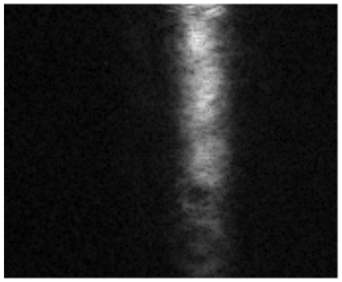


Glass reflectors attenuate intensity to avoid non-linear effects

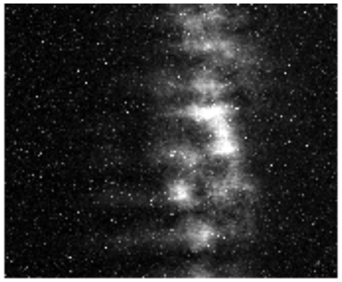
Spectra not analyzed yet

Small sampling (Φ1cm of Φ10cm) ought guarantee uniformity (Fourier optics relates focal plane to spatial frequency in near field as $f_x = x/\lambda f_{lens}$. Frequencies >1 cm^{-1} occur at focal positions >100 µm)

Non-uniformity induced by near-field diffraction from small aperture of sampling



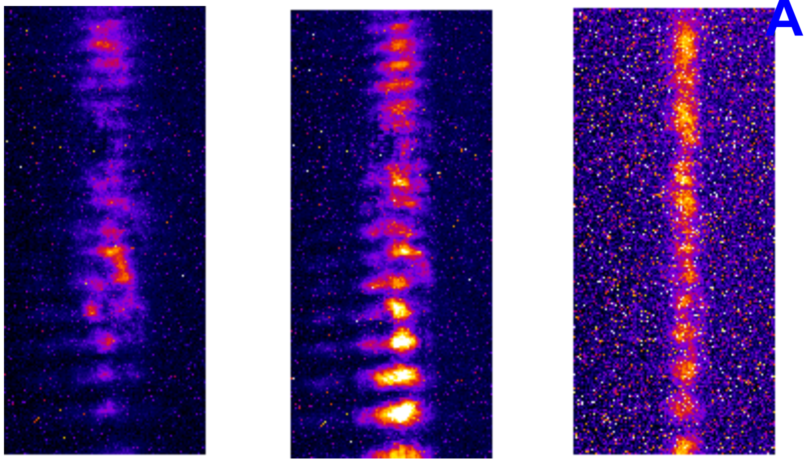
front-end



target-side (no significant Target attenuation)

Results show shortening

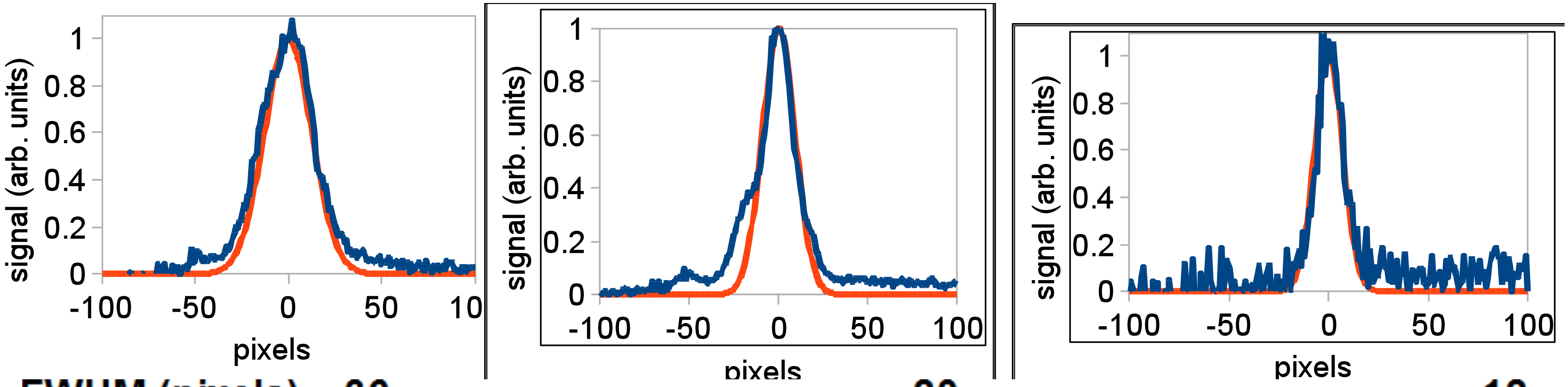
Post-target Autocorrelation images (I/P > 520 fs for all)



