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

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Motivation

Energetic ion beams are used today for a number of applications including

- Radiography
- Medical isotope production
- Hadron therapy → A-SAIL ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

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

- Also important… repetition rate!

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]

[1] *A.P.L. Robinson et al. NJP 10 013021. 2008*
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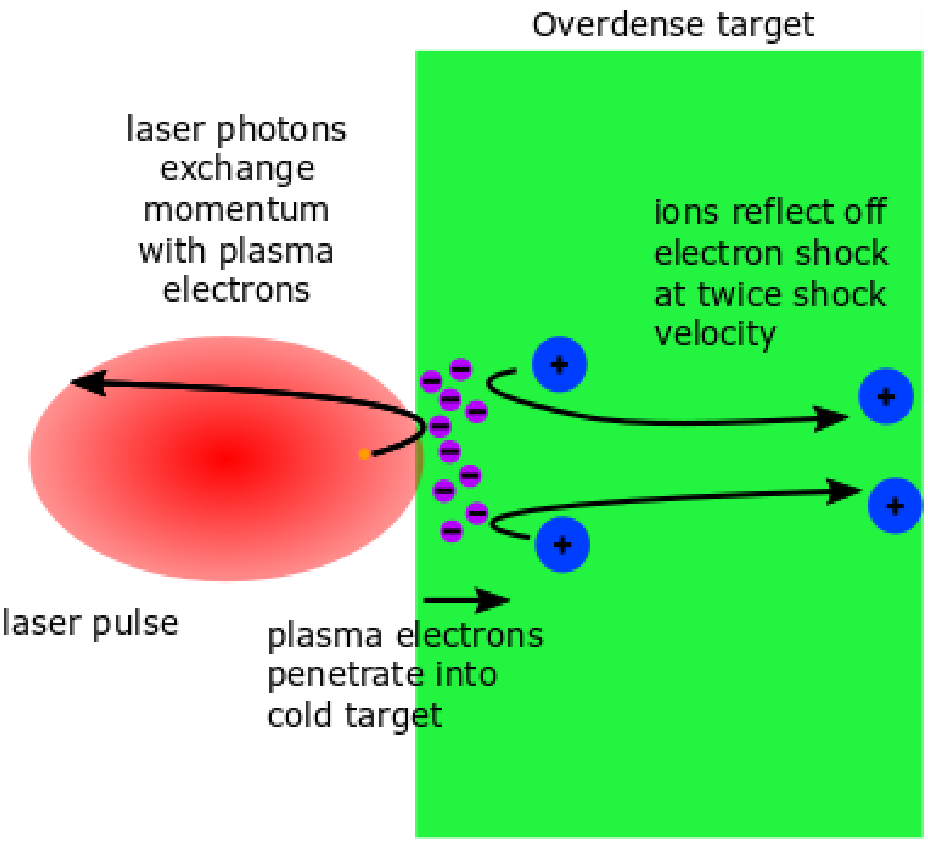

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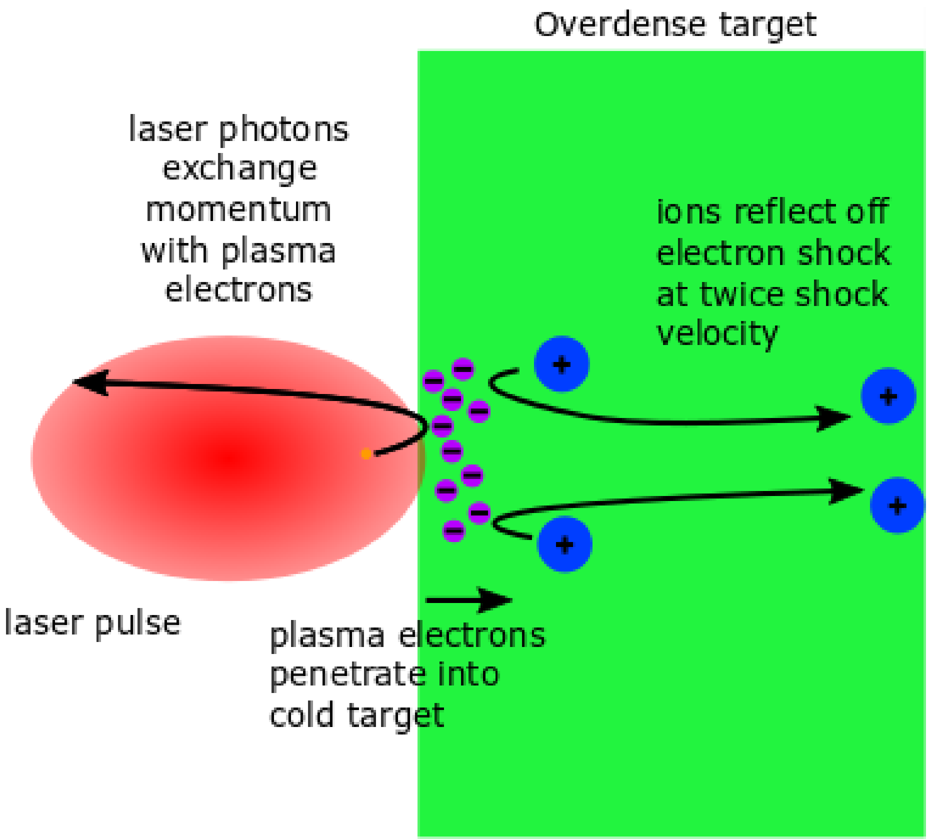

- A simple analytical model shows that the maximum energy during HB-RPA scales as $\varepsilon_{HB} \propto \frac{1}{n_e}$

