

Production of energetic ion beams using high intensity lasers

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LINAC14

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5 September 2014

Outline: Ion acceleration with lasers

- Thermal expansions
- Radiation pressure and relativistic transparency
- Hole-boring and shocks
- Future developments

Thermal Expansions

Sheath acceleration

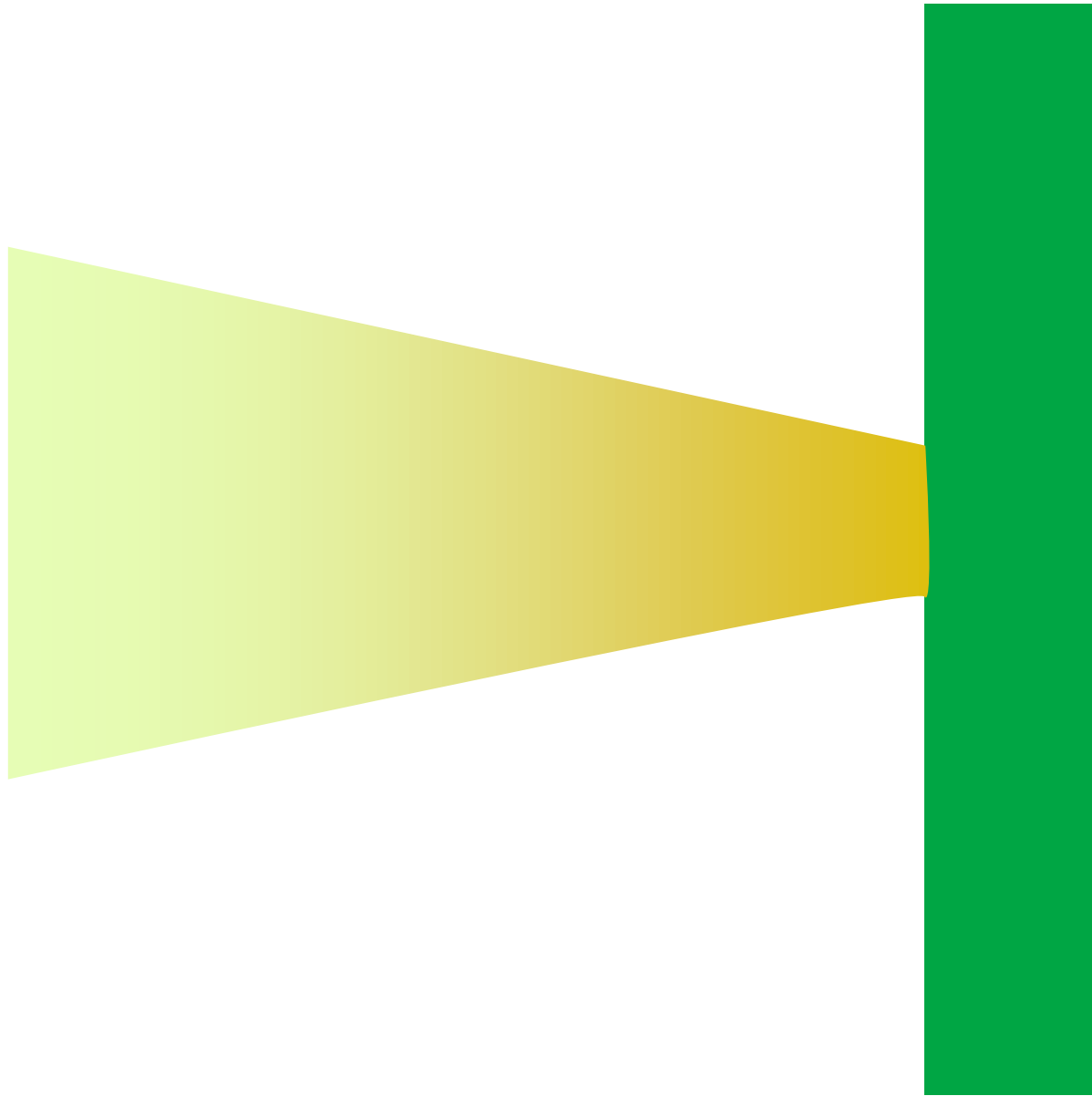


Sheath acceleration



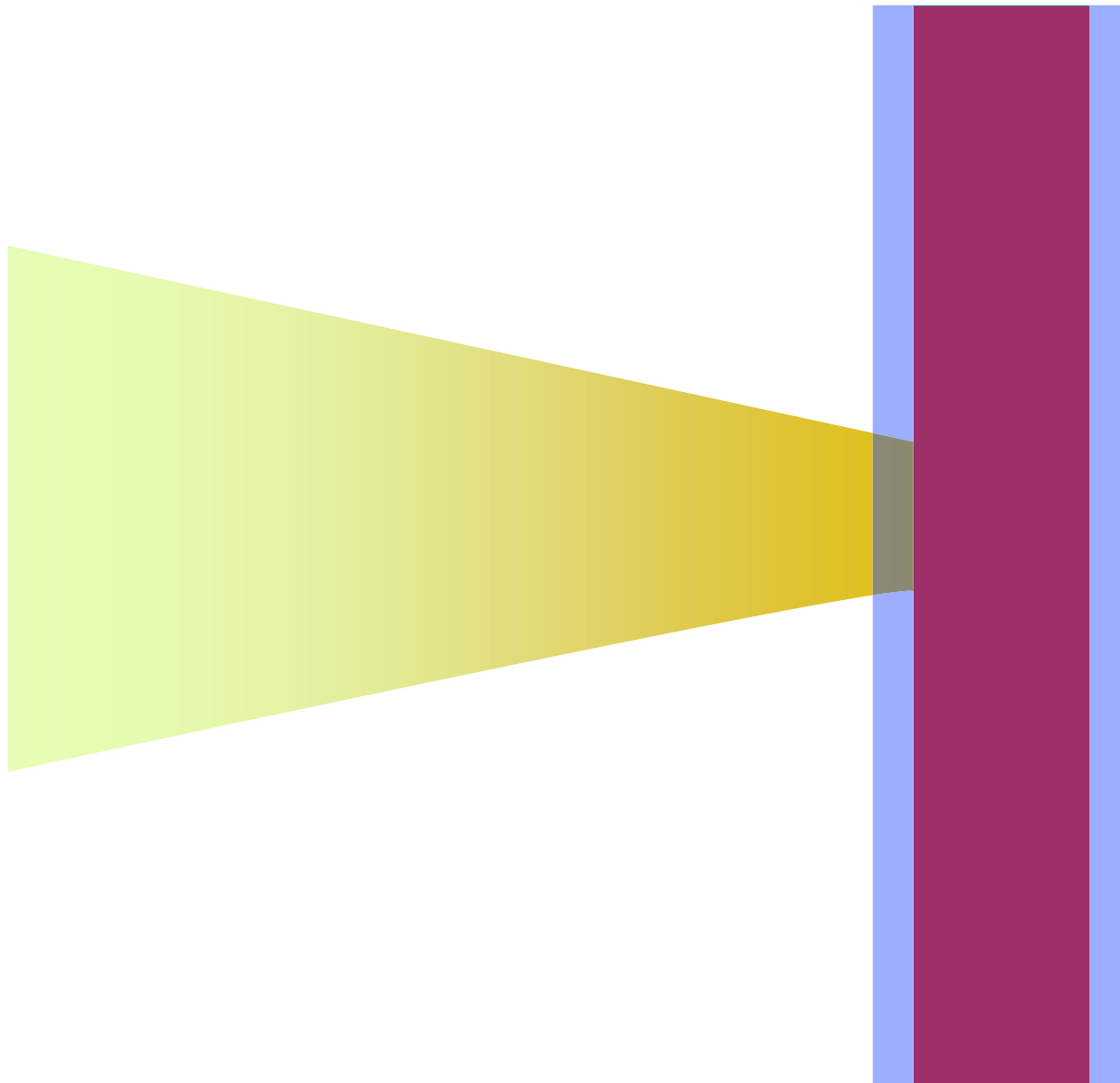
$$n > n_{cr} \equiv \epsilon_0 m_e \omega_0^2 / e^2$$

Sheath acceleration



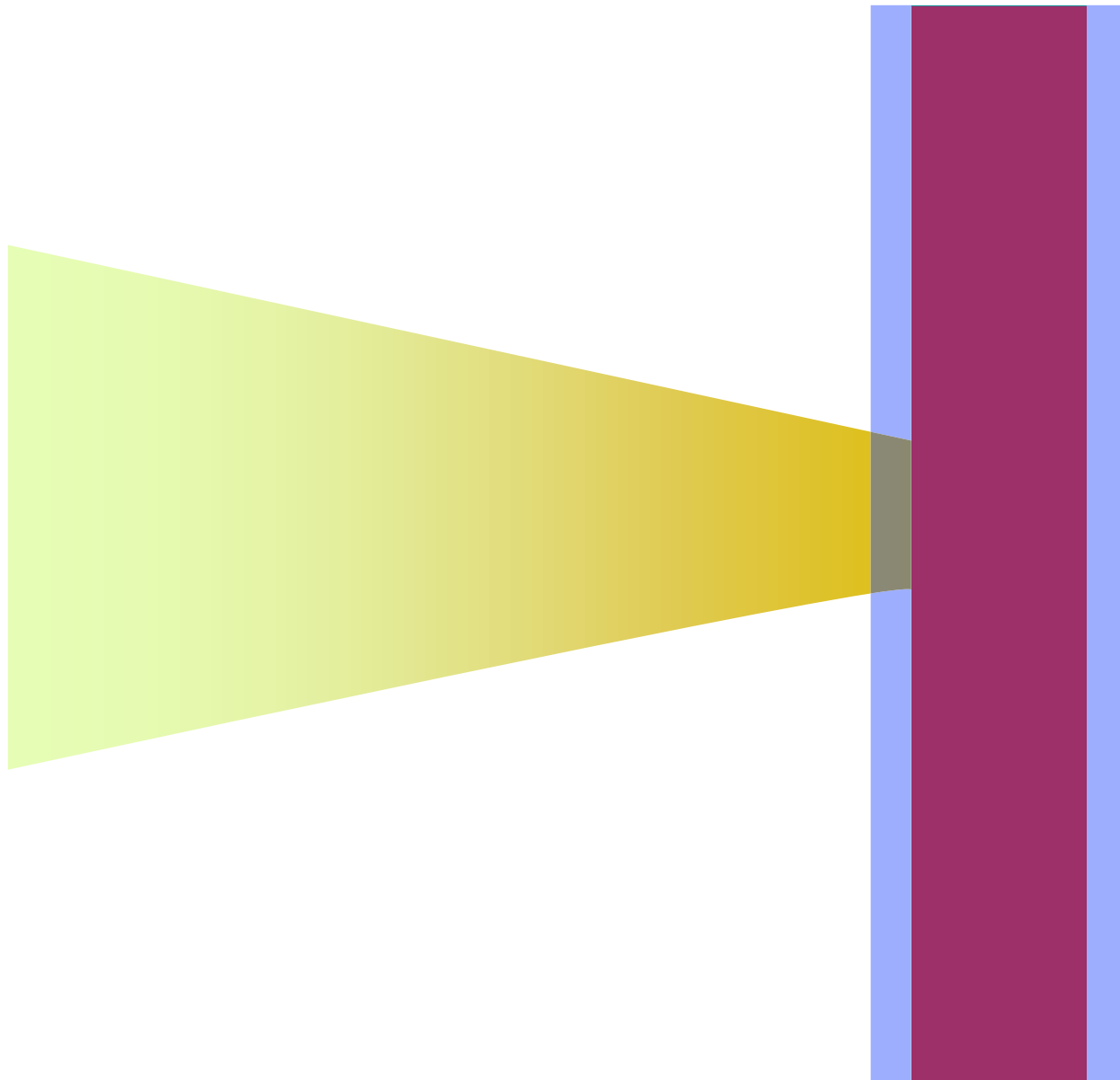
$$n > n_{cr} \equiv \epsilon_0 m_e \omega_0^2 / e^2$$

