Proton acceleration experiments with Z-Petawatt

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Outline

- **Proton acceleration with high-power lasers:**
  Target Normal Sheath Acceleration concept
- **Proton acceleration with mass-reduced targets:**
  Breaking the 60 MeV threshold
- **Proton beam divergence control:**
  Novel focusing target geometry
- **New experimental capability development:**
  Proton radiography on Z

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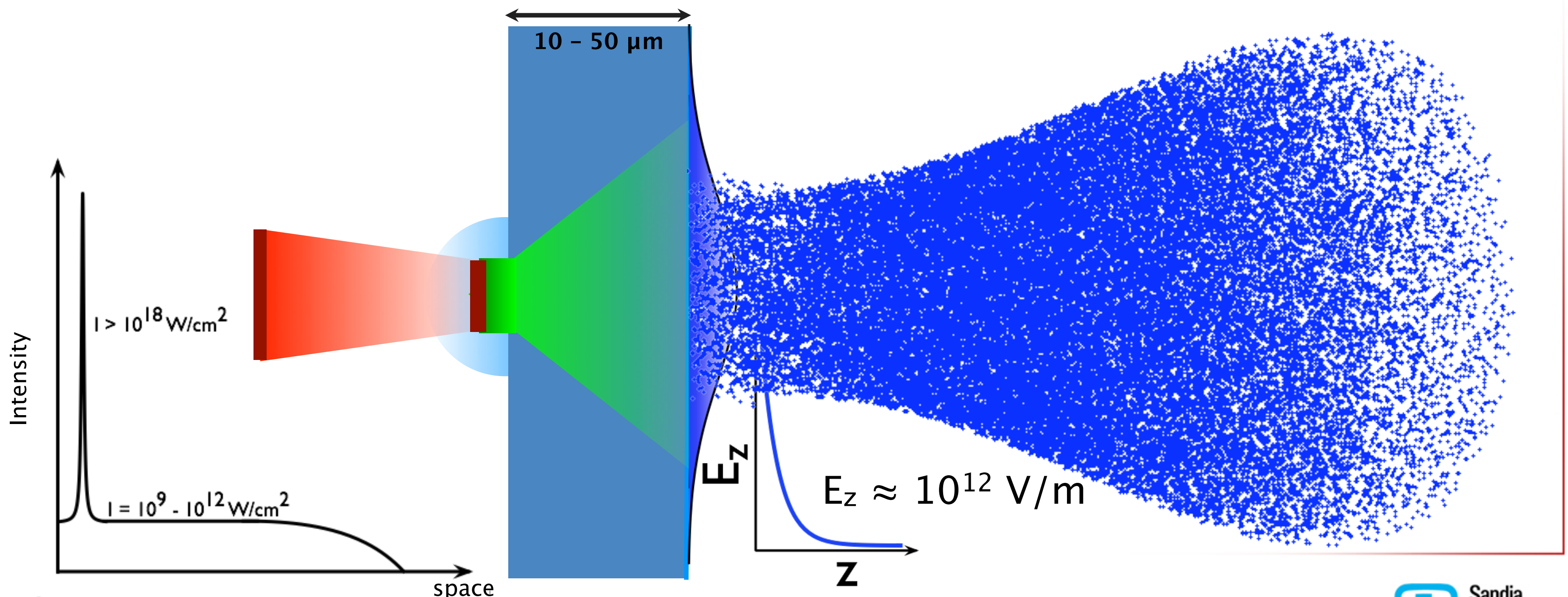
Laser ion acceleration:
Target Normal Sheath Acceleration (TNSA)

- **Laser pulse creates pre-plasma**
- **Main pulse accelerates electrons to MeV-energies**
- **Electron sheath generates electric field on rear side**
- **Transverse spread of sheath**
- **Field ionization and ion acceleration in normal direction**



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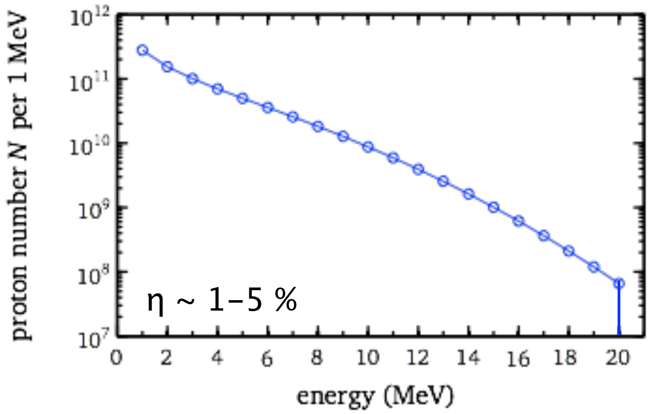
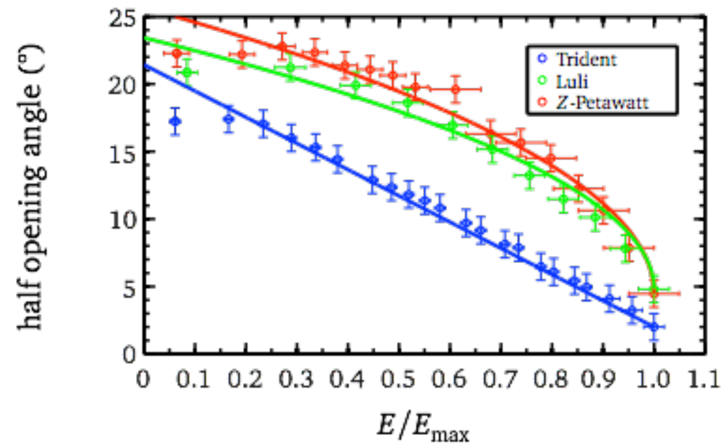
Target Normal Sheath Acceleration (TNSA): Typical beam parameters

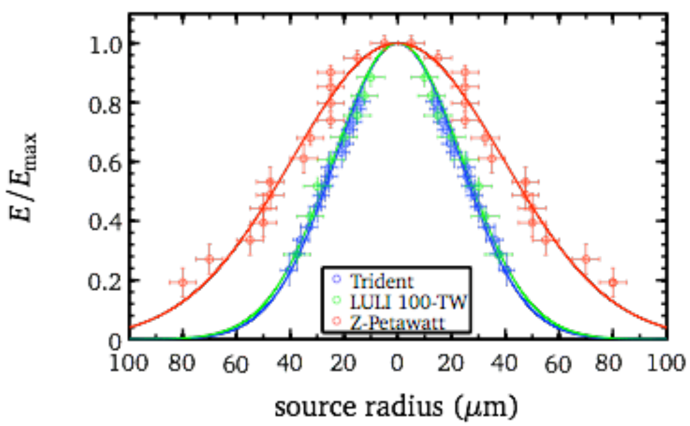
- **spectrum**



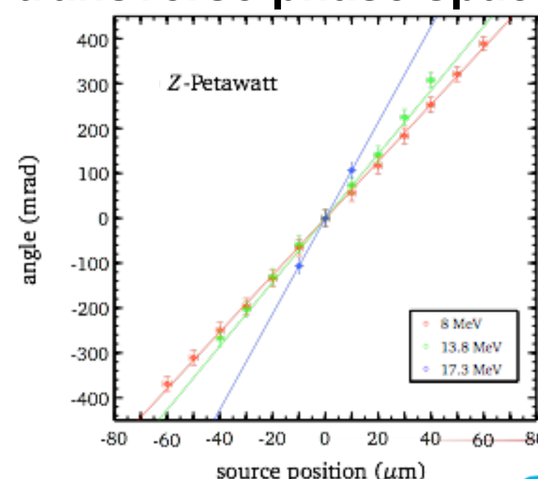
- **opening angle**



- **source size**



- **transverse phase space**



M.S. *et al.*, NIM A 577, 186 (2007); M.S. *et al.*, Phys. Plasmas 15, 053101 (2008), F. Nürnberg, M.S.. Et al., Rev. Sci. Instrum. 80, 033301 (2009)