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

[1] *A.P.L. Robinson et al. NJP 10 013021. 2008*
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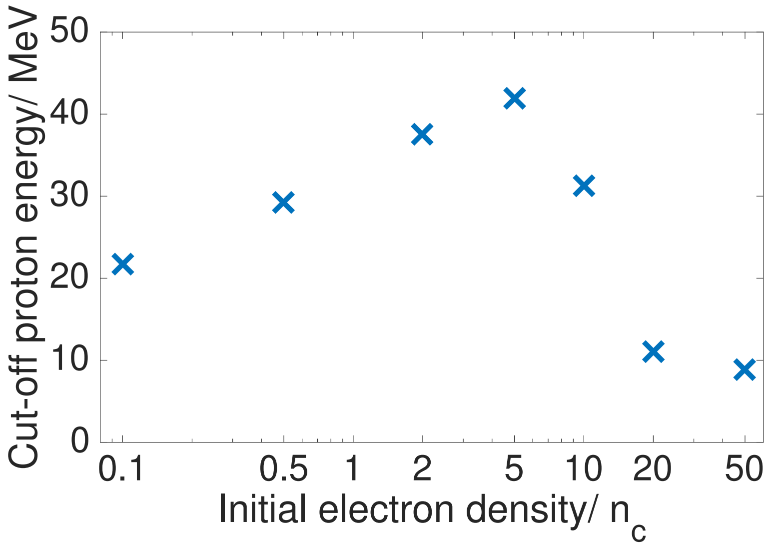
Optimum target density

- Simulations suggest optimal target density ~5n_c



$$n_c = \frac{4\pi^2 \epsilon_0 m_e c^2}{e^2} \gamma \frac{1}{{\lambda_L}^2}$$

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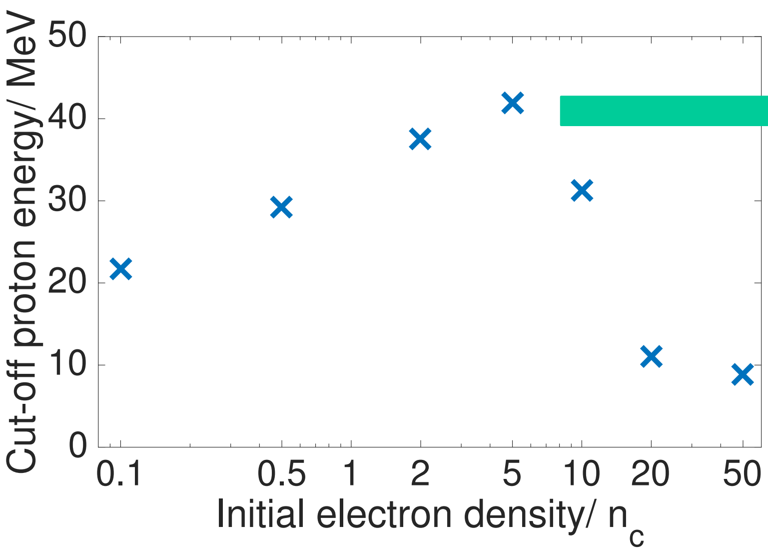

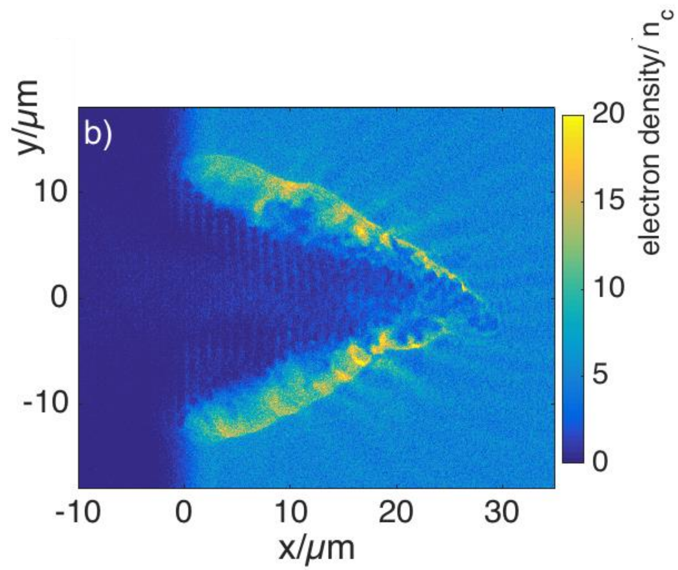

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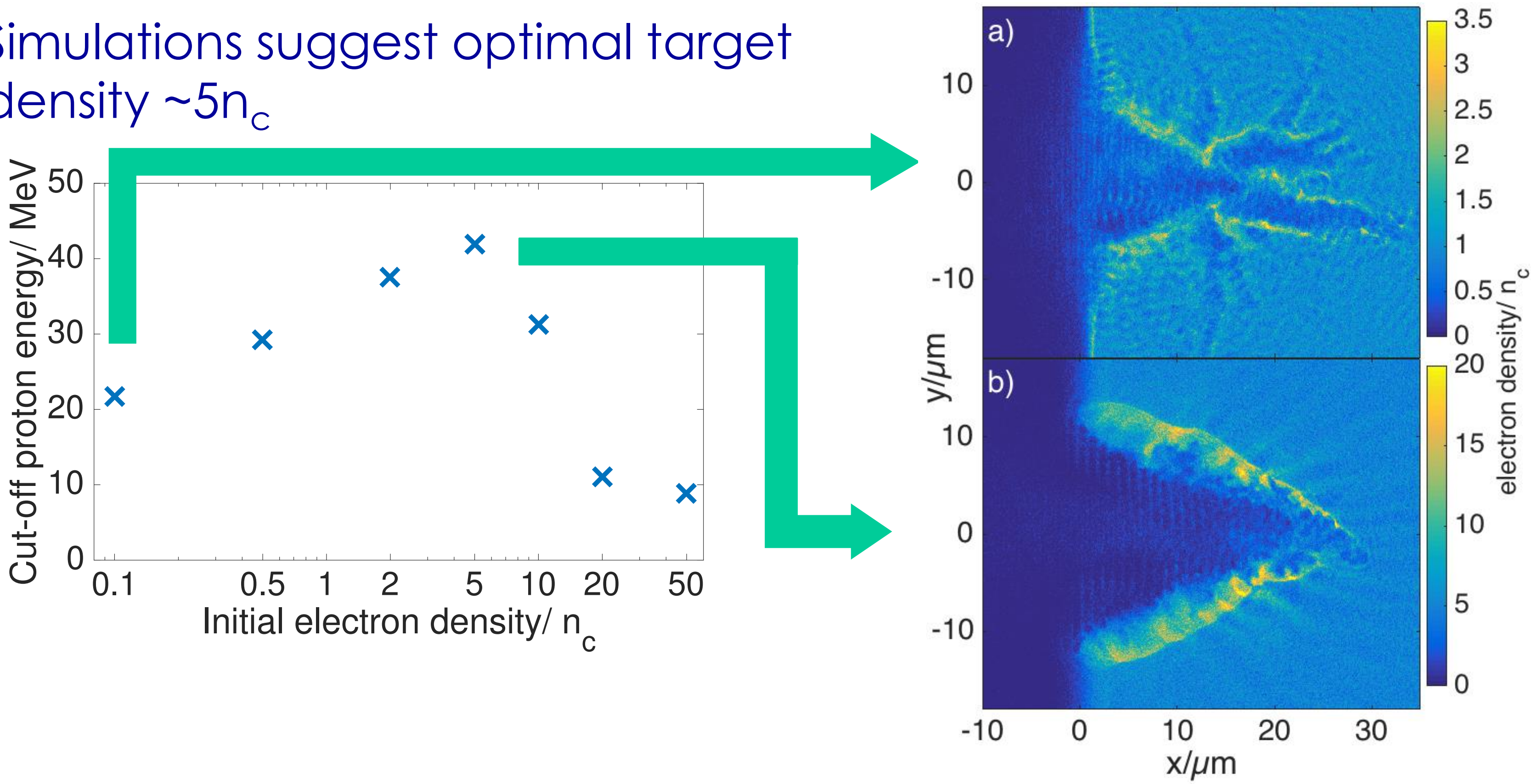