Sheath acceleration



$$n > n_{cr} \equiv \epsilon_0 m_e \omega_0^2 / e^2$$

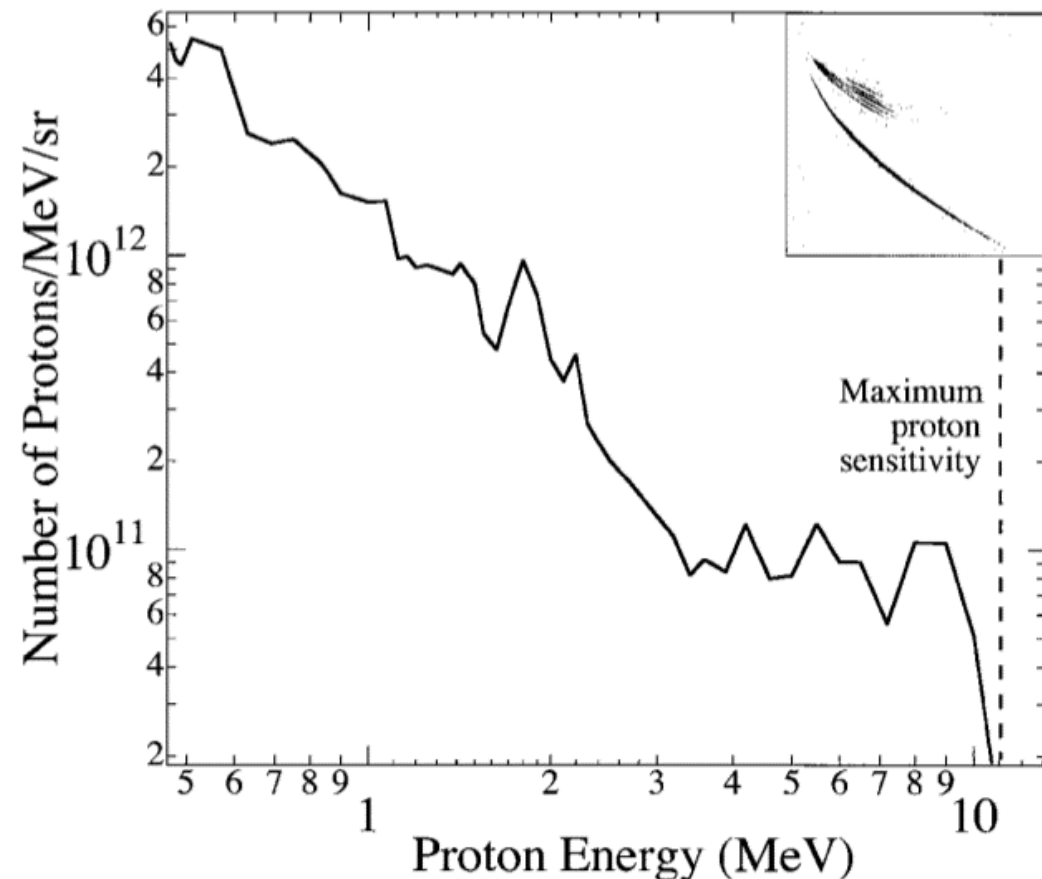
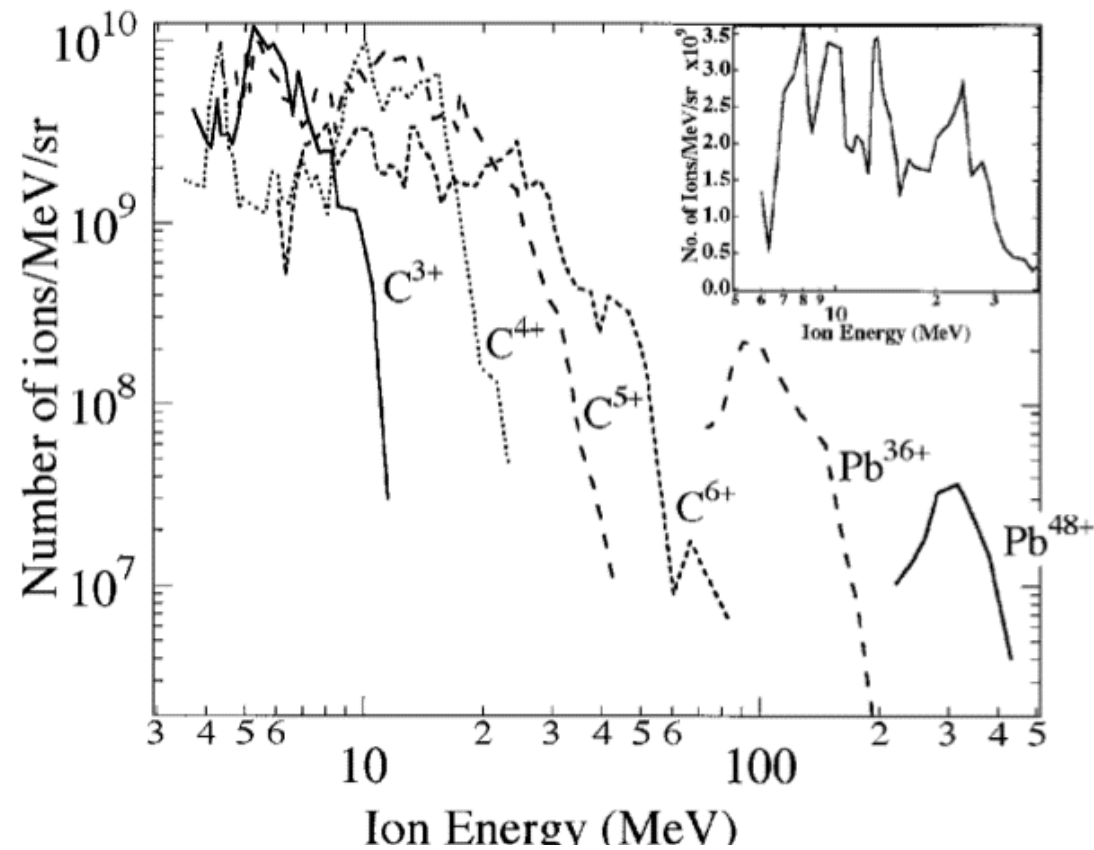
Sheath acceleration



$$n > n_{cr} \equiv \epsilon_0 m_e \omega_0^2 / e^2$$

$$\text{Energies} \sim \alpha k_B T_e \sim \alpha^* m_e c^2 (I \lambda^2)^{1/2}$$

Pros and cons



- Extremely high accelerating fields ($> 10^{12} \text{ Vm}^{-1}$) means:
 - short pulse
 - low emittance
 - compact size
 - high charge ($> 10^{13}$ protons $\approx \mu\text{C}$)

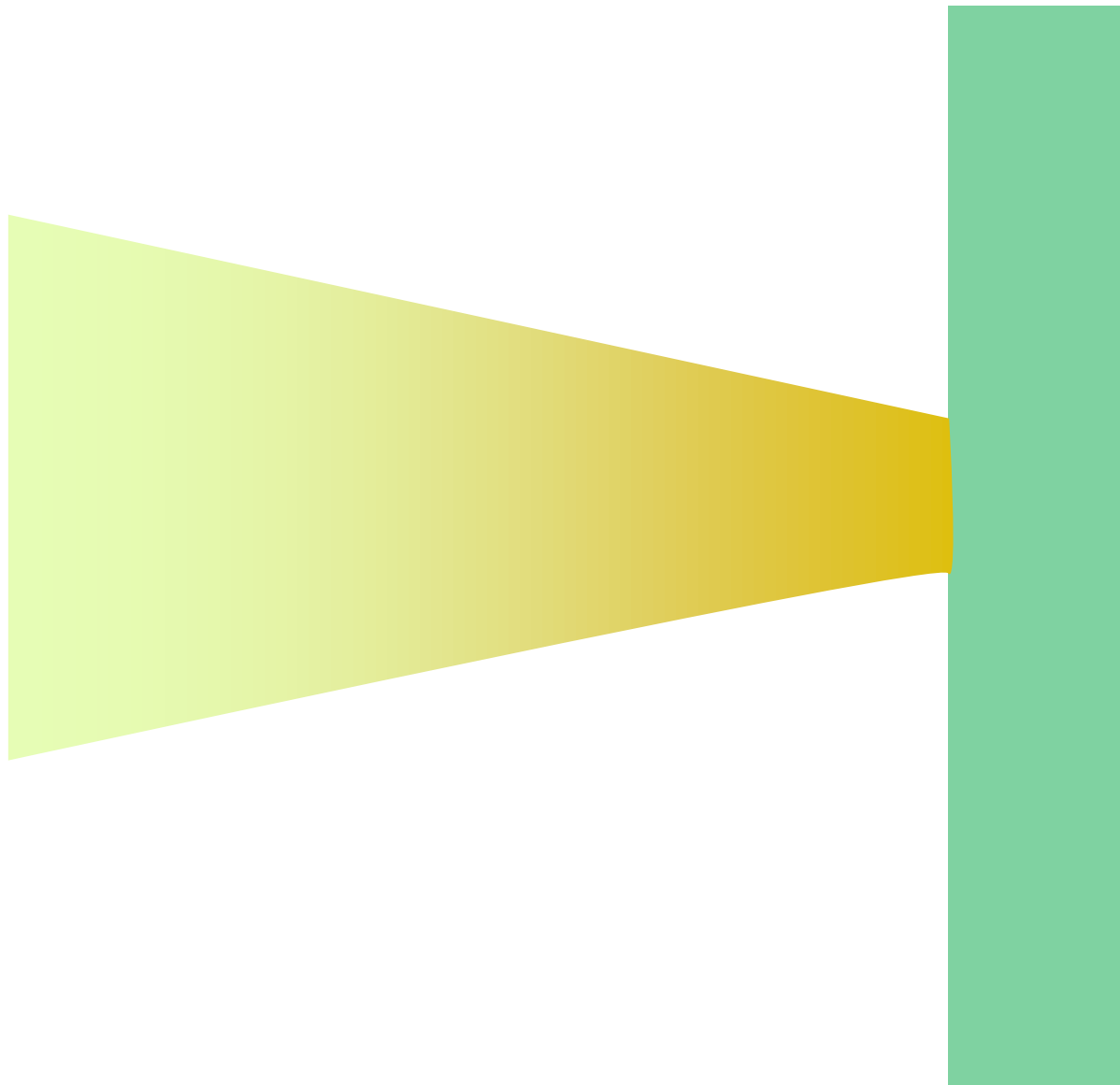
- Disadvantages:
 - Large energy spread
 - Poor energy scaling ($T_{hot} \propto (I\lambda^2)^{1/2}$)
 - Multiple ion species (especially impurities)