Comparison to other laser-acceleration mechanisms

- **Why do we investigate TNSA, and not other (new) acceleration mechanisms?**
  - **TNSA always works, no special target preparation necessary**
  - **High particle number, high energies (>50MeV w/ ZPW), very laminar beam**
  - **Optimum for medium-contrast laser such as ZPW**
  - **Potential for ion radiography/deflectrometry on Z**
- **Break-Out Afterburner/enhanced TNSA/RPA[1,2,3]:**
  - **requires ultrahigh contrast, ultrathin foils, (circular polarization)**
  - **ion beam profile unknown (only two experiments published)**
- **Shock-acceleration[4]:**
  - **High flux, strongly distorted beam profile**
- **Laser-induced Fusion (OMEGA)[5]:**
  - **Mono-energetic @ 15 MeV**
- **Skin-Layer Ponderomotive Acceleration (SLPA)[6]:**
  - **high number, but low energy**

1: L. Yin et al., Laser Part. Beams 24, 291 (2006)
2: A. Henig et al., Phys. Rev. Lett. 103, 045002 (2009)
3: A. Henig et al., Phys. Rev. Lett. 103, 245003 (2009).
4: A. Henig et al., Phys. Rev. Lett. 102, 095002 (2009).
5: C.K. Li et al., Rev. Sci. Instrum. 77, 10E725 (2006).
6: J. Badziak et al., PPCF 46, B541 (2004)

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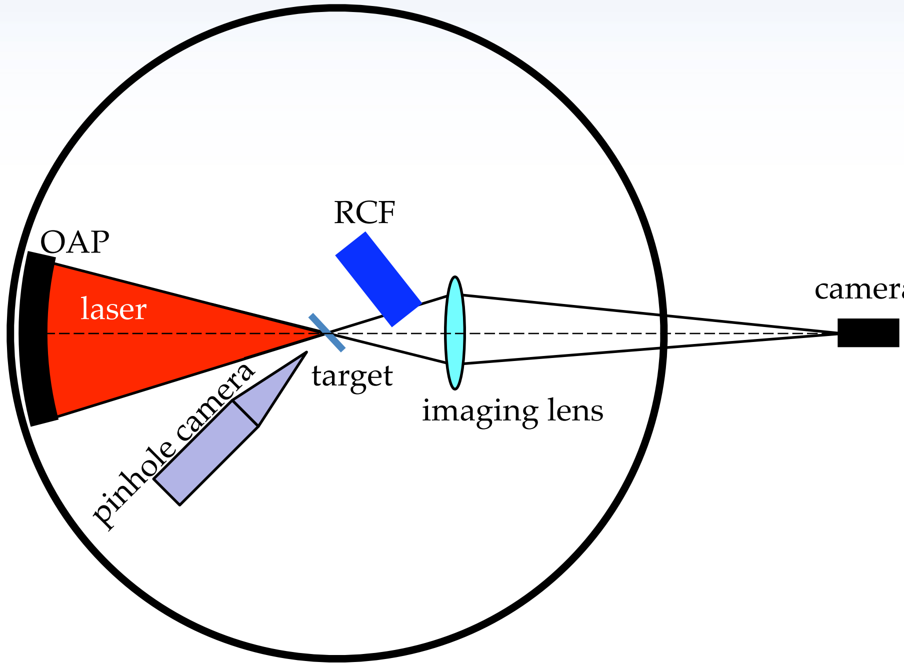
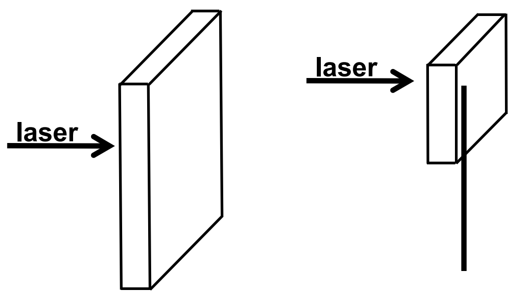
Experimental setup

100 TW target area

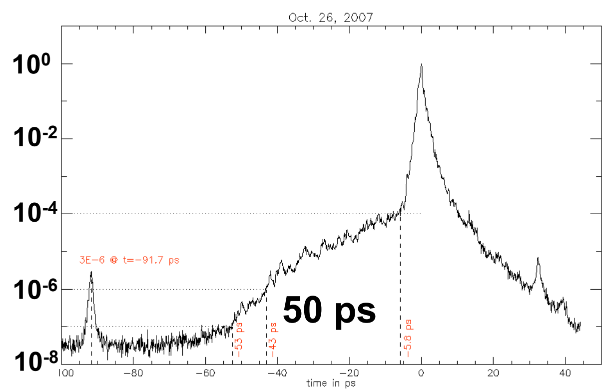
- laser parameters
  - E = 100 J ± 10%, t_p = 0.7 ps, λ = (1.054 ± 3) nm
  - focal spot: 5.7 μm FWHM (diff. limit: 5.66 μm)
  - 30% of energy in FWHM
  - 45 degree angle of incidence
  - I = 1.5 x 10^{20} W/cm^2
- targets:
  - copper or tin

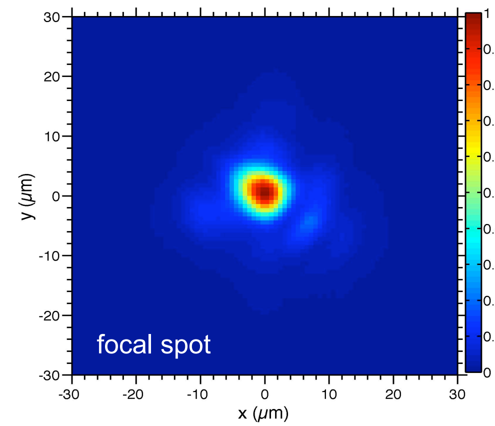




mm-size foils
25 μm thick

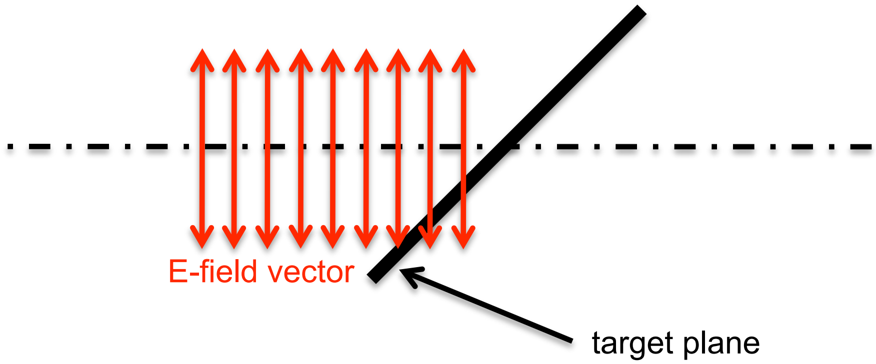
(250 μm)² area,
25 μm thick
“mass-reduced targets“