5 nm DLC **17 nm** **20 nm**

THINNER FOILS no change

THICKER FOILS Signal weakens and below detection at 300 nm

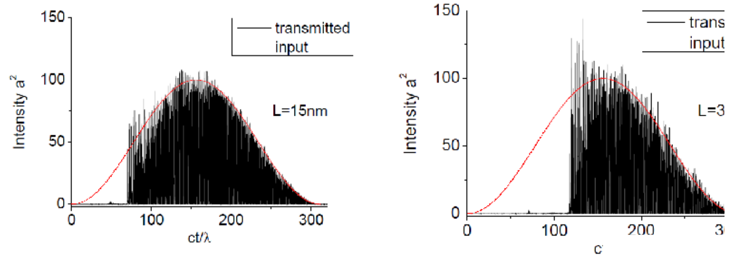


FWHM (pixels)	36	20	12
Duration (fs)	585	321	195

New single shot FROG works and will be able to measure truncated gaussian

Use nanofoil as temporal pulseshaper: simulations observe steep pulse cutoff

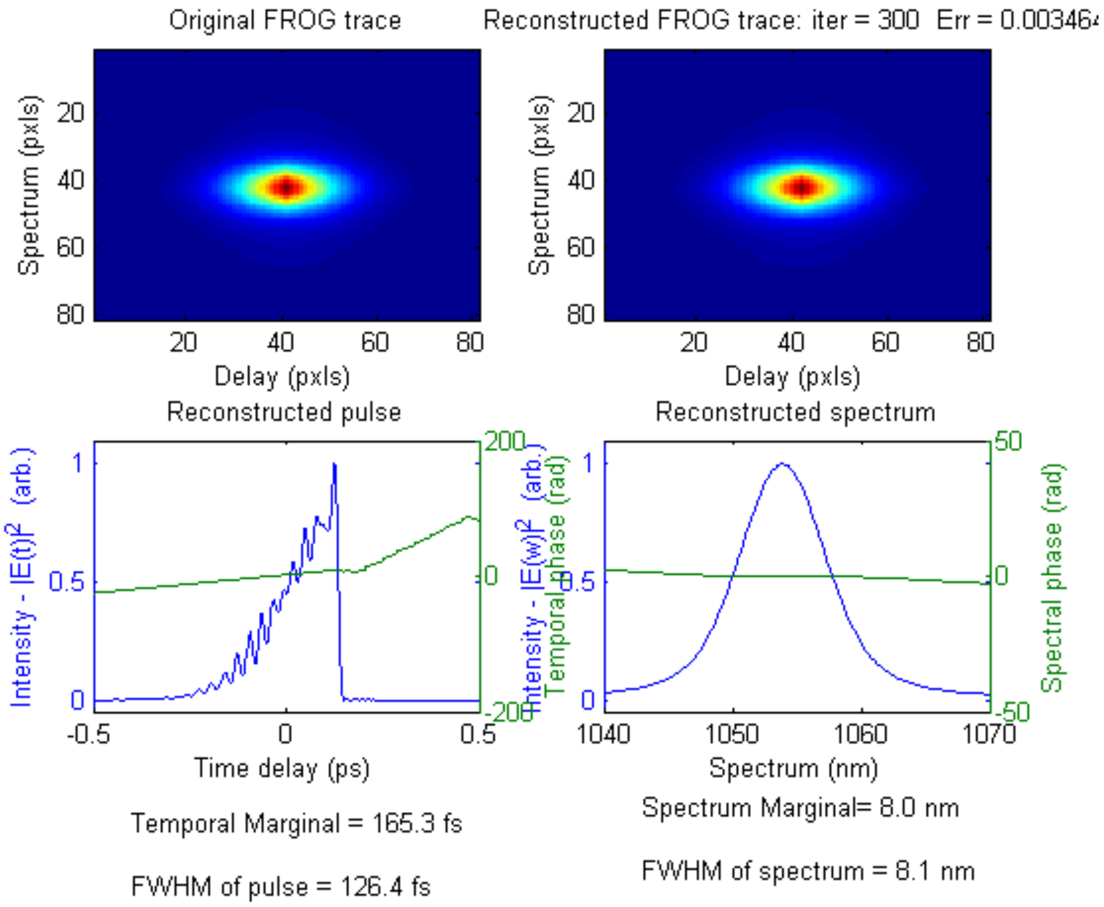
a=10, pulse FWHM=520fs, ne=700nc.



