Modification of proton spectra using optical shaping of over-dense gas jets

G.S. Hicks\textsuperscript{1}, O. Ettlinger\textsuperscript{1}, E. Ditter\textsuperscript{1}, M. Borghesi\textsuperscript{2}, D.C. Carroll\textsuperscript{3}, R.J. Clarke\textsuperscript{3}, T. Frazer\textsuperscript{4}, R.J. Gray\textsuperscript{4}, A. McIlvenny\textsuperscript{2}, P. McKenna\textsuperscript{4}, C.A.J. Palmer\textsuperscript{5}, Z. Najmudin\textsuperscript{1}

1) The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College, London SW7 2AZ, UK
2) Centre for Plasma Physics, Queen’s University Belfast, Belfast, BT7 1NN, UK
3) Central Laser Facility, STFC Rutherford Appleton Laboratory, Oxfordshire, OX11 0QX, UK
4) SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK
5) University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
Energetic ion beams are used today for a number of applications including

- Radiography
- Medical isotope production
- Hadron therapy

- Two of the requirements for hadron therapy are
  - Increase in maximum proton energy to 250MeV
  - Narrow energy-spread

- Also important… repetition rate!
• Hole boring radiation pressure acceleration (HB-RPA) is attractive as a solution since
  – It has a more favourable energy scaling than sheath acceleration [1]
  – Can produce narrow-energy spread beams [2]

Hole Boring RPA

- Hole boring radiation pressure acceleration (HB-RPA) is attractive as a solution since
  - It has a more favourable energy scaling than sheath acceleration [1]
  - Can produce narrow-energy spread beams [2]

Hole Boring RPA

- Hole boring radiation pressure acceleration (HB-RPA) is attractive as a solution since
  - It has a more favourable energy scaling than sheath acceleration [1]
  - Can produce narrow-energy spread beams [2]

- A simple analytical model shows that the maximum energy during HB-RPA scales as \( \varepsilon_{HB} \propto \frac{1}{n_e} \)

- But, target needs to be over-dense to the laser \( n > \gamma n_c \)

Optimum target density

- Simulations suggest optimal target density $\sim 5n_c$

\[ n_c = \frac{4\pi^2 \epsilon_0 m_e c^2}{e^2} \gamma \frac{1}{\lambda_L^2} \]
• Simulations suggest optimal target density $\sim 5n_c$

$$n_c = \frac{4\pi^2 \epsilon_0 m_e c^2}{e^2} \gamma \frac{1}{\lambda_L^2}$$
• Simulations suggest optimal target density \( \sim 5n_c \)

\[
n_c = \frac{4\pi^2 \epsilon_0 m_e c^2}{e^2 \gamma \lambda_L^2}
\]
Optimum target density

- Simulations suggest optimal target density $\sim 5n_c$

\[ n_c = \frac{4\pi^2 \varepsilon_0 m_e c^2}{e^2} \gamma \frac{1}{\lambda_L^2} = 1.1 \times 10^{21} \text{ cm}^{-3} \frac{\gamma}{\lambda_L \mu m^2} \]
Previous experiments at BNL

$\lambda_L = 10.6 \, \mu m$

$n_c = 9.9 \times 10^{18} \, cm^{-3}$

Achievable with a hydrogen gas jet with $\sim$8 bar backing pressure
Previous experiments at BNL

CO$_2$ laser ATF@ Brookhaven National Laboratory (BNL), USA

$\lambda_L = 10.6 \, \mu$m

$n_c = 9.9 \times 10^{18} \, \text{cm}^{-3}$

Achievable with a hydrogen gas jet with $\sim$8 bar backing pressure

C.A.J. Palmer et al.  
PRL 106, 014801 (2011)
Near-critical density targets

\[ \lambda_L = 10.6 \, \mu m \quad 9.9 \times 10^{18} \, \text{cm}^{-3} \]
\[ \lambda_L = 1.053 \, \mu m \quad 1.0 \times 10^{21} \, \text{cm}^{-3} \]

- Typical solid density $4 \times 10^{23} \, \text{cm}^{-3}$
- Typical gas density $10^{19} \, \text{cm}^{-3}$
- We need either-
  - Low density solid
  - High density gas
Gases vs Foams

Foams
- Low repetition
- Multi-species
- Debris
- May require homogenisation
+ Suitable density profile

Gas
+ High repetition
+ Single-species
+ Debris free
- Very high backing pressures required
- Unsuitable density profile

L. Willingale et al. PRI 102, 125002 (2009)
The density profile of a gas jet is not well suited for proton acceleration

A controlled pre-pulse can be used to shape the gas

Demonstrated at CO2 laser at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory [1,2]

But ATF laser intensity (in 2013) I=2.5x10^{16} Wcm^{-2}, a_0=1.4

Our goal is to build on this work at Vulcan Petawatt, CLF, UK

Interferometry of a n_e=2.5n_c helium plasma 250ps after the arrival of a 70mJ pre-pulse. [1]

• H$_2$ up to 240bar
  – Initial densities of $9 \times 10^{20}$ cm$^{-3}$
• Long pulse forms blast wave
  – $E=220$ mJ, $\tau=4$ ns
  – $I=4.7 \times 10^{13}$ Wcm$^{-2}$
• Short pulse accelerates protons
  – $E=353$ J, $\tau=610$ fs
  – $I=2.0 \times 10^{21}$ Wcm$^{-2}$
Experimental Setup

Long pulse beam

Probe beam

RCF stack

Thomson Parabolas

Electron spectrometer
Pure, non-thermal proton spectra observed

No optical shaping
-No forward going protons
-high energy bunch at end of thermal tail at 90 degrees
Pure, non-thermal proton spectra observed

No optical shaping
- No forward going protons
- High energy bunch at end of thermal tail at 90 degrees

L. Willingale et al. PRL 96, 245002 (2006)
Pure, non-thermal proton spectra observed

No optical shaping
- No forward going protons
- High energy bunch at end of thermal tail at 90 degrees

With optical shaping
- No transverse protons
- Single bunch and no thermal tail @5.9°
- Lower energy and lower flux

L. Willingale et. al, PRL 96, 245002 (2006)
Reproducibility

- Protons not detected on every shot
- Significant beam profile variability

Shot 199 - with blast wave, dispersed beam

Shot 202 - with blast wave, narrow divergence
Nozzle damage

Nozzle initial shape
Summary

• Gas targets are a promising solution to providing a high-repletion rate compatible target system

• Without optical shaping
  – No forward going protons detected
  – Transverse protons accelerated by shock acceleration

• With optical shaping
  – Transverse proton signal eliminated
  – Forward going, narrow energy spread proton beam generated

• Future
  – Higher density to generate steeper density profiles and limit instabilities
  – Mitigate nozzle damage