Generation of Monoenergetic Protons by Laser Acceleration of Multi-Ion Foils with Polarization Switch

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Outline

- Generation of monoenergetic ions to MeV level – laser radiation pressure acceleration
- Extended acceleration using multi-ion foils – a two-stage acceleration scheme combining radiation pressure and Coulomb repulsion
- Further acceleration with laser profile design – switch of laser polarization during acceleration
Radiation Pressure Acceleration

Ultra-dünne Folie

Robinson et al. 2008
Klimo et al. 2008
Yan et al. 2008
M. Schnürer et al., 2012
Radiation Pressure Acceleration of Quasi-monoenergetic Hadrons

Requirements:
- Circularly polarized laser
  - Avoiding electric oscillation and 2nd harmonics
- High contrast ratio (> $10^9$)
  - Minimizing pre-pulse
- Ultra-thin optimal target thickness
  - Stable ion trapping of double-layer structure

Advantage
- Monoenergetic ion spectra with high energy

Robinson et al. 2008
Klimo et al. 2008
Yan et al. 2008
M. Schnürer et al., 2012
1D Vlasov-Maxwell Simulation

Simulation optimal width $l_0 = 0.2 \lambda_L$

Simulation half the optimal width $l_0 = 0.1 \lambda_L$

Simulation twice the optimal width $l_0 = 0.4 \lambda_L$

Optimal thickness, stable ion trapping

Rayleigh-Taylor Instability (RTI) and Induced Transparency

$\alpha_0 = 25$
$n_{e0} = 41.7n_{cr}$
$l_0 = 0.2\lambda_L$

t = 14T_L

Proton density

Electron density

EM energy density

Proton energy spectra

$t = 15.5T_L$

$t = 17T_L$

Losing Monoenergetic Property
Multi-Ion Foils – Significantly Enhanced Proton Energy due to Longer Acceleration time

Carbon density

Proton density

Electron density

Proton energy

$
\begin{align*}
\alpha_0 &= 5.0 \\
n_{e0} &= 8.3 n_{cr} \\
l_0 &= 0.2 \lambda_L
\end{align*}
$

Longer acceleration time

Greater mono-energy

Scaling of Monoenergetic Proton with Different Carbon Concentration

Compared with pure hydrogen foil:
- Proton energy is 6x as much.
- Acceleration time is 10x extended.
1D Theoretical Model of Proton by Carbon Repulsion Shielded by Electrons

- Assuming protons as a test charge, the Poisson equation
  \[
  \frac{d^2 \phi}{dx^2} = \frac{en_0}{\varepsilon_0} \exp \left( \frac{e\phi}{k_B T_c} \right)
  \]
can be solved to obtain the equation of motion as

\[
\begin{aligned}
\frac{dx_p}{dt} &= v_p \\
\frac{d(\gamma_p v_p)}{dt} &= \frac{eE_x}{m_p} = \frac{e\sigma_{\text{net}}}{2\varepsilon_0 m_p} \coth \left( \frac{x_p - v_c t}{\varepsilon_0 k_B T} \right) e\sigma_{\text{net}}
\end{aligned}
\]

- Good agreement is achieved.

Further Improvement

- Since the **electron temperature** plays an important rule in deciding the shielding effect of Coulomb repulsion due to carbon ions, increasing it could slow down the returning electrons and boost the acceleration.

- **Linear polarized wave** – unwanted heating effect in radiation pressure acceleration now could be an advantage after transparency.
Polarization Switch – Simulation Setup

Switch to Linear Polarization
Initially Circular Polarization

\[ \sqrt{2} E_y \]
\[ E_z \]
\[ \lambda_L/4 \]
\[ \lambda_L \]
\[ L_{\text{switch}} \]
\[ L_{\text{rise}} \]
Comparison and Analysis – Electron Temperature

With Switch

Electron Temperature in COM Frame

Without Switch

Electrostatic Field

\[ a_0 = 5.0 \]
\[ n_{e0} = 8.3 n_{cr} \]
\[ l_0 = 0.2 \lambda_L \]

Electron Energy (MeV)

Proton energy spectra

<table>
<thead>
<tr>
<th>$t$</th>
<th>$kT/mc^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4.13</td>
</tr>
<tr>
<td>100</td>
<td>6.03</td>
</tr>
<tr>
<td>150</td>
<td>6.05</td>
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</tbody>
</table>
33% Boost in Monoenergy with Optimal Switching Time

\[ \alpha_0 = 5.0 \]
\[ n_{e0} = 8.3n_{cr} \]
\[ l_0 = 0.2\lambda_L \]
Conclusion

- Laser radiation pressure is useful in not only accelerating the proton mono-energetically, but also splitting the proton and carbon ion layers.
- Shielded repulsion can accelerate the protons stably and be modeled with good agreement.
- Switching the polarization increases the electron temperature after transparency and can significantly boost the obtainable energy.
Thank you!

Questions?