1D VPIC simulation (Hui-Chun Wu)
a=10, FWHM=520 fs,
ne=700 nc

Truncated Gaussian
used to create FROG

Full Gaussian
used to create FROG



Retrieved via algorithm

Nanotaragets can … … be a coherent x-ray source

- Relativistic High Harmonics
- Relativistic Electron Mirrors
- Coherent Thomson Scattering

Forward relativistic high harmonic generation from nano-DLC targets

Date: 05.09.09 **Shot:** 21246

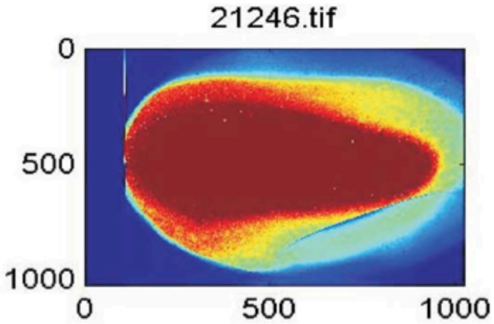
Laser: TRIDENT LANL
Energy: missing **Polarization:** LP
PM: no PM

Target: 10 nm DLC

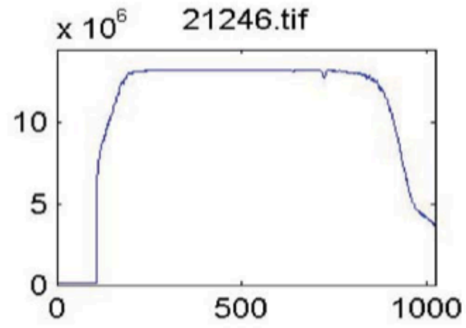
Spectrometer: ACTON VM-502
Focus: 2”Quartz, 45 deg., rcc _,__m
λc: 100nm **MCP,Phos.:** -1/2 kV

Other:

21246.tif



21246.tif



Date: 05.09.09 **Shot:** 21247

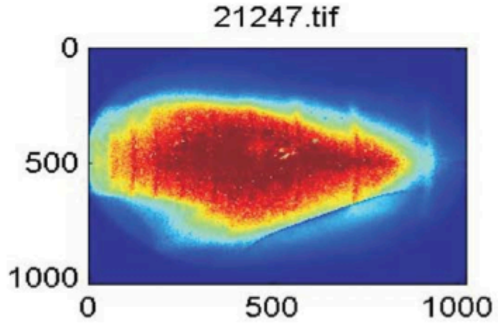
Laser: TRIDENT LANL
Energy: 80J **Polarization:** LP
PM: no PM

Target: 50nm DLC

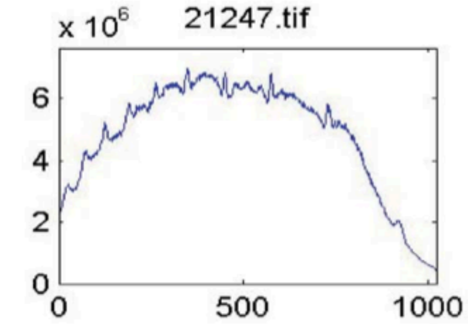
Spectrometer: ACTON VM-502
Focus: 2”Quartz, 45 deg., rcc _,__m
λc: 100nm **MCP,Phos.:** -1/2 kV

Other:

21247.tif



21247.tif



Date: 14.09.09 **Shot:** 21263

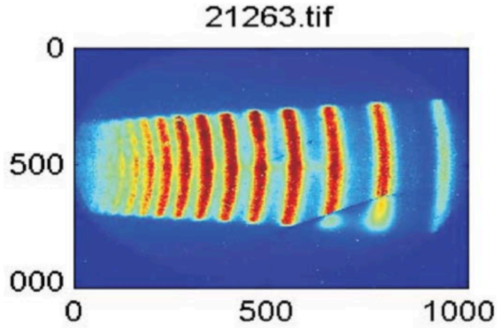
Laser: TRIDENT LANL
Energy: missing **Polarization:** LP
PM: no PM

Target: 200nm DLC

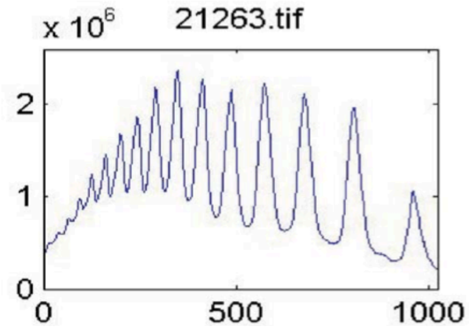
Spectrometer: ACTON VM-502
Focus: 2”Quartz, 45 deg., rcc _,__m
λc: 80nm **MCP,Phos.:** -1/2 kV

Other:

