Production of energetic ion beams using high intensity lasers

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Outline: Ion acceleration with lasers

- Thermal expansions
- Radiation pressure and relativistic transparency
- Hole-boring and shocks
- Future developments
Thermal Expansions
Sheath acceleration
Sheath acceleration

\[ n > n_{cr} \equiv \varepsilon_0 m_e \omega_0^2 / e^2 \]
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Energies \( \sim \alpha k_B T_e \sim \alpha^* m_e c^2 (I \lambda^2)^{1/2} \)
Pros and cons

- Extremely high accelerating fields (>10^{12} Vm^{-1}) means:
  - short pulse
  - low emittance
  - compact size
  - high charge (> 10^{13} protons ≈ μC)

- Disadvantages:
  - Large energy spread
  - Poor energy scaling (T_{hot} \propto (I\mathcal{L}^2)^{1/2})
  - Multiple ion species (especially impurities)

Radiation pressure and relativistic transparency
light-sail acceleration
light-sail acceleration
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**light-sail acceleration**

Radiation Force:

\[ F_R = (1 + R) A \frac{I_L}{c} \]

Acceleration:

\[ \rightarrow v_i = \frac{(1 + R) \tau I_L}{\rho d} \frac{1}{c} \]

Optimum Thickness:

\[ d_{opt} = a_0 n_e \]

- where \( d \) is in units of \((c/\omega_p)\)
- and \( n_e \) in units of \((n_{cr})\)
- for \( I \approx 10^{20} \text{ W cm}^{-2} \), \( d_{opt} \approx 5 \text{ nm} \)

Rayleigh-Taylor Instability

Rayleigh-Taylor Instability

Rayleigh-Taylor Instability

Simulation Conditions:
Laser: \( I = 10^{20}\, \text{Wcm}^{-2} \)  
\( a_0 = 10 \)  
\( \tau_L = 600\,\text{fs} \)
Target:  
\( d = 10\,\text{nm} \)  
\( n_e = 800n_c \)  

carbon 6+

Relativistic transparency


Protons/MeVsr

Carbons/MeVsr

Energy/nucleon (MeV/u)

Thickness (nm)

Energy/nucleon/MeVsr

Ener

gety/nucleon (MeV/u)

10

20

5

100 LP

20 CP

20 LP

5 CP

4 MeV 9 MeV 15 MeV

Buffered beam

Ring at low energies

10 nm DLC, LP

x10^{11}

x10^c

0 2 5 10 20

0 4 8 12
Buffering

Hole-boring and shocks
hole-boring
ing (ponderomotive)acceleration

\[ \nu_{hb} = ((1 + R)I/\rho c)^{1/2} \]
hole-boring
(ponderomotive)acceleration

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hole-boring (ponderomotive) acceleration

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hole-boring (ponderomotive) acceleration

- **CO₂ laser:**
  - \( \lambda = 10.6 \mu m \)
  - Pulse energy \( \sim 2-4 \) J
  - Pulse length \( \approx 10 \) ps
  - **Pulse train with 25 ps separation.**
  - Focal spot diameter \( \sim 60 \mu m \)

- \( I \sim 5 \times 10^{15} \) W/cm²

hole-boring (ponderomotive)
acceleration

- CO₂ laser:
  - \( \lambda = 10.6\mu m \)
  - Pulse energy \( \sim 2-4\) J
  - Pulse length \( \lesssim 10\) ps
  - Pulse train with 25 ps separation.
  - Focal spot diameter \( \sim 60\mu m \)

- \( I \sim 5\times 10^{15}\) W/cm²

hole-boring (ponderomotive) acceleration

- up to $\sim 10^9$ protons
  - 1000 brighter than previous modulated spectra.
- energy spread down to $\sim 4\%$
  - local emittance $\sim$ nm

hole-boring (shock) acceleration

Simulation Conditions:
Laser: Ionised H₂
\( a_0 = 0.9 \)
\( \tau_L = 6 \text{ps} \)
Target: Triangular density profile

hole-boring (shock) acceleration

Simulation Conditions:
- Laser: Ionised H₂
- Target: Triangular density profile
- \( a_0 = 0.9 \)
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hole-boring (shock) acceleration

