Working Group 6
Laser-Plasma Acceleration of Ions

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How do we go from ion acceleration to ion accelerator?

• Questions that need to be addressed to design Laser Ion Accelerator
  - What laser technologies are needed?
  - What target metrologies are warranted?
  - What ion acceleration mechanisms should be utilized?
  - What are the beam transport systems?
  - What is progress on applications?
Recently, a roadmap from ion acceleration to ion accelerator is presented

Basic Acceleration Mechanisms and Experimental Proton Energy Scalings

\[ \frac{a_0}{\varepsilon_p} \]

CE
Coulomb Explosion

RT
Radiation Pressure Acceleration

MVA
Magnetic Vortex Acceleration

TNSA
Target Normal Sheath Acceleration

\[ I \lambda^2 \frac{d_e}{\lambda^2 \sqrt{a_0}} \]

\[ \sqrt{a_0} \]

\[ d_e \]

10-60 fs
10-150 fs
0.3-1 ps
simulations

TNSA
RPA

\[ I \lambda^2 [W.\mu m^2/cm^2] \]

\[ (I \lambda^2)^{1/2} \]

30-60 fs
100-150 fs
0.3-1 ps
simulations

Medical applications

1-3 PW
0.01-10 Hz
10 PW <0.01 Hz

Deep penetration
of matter; deep probes

Swift ions inside matter; nuclear events

PW-class laser
Important components of ion acceleration

- Laser
- Target
- Ion acceleration
- Diagnostics
- Beam properties and transport
- Applications
There have been new developments in targets

Draco laser: 
~10 MeV with 1 um target 
~20 MeV with 10nm and PM

Liquid crystal

Cryogenic Jet

M. Kaluza

POLARIS laser pulses (1030 nm):
- up to 2.5 J within 217 fs
- contrast $2 \times 10^{-13}$...$2 \times 10^{-8}$
- $E_{\text{cutoff}} = 14$...21 MeV @ 2.5 J

Mass Limited Targets

K. Zeil

- Draco (2.5 J, 30 fs, plasma mirror)
- 20 MeV proton energy density tailoring with prepulses optimizes energy and beam profile

Structured Targets

A. Huebl

- experiment: P. Hilz et al. (LMU) PHELIX (GSI)
- Paul trap: truly isolated μm PMMA target

Gas Foil

A. Ting

Tunable, thin (~50um), pure hydrogen target operating from 0.3-0.75 $n_{\text{CRIT}}$

M. Helle

Y.-H. Chen

Measurements of charge and energy of electrons originating from planar, wedge, and needle tip targets
New Targets result in high energy proton beams

Laser proton acceleration from liquid crystal films of different thicknesses with ultra-high laser contrast


Cryogenic hydrogen jets:
- Pure proton target
- Cylindrical shape: (Ø 2.5, 1 μm)
- Plasma density: 30 n_c @ 800 nm
- Relativistic transparency regime
- Plasma dynamics via optical probing

High contrast proton acceleration at Draco (2.5 J, 30 fs, plasma mirror)

LSTI of OSU
- Linear Slide Target Inserter
- LCT film formation with thicknesses varying from 10 nm to > 40 μm
- Online thickness measurement

Target thickness scan
- Scan over wide range of thicknesses possible
- Directed p+-beams in target normal direction observed down to 10 nm thick targets

1) Helmholtz-Zentrum Dresden-Rossendorf 2) Ohio State University

11.8 MeV

Particle number / a.u.

Energy in MeV
Target Normal Sheath Acceleration (TNSA) is still widely investigated mechanism, but there are new mechanisms of ion acceleration. Among them, Coulomb assisted, Slow Wakefield, Relativistic Transparency, Staged Acceleration, and MVA are notable.