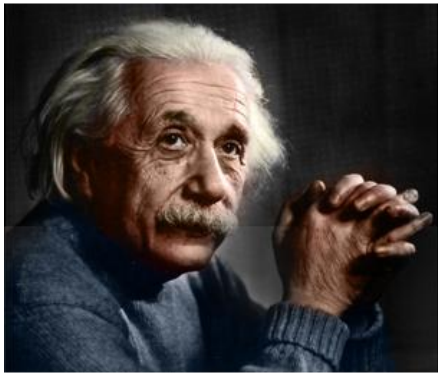
21263.tif



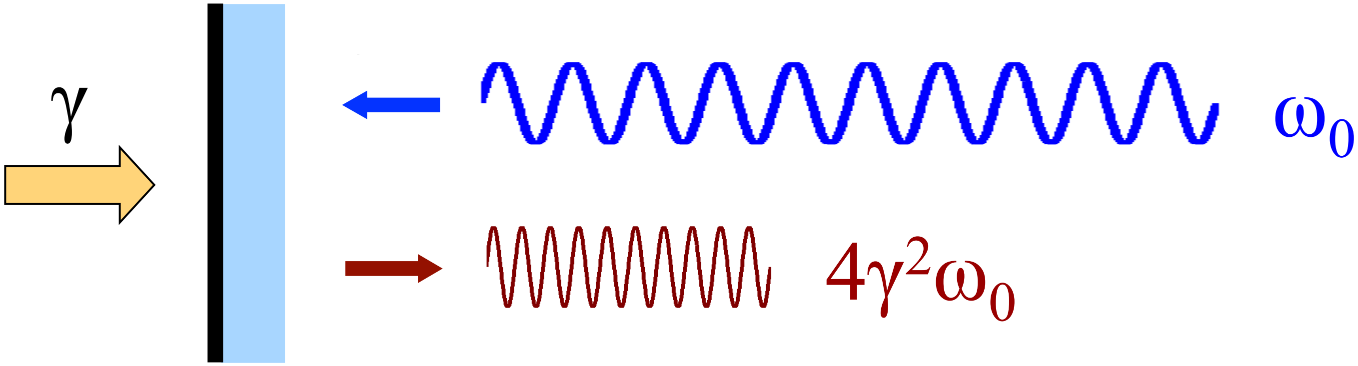
21263.tif

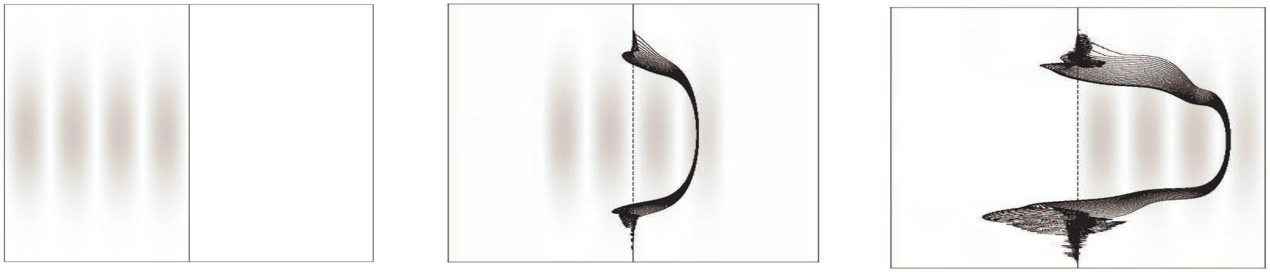


Coherent Thomson Scattering off a laser-driven Relativistic Electron Mirror

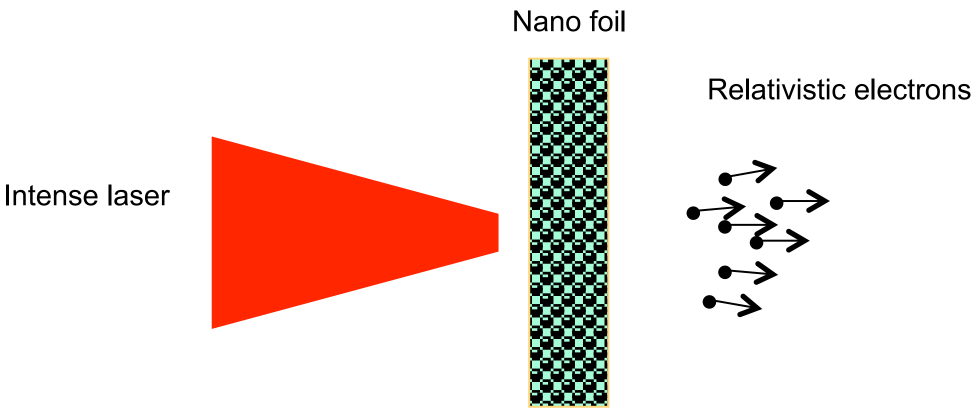


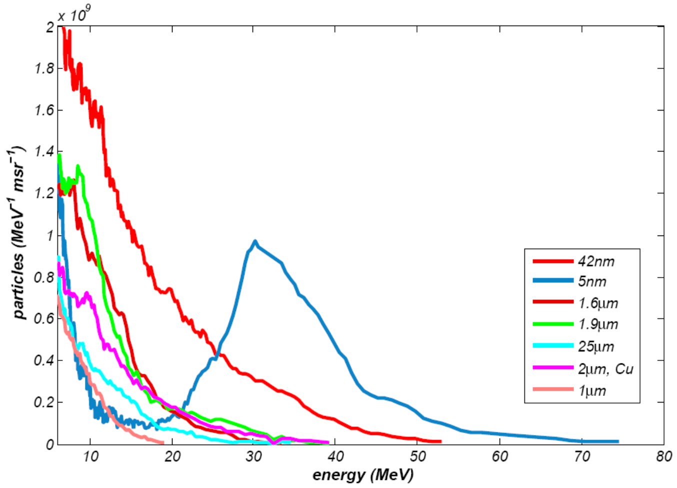
A. Einstein,1905.

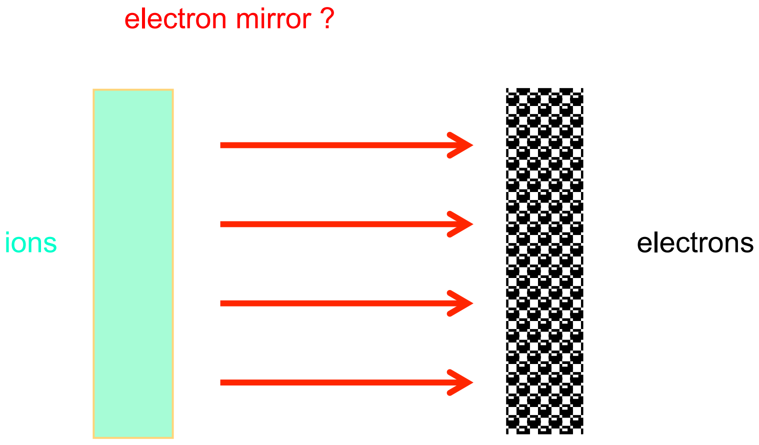




For very thin foils laser force can overcome restoring force of ions: Electron break-out observed on Trident!