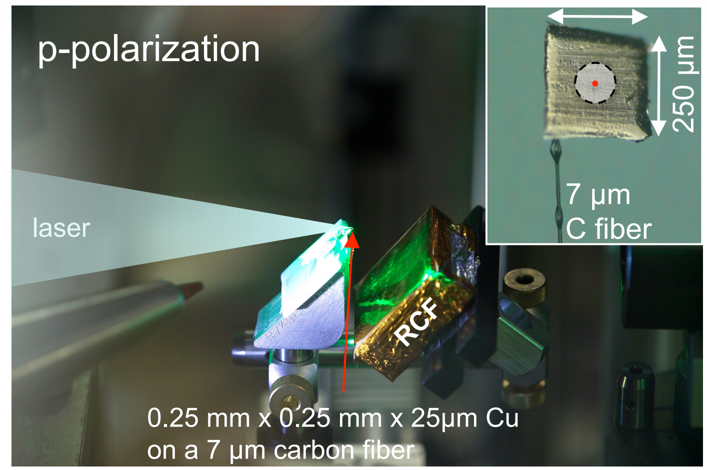




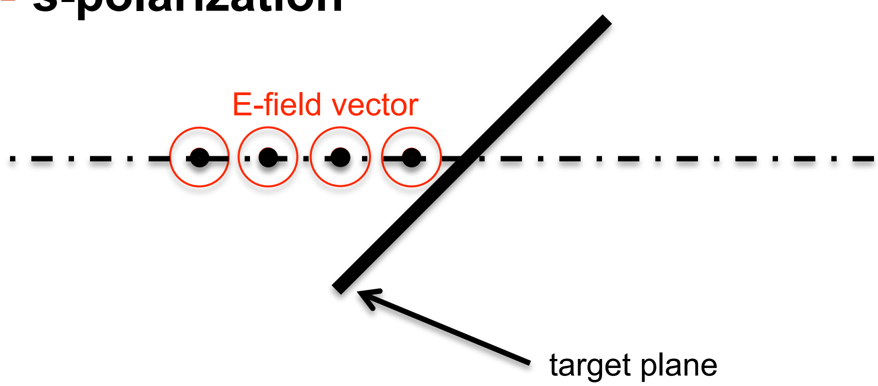
Proton acceleration experiments

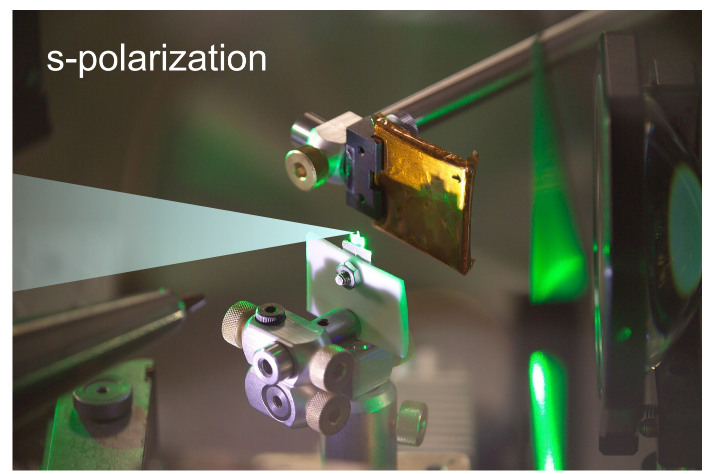
- ***p*-polarization**





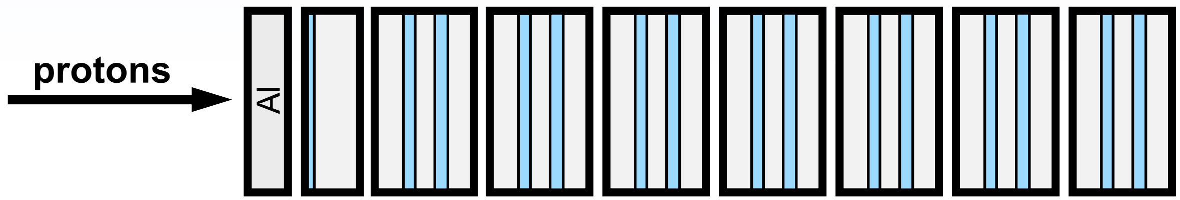
- ***s*-polarization**

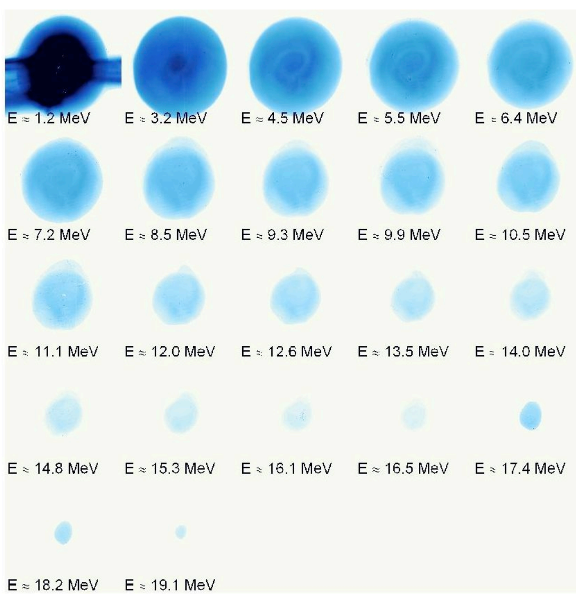


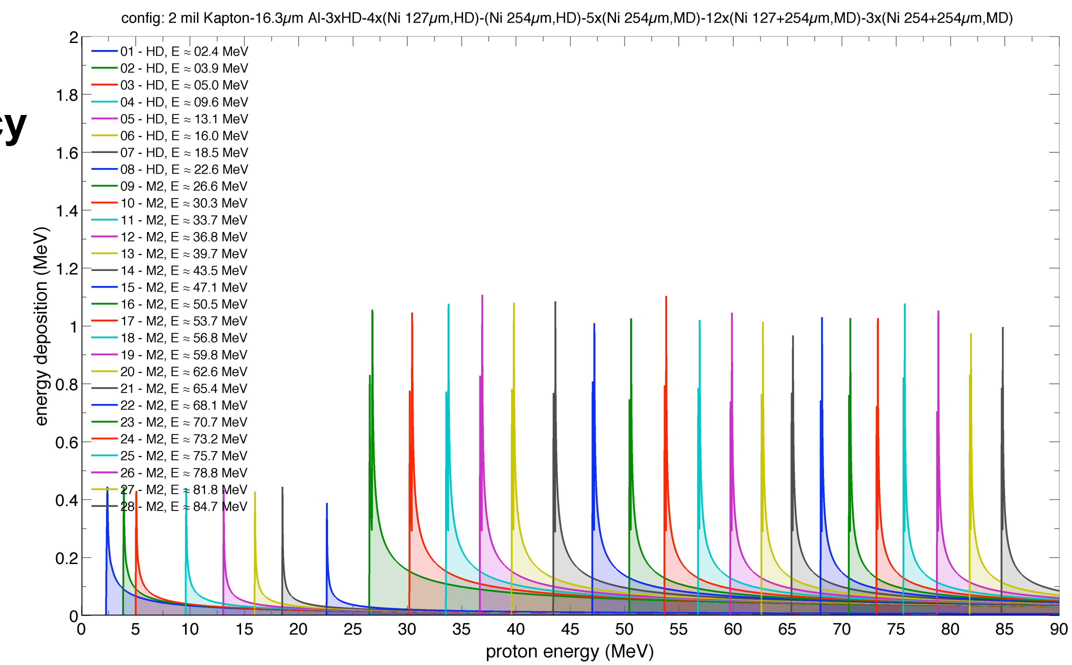


Radiochromic Film Imaging Spectroscopy

- **RCF stack measures:**
  - **beam profile**
  - **opening angle**
  - **spectrum**
  - **cut-off energy**
  - **energy conversion efficiency**