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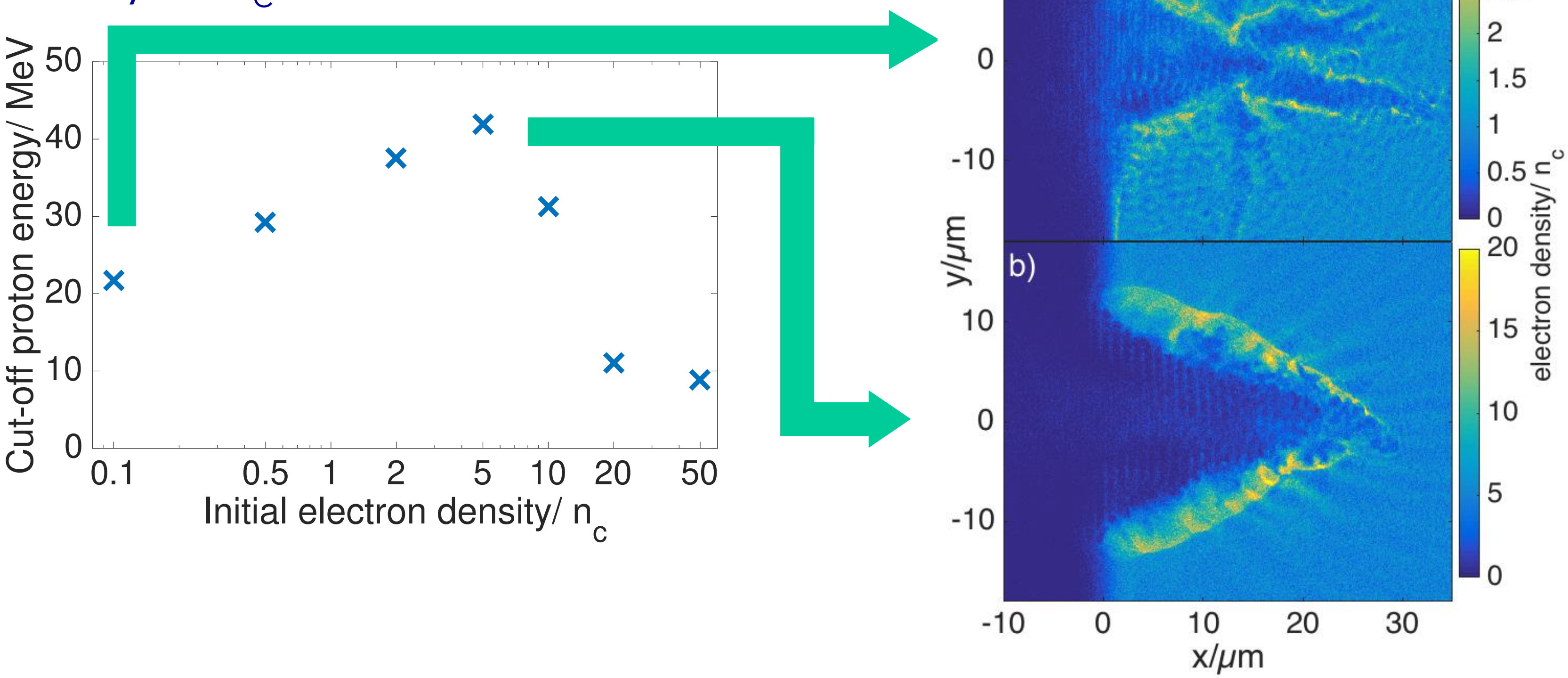

$$n_c = \frac{4\pi^2 \epsilon_0 m_e c^2}{e^2} \gamma \frac{1}{{\lambda_L}^2} = 1.1 \times 10^{21}\,\mathrm{cm}^{-3}\ \frac{\gamma}{{\lambda_{L_{\mu m}}}^2}$$