$E_s = 4\pi e N_e L$

Parameter region :

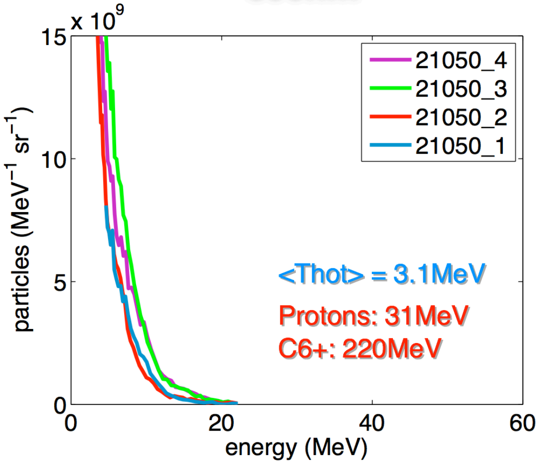
$E_L >> E_s$

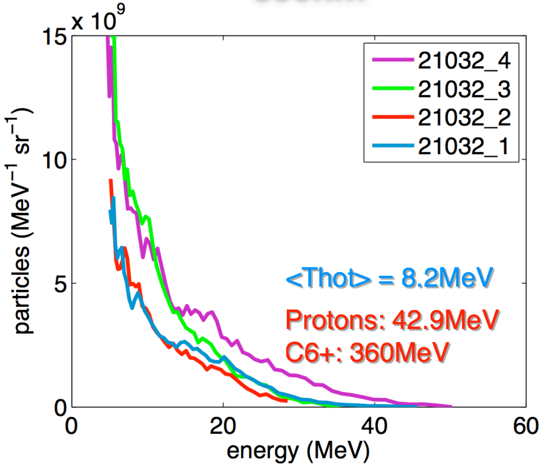
$a_0 >> \varepsilon_0 = 2\pi (N_e/N_c)(L/\lambda_0)$ (Norm.)

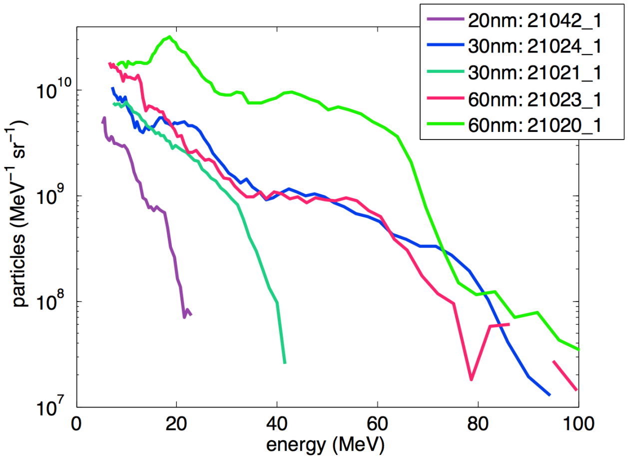
$I_0 = a_0^2 \times 1.37e18\ \mathrm{W/cm^2}/(\lambda_{\mu m})^2$

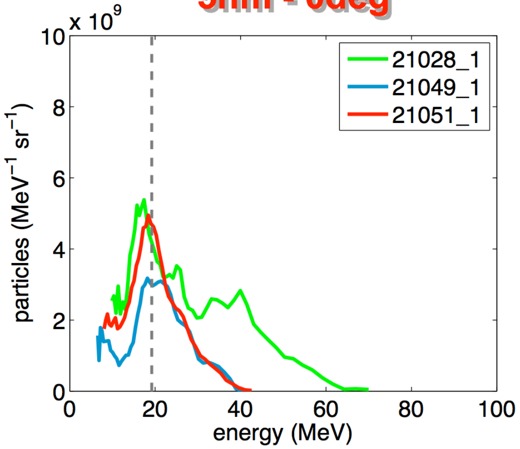
$a_{0,\mathrm{Trident}} = 20$, $\varepsilon_{0,\ \mathrm{Graphene}} = 1$