Radiation pressure and relativistic transparency

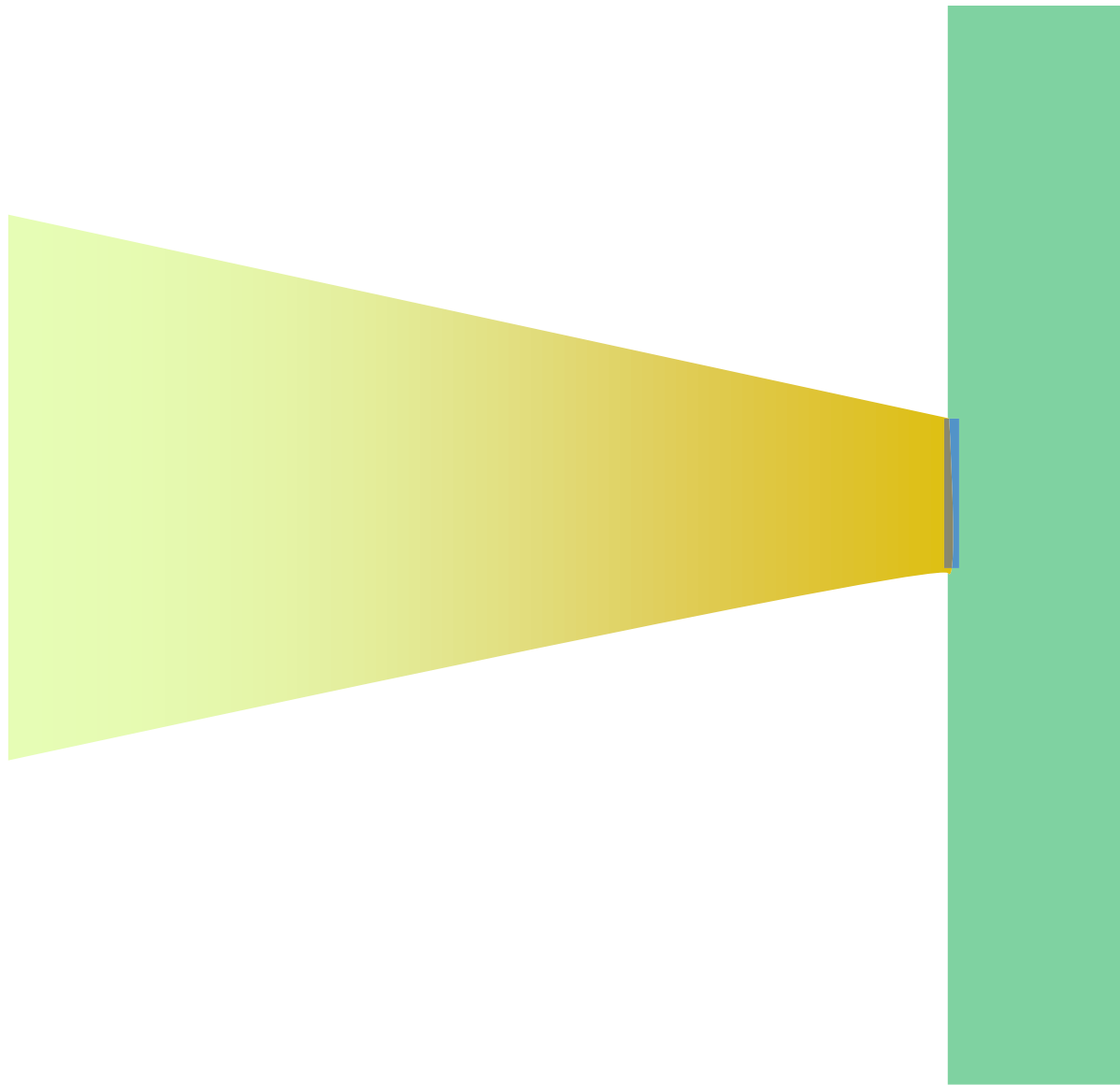
light-sail acceleration



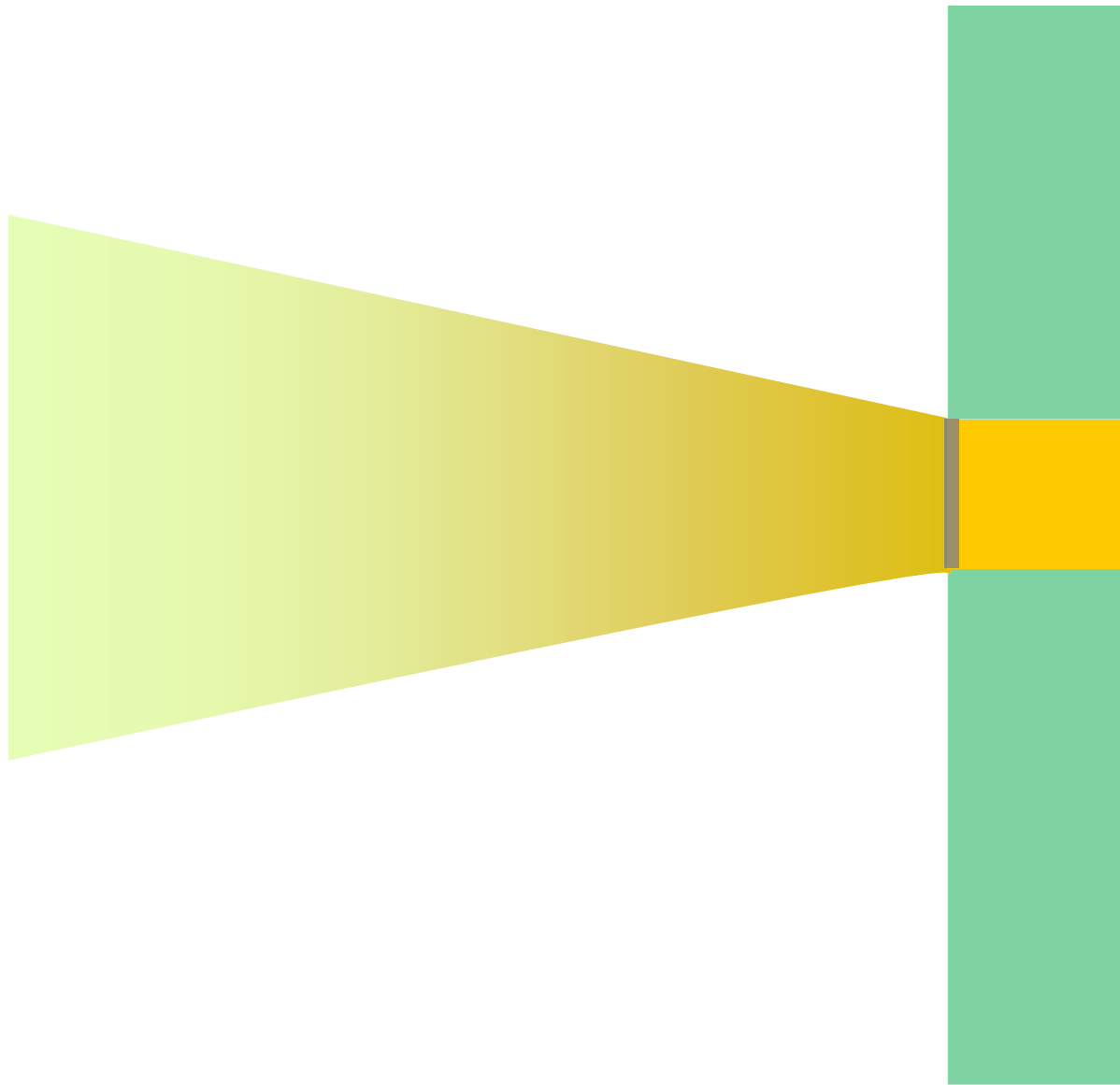
light-sail acceleration



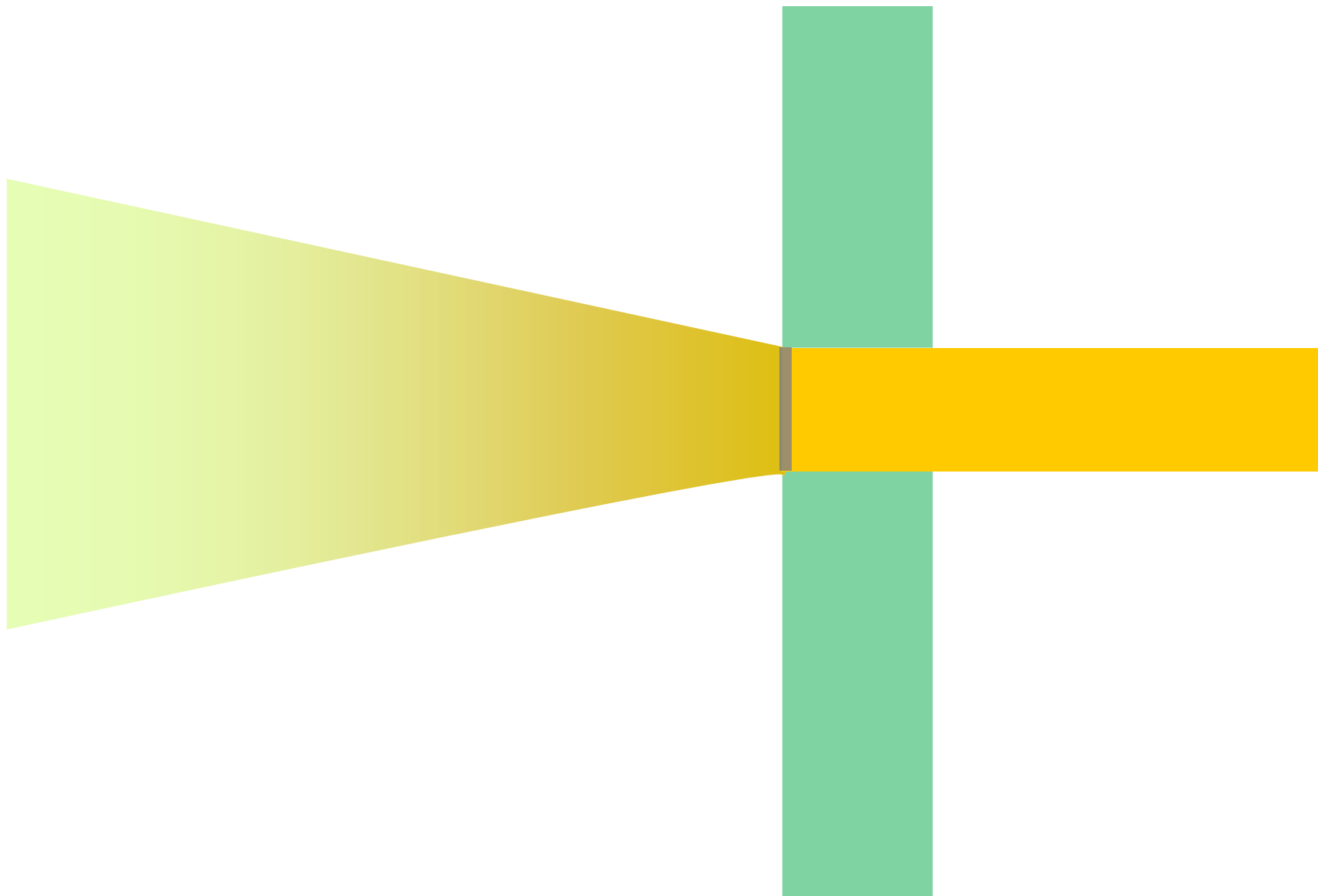
light-sail acceleration



light-sail acceleration

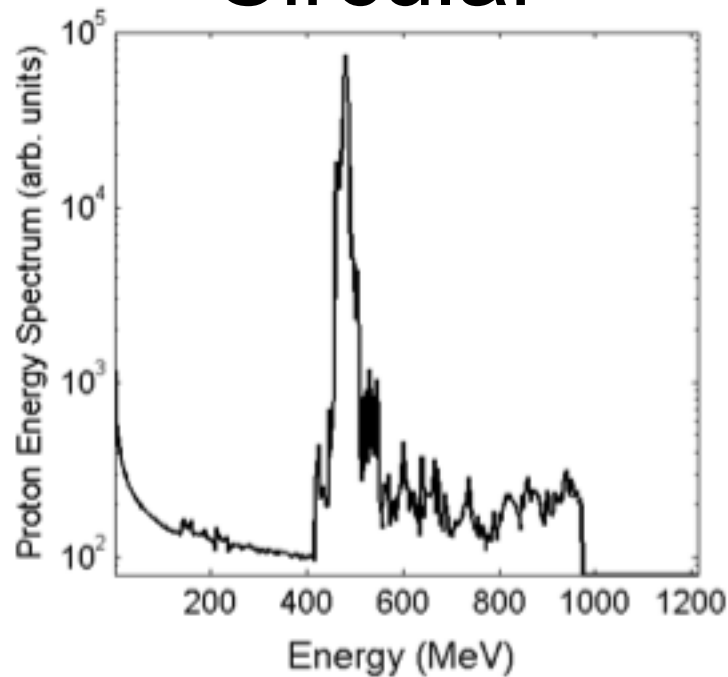


light-sail acceleration

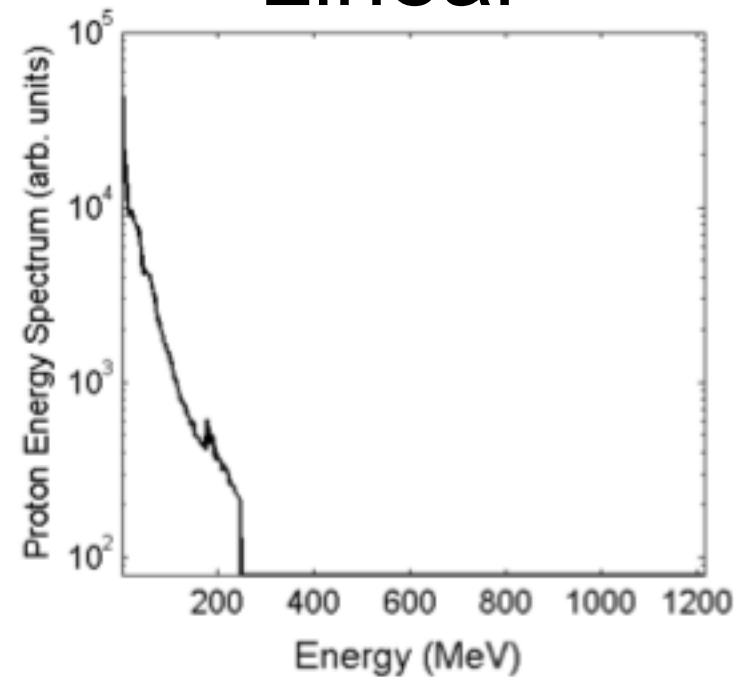


light-sail acceleration

Circular



Linear



Radiation Force:

$$F_R = (1 + R)A \frac{I_L}{c}$$

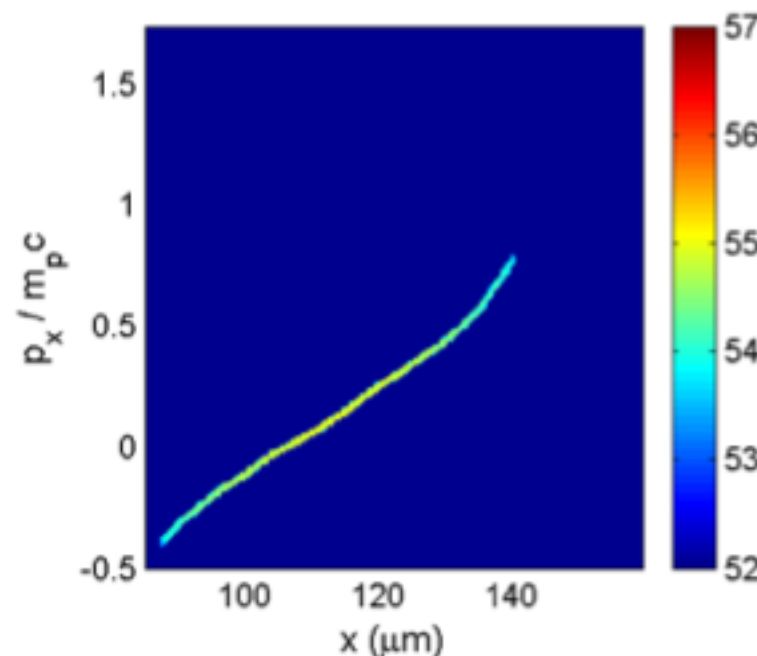
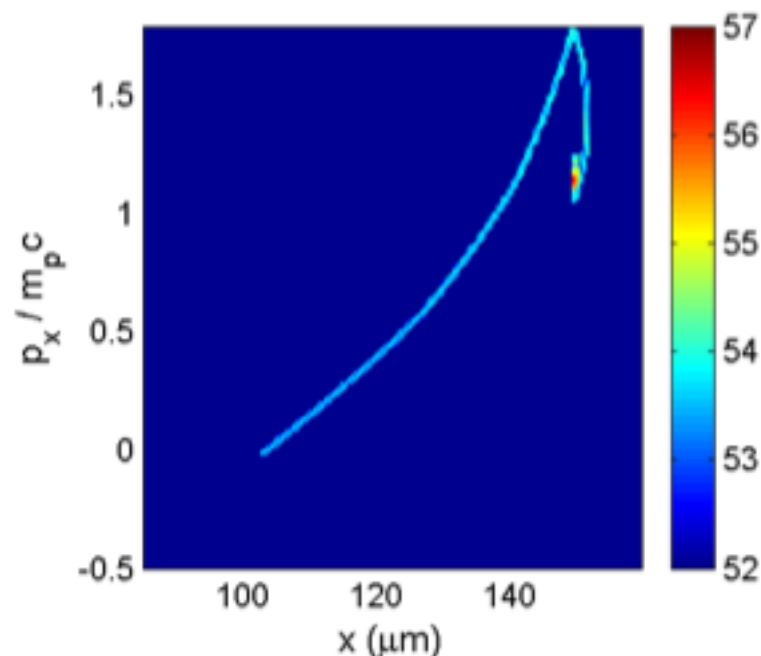
Acceleration:

$$\rightarrow v_i = \frac{(1 + R)\tau}{\rho d} \frac{I_L}{c}$$

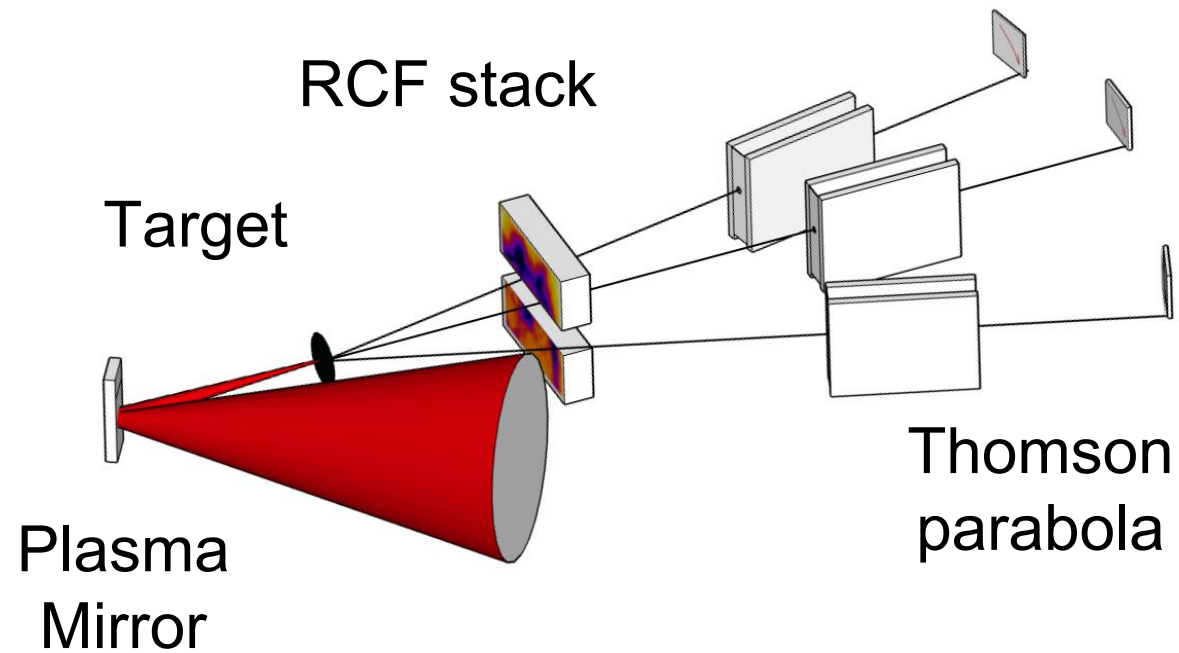
Optimum Thickness:

$$d_{opt} = a_0 n_e$$

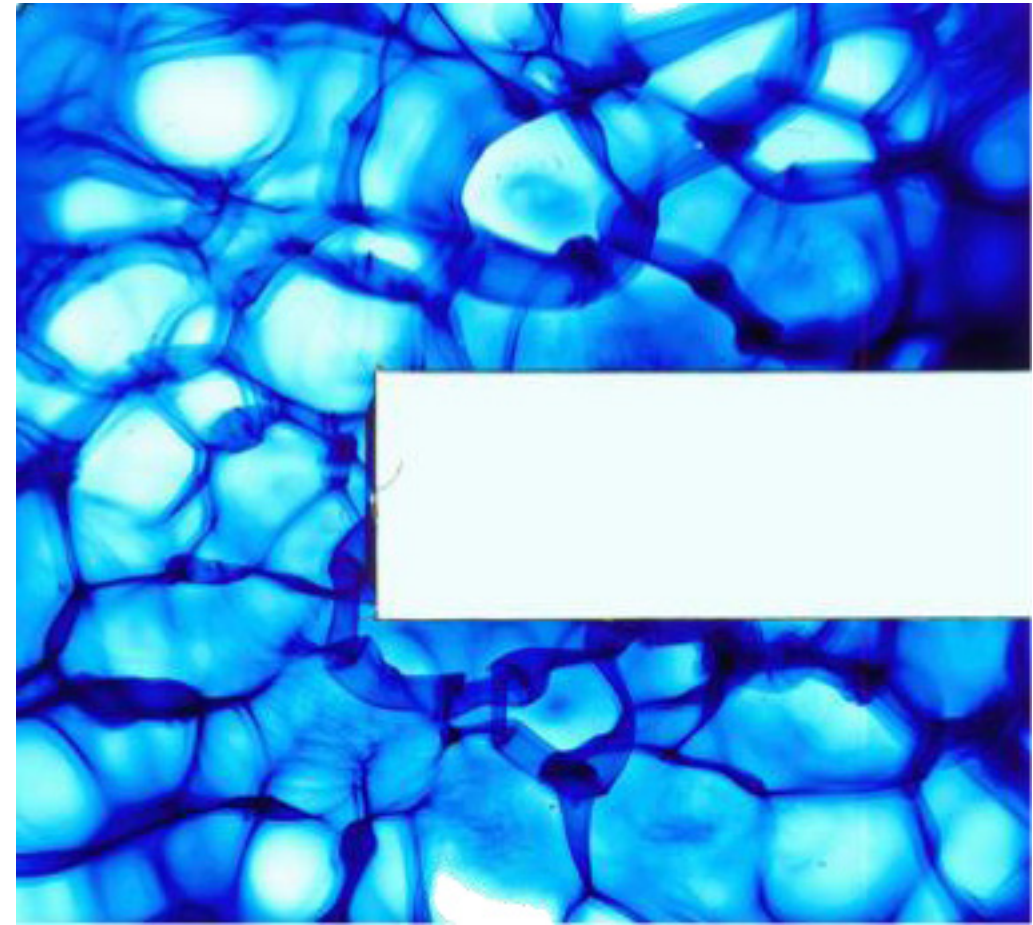
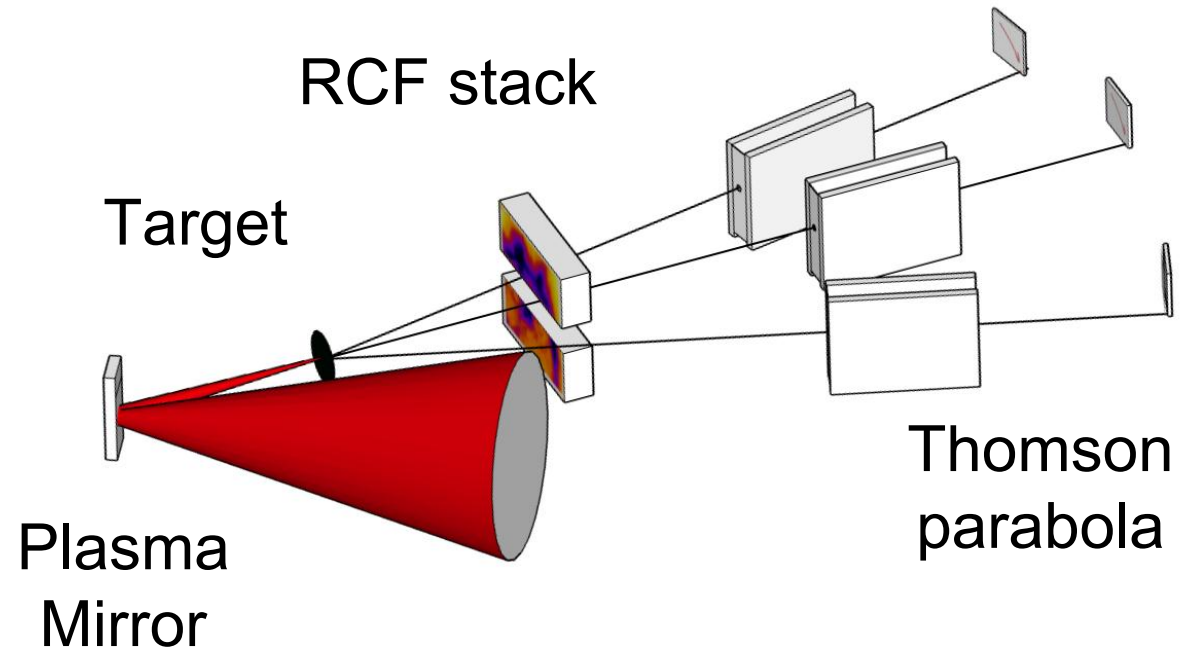
- where d is in units of (c/ω_p) and n_e in units of (n_{cr})
- for $I \approx 10^{20} \text{ Wcm}^{-2}$, $d_{opt} \approx 5 \text{ nm}$