F. Nürnberg, M.S. *et al.*, Rev. Sci. Instrum. **80**, 033301 (2009)

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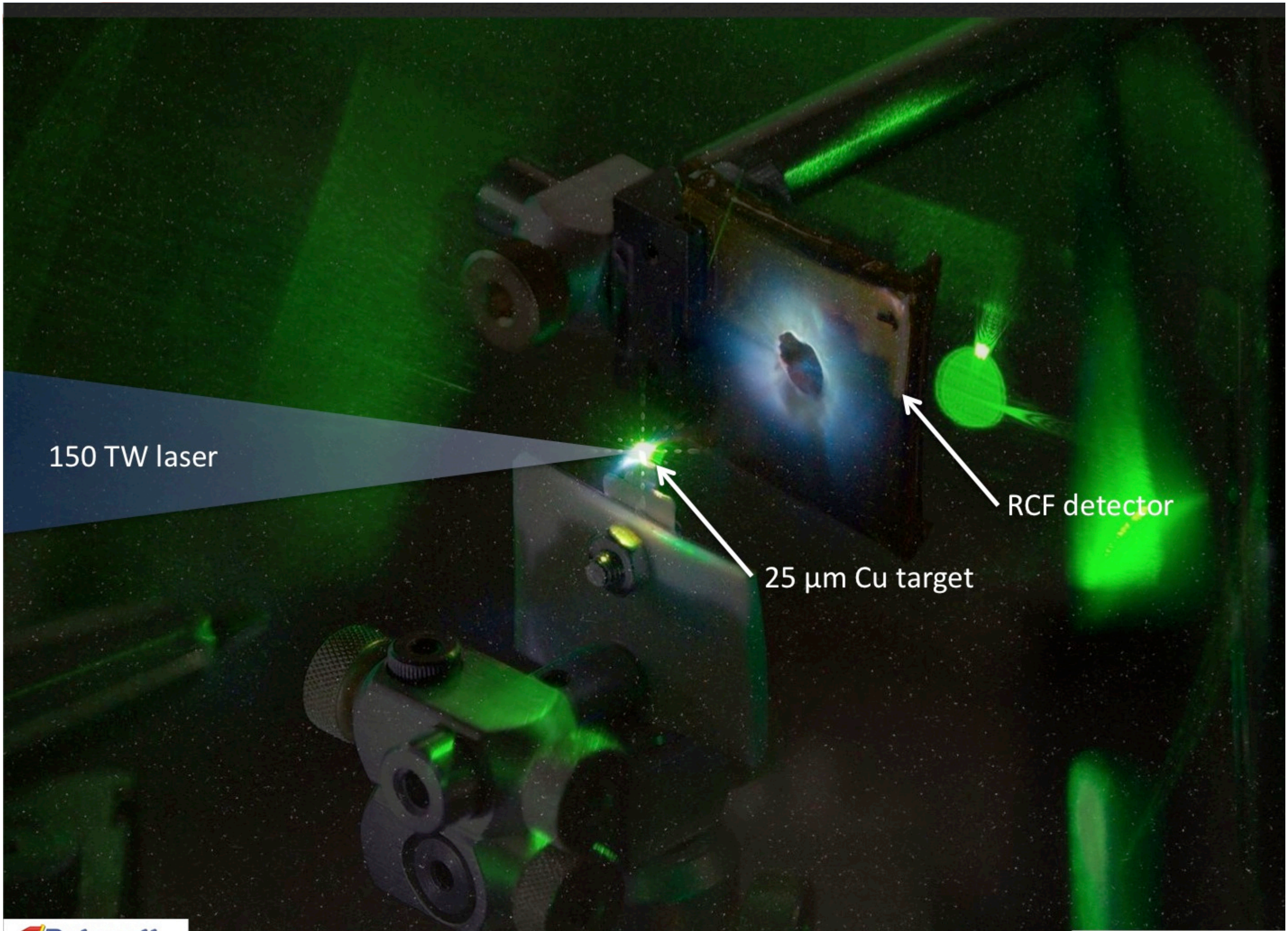

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Result: >65 MeV with 150 TW!

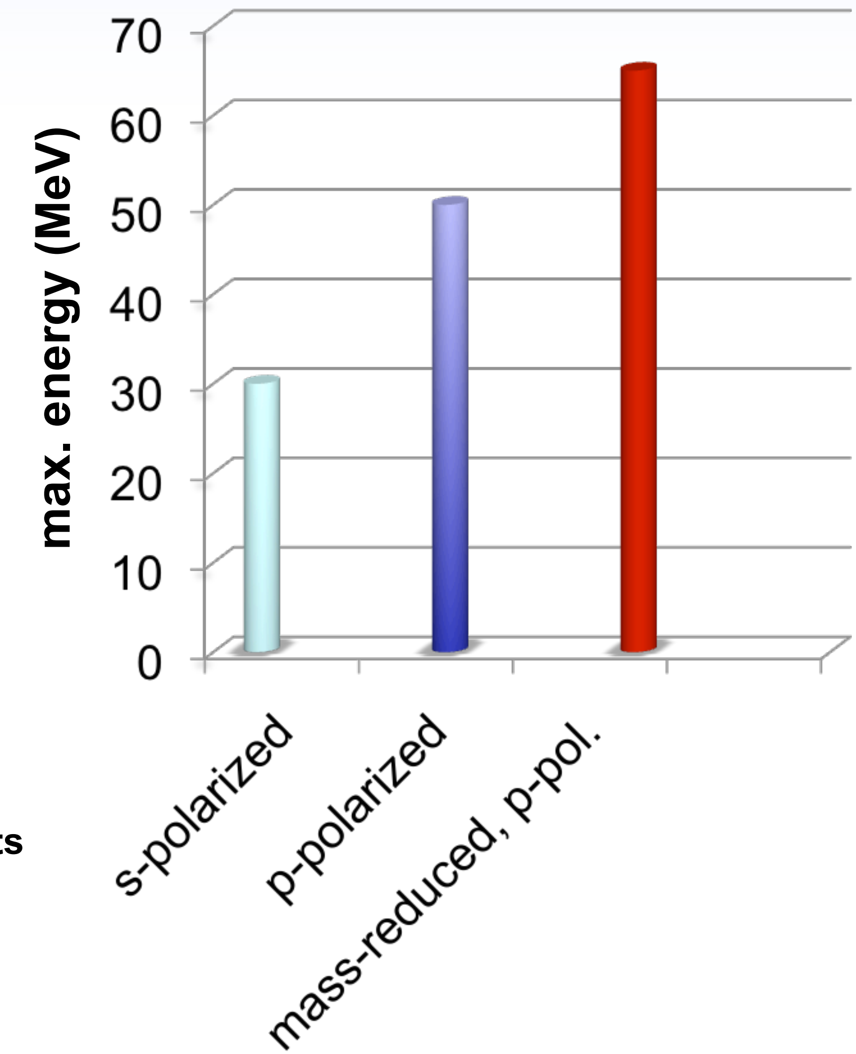
- **Maximum energy depends on polarization:**
  - **s-pol.: E_{max} = 35 MeV**
  - **p-pol.: E_{max} = 50 MeV**