Previous experiments at BNL

CO_2 laser ATF@ Brookhaven National Laboratory (BNL), USA

$$\lambda_L = 10.6\,\mu\text{m}$$

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

Achievable with a hydrogen gas jet with ~8 bar backing pressure

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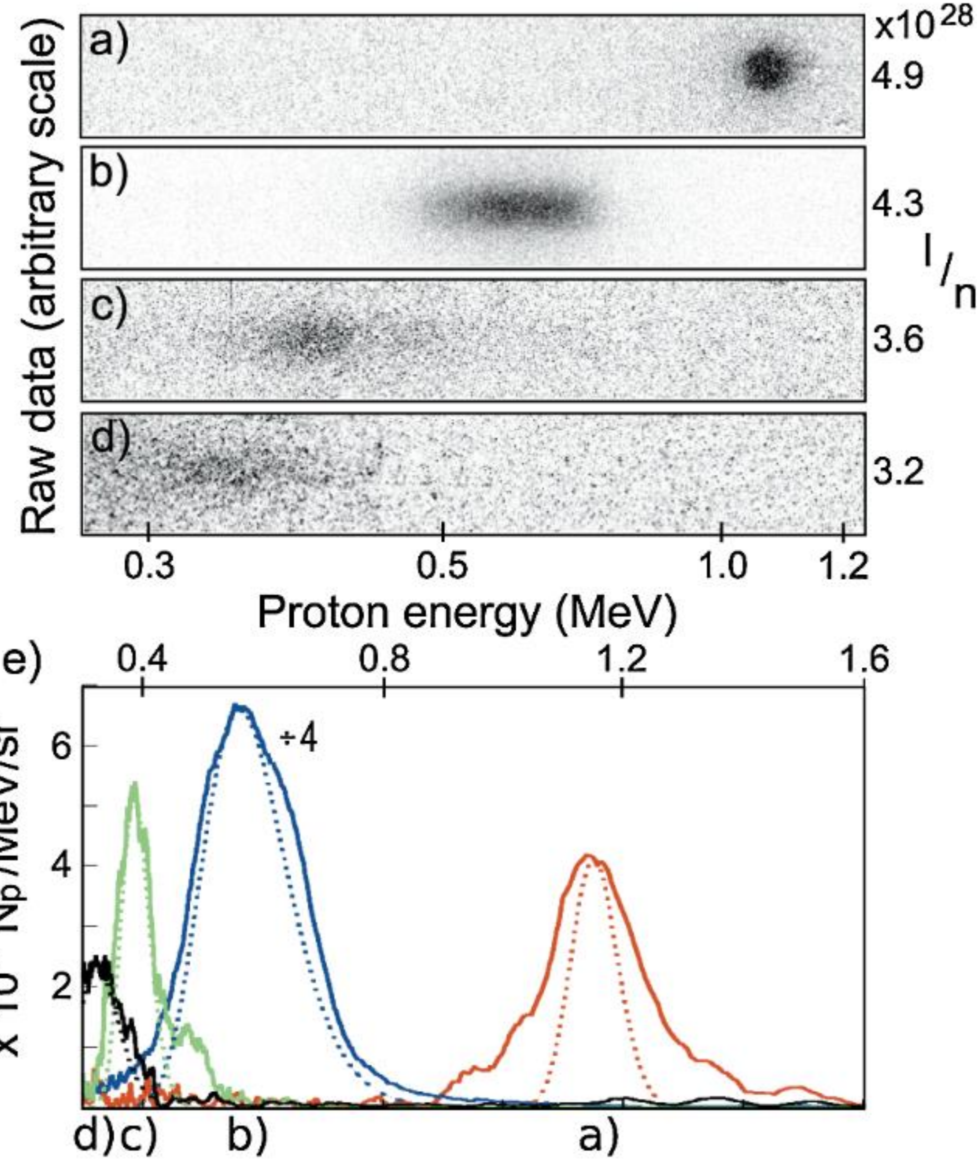


C.A.J. Palmer et al.
*PRL **106**, 014801 (2011)*

Near-critical density targets

$$\lambda_L = 10.6\,\mu\text{m} \qquad 9.9 \times 10^{18}\,\text{cm}^{-3}$$

$$\lambda_L = 1.053\,\mu\text{m} \qquad 1.0 \times 10^{21}\,\text{cm}^{-3}$$

- Typical solid density 4×10^{23} cm^{-3}
- Typical gas density 10^{19} 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

L.Willingale et al. PRl ***102****, 125002 (2009)*

J.H. Bin et al. PRl ***115****, 064801 (2015)*

Gas

+High repetition

+Single-species

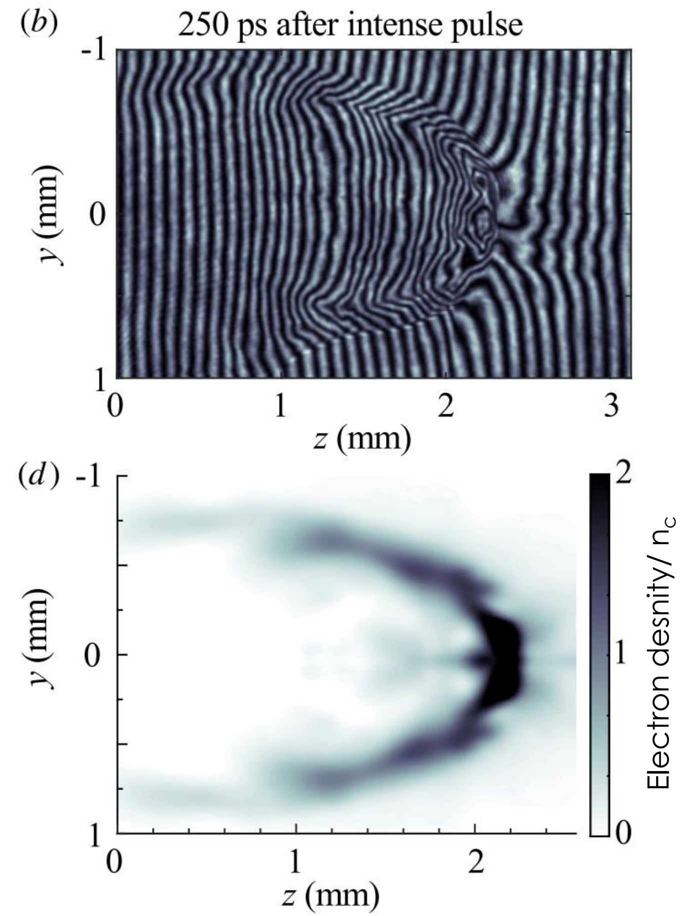
+Debris free

-Very high backing pressures required

-Unsuitable density profile

Optical-shaping of gas jets

- 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 CO_2 laser at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory [1,2]
- But ATF laser intensity (in 2013) $I=2.5\times10^{16}$ 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]