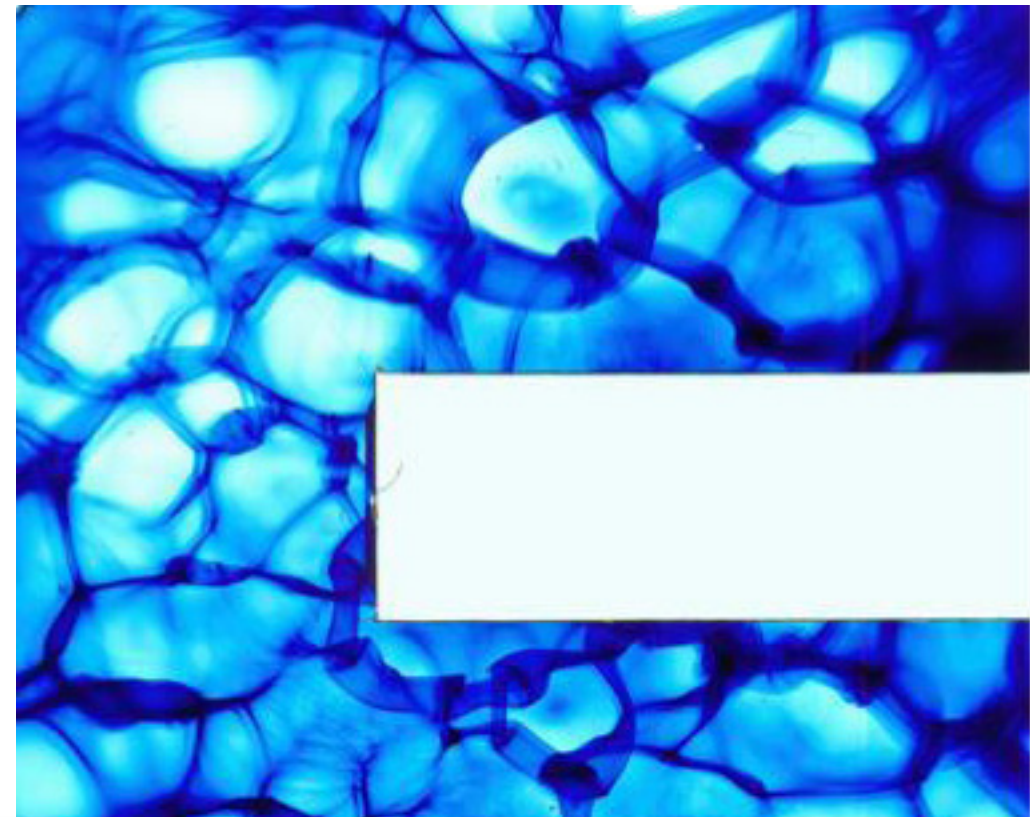
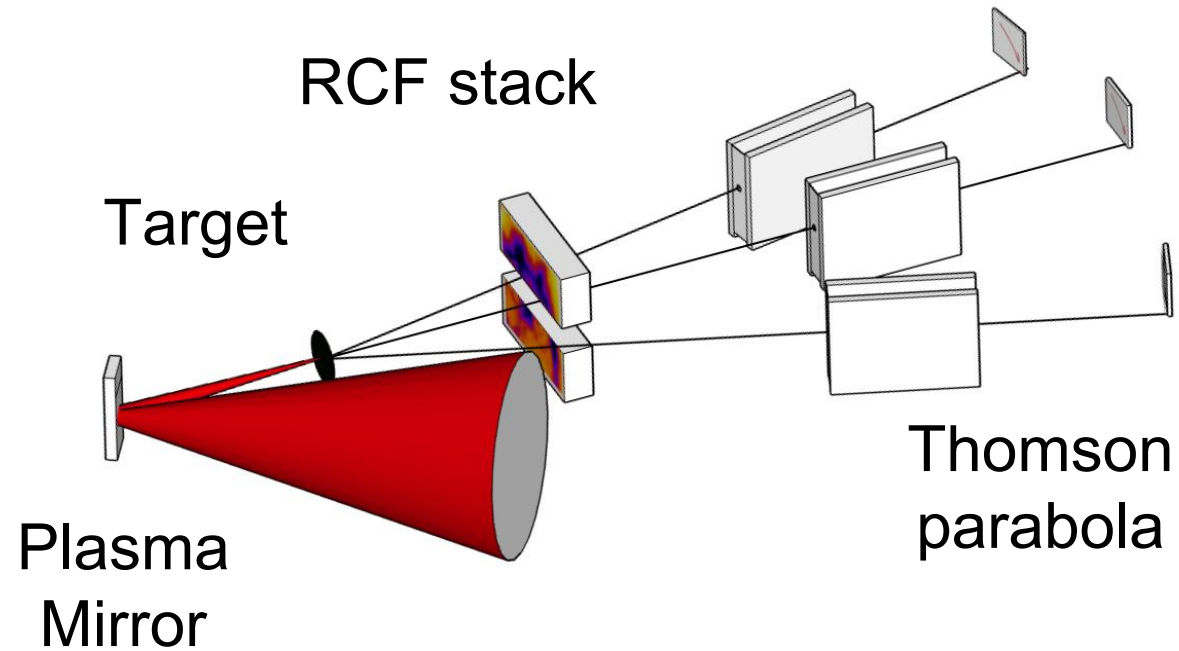
Rayleigh-Taylor Instability



Rayleigh-Taylor Instability



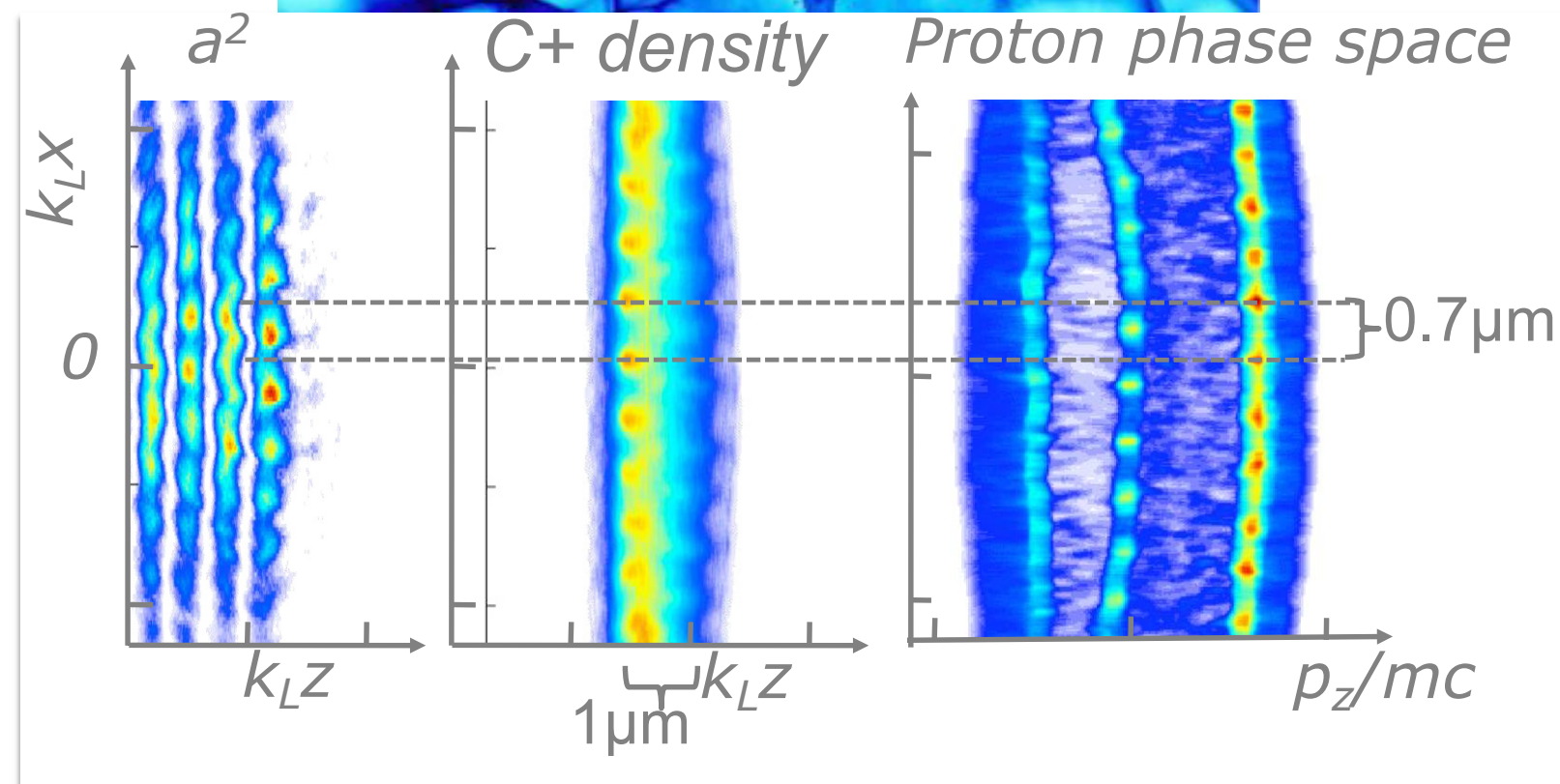
Rayleigh-Taylor Instability



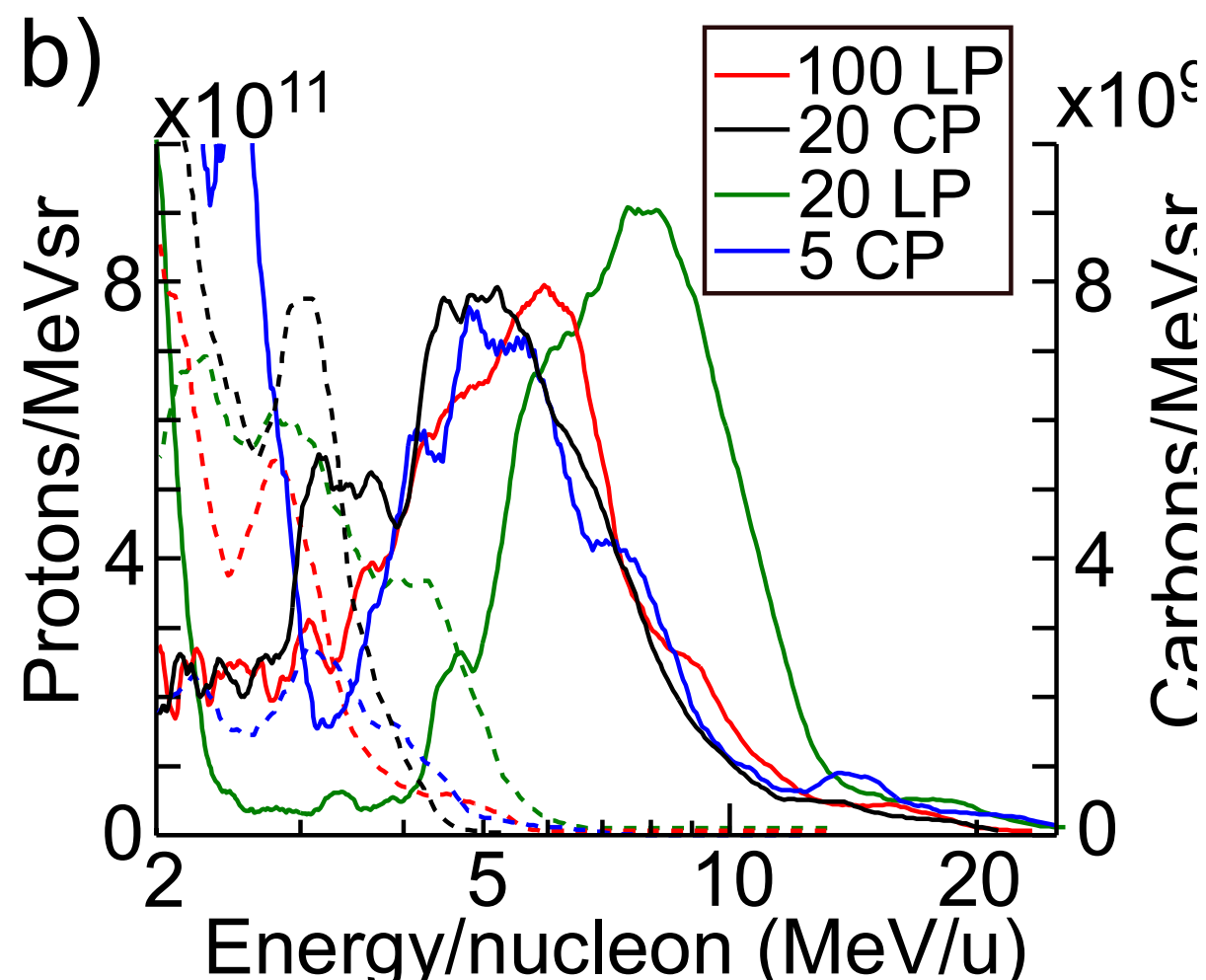
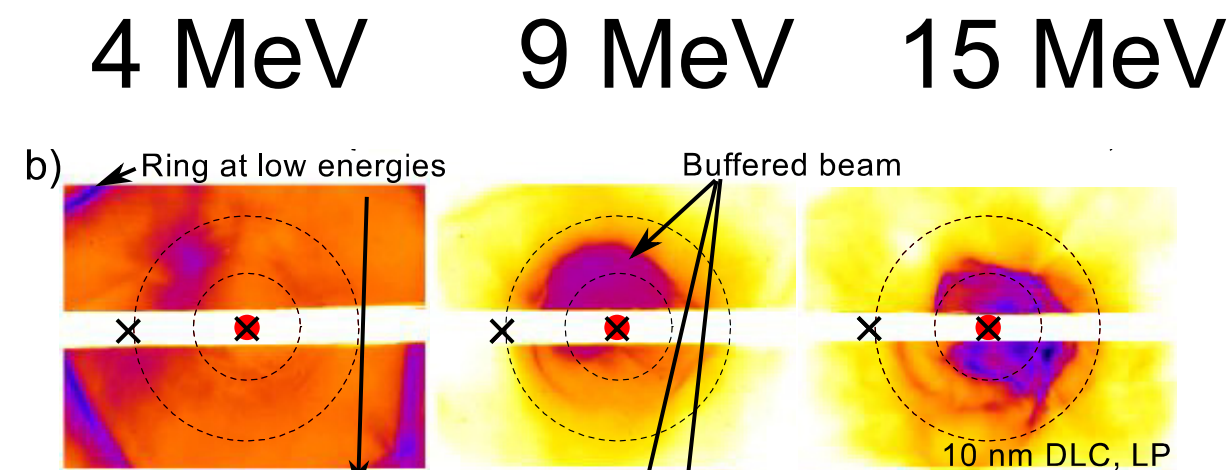
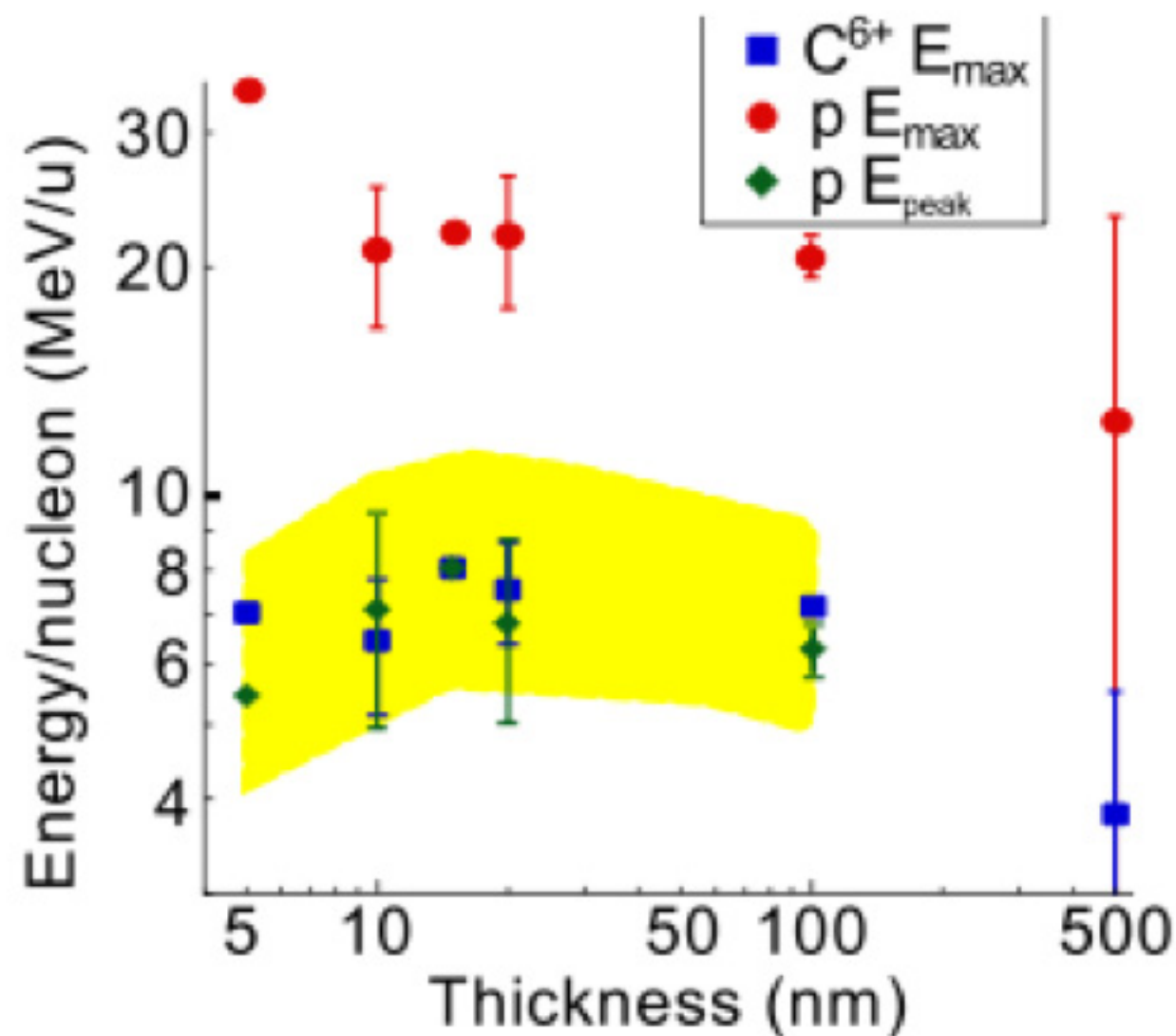
Simulation Conditions:

Laser: $I = 10^{20} \text{ W cm}^{-2}$
 ($a_0 = 10$)
 $\tau_L = 600 \text{ fs}$

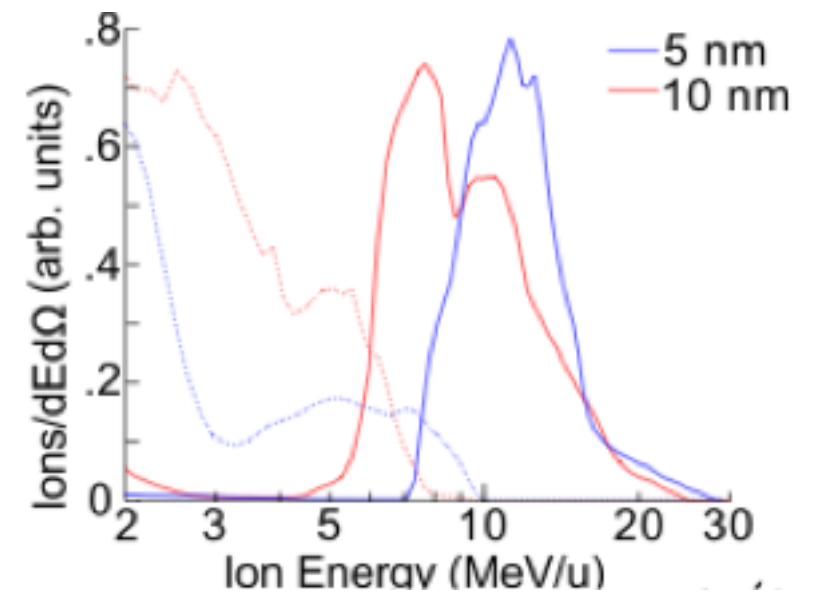
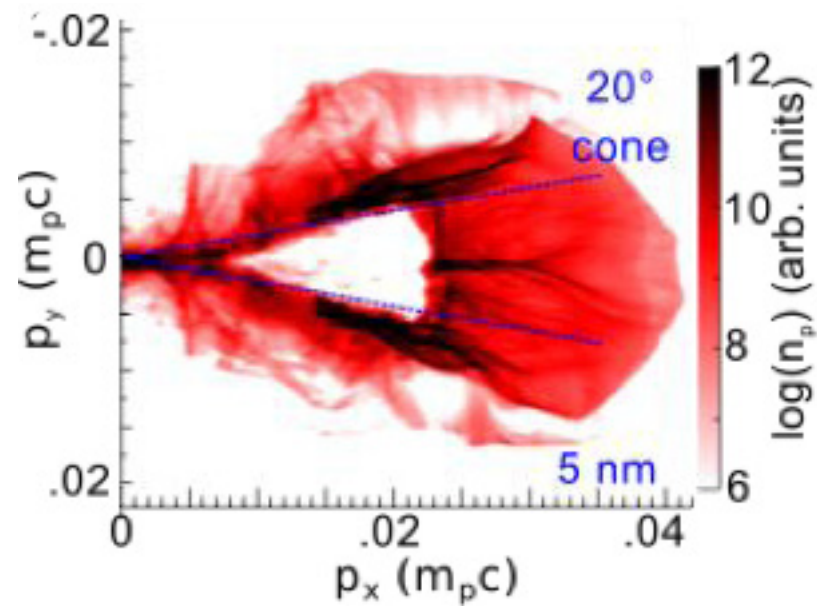
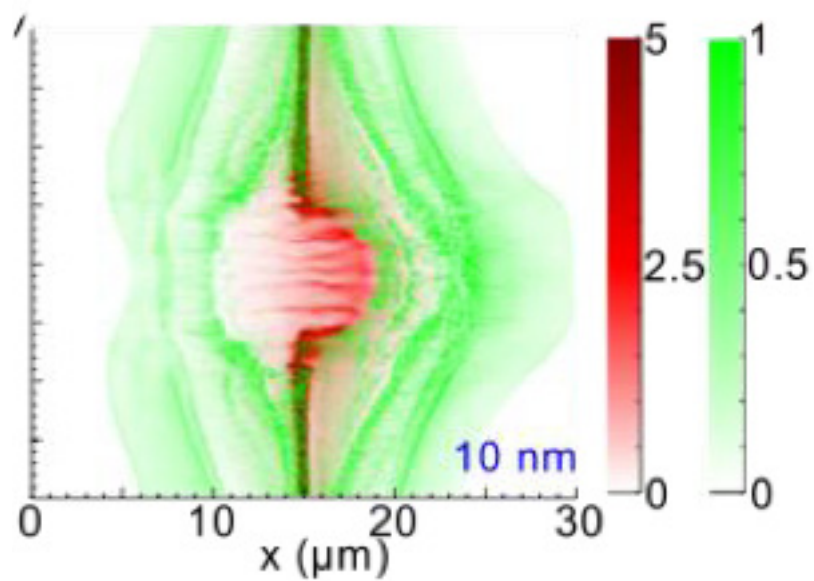
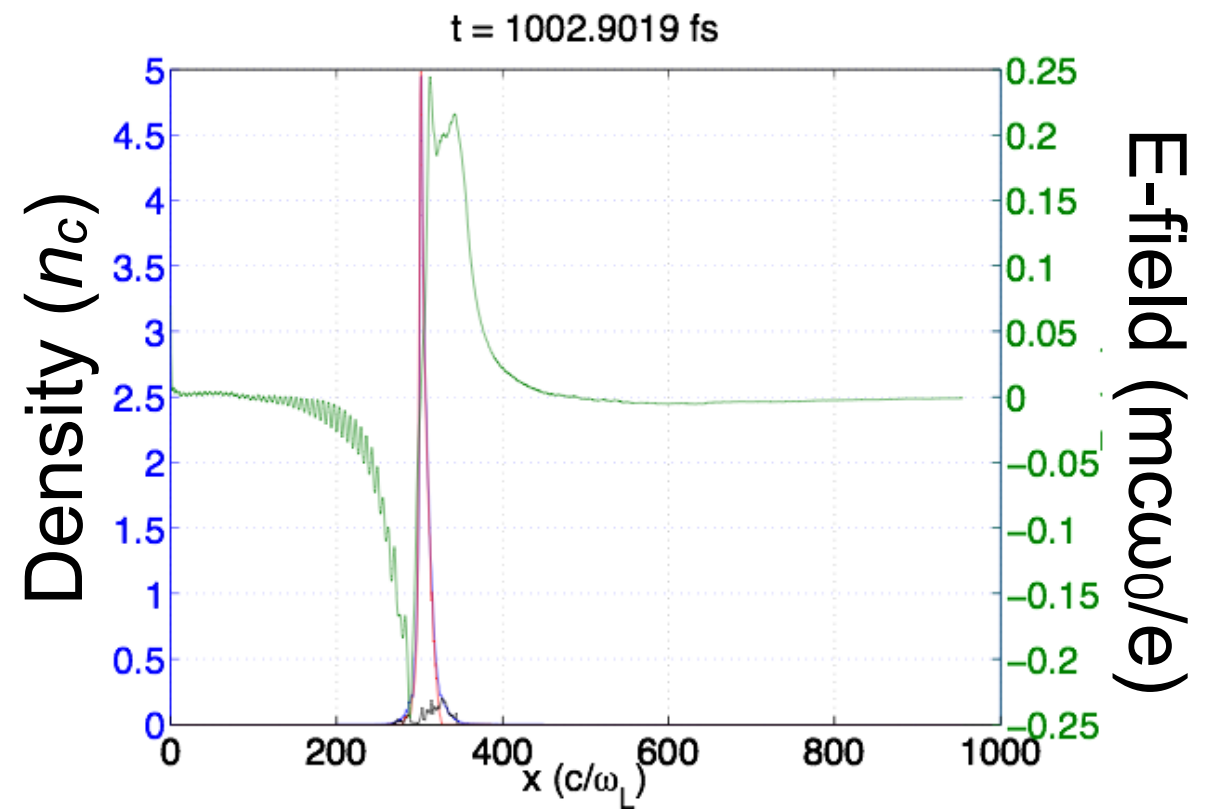
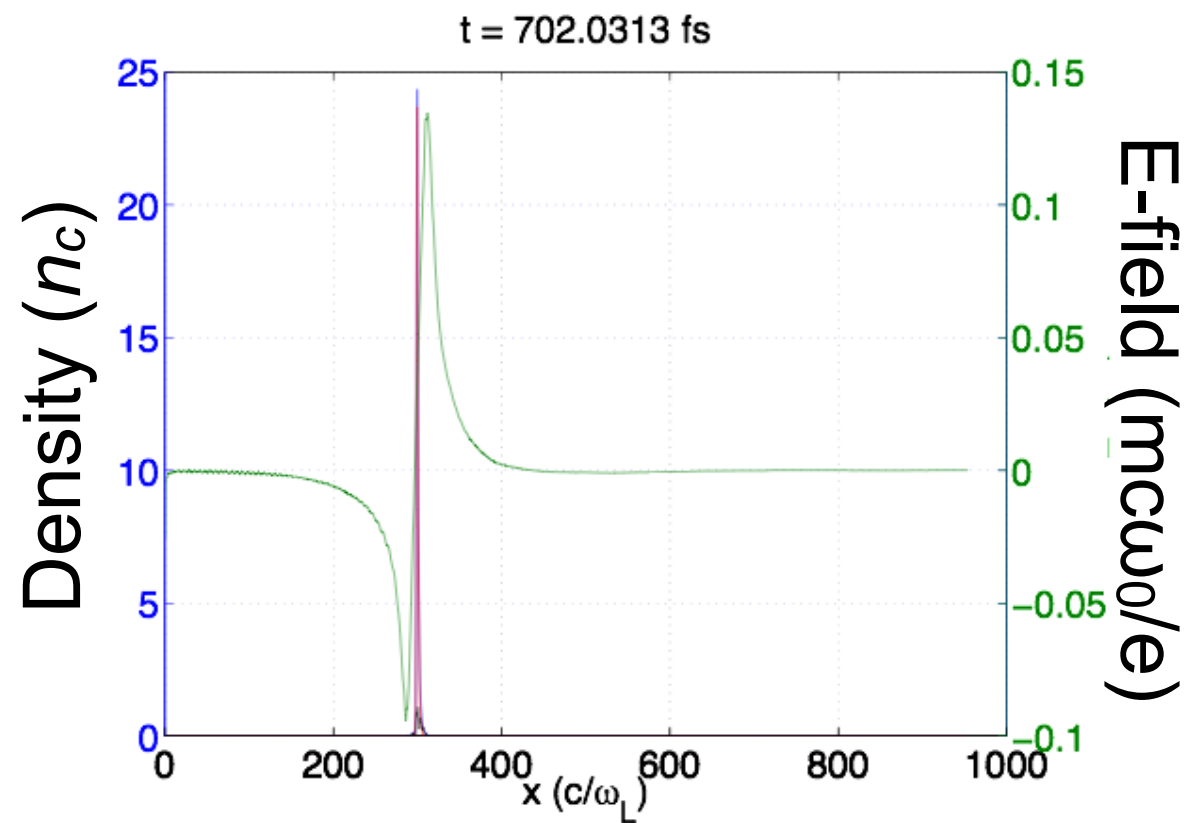
Target: $d = 10 \text{ nm}$
 carbon 6+
 $n_e = 800 n_c$