Simulation Conditions:
Laser: Target:
a₀ = 0.9 Ionised H₂
τₗ = 6 ps Triangular density profile

scale-length manipulation

# Summary of Mechanisms

<table>
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<tr>
<th>Mechanism</th>
<th>Laser</th>
<th>Target</th>
<th>Ions</th>
<th>Energies</th>
<th>Pro</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheath</td>
<td>High intensity</td>
<td>Thin (~μm) foils</td>
<td>Protons (high-Z required target cleaning)</td>
<td>~50 MeV protons ~200 MeV C</td>
<td>High number, short pulse length</td>
<td>Mixed species, low rep-rate, thermal beam, poor energy scaling</td>
</tr>
<tr>
<td>Light-sail</td>
<td>High intensity low prepulse</td>
<td>Ultrathin (~nm) foils</td>
<td>Protons (high-Z require cleaning)</td>
<td>~10 MeV/u</td>
<td>High number, v. short pulse length, good emittance</td>
<td>poor beam quality, difficult target try</td>
</tr>
<tr>
<td>Hole-boring</td>
<td>Infra-red (adjustable prepulse)</td>
<td>Gas (~mm) (~ncr)</td>
<td>Any gaseous species</td>
<td>~1 MeV/u</td>
<td>Good number, low energy spread, high rep-rate</td>
<td>No targets for optical lasers</td>
</tr>
</tbody>
</table>
Future Considerations
A Gabor lens used for both focusing and energy selection.

Gabor lens focuses both transverse dimensions simultaneously, thereby significantly reducing throughput.

Gabor Lens

A Gabor lens is a space-charge lens first proposed in 1947.

Requires reduced magnetic field for focusing ions, compared to solenoids:

\[ B_{GPL} = B_{sol} \sqrt{\frac{m_e}{m_{ion}}} Z. \]

Has recently been considered for focusing laser generated ion beams.

Beamline using laser generated ions

Scanned RCF from Astra Gemini experiment

Dose map

Spectrum Before lens

After lens and aperture

Proposed Applications:
Radiobiology with varying ion species, Radio-isotope production
Scaling of Hole-boring acceleration

Peak Energy (MeV) vs. Intensity (Wcm⁻²)

Total number vs. Intensity (Wcm⁻²)
Scaling of Hole-boring acceleration

Scaling of Hole-boring acceleration

Scaling of Hole-boring acceleration

- Laser peak intensity: $4.0 \times 10^{22}$ Wcm$^{-2}$
- duration: 15fs
- Peak energy: 1.32GeV
- energy spread: 28%
- divergence: 9.2°
- total charge of bunch: 6.5nC
- spot size of the bunch: 2.9 μm
- Laser spot size: 4 μm

Collaborators

THIN FOIL EXPERIMENT:


**Queens University Belfast:** H. Ahmed, M. Borghesi, K. Kakolee, S. Kar, R. Prasad, M. Yeung and M. Zepf

**LULI, École Polytechnique:** B. Albertazzi, J. Fuchs, M. Nakatsutsumi

**LMU München/ MPQ Garching:** P. Hilz, D. Kiefer

**Graduate School of Engineering, Osaka:** R. Kodama, A. Kon, M. Tampo

**SUPA, Strathclyde:** D. A. MacLellan, P. McKenna, G. Scott

**Central Laser Facility, RAL:** D. C. Carroll, R. Heathcote, D. Neely, M. M. Notley

GAS JET EXPERIMENT:

**JAI Imperial College London:** N. Dover, C. Palmer, J. Schreiber

**ATF, BNL:** O. Tresca, I. Pogorelsky, M. Babzien, M. Ispiryan, M. N. Polyanskiy, V. Yakimenko

**Stony Brook University, USA:** N. Cook, C. Maharjan, P. Shkolnikov.

BEAMLINE:

**Imperial College London:** C. Hughes, P. Posocco, J. Pozimski

**JAI Imperial College London:** G. Hicks, O. Ettlinger, N. Dover

SIMULATIONS:

**JAI Imperial College London:** J. Yu, N. Dover
Conclusions

- Buffering enhances proton acceleration from thin foils.
- Scale-length manipulation of gas profiles allows direct helium acceleration from gas targets
- Beam line based on Gabor lens simulated
- Hole-boring acceleration to GeV energy level simulated
- Time is ripe to marry laser and conventional techniques!