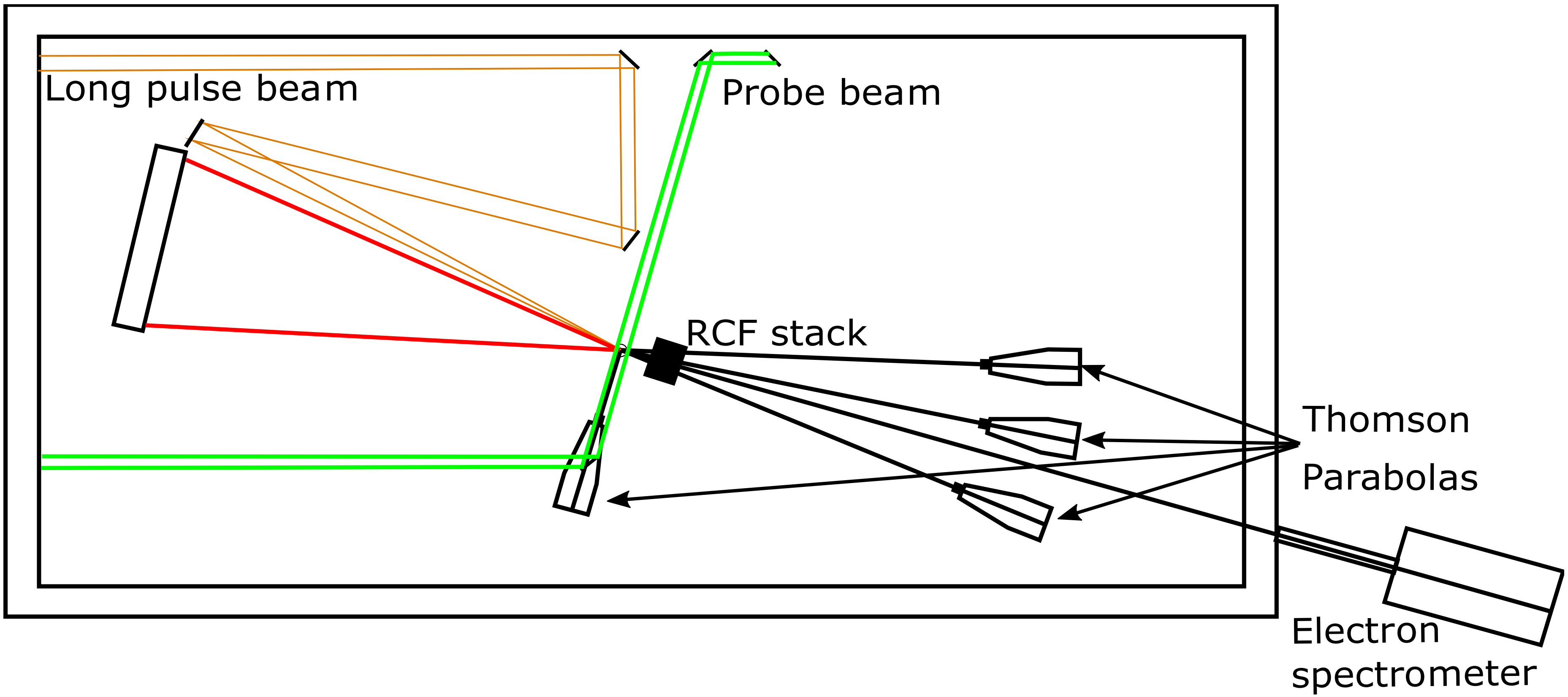
[1] O. Tresca PRL ***115****, 094802, 2015*

[2] N.P. Dover JPP ***92****, 415820101, 2016*

Experiment at Vulcan Petawatt

- H_2 up to 240bar
  - Initial densities of $9\text{x}10^{20}$ cm^{-3}
- Long pulse forms blast wave
  - E=220 mJ, τ=4 ns
  - I=$4.7\text{x}10^{13}$ Wcm^{-2}
- Short pulse accelerates protons
  - E=353 J, τ= 610 fs
  - I=$2.0\text{x}10^{21}$ Wcm^{-2}

