Ion Acceleration from the Interaction of Ultra-Intense Laser Pulse with a Thin Foil

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Ion Acceleration
Has Been Observed Experimentally

R.A. Snavely et al., Phys. Rev. Lett. 84, 2945 (2000);

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Well Characterized Laser-Ion Beams will Have Many Applications

- Warm Dense Matter
- Isotope Production
- Proton Radiography
- Neutron Source

At $I > 10^{19} \text{ W/cm}^2$, ions are accelerated to MeV-range energies.
Three Principle Mechanisms of Ion Acceleration

I. Thermal Expansion

- Ions reach average plasma temperature
  \[ E_{ion} \propto kT \]
- Ions reach energies of thermal sound speed.
  \[ E_{ion} < 1 \text{ MeV} \]

II. Ponderomotive Potential

- Maximum energy approx. laser ponderomotive potential
  \[ U_p = \left( \sqrt{1 + \frac{I \lambda^2}{1.3 \times 10^{18}}} - 1 \right) mc^2 \]
  \[ E_{ion} = 1-3 \text{ MeV} \]

III. Target Normal Sheath Acceleration

- Electrostatic sheath is formed by hot electrons.
  \[ \vec{E} \propto \frac{T_{hot}}{e\lambda_0} \]
- Surface atoms are field ionized and accelerated
  \[ E_{ion} > 10 \text{ MeV} \]


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Which is the dominant acceleration mechanism?

Where do the energetic protons originate?

- Front Surface $\rightarrow$ Ponderomotive Acceleration
- Back Surface $\rightarrow$ Target Normal Sheath Acceleration

Previous experiments have studied the mechanism by removing the contamination layer.

- Resistive Heating$^1$ removes contamination from all surfaces
- Laser Ablation$^2$ dramatically perturbs back surface

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1M. Hegelich et al.,
2A. Mackinnon et al.,
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Description of Ion Sputter Gun

• 3-cm Argon Ion Source
• Beam Voltage 500 V
• Beam Current 10 mA
• Etch Rate $\sim 170$ Å/min
Experimental Setup of Ion Sputter Gun

Ion gun (in target chamber) positioned to etch back surface of target.

JanUSP Laser:
\[ E_L = 10 \text{ J}, \quad \tau = 100 \text{ fs} \]
\[ I > 10^{20} \text{ W/cm}^2 \]

Sputter gun can be positioned to etch either the front or back surface of the laser target.
Photographs of Experimental Setup

Ion Gun Off

Ion Gun On

Ion sputter gun shown in the JanUSP target chamber. Source is positioned to etch back surface of the laser target. Radiation is visible when source is on.
Proton Beam from 15-µm Thick Au Targets

Etching back surface of the target has dramatic effect on proton beam.
Quantitative Analysis of Au Target Shots

At $E > 5$ MeV, the proton beam can be fit to a Maxwellian distribution,

No etching (●) and etching only the front surface (■) produced proton beam with $\sim 1\%$ of laser energy.

Etching back surface (▲) produced no signal above background levels.
Particle-In-Cell Simulations
Agree Well With Experimental Results

- Back surface protons obtain $E_{\text{max}} = 13$ MeV.
- Front surface protons obtain $E_{\text{max}} = 4$ MeV.
- Heavy (gold) ions obtain $E_{\text{max}} = \text{tens of MeV}$.

Experiment and theory support evidence for back surface acceleration mechanism.
APPLICATIONS
Ion Beam Can Be Ballistically Focused

Heating at Constant Volume

- high energy density (> $10^5$ J/g)
- picosecond ($10^{-12}$) time scale
- warm dense plasma 23 eV

Streak camera images space- and time-resolved thermal emission at 570 nm with an 800 µm spatial region and 1 ns window.

New opportunities in high energy-density physics and fusion energy research

Positron Emission Tomography
PET imaging is unique in that it shows the chemical function of organs and tissue, while other techniques (X-ray, CT, MRI) show only structure.

Clinical Applications of PET
• Oncology
• Cardiology
• Neurology

Academic Applications of PET
• Cognitive Processes
• Organ Function

Proton Activated Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life</th>
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<tbody>
<tr>
<td>$^{15}$O</td>
<td>2 min.</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>10 min.</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>20 min.</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>110 min.</td>
</tr>
</tbody>
</table>
High Resolution Proton Radiography

Radiograph Characteristics

- 2–3 $\mu$m resolution
- picosecond ($10^{-12}$) time scale
- diagnose ICF capsules
- diagnose plasma E-fields

Table-Top Short-Pulse Neutron Source

- Deuterons are accelerated into tritium target
- Short pulses (< 1 ps) of 14-MeV fusion neutrons
- Time resolved neutron damage studies
Proton fast ignition is well suited for heavy-ion fusion hohlraum designs.

Ion-driven fast ignition circumvents difficulties of ion acceleration, pulse compression, focusing and transport.

Conclusion

Laser-Acceleration of Ions Has Been Observed

- At $I > 10^{19} \text{ W/cm}^2$ Ions Accelerated to $E > 10 \text{ MeV}$
- Many Institutions Currently Studying Laser-Ion Acceleration

Experiments and Simulations

- Protons Originate from Back Surface of Laser Target (TNSA model)
- Beam Can Be Ballistically Focused by Target Geometry

Potential Applications Include

- Warm Dense Matter
- Isotope Production
- Proton Radiography
- Table-Top Neutron Source