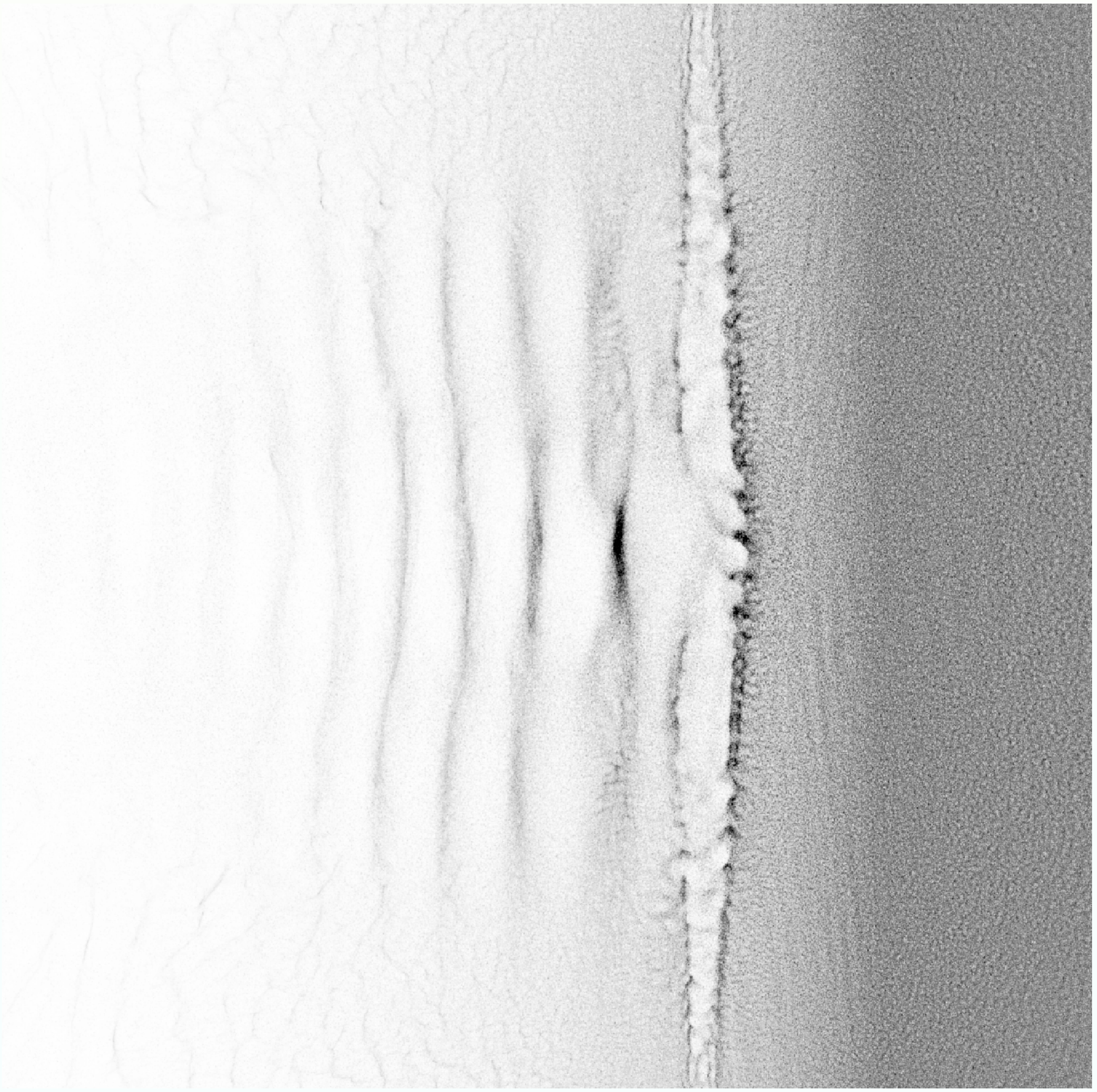
John Adams Institute for Accelerator Science

MURI MIR
MID-INFRARED STRONG-FIELD INTERACTION

Imperial College London

Plasma Gratings For Ion Acceleration



Oliver Ettlinger

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Imperial College London

EAAC

19th September 2019

http://www3.imperial.ac.uk/johnadamsinstitute

Thanks

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N.P. Dover*, E-J. Ditter, G.S. Hicks, Z. Najmudin

BROOKHAVEN NATIONAL LABORATORY
Accelerator Test Facility

M.N. Polyanskiy, I.V. Pogorelsky, M. Babzien

United States Naval Research Laboratory

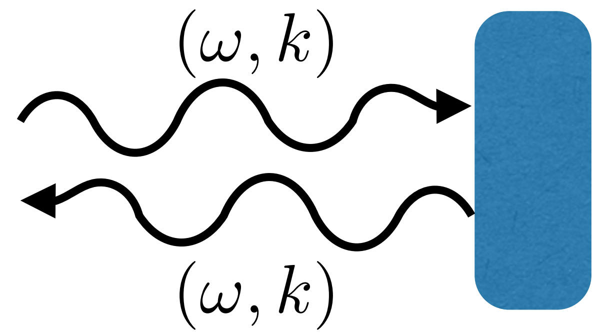
Y. Chen, M.H. Helle, A. Ting, D.F. Gordon

*now at QST, Japan

Some Motivation…

- Shock based acceleration schemes offer improved ion energy scaling…

$$\Delta p = (1 + R)\hbar k$$



$$f_p = \frac{-e^2}{2m_e {\omega_L}^2}\nabla E^2$$

$$P_R = (1 + R)(I/c)$$

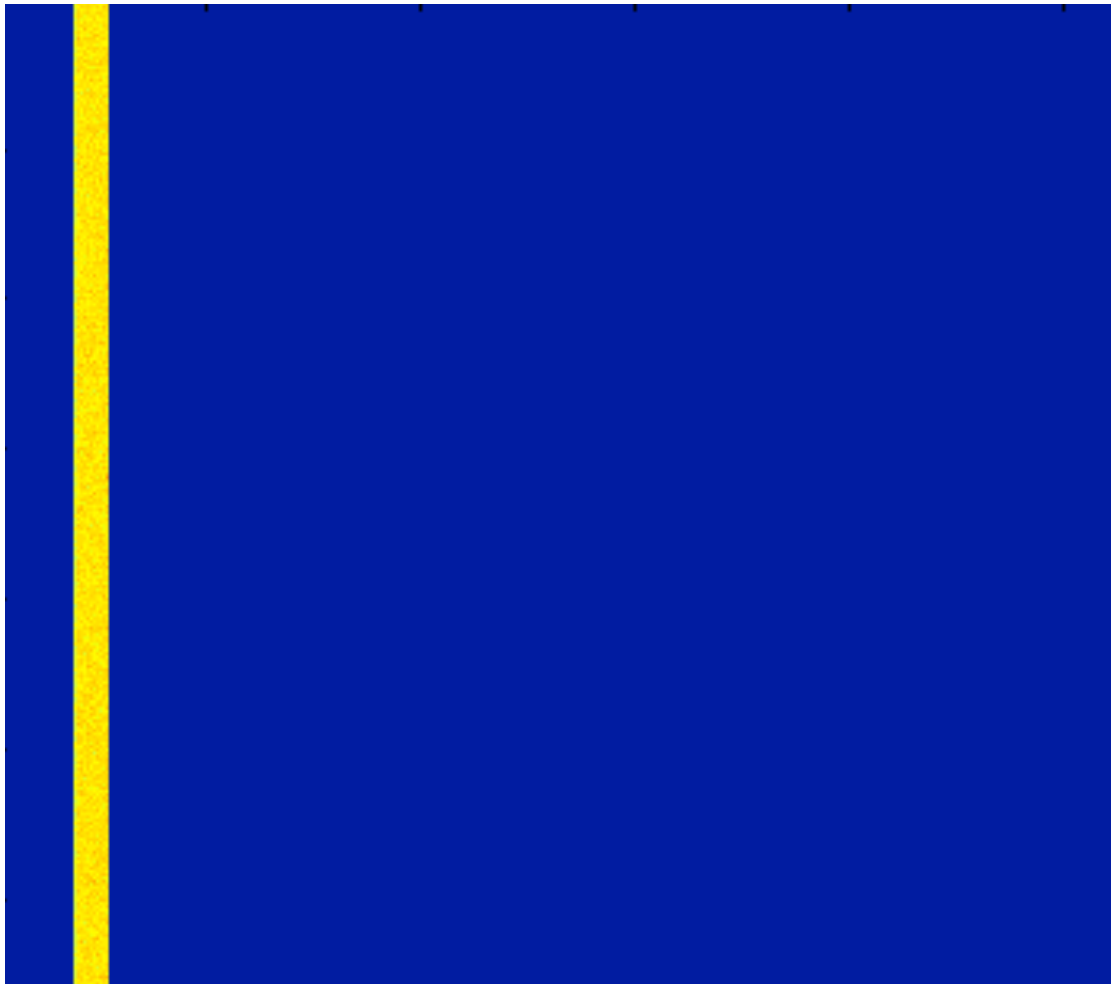
Electrons snowploughed into target, forming space charge field and accelerating ions

For thick targets, hole-boring: $E_i \propto \frac{I}{n}$

For thin targets, light-sail: $E_i \propto \frac{I^2}{n}$

Some Motivation…

When things work well:



For thin targets:

$$E_i \propto \frac{I^2}{n_i}$$

Some Motivation…

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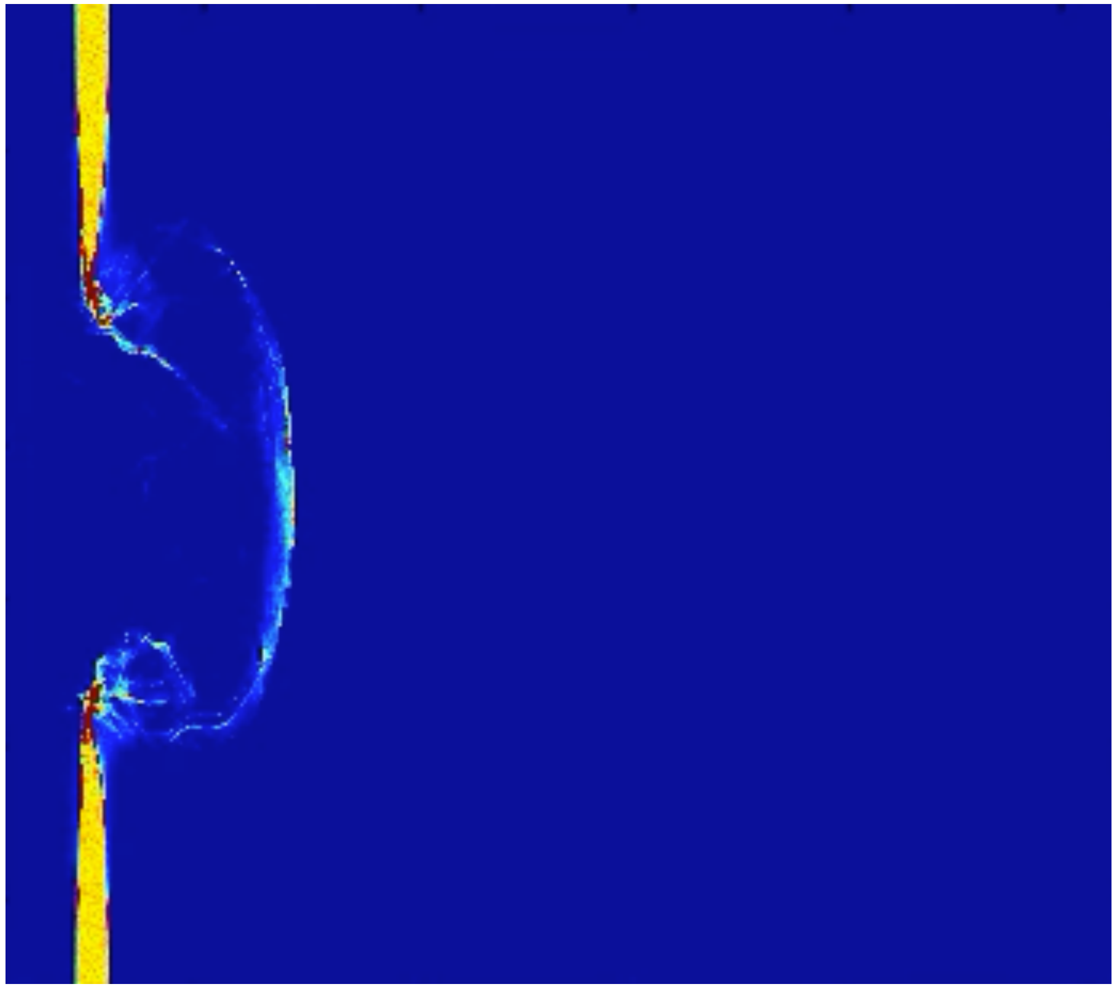


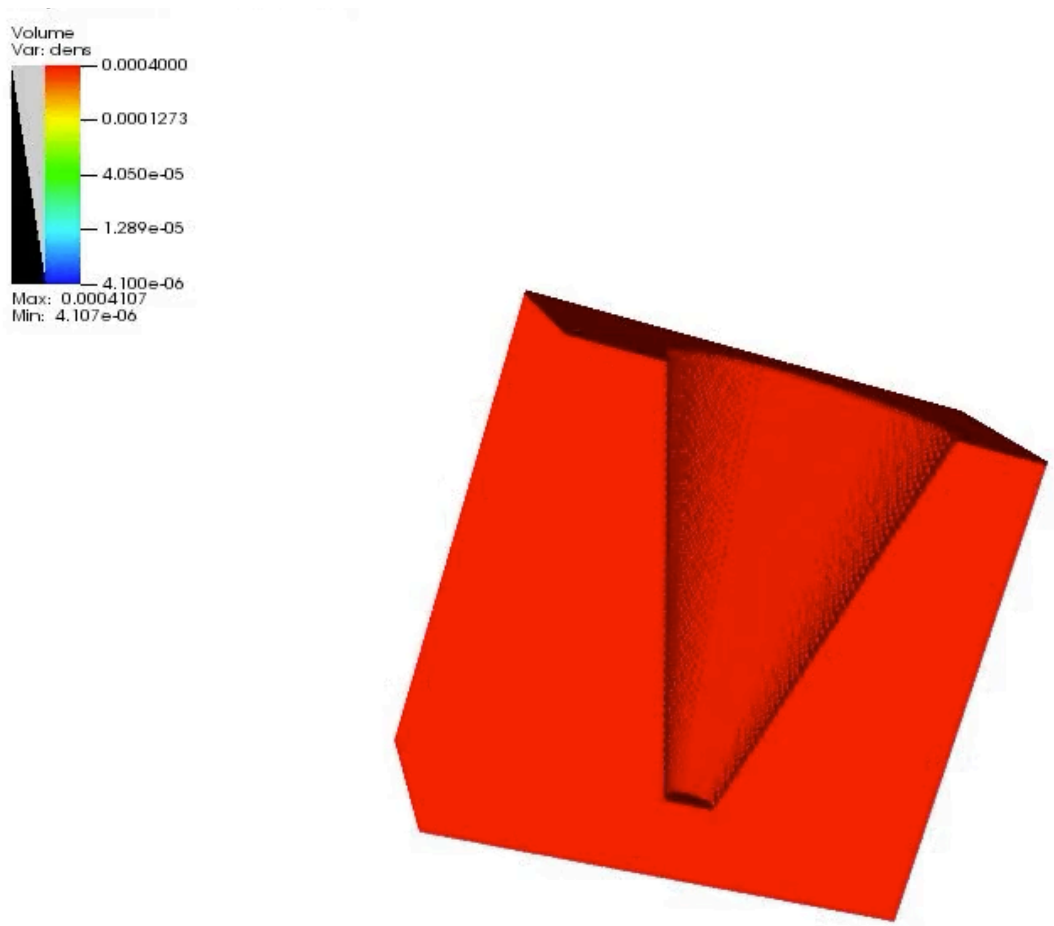
For thin targets:

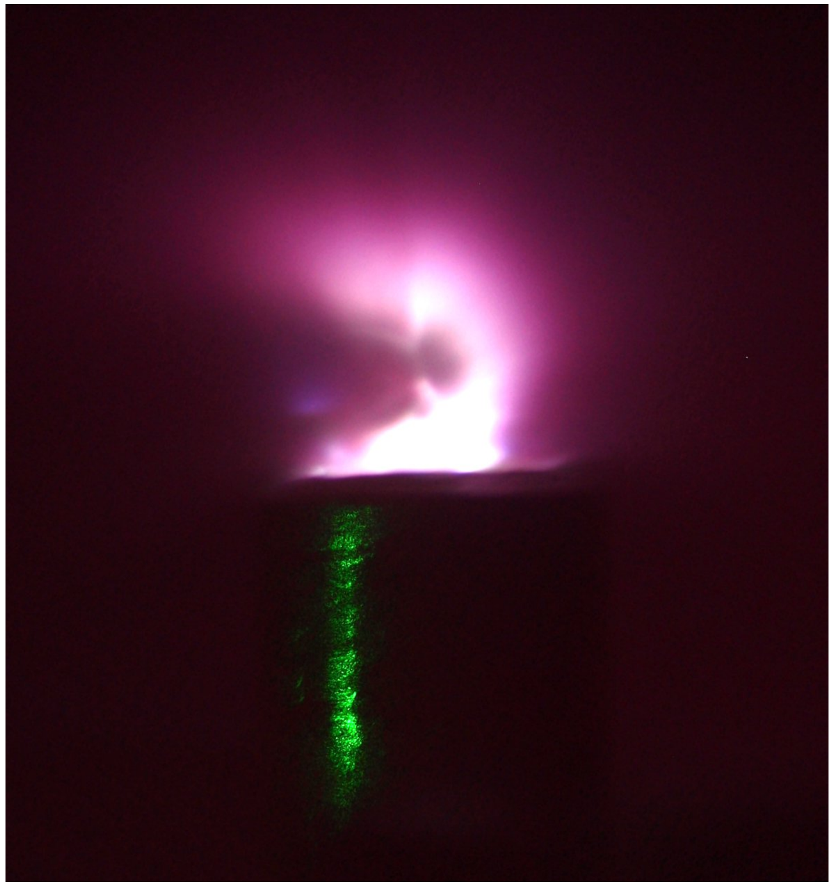
$$E_i \propto \frac{I^2}{n_i}$$

Typically requires thin-foils - low repetition rate…

Gas Targets

- Benefits:
  - High repetition rate; Low debris; Single, easily variable ion species; Simple density variation





Courtesy Robbie Watt, Imperial

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Gas Targets

- Benefits:
  - High repetition rate; Low debris; Single, easily variable ion species; Simple density variation
- Drawbacks:
  - Sub-optimal density profile - long scale lengths; hard to achieve over-critical densities

Gas Targets

- Benefits:
  - High repetition rate; Low debris; Single, easily variable ion species; Simple density variation
- Drawbacks:
  - Sub-optimal density profile - long scale lengths, hard to achieve over-critical densities

