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

$E_z \approx 10^{12} \text{ V/m}$
Target Normal Sheath Acceleration (TNSA): Typical beam parameters

- **spectrum**

  ![spectrum graph]

  \[ \eta \approx 1-5\% \]

- **opening angle**

  ![opening angle graph]

- **source size**

  ![source size graph]

- **transverse phase space**

  ![transverse phase space graph]
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\textsuperscript{1,2,3}:
  - requires ultrahigh contrast, ultrathin foils, (circular polarization)
  - ion beam profile unknown (only two experiments published)

- Shock-acceleration\textsuperscript{4}:
  - High flux, strongly distorted beam profile

- Laser-induced Fusion (OMEGA)\textsuperscript{5}:
  - Mono-energetic @ 15 MeV

- Skin-Layer Ponderomotive Acceleration (SLPA)\textsuperscript{6}:
  - high number, but low energy

\textsuperscript{1}: L. Yin et al., Laser Part. Beams 24, 291 (2006)
\textsuperscript{5}: C.K. Li et al., Rev. Sci. Instrum. 77, 10E725 (2006).
\textsuperscript{6}: J. Badziak et al., PPCF 46, B541 (2004)
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**Experimental setup**

### 100 TW target area

- **laser parameters**
  - $E = 100 \, \text{J} \pm 10\%$, $t_p = 0.7 \, \text{ps}$, $\lambda = (1.054 \pm 3) \, \text{nm}$
  - focal spot: $5.7 \, \mu\text{m}$ FWHM (diff. limit: $5.66 \, \mu\text{m}$)
  - 30% of energy in FWHM
  - 45 degree angle of incidence
  - $I = 1.5 \times 10^{20} \, \text{W/cm}^2$

- **targets:**
  - copper or tin

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**Diagram: Light Source with Laser Parameters and Target Details**

- Laser with parameters $E$, $t_p$, and $\lambda$.
- Focal spot size and energy distribution.
- Targets: copper or tin, (250 $\mu$m)$^2$ area, 25 $\mu$m thick, "mass-reduced targets".

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**Graphs:**

- Time vs. intensity graph with a peak indicating laser pulse duration.
- Focal spot size and intensity distribution.

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**Logos:**

- Petawatt
- Sandia National Laboratories
Proton acceleration experiments

- **p-polarization**
  - E-field vector
  - Target plane

- **s-polarization**
  - E-field vector
  - Target plane

**Image:**
- 0.25 mm x 0.25 mm x 25 µm Cu on a 7 µm carbon fiber
- P-polarization
- S-polarization
- Laser
Radiochromic Film Imaging Spectroscopy

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

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

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

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)
Energy spectra closely follow quasi-neutral expansion:\(^1\):

\[
\frac{dN}{dE} = \frac{N_0}{\sqrt{2 E k_B T_e}} e^{-\sqrt{\frac{2 E}{k_B T_e}}}
\]

Flat foil (FF), s-polarized:
\(N_0 = 1.8 \times 10^{13}\)
\(k_B T_e = 0.76\) MeV

Flat foil, p-polarized:
\(N_0 = 1.8 \times 10^{13}\)
\(k_B T_e = 1.4\) MeV

Mass-reduced target (MRT), p-polarized:
\(N_0 = 6 \times 10^{13}\)
\(k_B T_e = 1.4\) MeV

\(k_B T_e\) from ponderomotive potential: 5 MeV
\(N_{\text{total}}\) on MRT rear surface\(^2\): \(~ 6 \times 10^{13}\)

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 $\rightarrow$ 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

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

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)
2D PIC simulations: real space

This work has been performed in collaboration with TU Darmstadt, Germany
2D PIC simulations: phase-space

Differences for APOLLO:
- collimated beam in center
- large-divergent, low-energy part
- lower $E_{\text{max}}$

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Experimental results

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

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

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

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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)
Ion radiography/deflectometry on Z

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

Modified 25 keV x-ray backlighter setup

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

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