- **Reduction of target mass and p-pol.:**
  - **E_{max} >65 MeV!**

- **Comparison: 67 MeV with flat-top-cone targets at 200 TW TRIDENT laser (S. Gaillard, T. Kluge *et al.,* M.S., submitted)**

- **Energy conversion efficiencies:**
  - **flat foil, s-pol.[1]: 1 %**
  - **flat foil, p-pol.: 3-4 %**
  - **mass-reduced target, p-pol.: ~7 %**

- **Energy-dependent divergence is similar for all shots**



[1]D.S. Hey et al., Phys. Plasmas 16, 123108 (2009)

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Energy spectra

Energy spectra closely follow quasi-neutral expansion[1]:

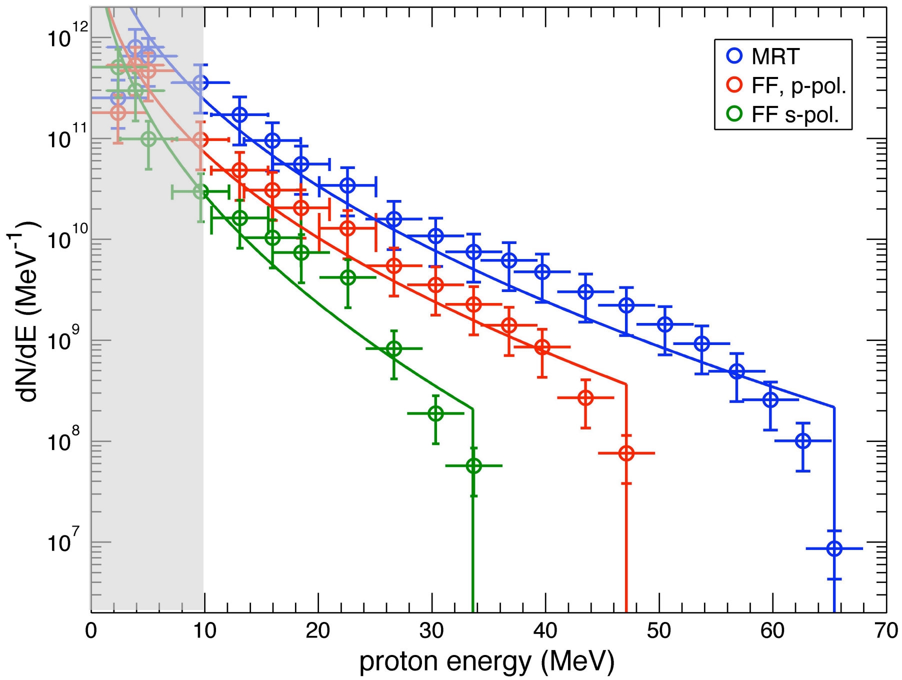
$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{N_0}{\sqrt{2\,E\,k_B T_e}}\, e^{-\sqrt{\frac{2E}{k_B T_e}}}$$

Flat foil (FF), s-polarized:
N_0 = 1.8 x 10^{13}
k_BT_e = 0.76 MeV

Flat foil, p-polarized:
N_0 = 1.8 x 10^{13}
k_BT_e = 1.4 MeV

Mass-reduced target (MRT), p-polarized:
N_0 = 6 x 10^{13}
k_BT_e = 1.4 MeV

k_BT_e from ponderomotive potential: 5 MeV
N_{total} on MRT rear surface[2]: ~ 6 x 10^{13}



[1]P. Mora, Phys. Rev. Lett. 90, 185002 (2003)
[2]M. Allen et al., Phys. Rev. Lett. 93, 265004 (2004)

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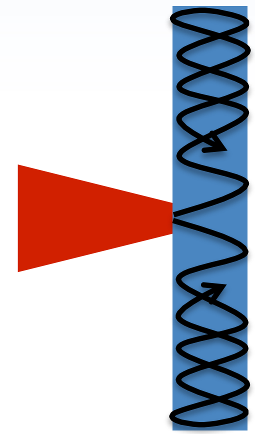
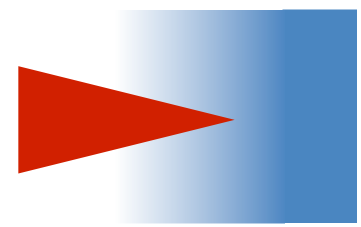
Higher energies with mass-reduced targets

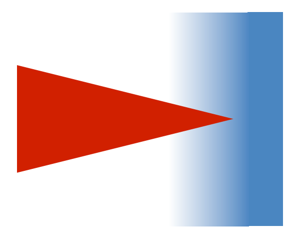
- **Possible explanations:**
  - **Transverse re-circulation inside foils (see Ref. 1)**
    - **confines hot electron population**
    - **Ref. 1: results in hotter, denser, and more homogeneous sheath**
    - **hotter: $k_B T_e$ equal, not confirmed**
    - **denser: higher N_0, confirmed**
    - **more homogenous sheath → lower divergence: not confirmed**



  - **Different pre-plasma conditions**
    - **MRT could be more efficiently pre-heated by pre-pulse**
    - **larger scale length pre-plasma could enhance absorption**
    - **can be investigated numerically**
    - **see talk by Alex Arefiev**



  - **Something new ?!**



- **Fully explicit 2D PIC-simulations and analytical work are on-going right now**

[1]S. Buffechoux et al., Phys. Rev. Lett. 105, 015005 (2010)