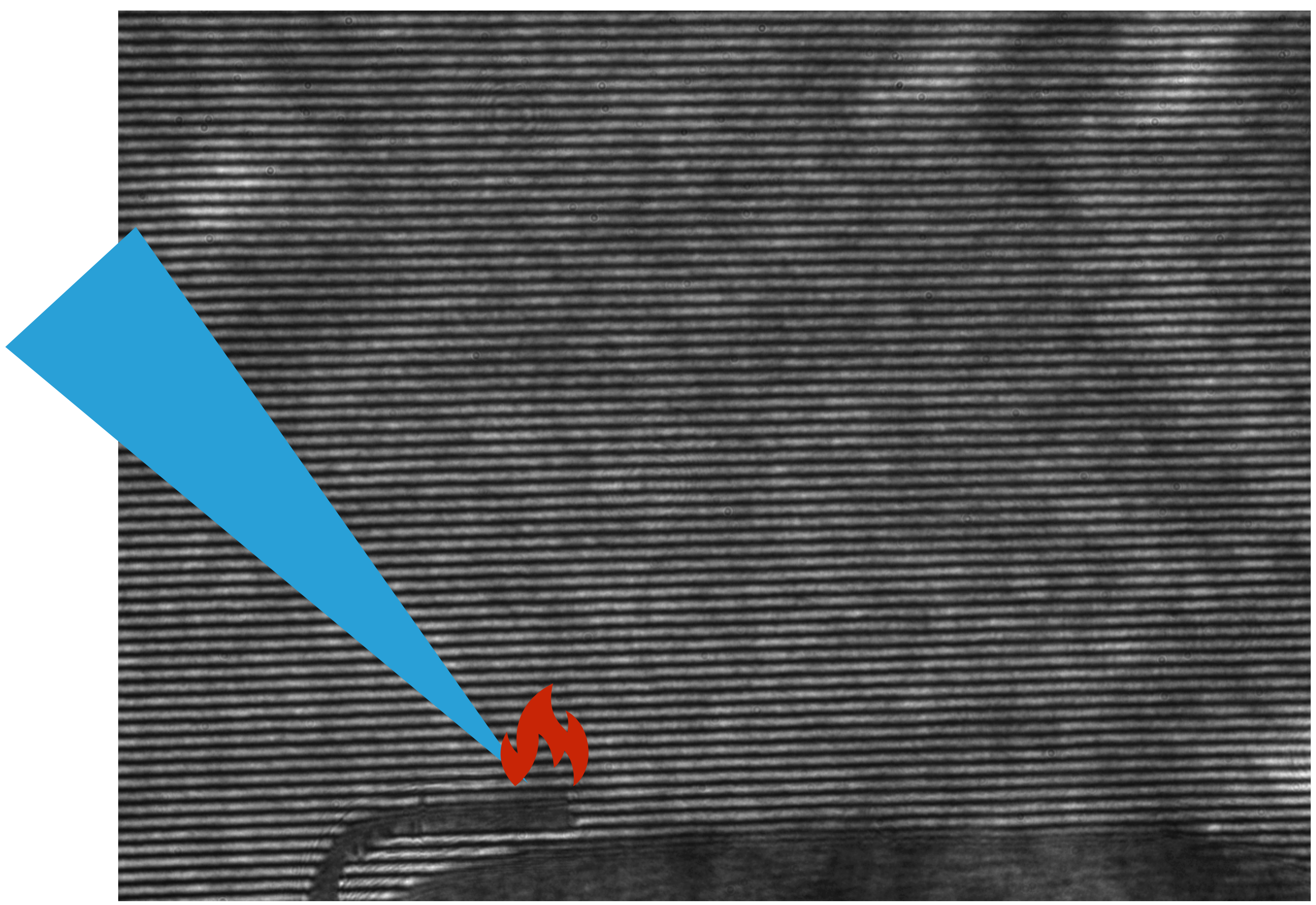
Longer laser wavelengths

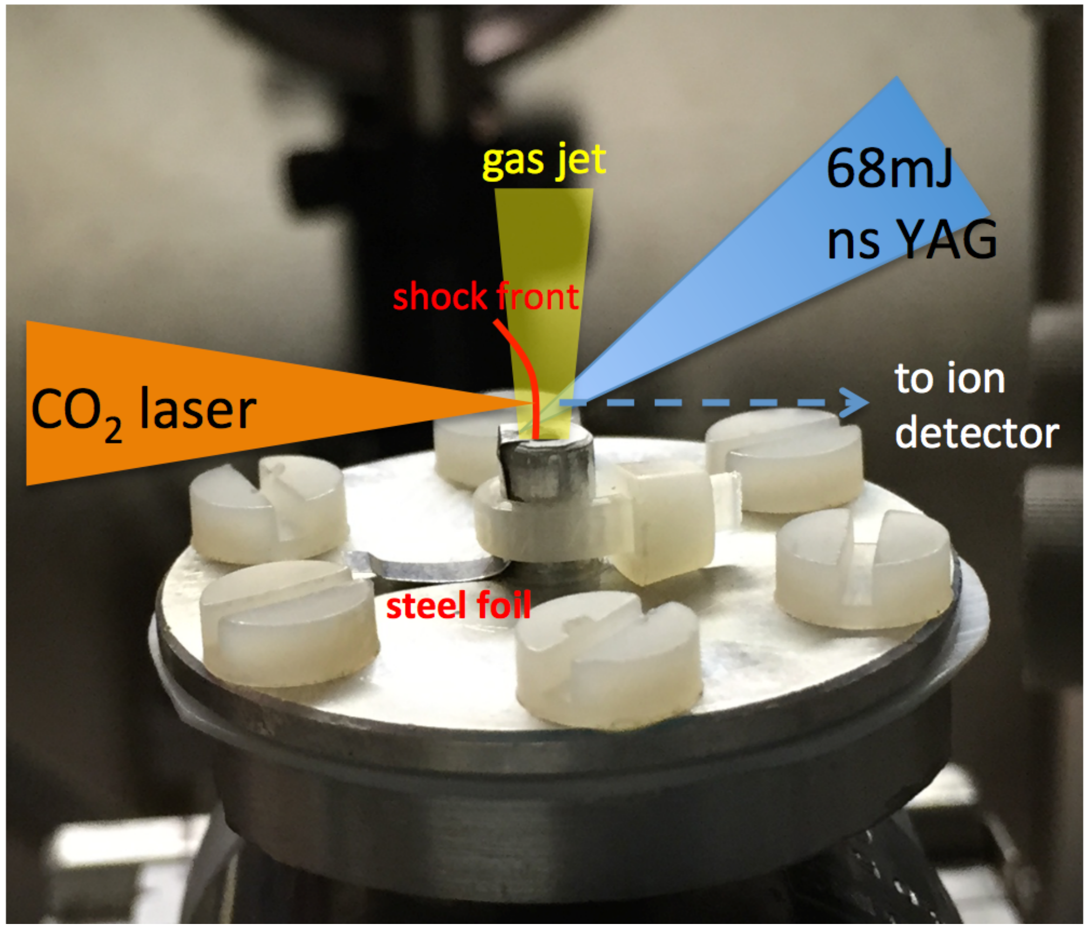
$$n_c \propto \frac{1}{\lambda^2}$$

Modify gas profile - or take advantage of it?

