Intense Ion Beams from relativistic laser plasmas – a promising acceleration mechanism

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Ultra High Intensity Laser

Interaction zone
E-Field = $3 \times 10^{11}$ V/cm
$E_{osc}(e^-) = 10$ MeV

Energy: 50-500 J
Pulse duration: 500 fs
Intensity: $10^{20}$ W/cm²

Electron beam
$T_e = 3$ MeV/k_B
$N_e = 10^{14}$
Discovery of intense Proton beams at the Petawatt Laser

$10^{13}$ Protons per shot
Energy up to 50 MeV
Time < 10 ps
I > 50 MA
Target Normal Sheath Acceleration (TNSA)

Electrons are accelerated by the ponderomotive force

Laser

Preplasma

Electron sheet

Target charges up and confines electrons

Hot electrons

Protons

Protons are accelerated by the electron sheath
Experimental Setup

Laser:
Luli 100 TW Laser System
30-35 J in 300-500 fs
Intensity: $5 \times 10^{19}$ W/cm$^2$

Diagnostics:
Proton spectrometer
Thomson parabola
RCF
Neutron TOF
Nuclear activation
Beam parameters

RCFs placed behind the target show homogenous spatial distribution and energies > 25 MeV

$10^{12}$ Protons
Time < 10 ps
Energy > 25 MeV
Transverse beam profile

- Experiments at Petawatt showed normalized emittance $< 0.53 \pi$ mm mrad (limited by detector resolution)
- Improved diagnostic at LULI could lower this value to $0.06 \pi$ mm mrad
Structured Targets

Structures on the backside of the target shape the accelerating electric field and the proton beam.

The profile is kept due to the beam quality.

⇒ Beam profile can be shaped by specially designed targets.

6 MeV  10 MeV
Influence of the laser focus

Asymmetric laser focus produces an asymmetric proton beam

Proton beam shaping possible with a suitable laser focus
Acceleration of Ions

Ions are shielded by the accelerated protons

Removing the hydrogen of the target by heating

Unheated Target

Heated Target
Proton radiography

Due to the proton-matter interaction proton radiography can shadowgraph light ions in an environment of heavy material.

⇒ Complementary diagnostic to x-ray radiography

Laser accelerated protons with their excellent beam quality offer radiography with high spatial and temporal resolution.
Electric field mapping

- Direct mapping of electric fields with high temporal resolution
- Different time of flight for different energies offers mapping at different times in one shot

Pulsed neutron source

Accelerated deuterons are used for $D+D \rightarrow ^3\text{He}+n$ reactions
Injector for accelerators

Laser accelerated ions could be an alternative for classical ion sources and injectors

Advantages:
- Beam parameters and quality are comparable or better
- Smaller size and easier to operate

Open questions:
- Phase space matching
- Low repetition rate
Phase space matching

Transverse:
- Large divergence requires strong focusing quadrupoles ($B \sim 2.5$ T)

Longitudinal:
- use only a small part of energy spectrum for classic accelerators ($5 \times 10^9$ at 20 MeV)
- high gradient accelerator (DWA)
Laser improvement

- Practical applications require high repetition rate
- Repetition rate limited by cooling time due to inefficient pumping with flash lamps

→ Pumping of the laser with laser-diodes

POLARIS project (Jena, Germany):  
150 J in 150 fs → 1 PW  
0.1 Hz repetition rate
Conclusion and Outlook

• Ion beams from relativistic laser plasmas have unique properties
• Beam shaping possible (focus, target)
• Serveral applications (radiography, fast ignitor, neutron source)
• Alternative for classical injectors in special cases
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