Experimental Setup

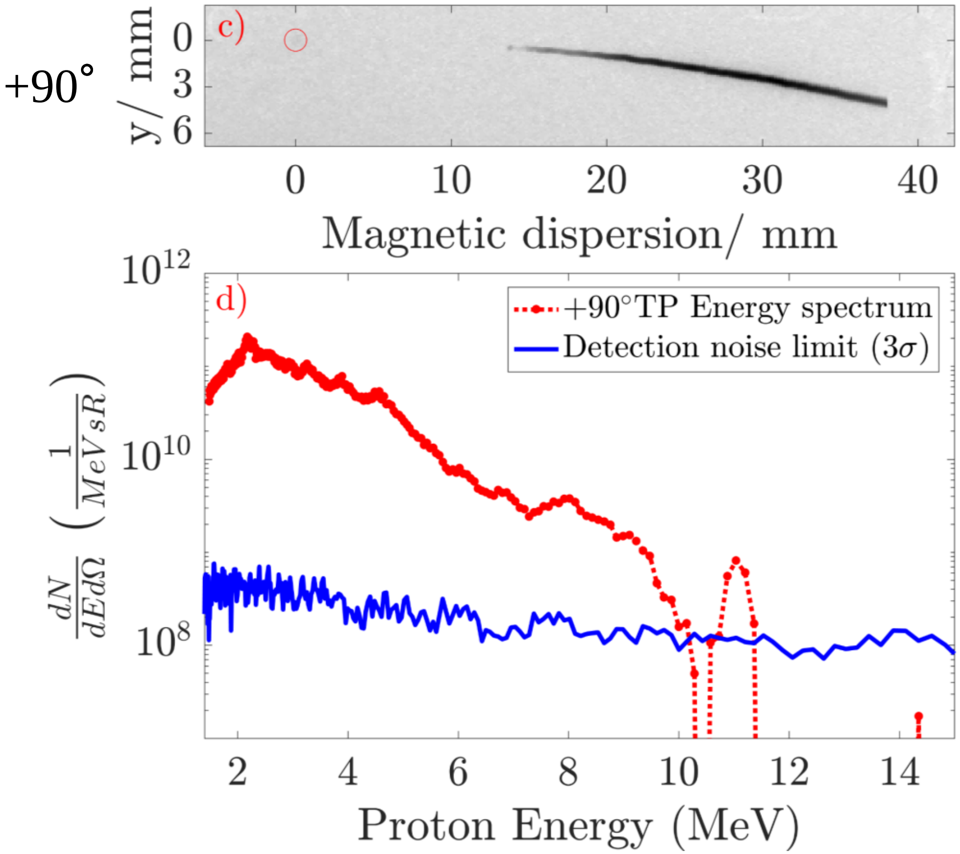


Pure, non-thermal proton spectra observed

No optical shaping

-No forward going protons

-high energy bunch at end of thermal tail at 90 degrees



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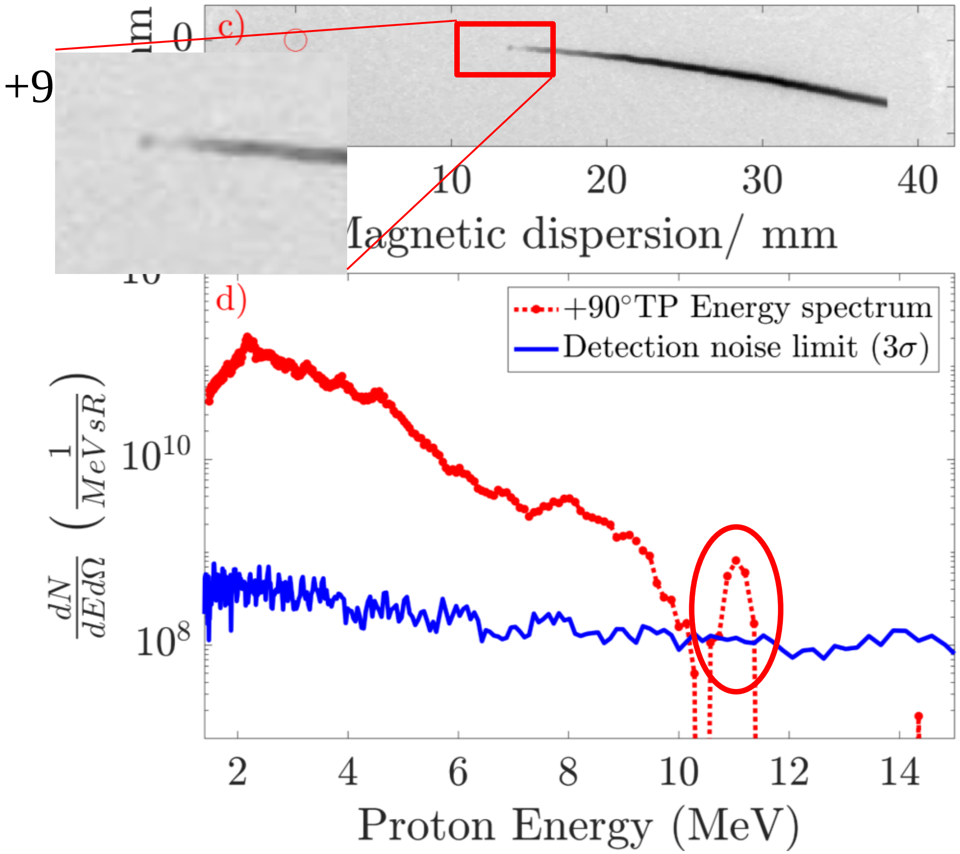