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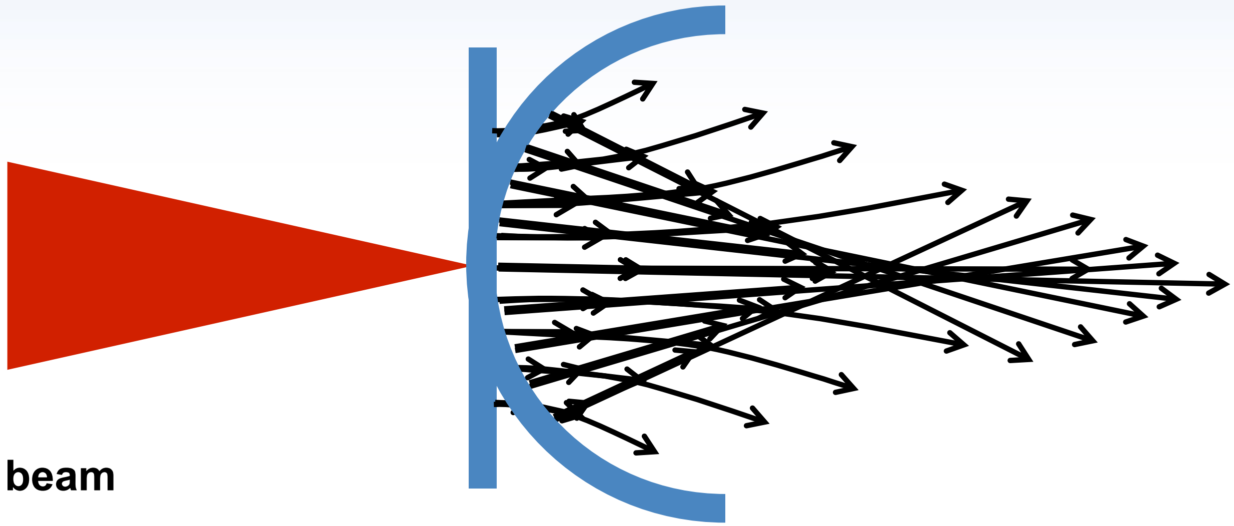
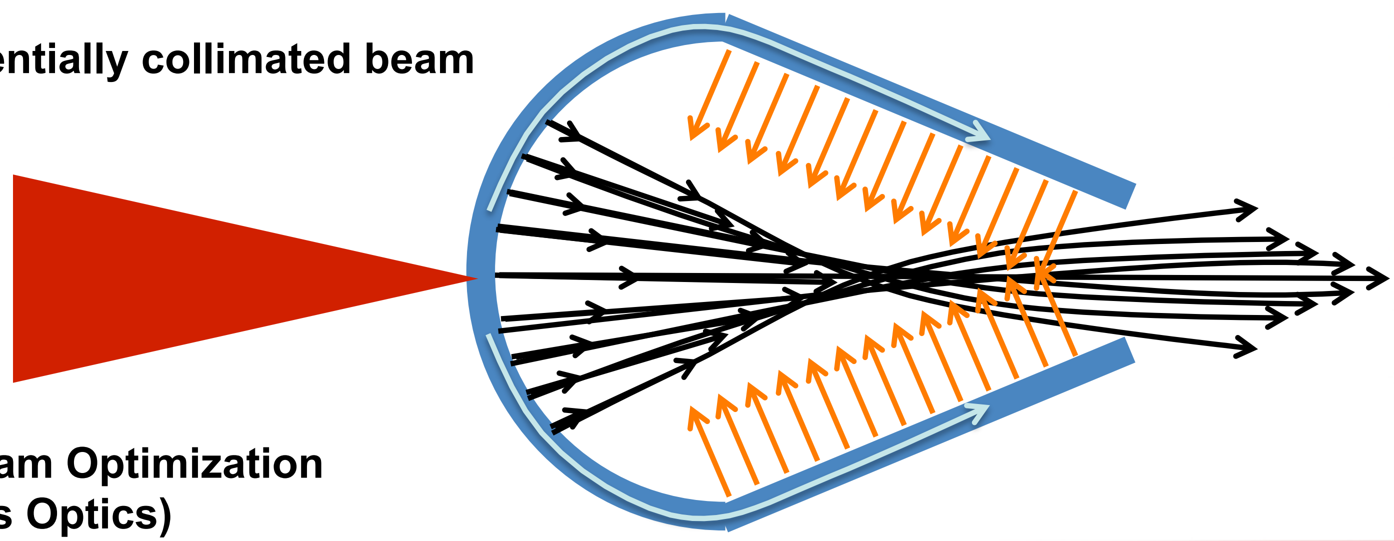
Concept



flat foil: divergent beam

hemi: focusing, then divergent beam

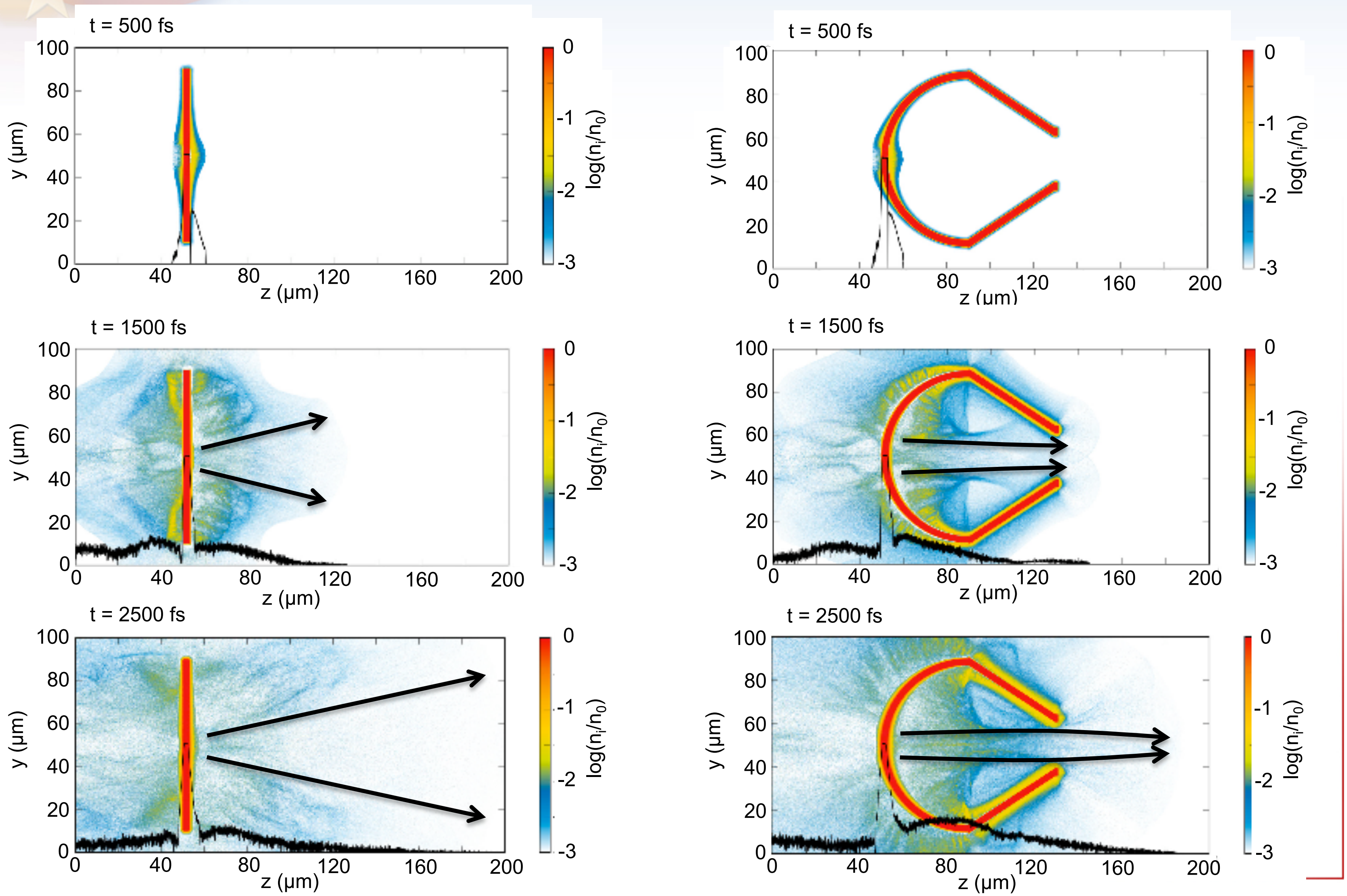
hemi + cone: potentially collimated beam



"APOLLO" target
(Autoeletric Proton beam Optimization
with a reLativistic Lens Optics)