Gas Targets

- Both of these can be overcome with target shaping

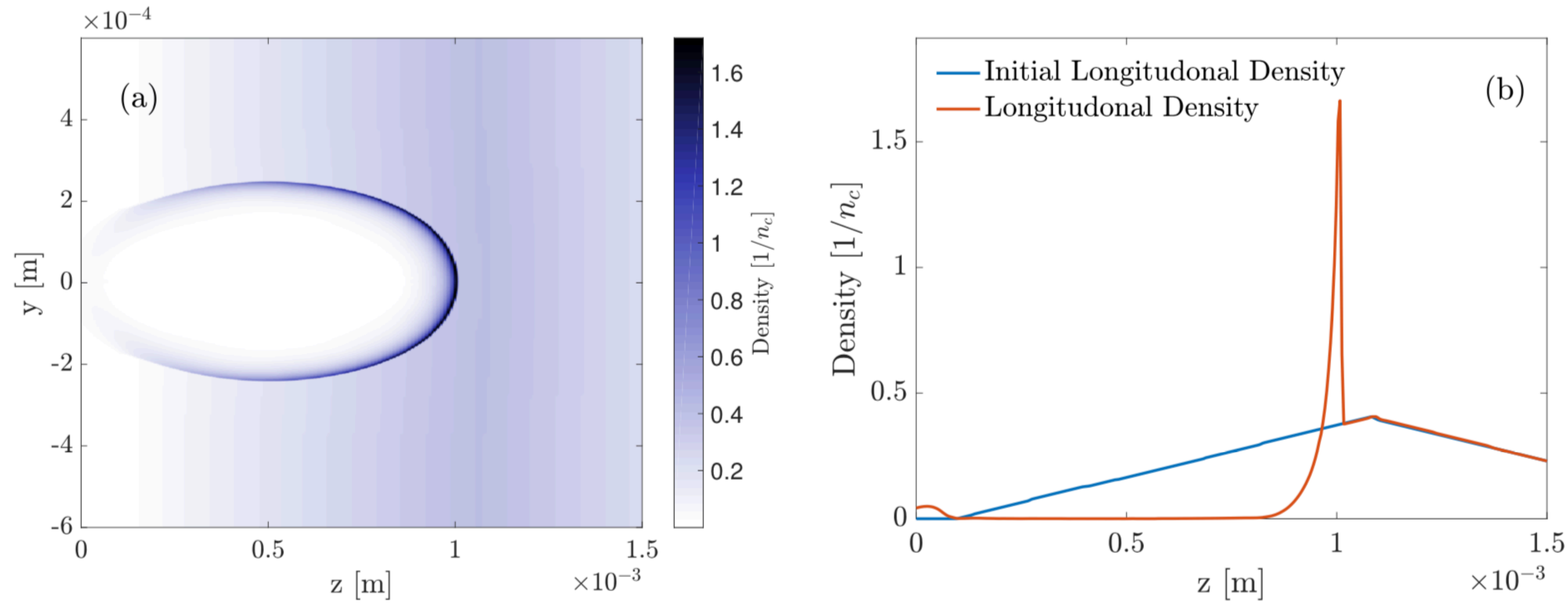




- Blast wave - self-similar shock expansion - properties well defined

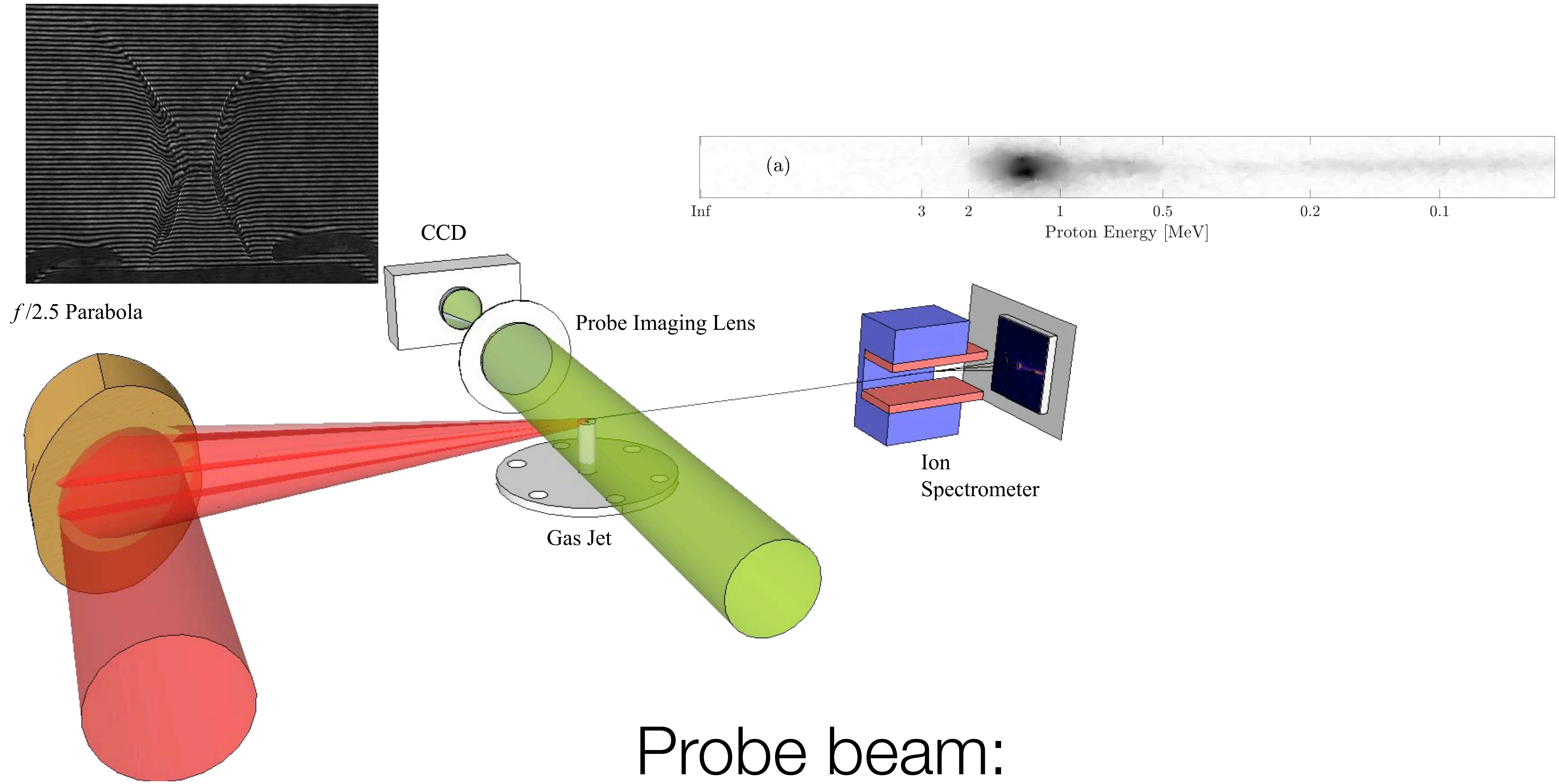
Gas Targets

- Both of these can be overcome with target shaping



- Self-similar expansion - shock properties well defined

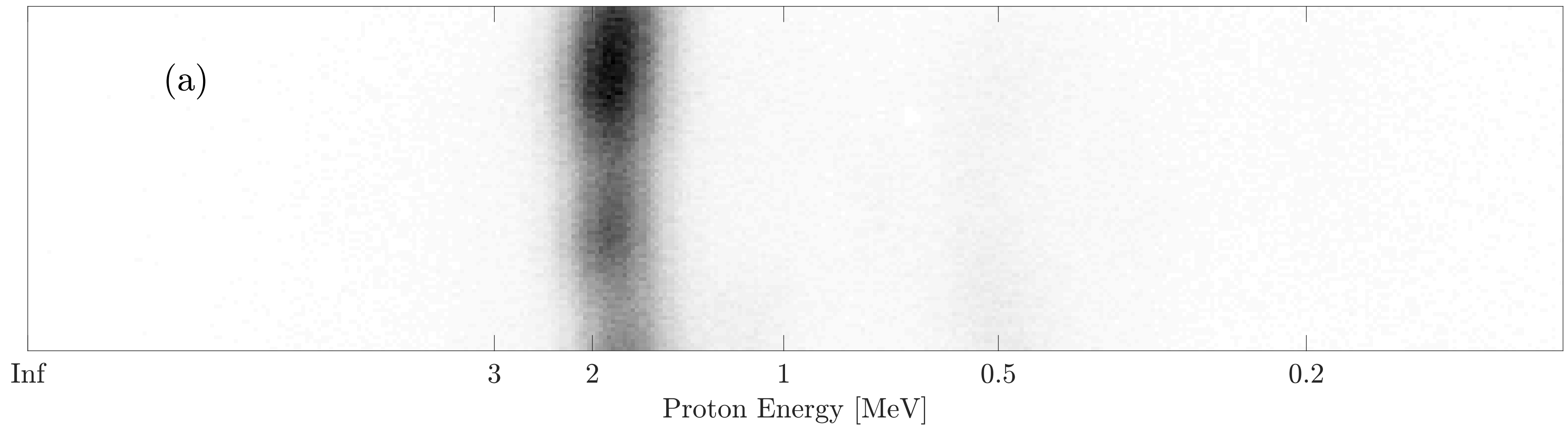
Experimental Layout



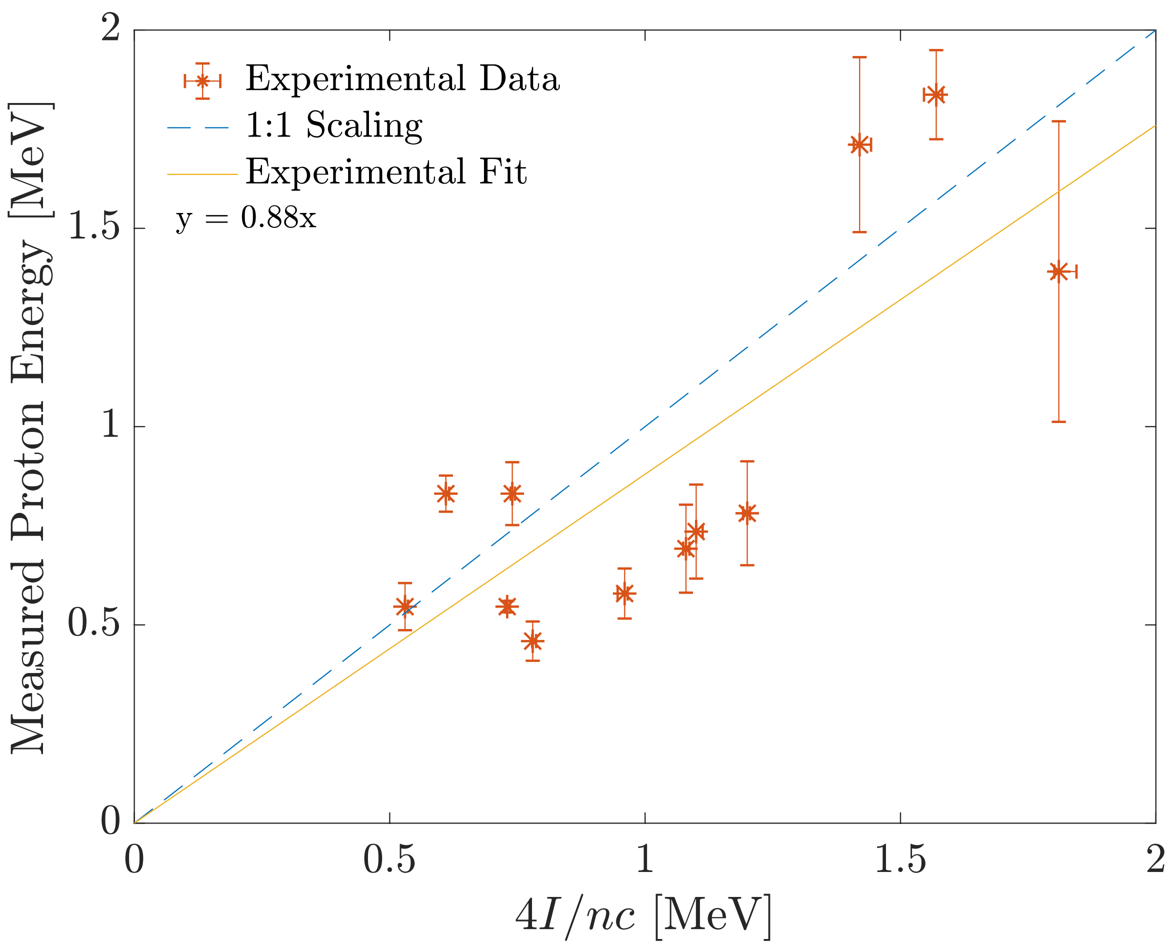
CO_2 beam:
$\lambda = 10.6\ \mu m$,
1.1J in 5ps, ~0.2TW
$I = 5.9\times10^{15}\ Wcm^{-2}$