- **Coulomb assisted**
- **Slow Wakefield**
- **Relativistic Transparency**
- **Staged Acceleration**
- **MVA**

New mechanisms include:
- SWA (Sahai and Pak)
- RPA (Sahai and Pak)
- Y.-H. Chen
- F. Fuiza
- A. Pak
- A. Ting
- M. Helle
- J. Isaacs
- G. Hicks

- High energy of up to 53 MeV at detector limit of $3 \times 10^8$ protons MeV$^{-1}$sr$^{-1}$
- Energy on-target: 340 ± 40 J (Vulcan Petawatt)

Theoretical and instabilities contributions come from Y. Wan and S. Bulanov.
Several groups have reported quasi-mono-energetic ion beams

Quasi Mono-Energetic Ion Acceleration from Mass-Limited Targets with Realistic Laser Contrast

- experiment: P. Hilz et al. (LMU) PHELIX (GSI)
- Paul trap: truly isolated μm PMMA target
- 3D3V simulation: PIconGPU
- 15MCPUhrs (½ GPUhrs), ¼ PByte data, Titan (ORNL) Incite Award
- conversion: 500 fs PHELIX laser to 4 μm quasi mono-energetic protons
- very directed forward charge / sr: 35-50x of non-directed Coulomb, >= TNSA
- stable acceleration, reliable suppression of filamentation in expanded target

Target parameters:
- solid H₂ filament,
- 12.5 μm diameter
- stability: 4.0 μm rms

Proton beam results:
- \( E_{\text{cutoff}} = 14 \ldots 21 \text{ MeV} \) @ 2.5 J
- homogeneous beam profile (>10° half angle)
- Efficiency > 10 % (into \( E > 3 \text{ MeV} \))
Simulations indicate acceleration results from electromagnetic fields produced from high current, wakefield accelerated e-beam. This process yields a 5x increase in axial proton energy and ~100x reduction in beam divergence.

2D simulations significantly overestimate peak ion energy, however energy gains are still impressive compared to TNSA.

Signatures of Magnetic Vortex Acceleration from a Gas Foil

Proton Spectrum from 10μm H₂ Jet at 5x10¹²W/cm²

Omega EP experiments w/ ablated foil (A. Pak et al.)
There is some progress in diagnostic development

Thompson Parabola

CR39

Diagnostic

Electrons

Louise Willingale, Alexey Arefiev, et al

A. Zigler
Hebrew University of Jerusalem, Israel
SPARC Lab, INFN Frascati Italy

Self-induced Relativistic Transparency: Wave focusing in $n_e > n_c$ region

Pre-accelerated electrons can rapidly gain significant energy

Titan laser experiment: 120 J, 1 ps
Low density foam targets

Surprising result: Enhanced superponderomotive electron tail for targets with $n_c < n_e < n_{\gamma c}$

Target structure effecting the quantity and energy of escaping electrons - pointing out to field enhancement

For the same laser intensity of $10^{18}$W/cm$^2$ we measured 7nC of escaped electrons from a needle tip of in comparison 1.2 nC from thin foil
Demonstration of applications of ion beam

Achievements of the LIGHT project (D. Schumacher)
- time and space compression of protons
  - \( t_{\text{bunch}} = 209 \) ps
  - \( I = 400 \) mA
  - Intensity: \( 3.2 \) A/cm\(^2\)
- transport of laser accelerated fluorine for 6 m time and space compression of fluorine
  - energy compression with a rf resonator
  - \( \Delta E/E_0 = 2.7\% \pm 1.7\% \)
  - \( n_p = 1.7 \times 10^9 \pm 15\% \)
  - transversal \( 15 \times 15 \) mm\(^2\)

Laser Neutron Production
(recent results from TRIDENT and PHELIX lasers)
- Source size: measured down to 1.2 mm can go sub mm for 500 µm if you accept Be evaporation
- high single pulse directed neutron beam
  - \( 1.3 \times 10^9 \) n/sr equivalent
  - \( 1.6 \times 10^{11} \) n for a 4 pi source
- Neutron Brilliance:
  - Best assumption: in \( 10^{-9} \) s and 10% Bandwidth
  - \( 10^9 \) n/sr @ 10 MeV leads to \( 10^{17} \) n/s/sr/10%
  - \( 10^9 \) n/sr @ 1 MeV leads to \( 10^{18} \) n/s/sr/10%
- Spectrum:
  - Adjustable with peak energy from 5 to 70 MeV

BELLA-I proposal (S. Steinke)
- First laser driven single shot neutron resonance spectroscopy using high-energy and epithermal neutrons
Challenges for ion acceleration?

• Stable ion acceleration is required for medical applications
  - spectral (particle energy) control
  - particle bunches of high charge
  - short duration
  - low emittance
  - beam transport

• Are we ready for high rep. systems
  - Targetry
  - Diagnostics
  - Data collection

• Ion energy scalings in different energy regimes are not well understood
Thank you!