Relativistic transparency



Buffering



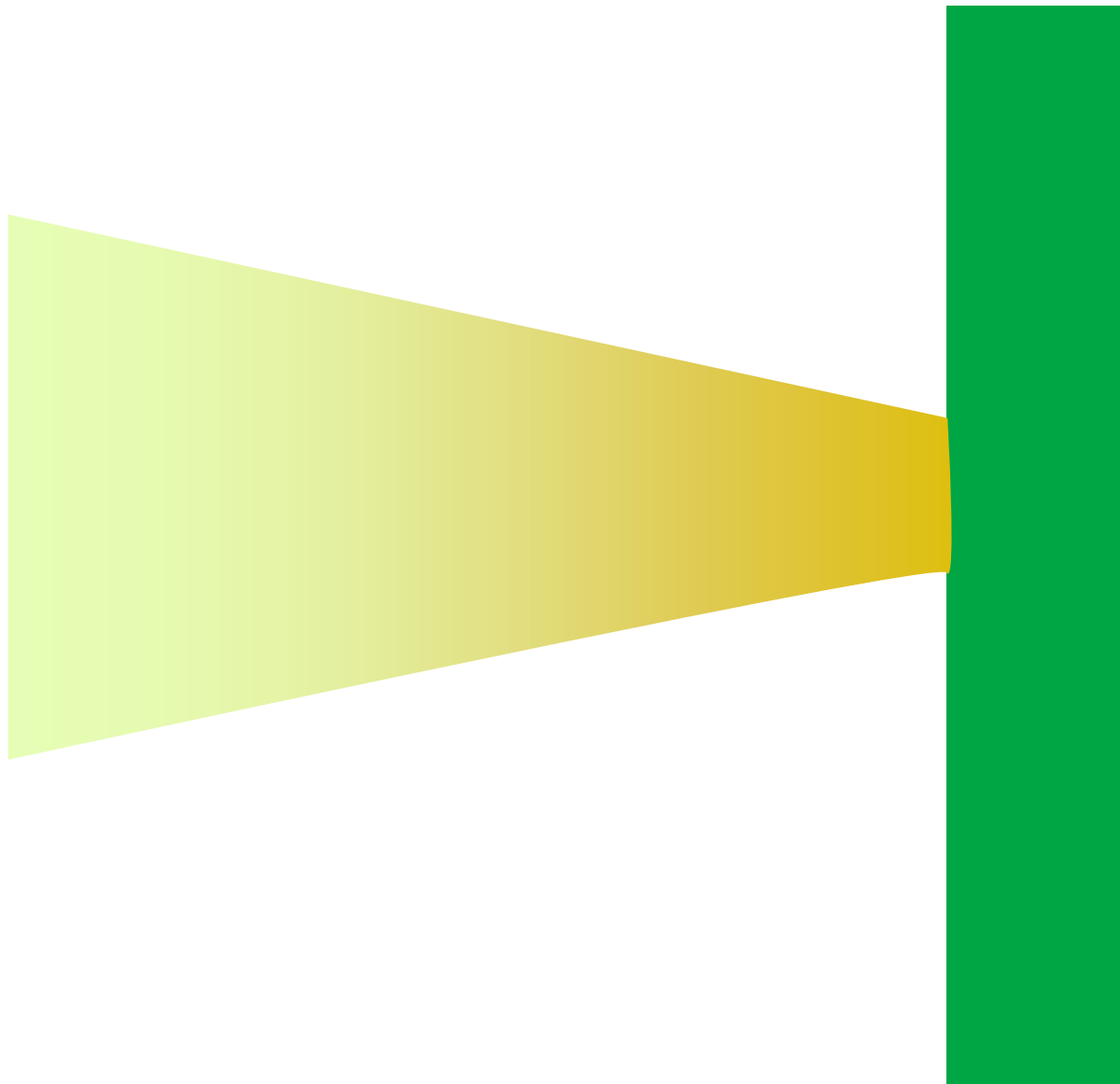
Hole-boring and shocks

hole-boring (ponderomotive) acceleration



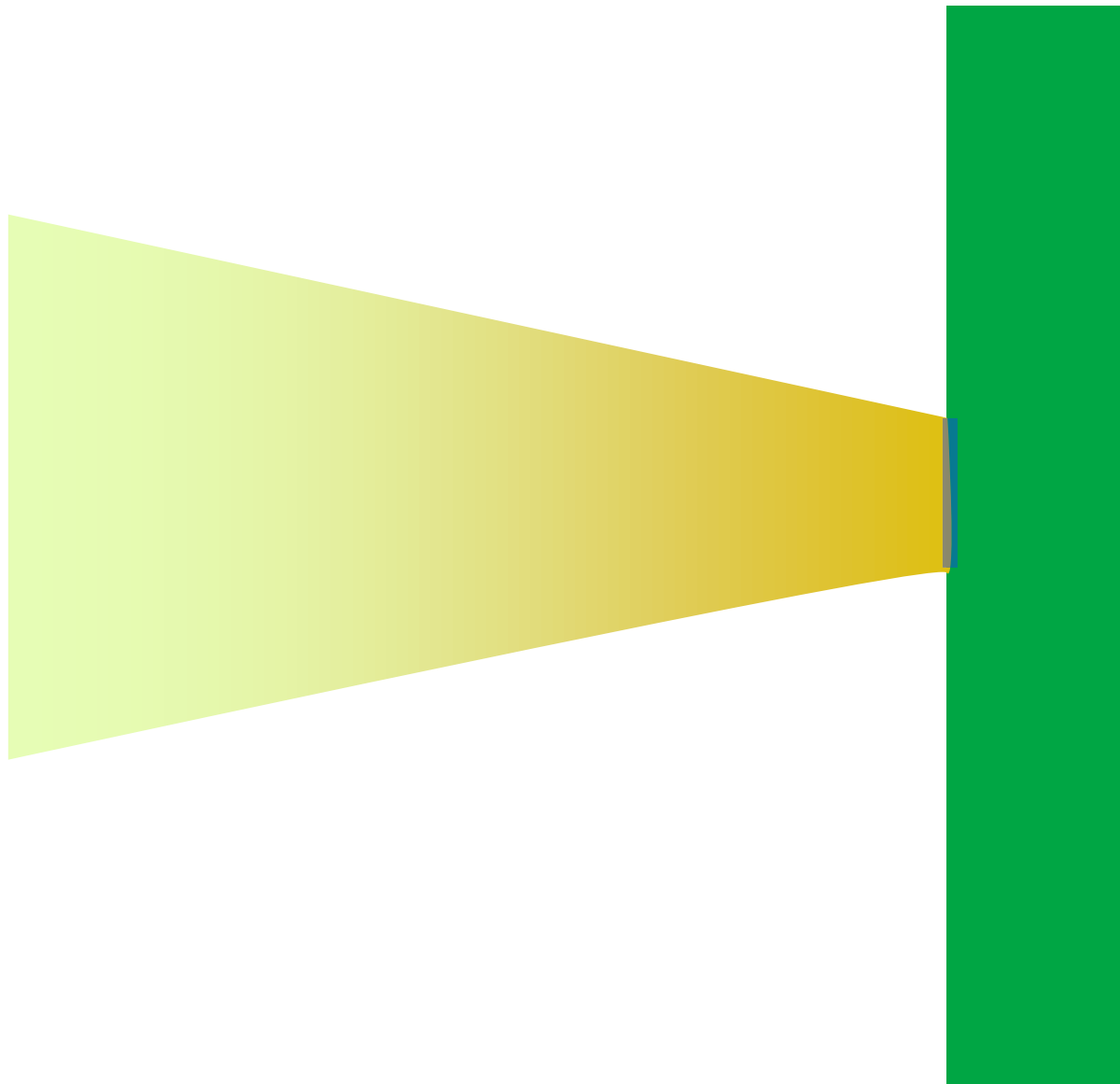
$$v_{hb} = ((1 + R)I / \rho c)^{1/2}$$

hole-boring (ponderomotive) acceleration



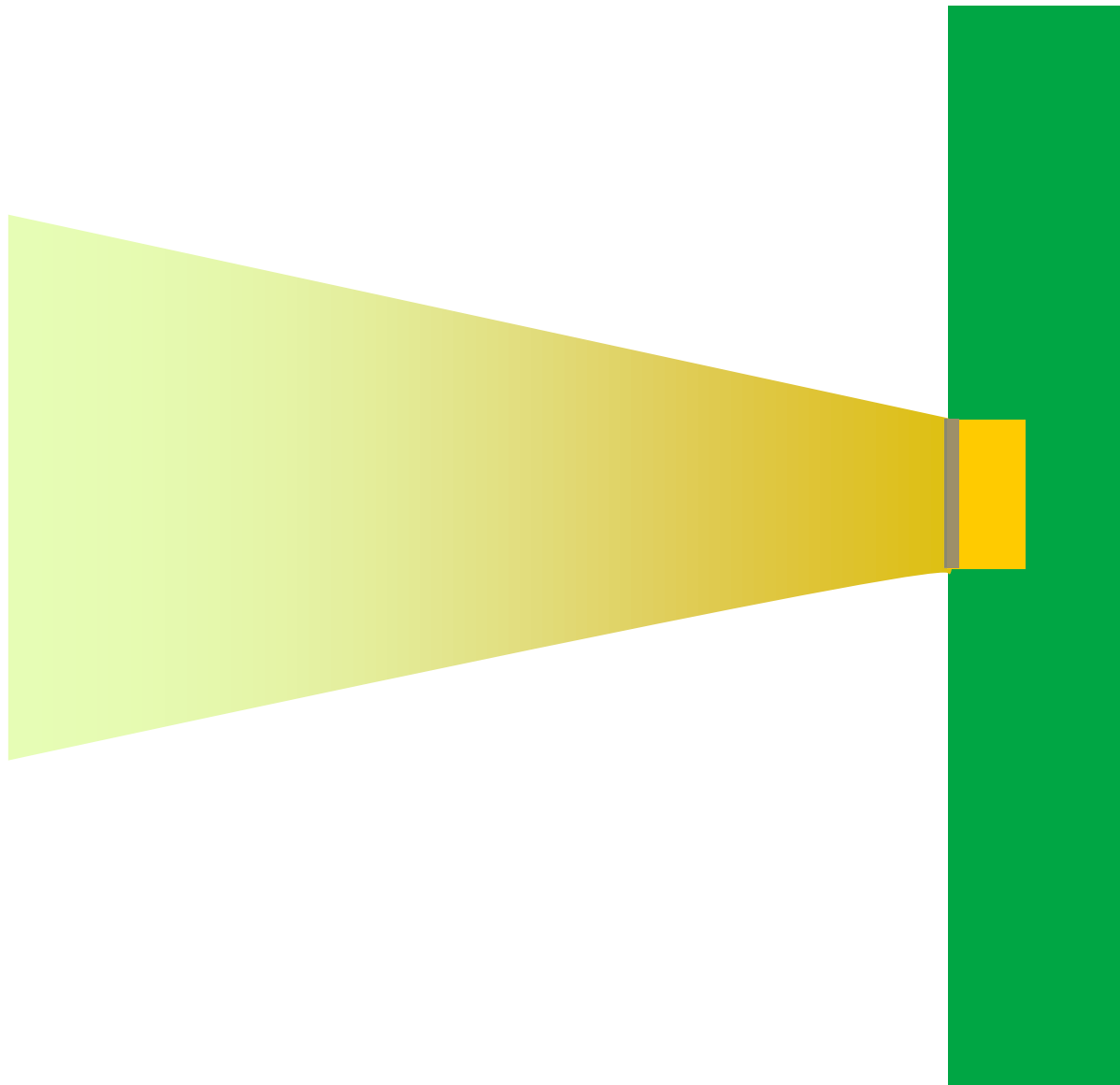
$$v_{hb} = ((1 + R)I/\rho c)^{1/2}$$

hole-boring (ponderomotive) acceleration



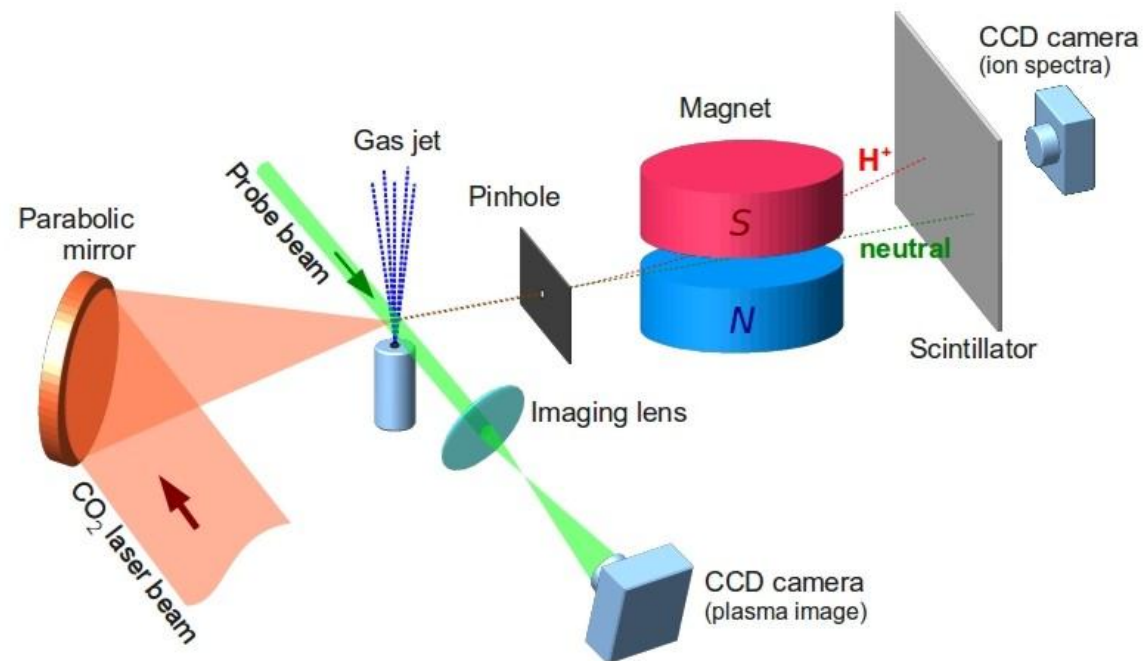
$$v_{hb} = ((1 + R)I/\rho c)^{1/2}$$

hole-boring (ponderomotive) acceleration