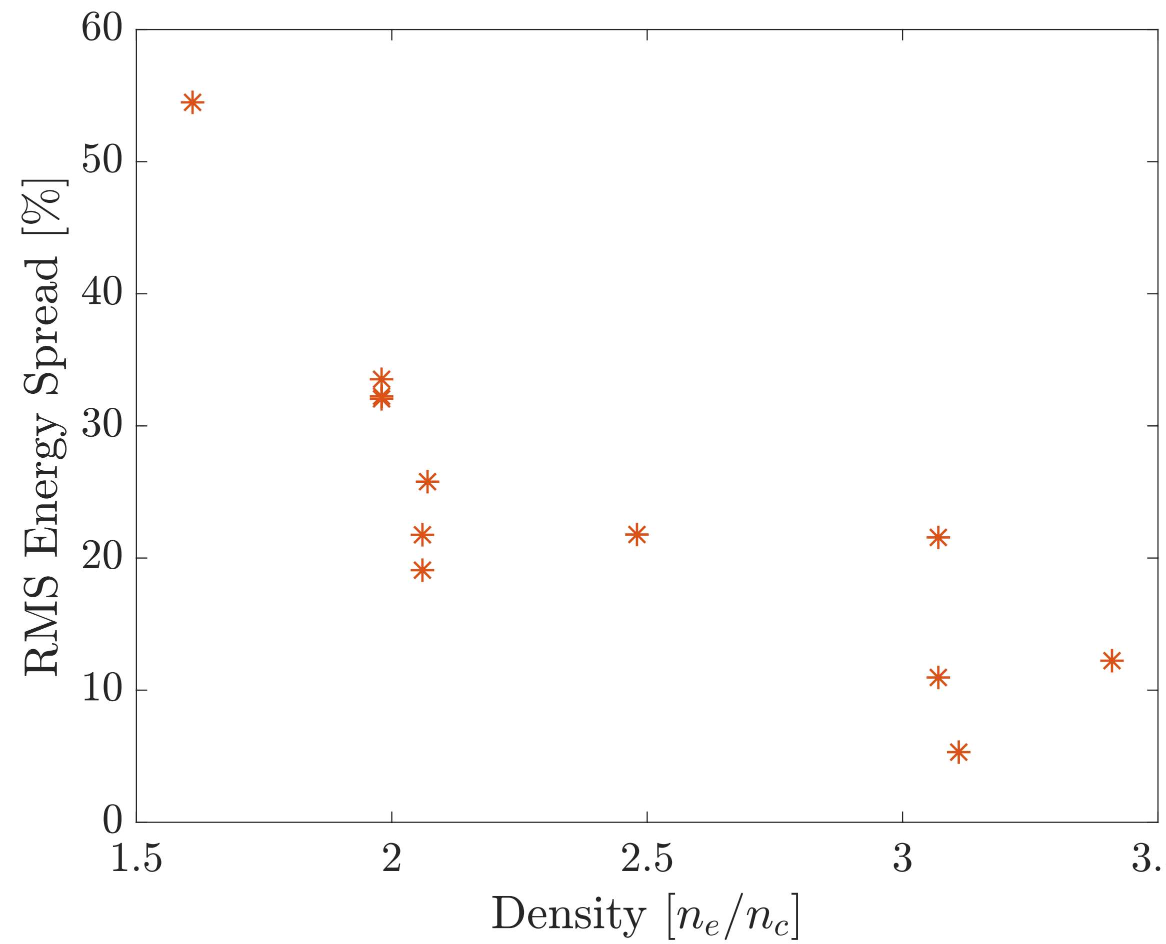
Probe beam:
$\lambda = 532$ nm,
14ps

Works well in HB scheme



$$E_i = \frac{4I}{n_i c}$$





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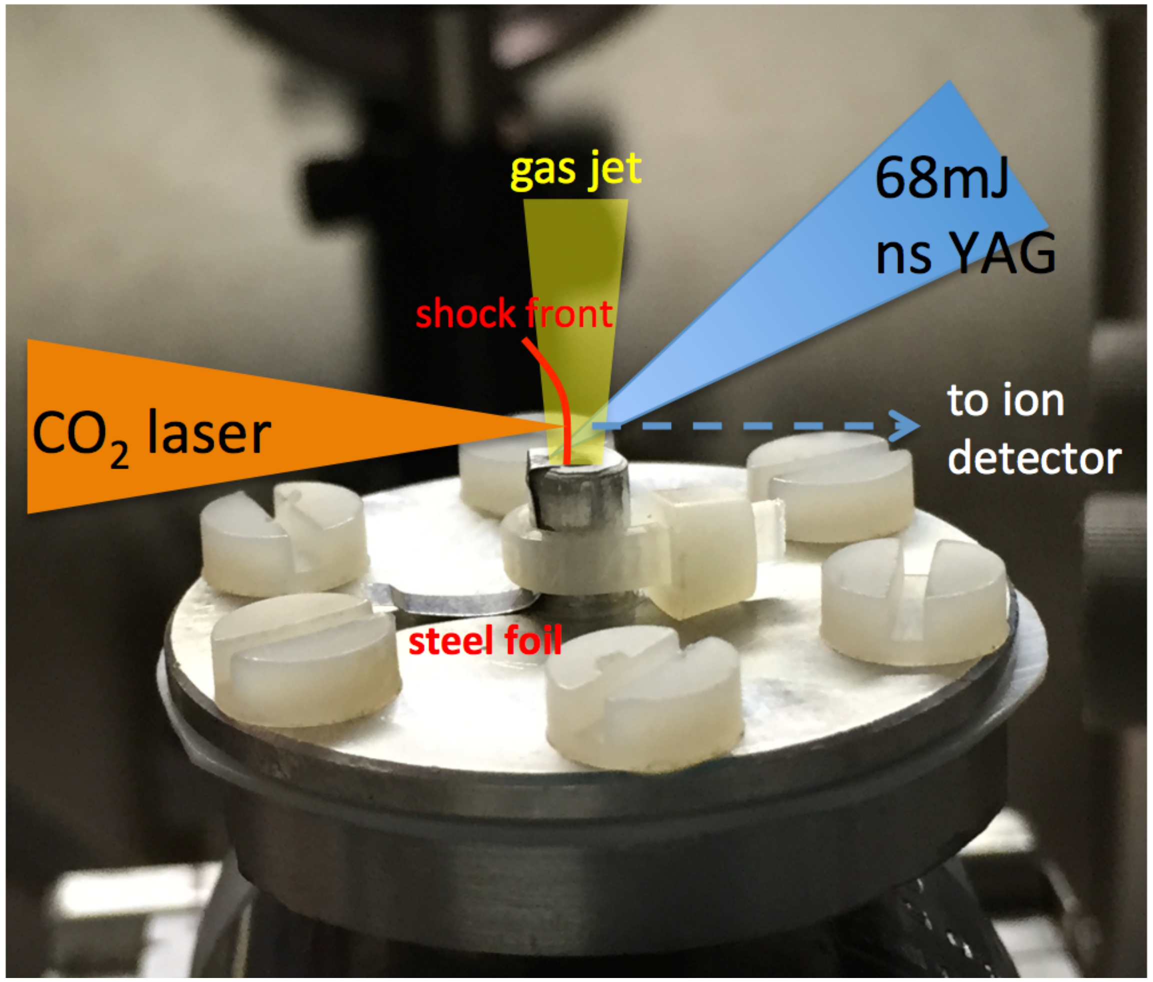
Can we improve further?

- Make ‘thin’ near-critical targets to exploit the light-sail regime to exploit better scaling?



$$L_{opt} \sim \sqrt{\frac{I_L}{n_i^2}}$$

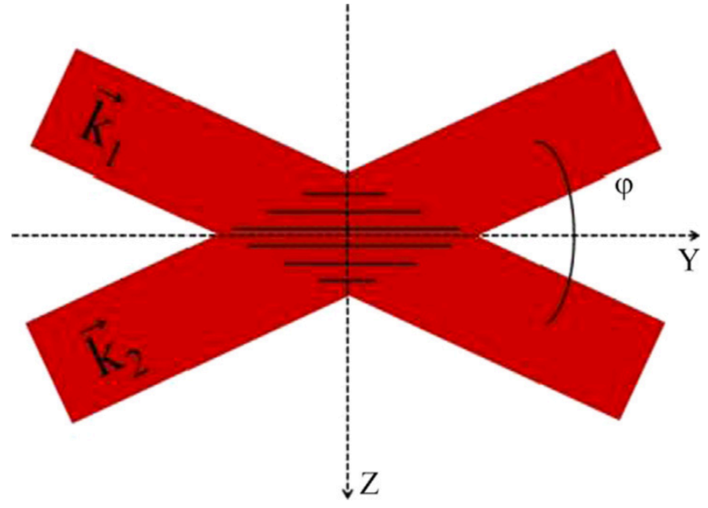
$$\approx 1\ \mu m$$

Typical scale of shocked gas structure ~100μm

→ too big!

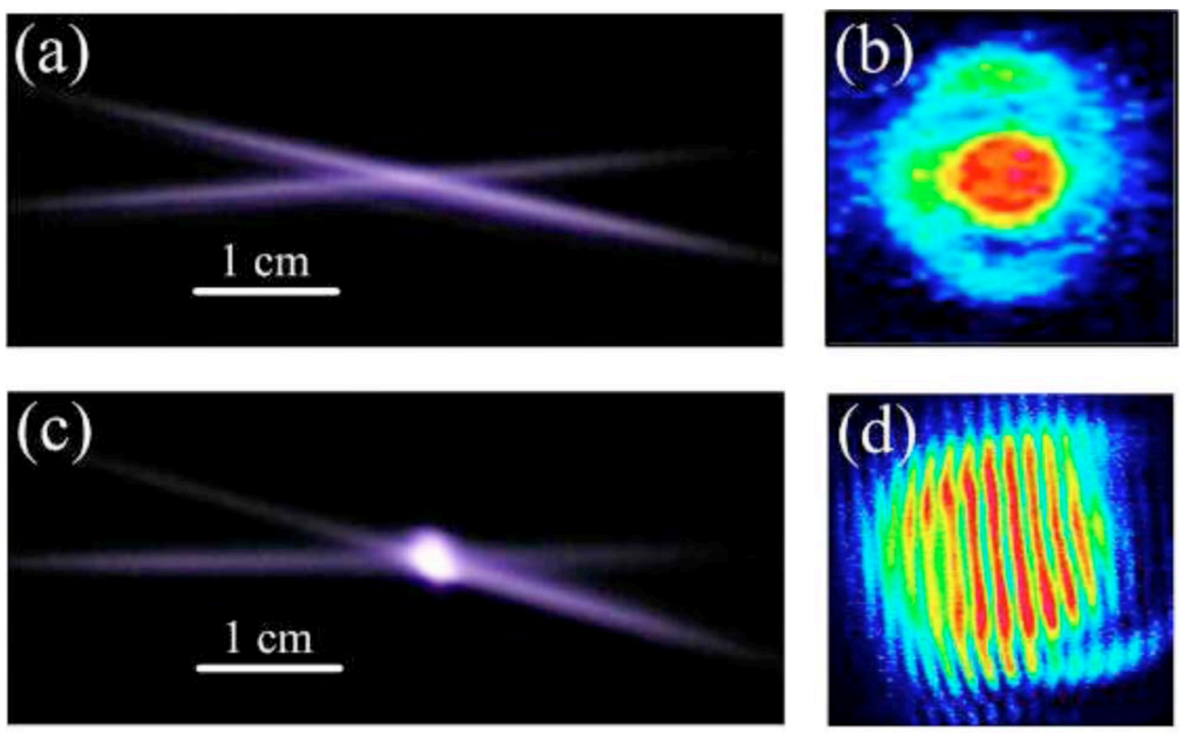
Plasma Gratings

- Studied theoretically and experimentally for use as an alternative for high intensity laser pulse stretching/ compression



$$\Psi(y,z) = A_1 exp\left(ikz\cos\frac{\phi}{2} + ikz\sin\frac{\phi}{2}\right) + A_2 exp\left(ikz\cos\frac{\phi}{2} - ikz\sin\frac{\phi}{2}\right)$$

Jarnac et al. *Optics Comms.* **312** (2014)



Top view Transverse view

Yang et al. *Optics Lett.* **34** (2009)

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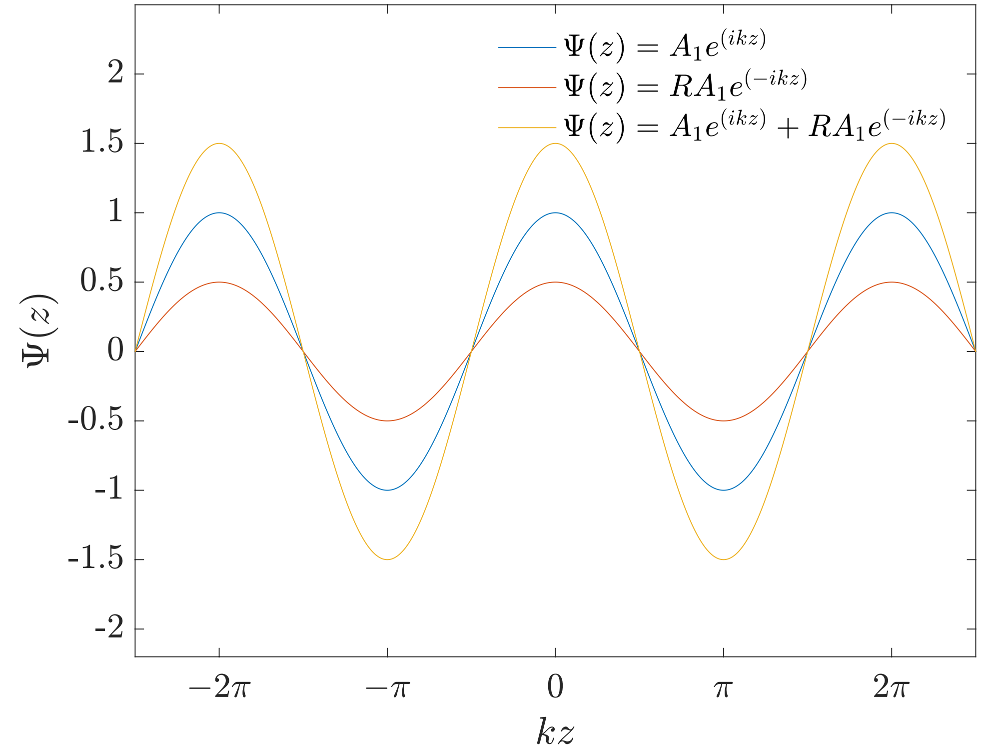
Plasma Gratings - Standing Wave

- What if a single, slowly varying pulse incident on the critical surface of a plasma?

$$\Psi(z) = \underbrace{A_1 exp\,(ikz)}_{\text{Incident beam}} + \underbrace{[R \cdot A_1]\ exp\,(-ikz)}_{\text{Reflected beam}}$$

