Bulk ion acceleration from ultrathin foils in PW-class interactions on the ASTRA GEMINI laser

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• Laser-driven ion acceleration from ultrathin foils: Radiation Pressure Acceleration (RPA)
• Experiments on ASTRA-GEMINI
  • Past – Previous work. Polarization dependence of RPA
  • Current:
    • Intensity dependent optimum thickness for RPA
    • Multi-Species Effects
    • Species dependent RPA – PIC simulations
Ion Acceleration – RPA

Why RPA?

• Desirable Scaling with Intensity
  • $E_{LS} \propto I^2$
  • $E_{HB} \propto I$
• Potential for quasi mono-energetic spectrum
• Bulk Ion acceleration – heavy ions e.g. C$^{6+}$

Drawbacks

• Low areal density – Ultra-thin foils / low density foams required
• Ultra-high contrast needed – limited by transparency effects
Ion Acceleration – RPA

Accessing the RPA regime
• \( a_0 = \pi \frac{n_e \ell}{n_c \lambda} = \zeta \)

For amorphous carbon foils \( \rho \approx 350n_c \) hence \( \ell \approx 10nm \)
• Use of circular polarisation (CP) – Reduces electron heating by removing oscillating \( J \times B \) term
### ASTRA - GEMINI

#### CLF – RAL UK

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Wavelength</td>
<td>800nm</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>40fs FWHM</td>
</tr>
<tr>
<td>Contrast</td>
<td>$10^{12}$ (After DPM)</td>
</tr>
<tr>
<td>Energy on Target</td>
<td>6J</td>
</tr>
<tr>
<td>Intensity</td>
<td>$5 \times 10^{20}$ W/cm²</td>
</tr>
</tbody>
</table>

![Diagram of ASTRA-GEMINI setup](image)
Polarisation Dependence RPA - 2013

- Higher ion energies shown for CP – vs linearly polarised (LP)
- Particularly C\textsuperscript{6+} - evidence of bulk acceleration


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- Good agreement with 2D/3D simulations
- LP target becomes transparent much earlier, reduces bulk ion acceleration

1A. Macchi, S. Vehgini and F. Pagoraro PRL 103, 085003 (2009)
2B. Gonzalez-Izquierdo et al Appl. Sci. 2018, 8, 336

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- Particularly C$^{6+}$ - evidence of bulk acceleration
- Good agreement with 2D/3D simulations
- LP target becomes transparent much earlier, reduces bulk ion acceleration
- Energy gain for CP follows the expected energy evolution for LS for a gaussian pulse for longer than LP

\[ \beta = \frac{v}{c}, \quad \beta_{LS} = \frac{(1 + \epsilon)^2 - 1}{(1 + \epsilon)^2 + 1} \]

\[ \epsilon = \frac{2 \mathcal{F}(t)}{\rho \ell c^2} \]


Optimum Thickness - 2017

• Presence of an optimum thickness (15nm) for RPA (33MeV/n – 400MeV)
• C\textsuperscript{6+} Energies decrease < 15nm since target goes transparent earlier in the pulse

• Proton energies do not follow the same trend with thickness
Protons (q/m = 1) are usually accelerated over C^{6+} (q/m = \frac{1}{2}) in the presence of a sheath field.

RPA should present similar energies per nucleon for the species.

The optimum thickness for C^{6+} produces a local minimum in proton energies.

They increase again as the target goes transparent earlier.

15nm > analytical prediction (10nm)
Intensity Scaling - 2017

- Intensity (energy) scan shows another huge difference in the acceleration of the 2 species
- Comparing optimum thickness between PIC (10nm) and experiment (15nm).
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- Comparing optimum thickness between PIC (10nm) and experiment (15nm).
- Simple 2D PIC overestimates C$^6+$ scaling compared to experiment $I^2 \rightarrow I^{1.2}$ due to later onset of transparency – Still RPA regime
- Simple 2D PIC does not account for the difference in the species
- Independent of proton concentration/location
RPA - PIC

• Considering laser pedestal and rising edge after plasma mirrors
• Plasma mirrors activated a few ps before the pulse, target begins to expand.
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• Plasma mirrors activated a few ps before the pulse, target begins to expand.

• Parts of the target become underdense

• Target recompresses during the rising edge of the pulse

• ‘Overdense areal density’ decreases
Multi-species acceleration

• Protons are mostly accelerated by the plasma expansion (few MeV) / sheath effects
• Carbon is initially accelerated by RPA
• Target (optimum thickness) goes transparent just after the peak of the pulse as the density drops
• RPA shuts off, enhanced acceleration takes place with transparency effects
• Followed by sheath effects
Multi-species scaling

• Running an intensity scan shows the different scaling of carbon vs protons
• Carbon scaling indicates RPA (early shut off due to transparency)
• Protons scaling similar to sheath effects acceleration
PIC thickness scan

- Plasma temperature increases for thinner targets - thick targets have a smaller separation between carbon and protons
- Optimal thickness means carbon gets greater acceleration over protons
- <15nm, earlier onset of transparency reduces carbon acceleration in favor of protons
- Results in dip in optimum thickness
Acceleration contributions

• Cutting the pulse at different points allows a determination of which mechanisms dominate
• 70% comes from RPA and subsequent sheath effects
• 30% contribution from transparency
• Measurement still under investigation!
Summary

- Demonstrated the effect of polarization on the transition to LS acceleration (25MeV/u carbon)
- Demonstration of (intensity dependent) optimum thickness for RPA – 15nm, producing 33MeV/u carbon
- Contribution of RPA to species dependent ion acceleration – ion energy scaling depends on the species
  - Carbon accelerated in RPA regime, protons accelerated in the expansion/sheath acceleration regime
Acknowledgements

• QUB – H. Ahmed, P. Martin, S. Kar and M. Borghesi
• Strathclyde – S. D. R. Williamson and P. McKenna
• Imperial – E. J. Ditter, O. Ettlinger, G. S. Hicks and Z. Najmudin
• ELI-NP – D. Doria
• LuLi – L. Romagnani
• CLF – N. Booth, G. G. Scott and D. Neely
• Pisa – A. Macchi

Thanks for listening!
Future Scaling

- Increasing the intensity to 1PW regime will result in an increase in optimal thickness – energy scaling reduces to linear
- Optimum thickness will only scale $I^{1/2}$: still in the ultra-thin range
- Increased pedestal level likely to have more of an effect in this regime

\[
L_{\text{optimum}} = \frac{a_0}{\frac{\pi}{n_e}} \frac{n_{\text{crit}}}{\lambda} \quad a_0 \propto \sqrt{I}
\]

\[
E_{\text{max}} \propto \left( \frac{a_0 \tau_p}{\chi} \right)^2 \quad \chi = \frac{\rho L_{\text{optimum}}}{\lambda m_p n_c}
\]