This work has been performed in collaboration with TU Darmstadt, Germany

2D PIC simulations: real space



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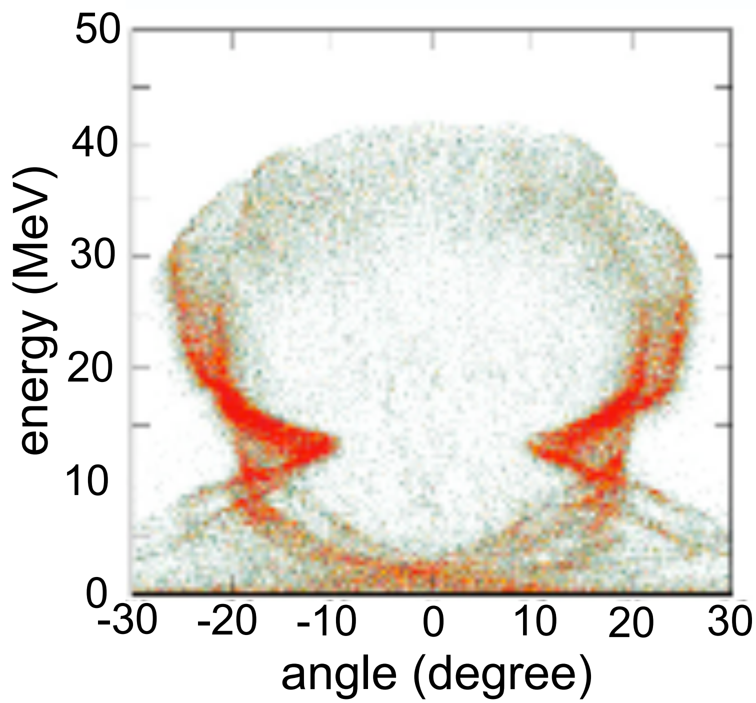
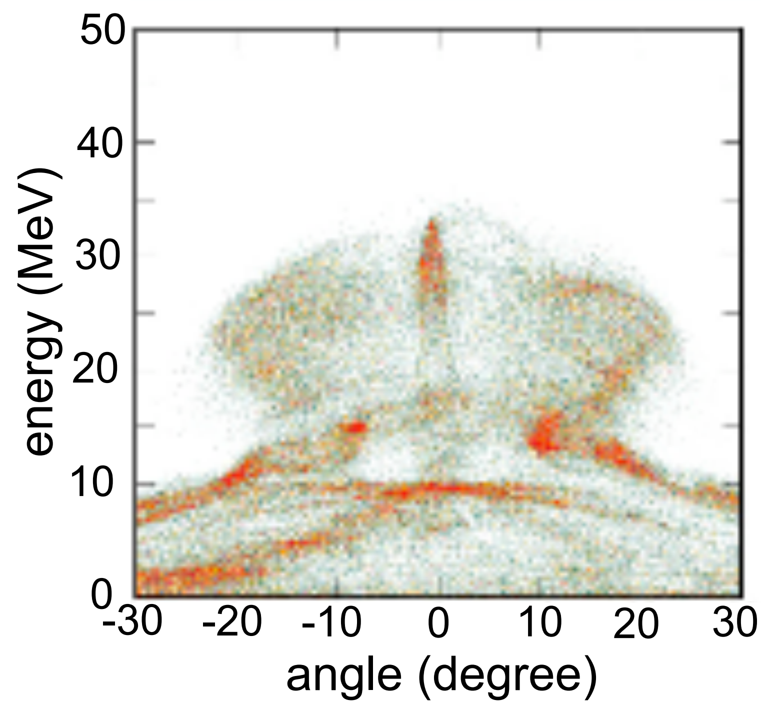
2D PIC simulations: phase-space

flat foil



APOLLO

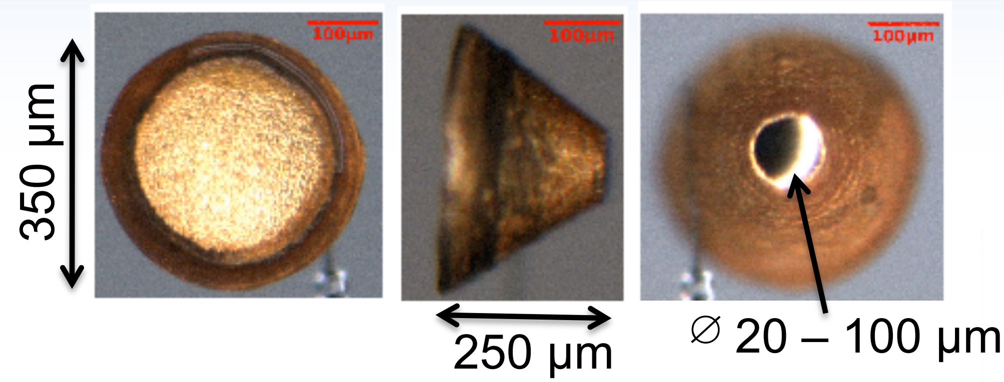


Differences for APOLLO:

- **collimated beam in center**
- **large-divergent, low-energy part**
- **lower E_{max}**

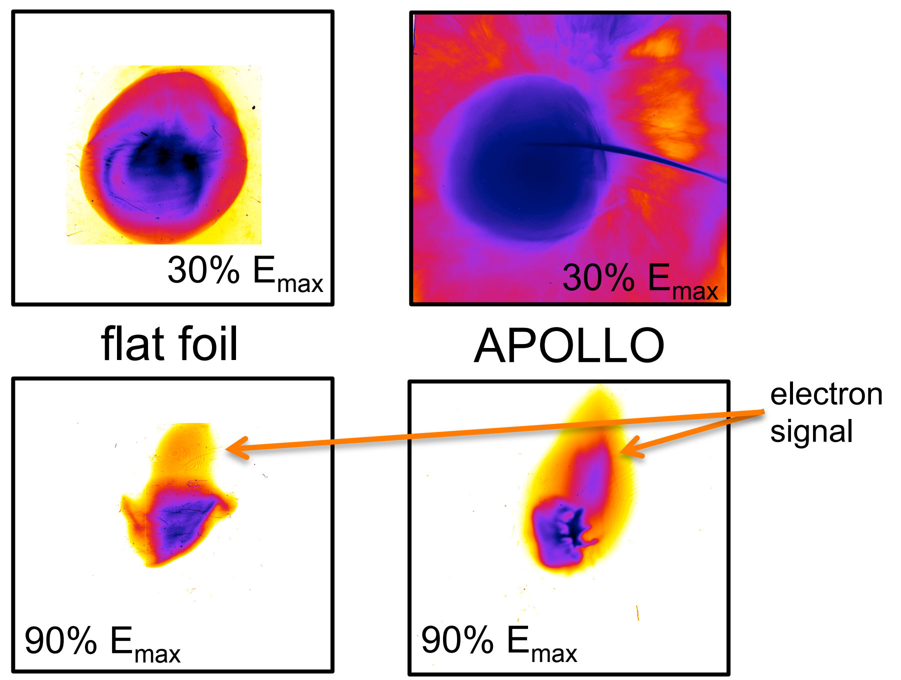
This work has been performed in collaboration with TU Darmstadt, Germany

Experimental results



flat foil:
- E_{max} = 45-50 MeV
- homogeneous profile
- decreasing divergence w/ energy

APOLLO:
- E_{max} = 30 MeV
- collimated feature in beam
- large-divergent low-E protons
- slight poynting error -> alignment error
- stronger electron signal



Conclusions:
- APOLLO can guide protons
- lower E_{max}
- higher low-energy proton yield
- higher proton number on axis
- absolute numbers TBD