$R = \text{Reflection coefficient}$

$\text{Intensity} = |\Psi(z)|^2$



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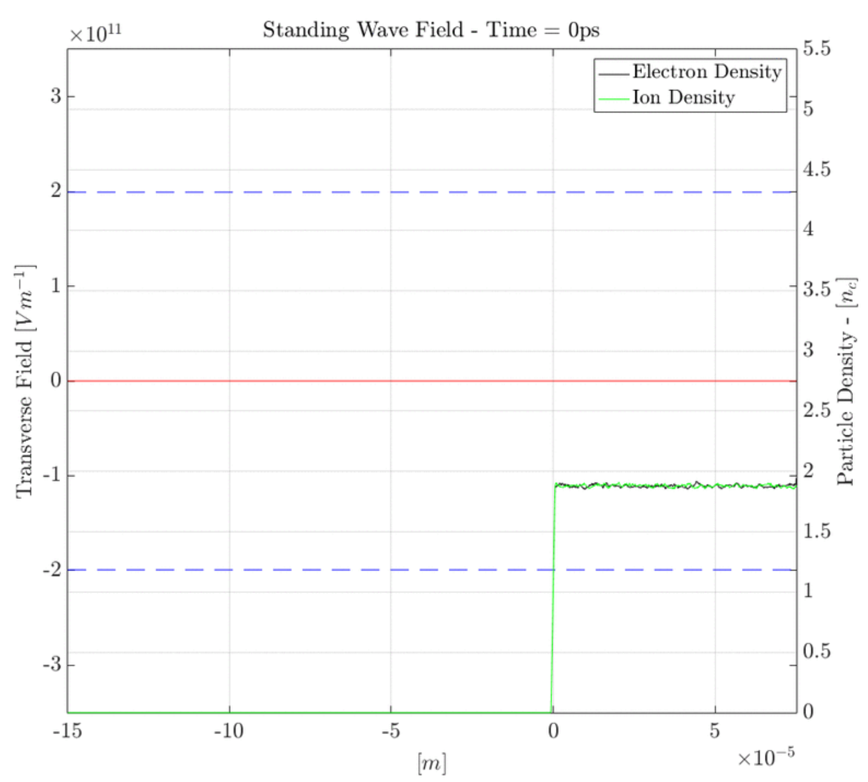
Plasma Gratings - Standing Wave in Vacuum

- What if a single, slowly varying pulse incident on the critical surface of a plasma?

$$\Psi(z) = \underbrace{A_1 exp\,(ikz)}_{\text{Incident beam}} + \underbrace{[R \cdot A_1]\; exp\,(-ikz)}_{\text{Reflected beam}}$$

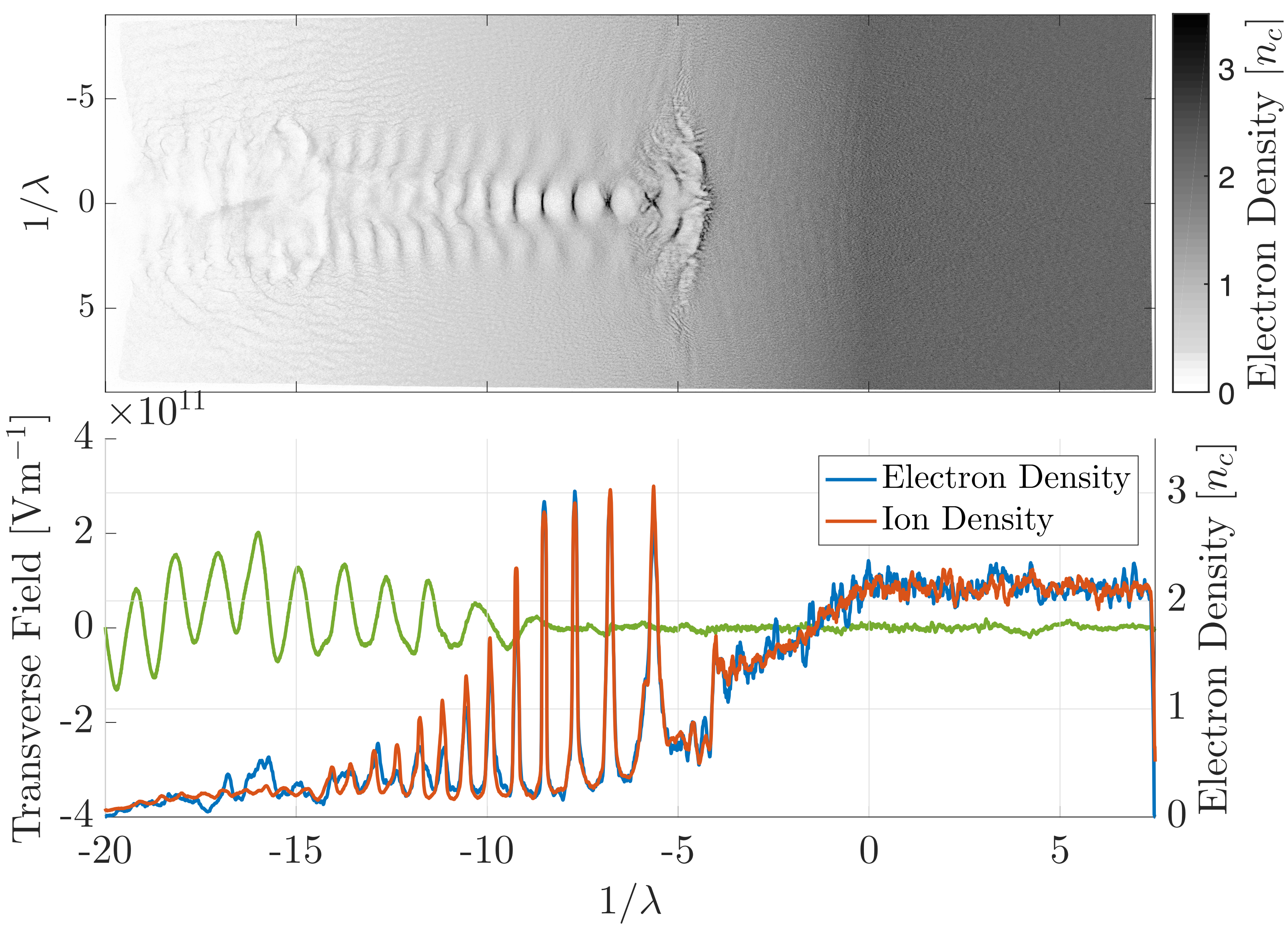
$R = \text{Reflection coefficient}$

$\text{Intensity} = |\Psi(z)|^2$



Plasma Gratings

- In the presence of an under-dense plasma, the ponderomotive force leads to grating formation



C. S. Brady and T. D. Arber, PPCF, **53**, 2011

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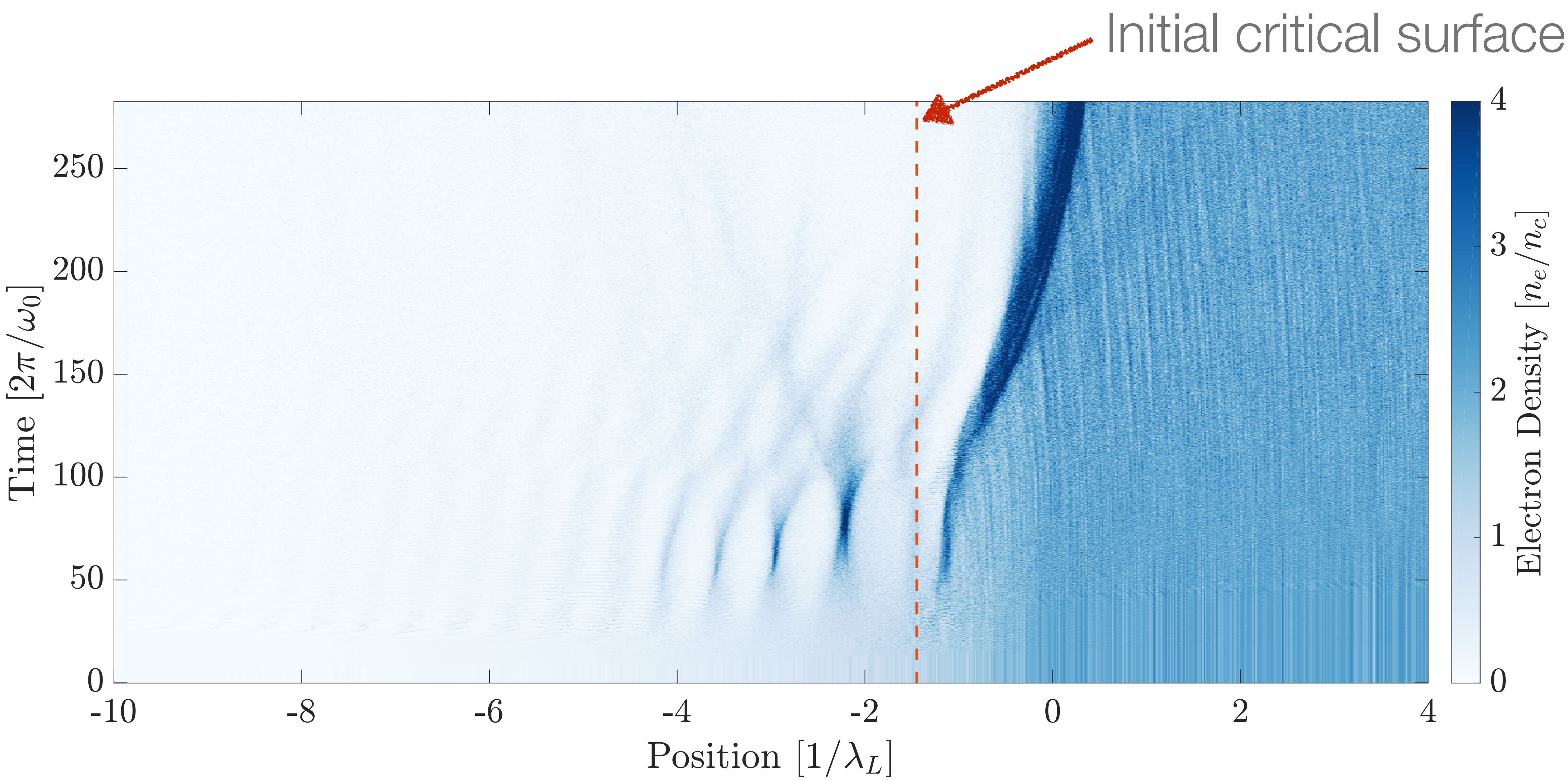
Plasma Gratings