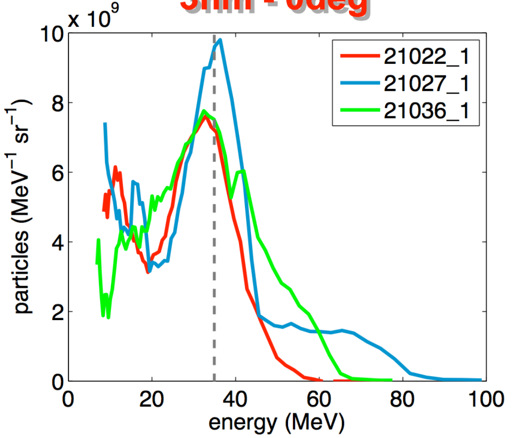
Electron temperature rises with decreasing foil thickness until spectra become mono-energetic


600nm


300nm


20 – 60 nm

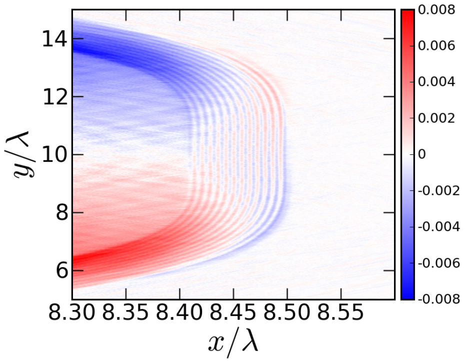

5nm - 0deg

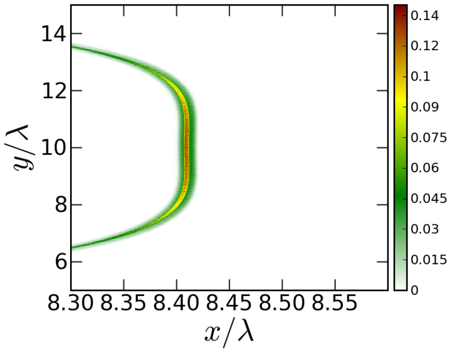

3nm - 0deg

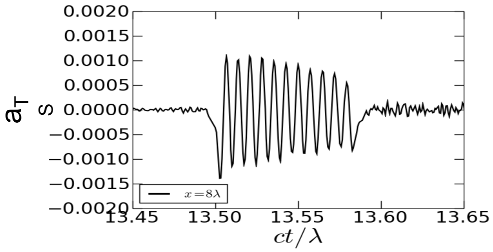
Typical laser parameters:

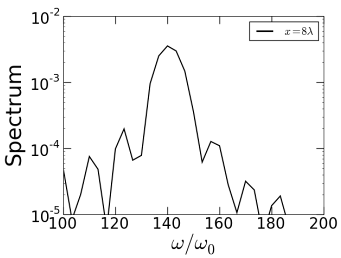
- E = 80 -100 J on target
- τ = 500 – 600 fs FWHM
- contrast ~10^{-12} @ 0.5 ns
- contrast ~10^{-7} @ 5 ps
- 50% E_{laser} in r_{ave} = 3.5 μm
- 10% E_{laser} in r_{ave} = 1 μm
- $I_{3.5\mu m} = 2 \times 10^{20}$ W/cm^2
- $a_{ave} = 13$
- $I_{3.5\mu m} = 5 \times 10^{20}$ W/cm^2
- $a_{ave} = 20$

Expected Performance:









- a_0=3.5: λ_{ts}=5.7nm (217eV) and duration 267as.
- coherence w/o compression:
  - N_e~ 10^{24} e-/cc ⇒ λ_{ts}= 10^{-8} cm ⇒ E_{photon} = 12 keV

  ⇒ γ = 55, a_0 = 10, I = 10^{20} W/cm^2
- simulations observe 50x compression of e- layer:
  - N_e~ 5x10^{25} e-/cc ⇒ λ_{ts}= 2.7x10^{-9} cm ⇒ E_{photon} = 45 keV

Summary

- Combination of nm-scale targets and ultrahigh contrast pulses leads to a paradigm shift in relativistic laser-matter interaction.

- We have demonstrated the production and integration of nm-scale targets and ultraclean pulses.

- This enables new particle acceleration mechanisms (BOA, PSA/ALPA):
  - IFI energies (500 MeV) reached with modest laser
  - IFI efficiencies (>10%) achieved: 80 MeV C6+ @ 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)