This work has been performed in collaboration with TU Darmstadt, Germany

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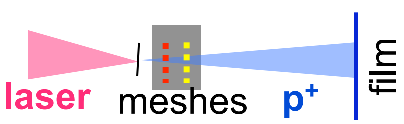
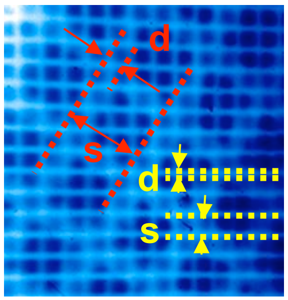
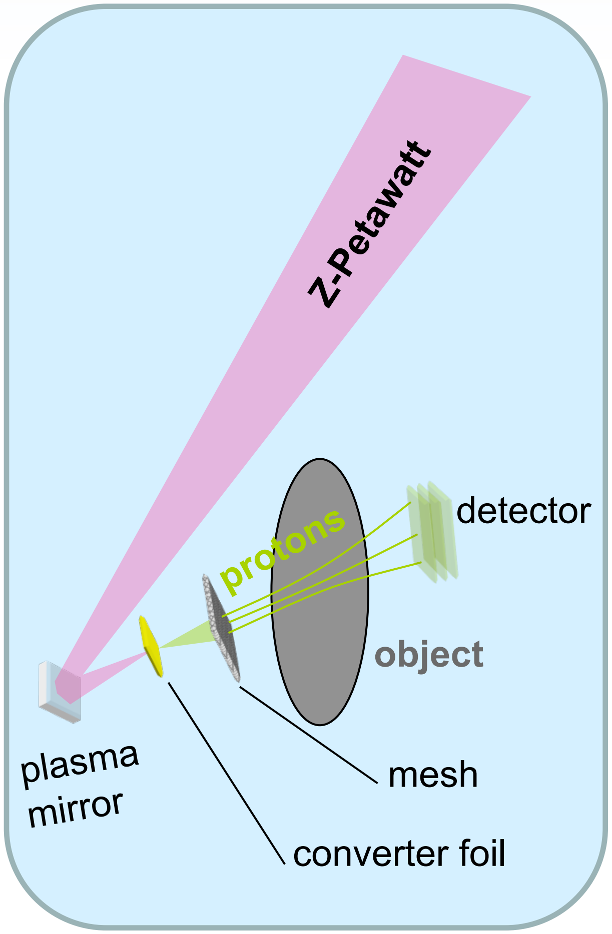
Ion radiography/deflectometry on Z

- New LDRD starting October 2010
- Use Z-Petawatt to generate ion beams in Z center section
- Ion radiography/deflectometry:
  - provides electromagnetic field mapping
  - high spatiotemporal resolution (8 μm measured @ SNL)
- Proposed scenarios:
  - measure return can B-field
  - instabilities in ICF capsule compression[1]
  - Compressed magnetic field probing (MagLIF[2])
  - Astrophysical jet probing (JetPAC[3])
- 3D particle ray-tracing needs to be developed



Ni meshes:
d 8.6 μm
s 34 μm





[1]Rygg et al., Science 319, 1223 (2008)
[2]Slutz et al., PoP 17, 056303 (2010)
[3]A. Frank, *Resolving the Issue*, proposal submitted to U.S. DoE (2008)

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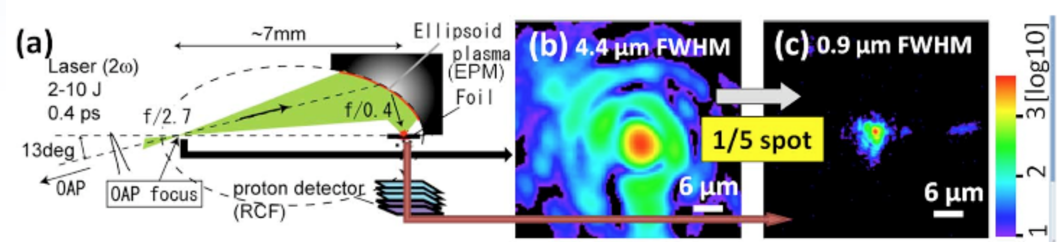
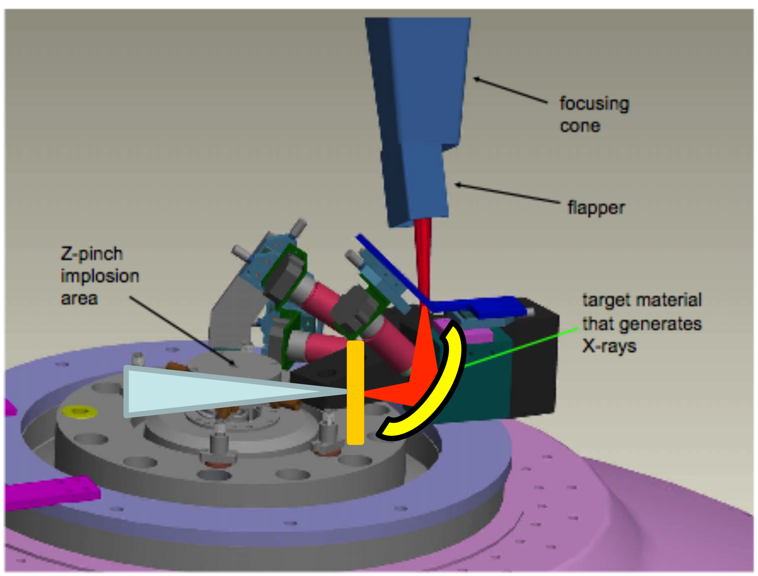
Ion radiography/deflectometry on Z

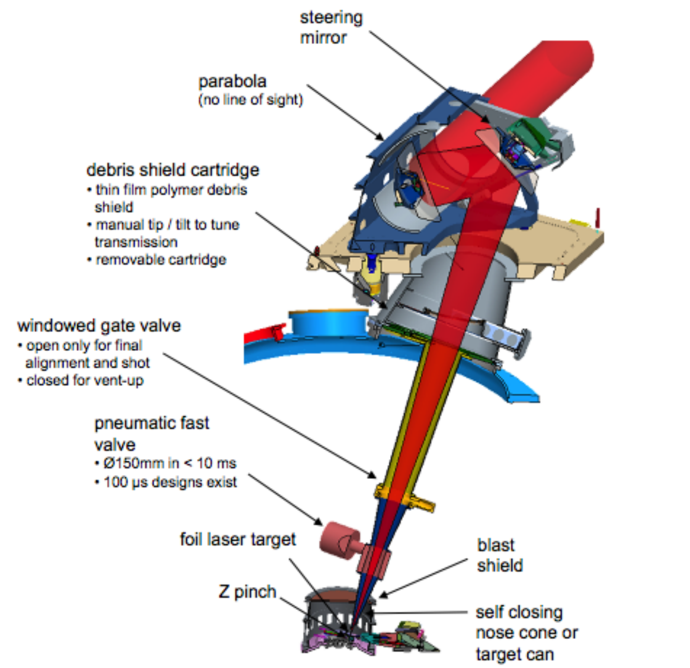
- **Application on Z requires development of sacrificial focusing plasma mirror**
- **Experiments planned this year**



J. Fuchs et al., personal communication; M. Nakatsutsumi et al., Optics Letters 35, 2314 (2010)



Modified 25 keV x-ray backlighter setup



J. Schwarz et al., PRST-AB 13, 041001 (2010)

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Conclusions

- **Proton acceleration with mass-reduced targets:**
  - **above 60 MeV energy**
  - **about 2 x higher conversion efficiency**
  - **higher proton number**

- **APOLLO targets:**
  - **divergence control for higher energies**
  - **high number of low-energy protons**
  - **reduced maximum energy**
  - **good news for Proton Fast Ignition Concept**

- **Proton radiography on Z:**
  - **new experimental capability development**
  - **requires focusing plasma mirrors**
  - **can provide high-quality electromagnetic field measurements on Z**