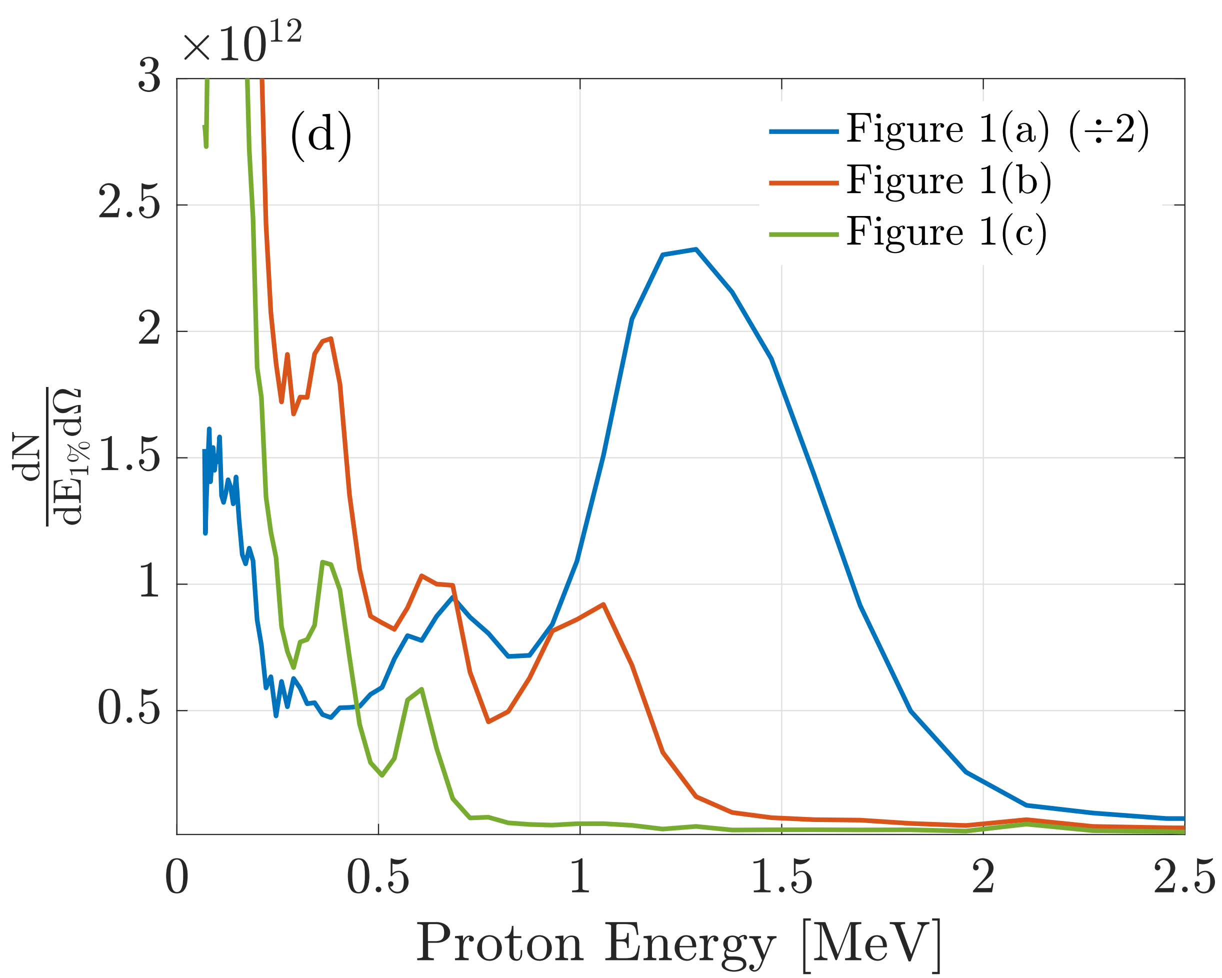
- Structures are transient, lasting only a few picoseconds
- Width of the grating elements of the order a few microns

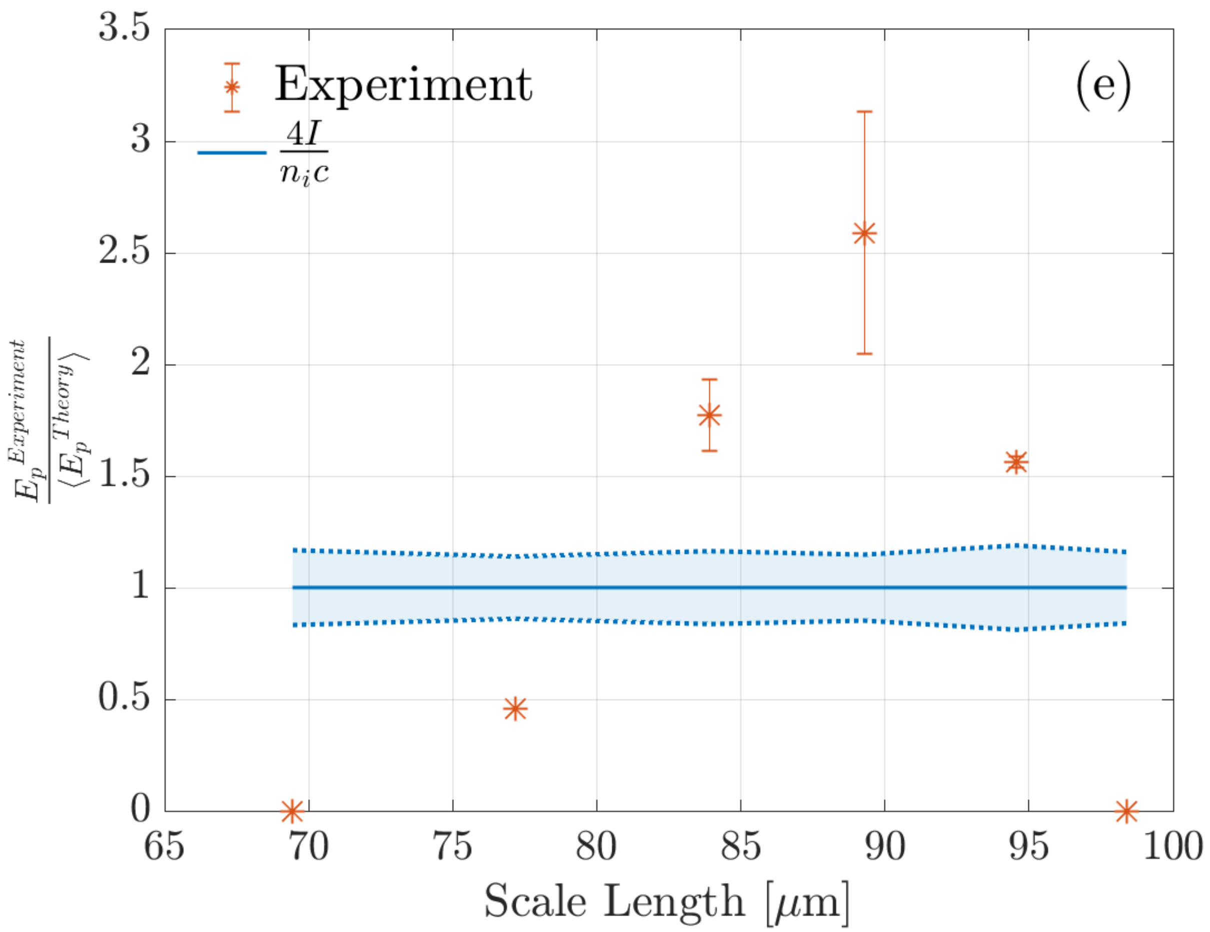


Experimental Signatures

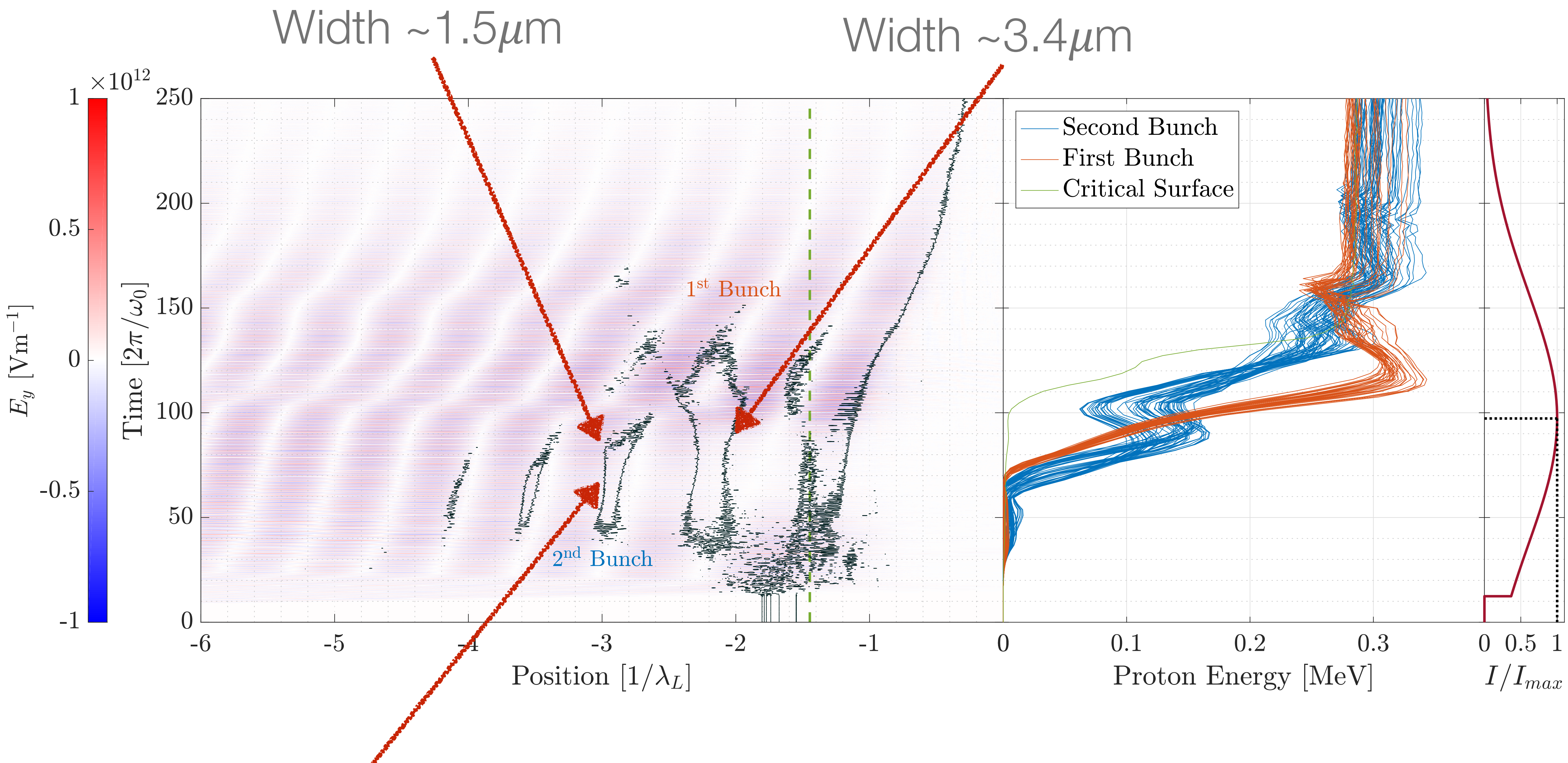
- Multiple ion spectral features
- Higher than expected HB proton energy scaling