K. Krushelnick et al. PRL 83, 4 (1999)

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

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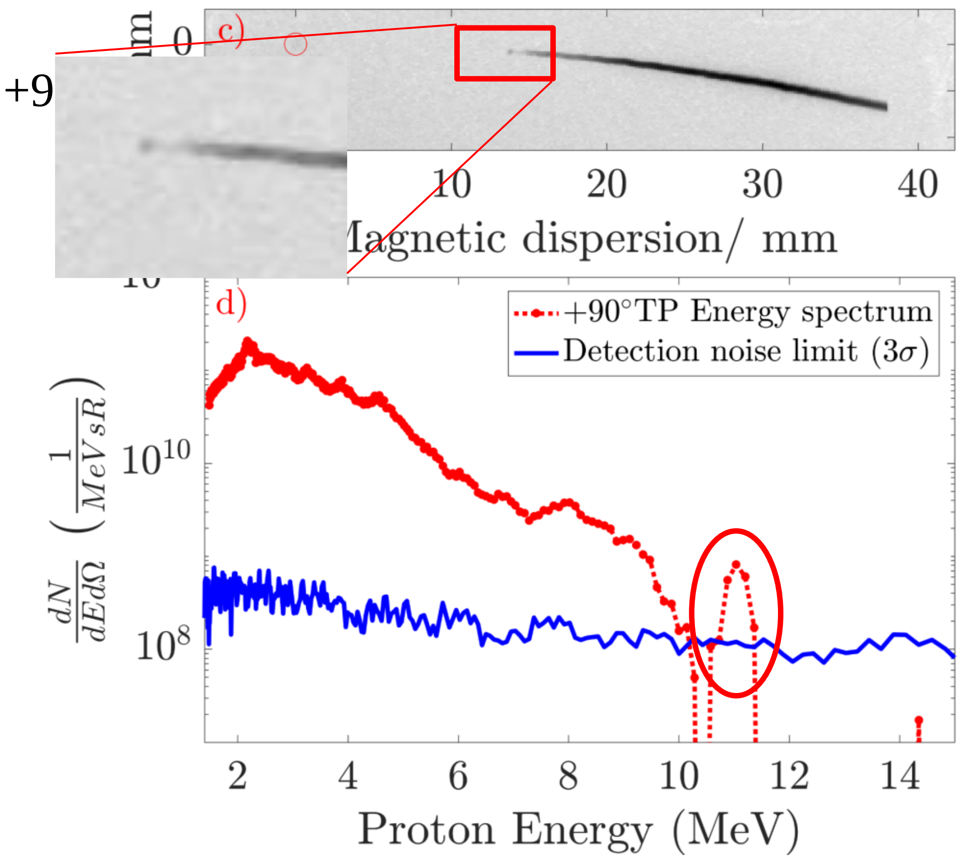
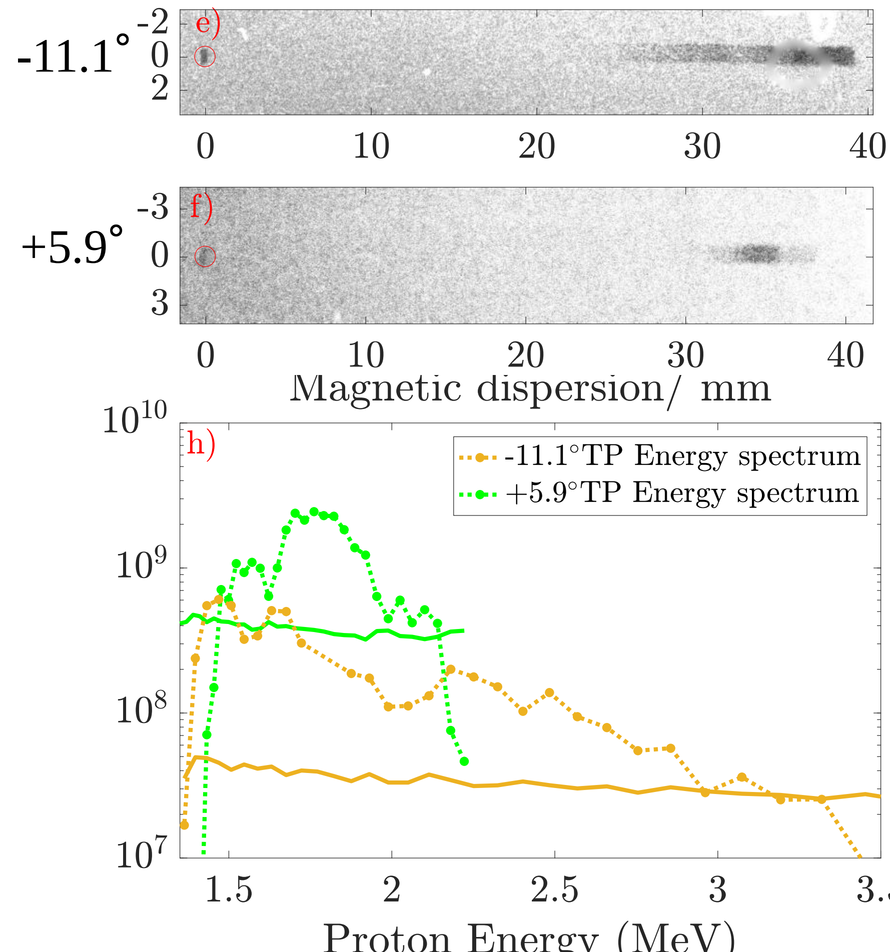


With optical shaping

-No transverse protons

-Single bunch and no thermal tail @5.9°

-Lower energy and lower flux



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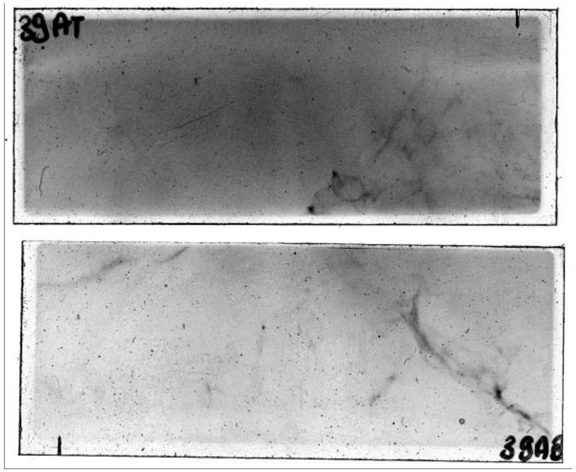
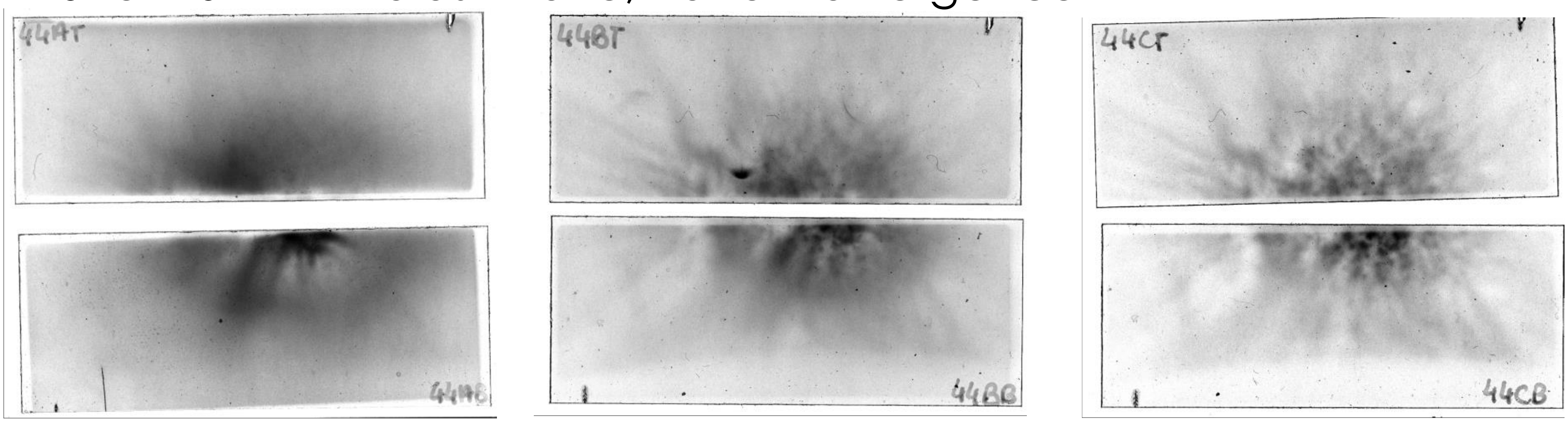
Reproducibility