$$E_i = \frac{4I}{nc}$$





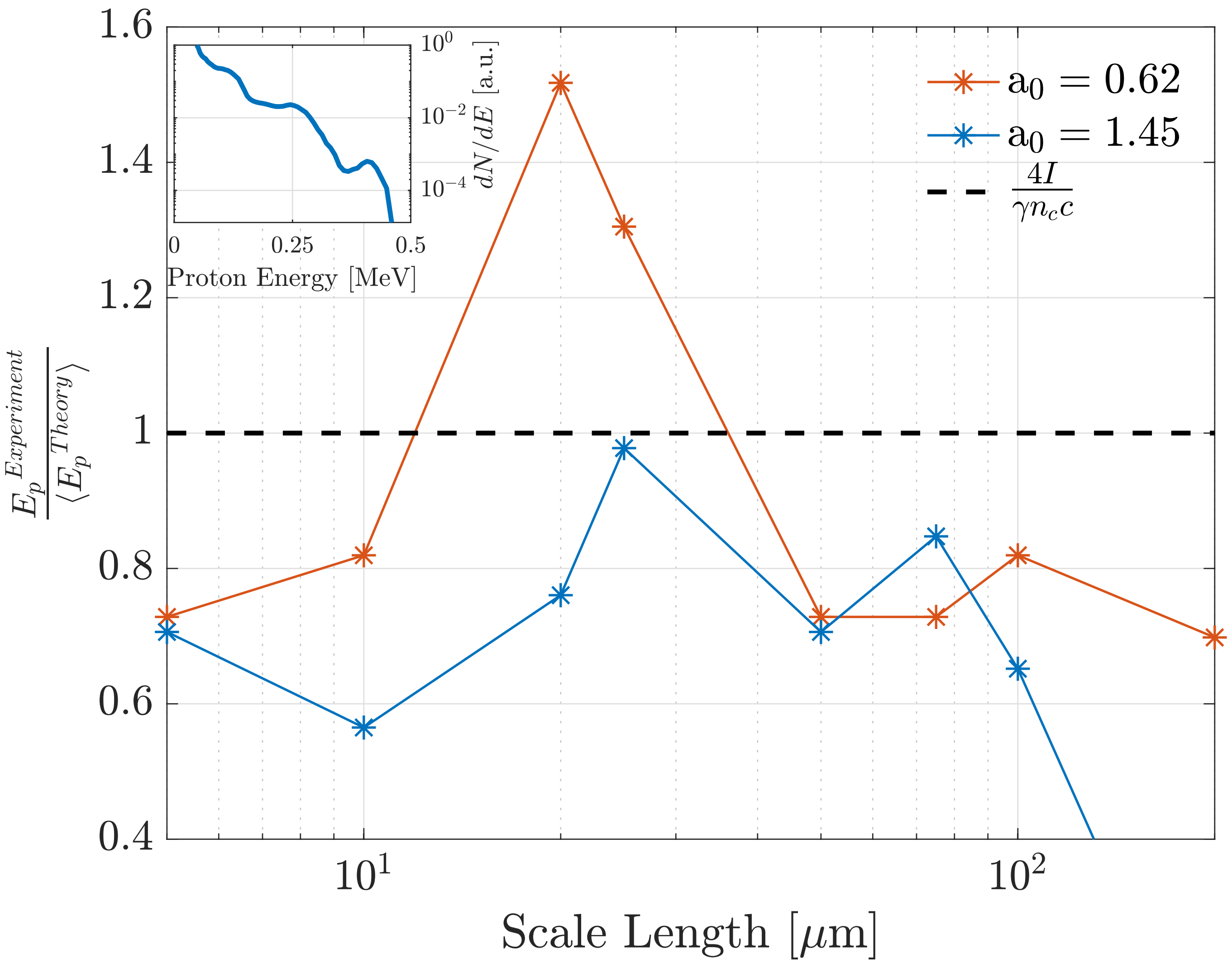
Experimental Signatures - Explanation

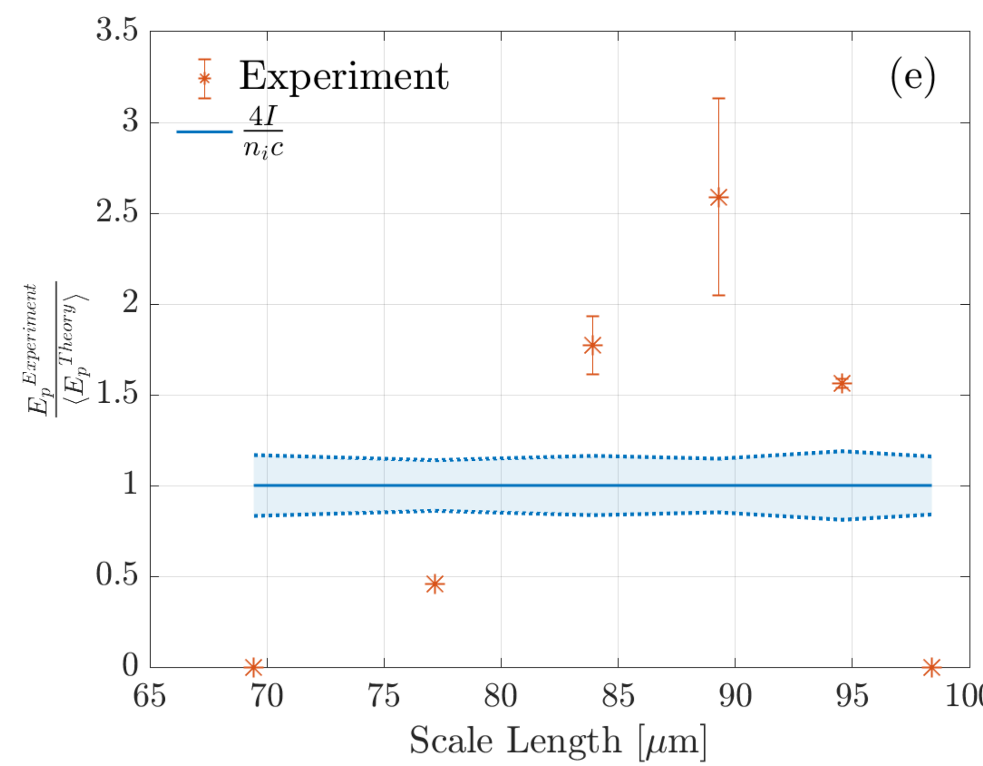


Initial energy gain agrees well with predicted LS scaling → Although actual picture in this case more complicated

Experimental Signatures - Explanation

- Multiple ion spectral features



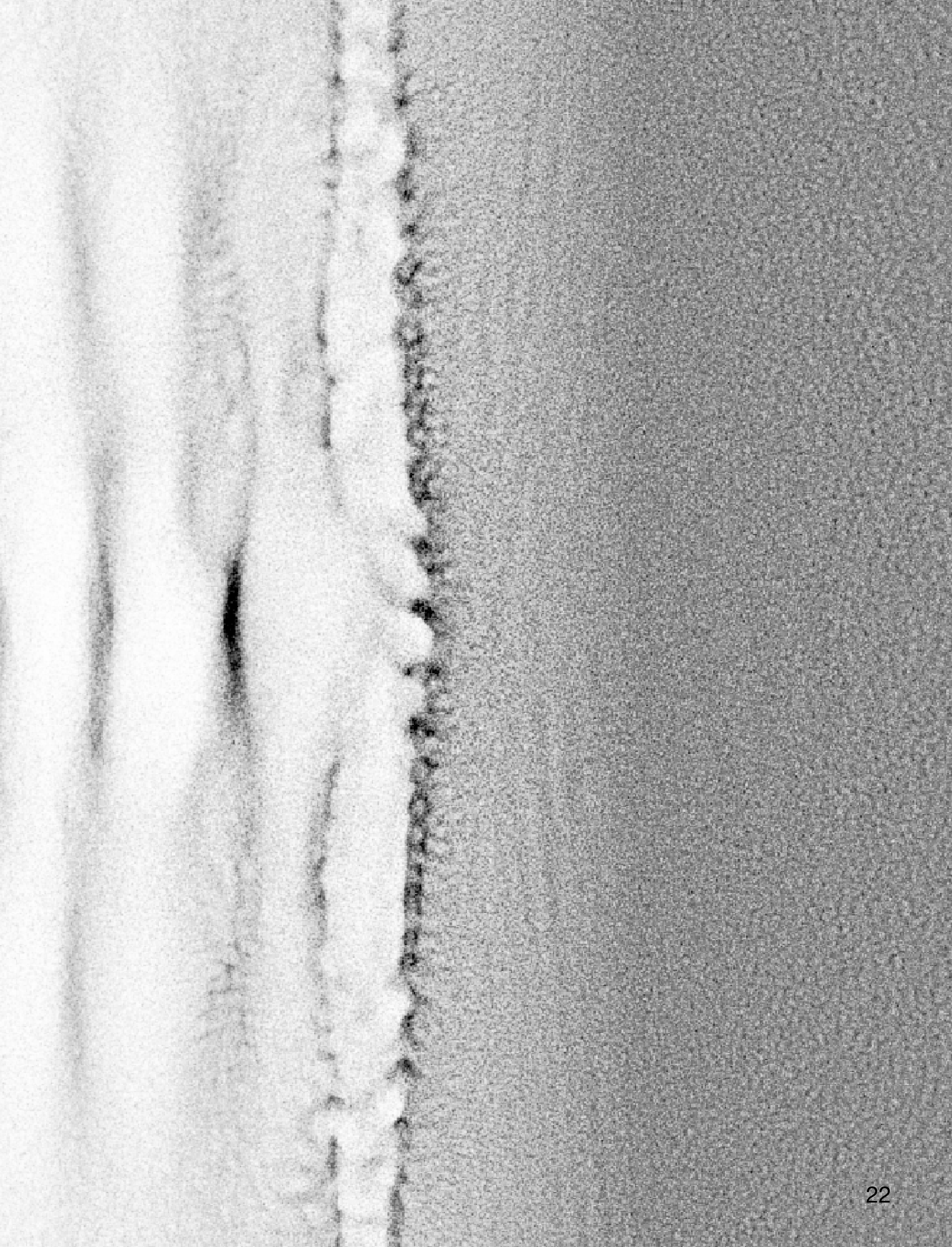


Difference in scale lengths due to density steepening due to ps scale pre-pulse

Summary

- Plasma grating structures have been demonstrated as a novel target for shock accelerated ions

- Route to possible target for high repetition rate LS acceleration



Thank you for listening.
Questions?