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

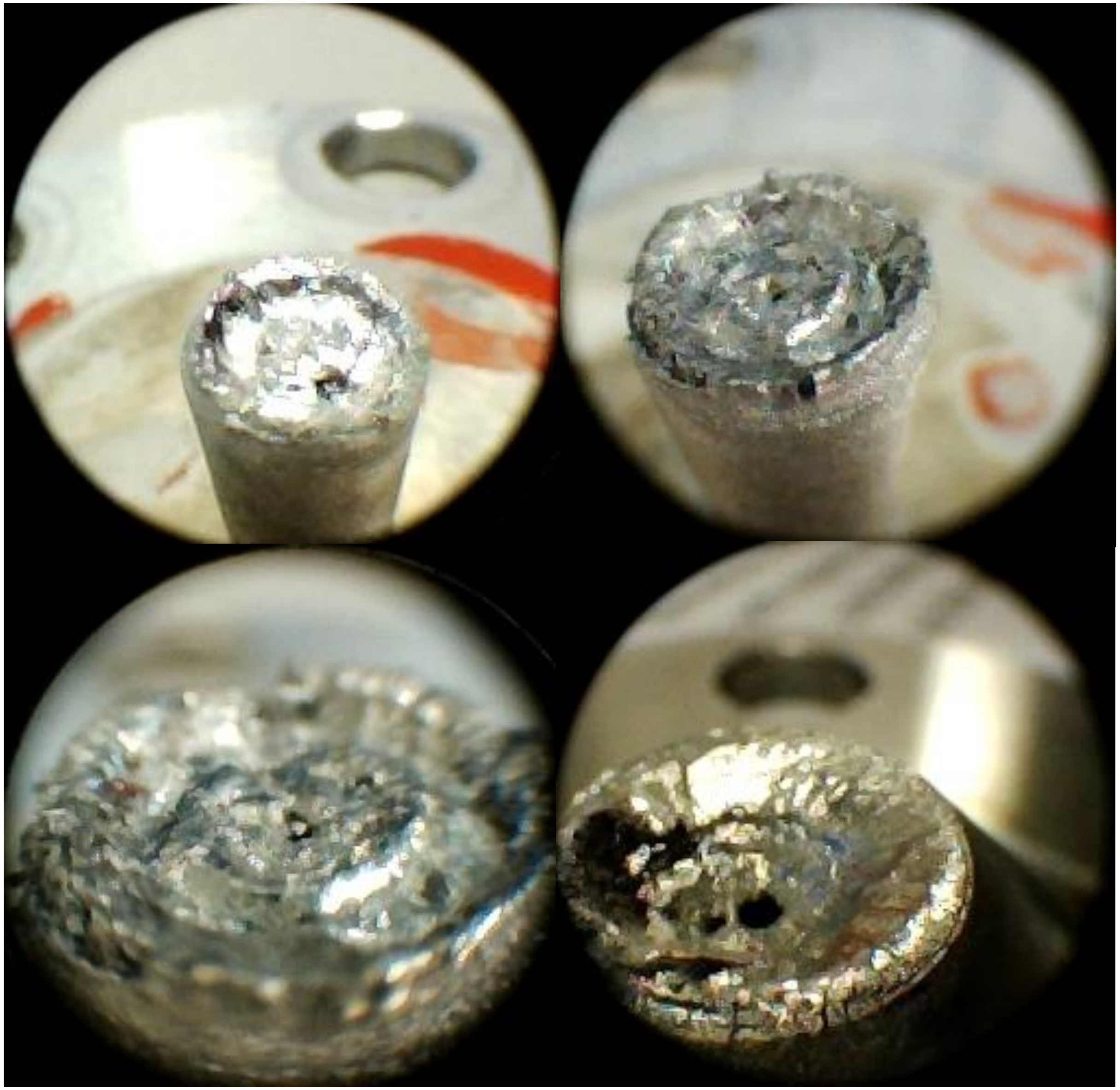
Shot 199- with blast wave, dispersed beam

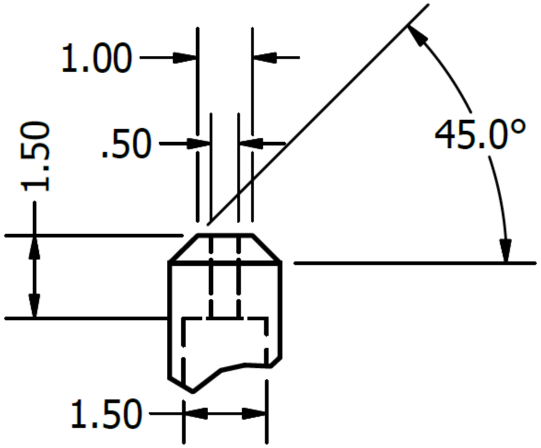


Shot 202- with blast wave, narrow divergence



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 a limit instabilities
  - Mitigate nozzle damage