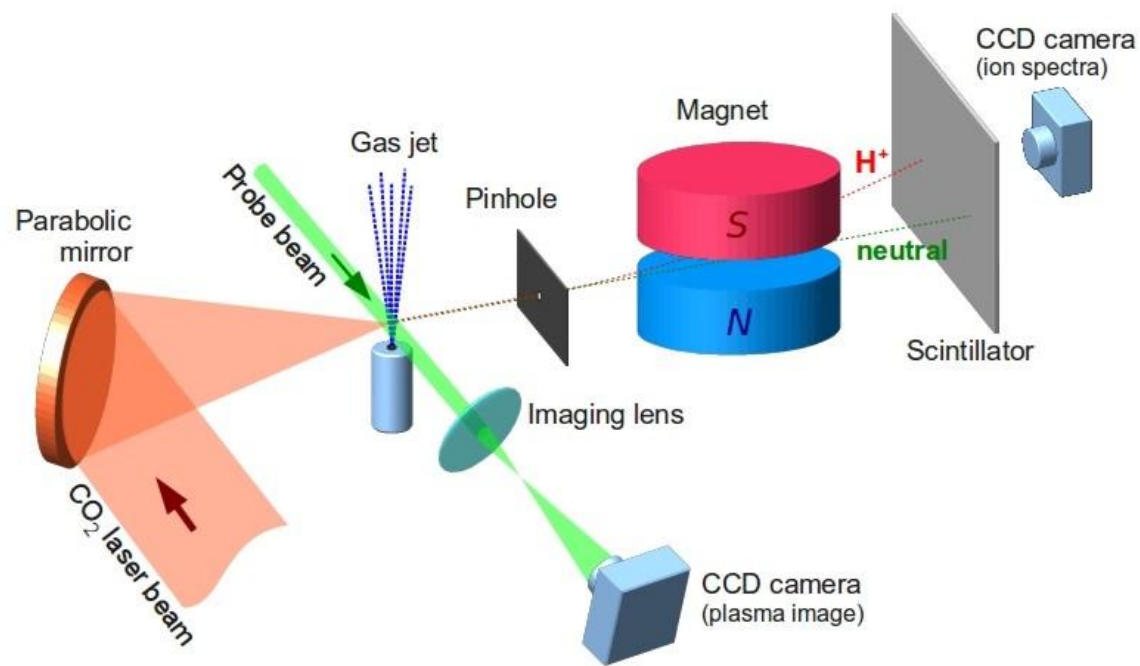
$$v_{hb} = ((1 + R)I / \rho c)^{1/2}$$

hole-boring (ponderomotive) acceleration

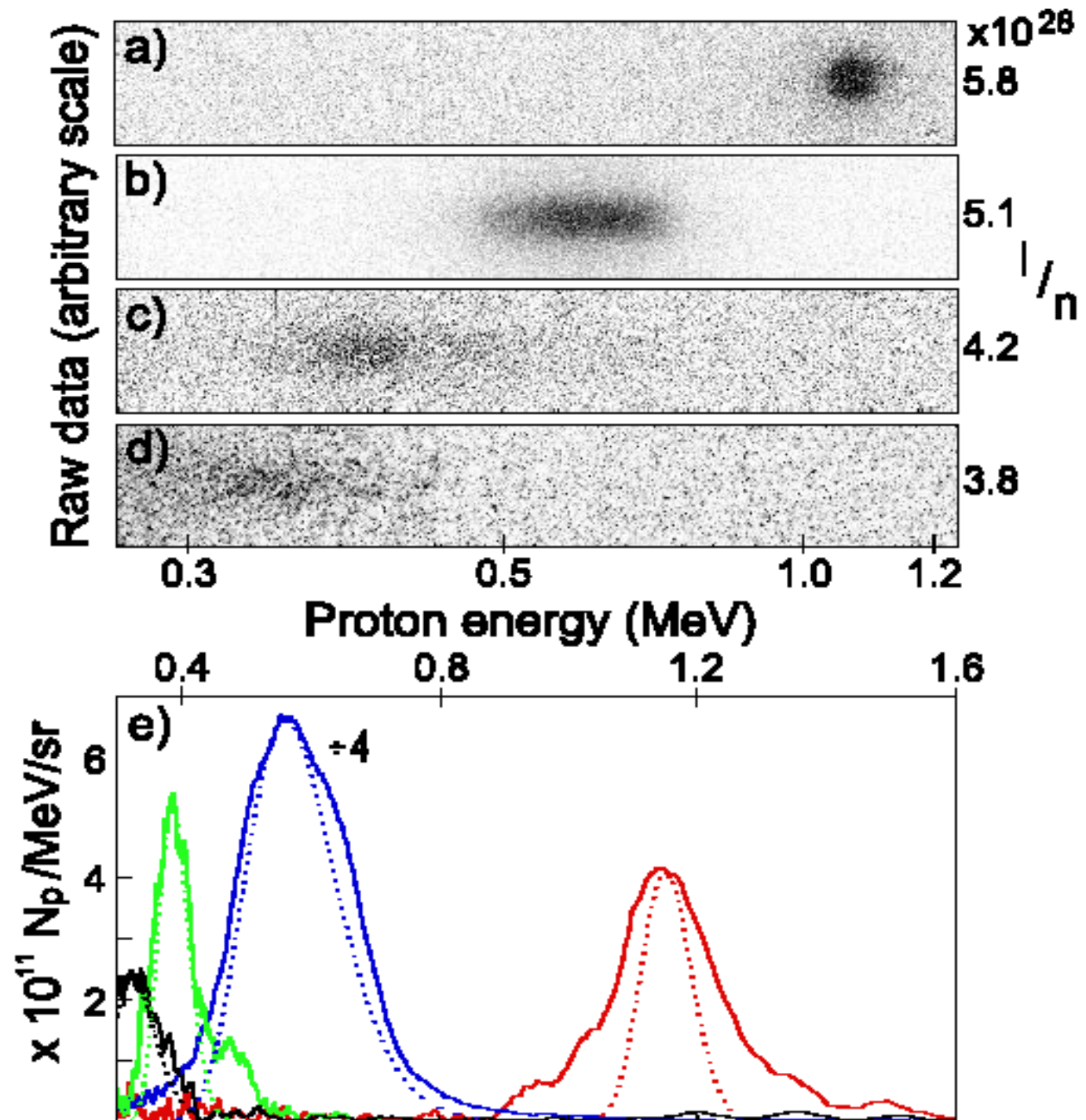


- CO₂ laser:
 - $\lambda = 10.6 \mu\text{m}$
 - Pulse energy $\sim 2\text{-}4 \text{ J}$
 - Pulse length $\lesssim 10 \text{ ps}$
 - **Pulse train with 25 ps separation.**
 - Focal spot diameter $\sim 60 \mu\text{m}$
- $I \sim 5 \times 10^{15} \text{ W/cm}^2$

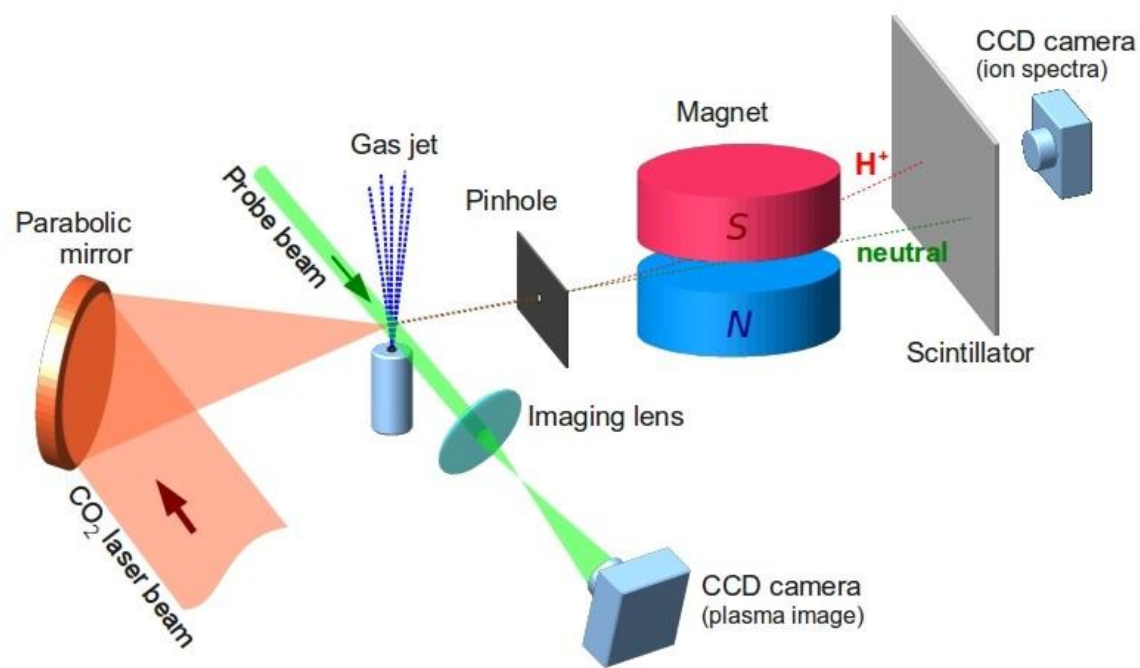
hole-boring (ponderomotive) acceleration



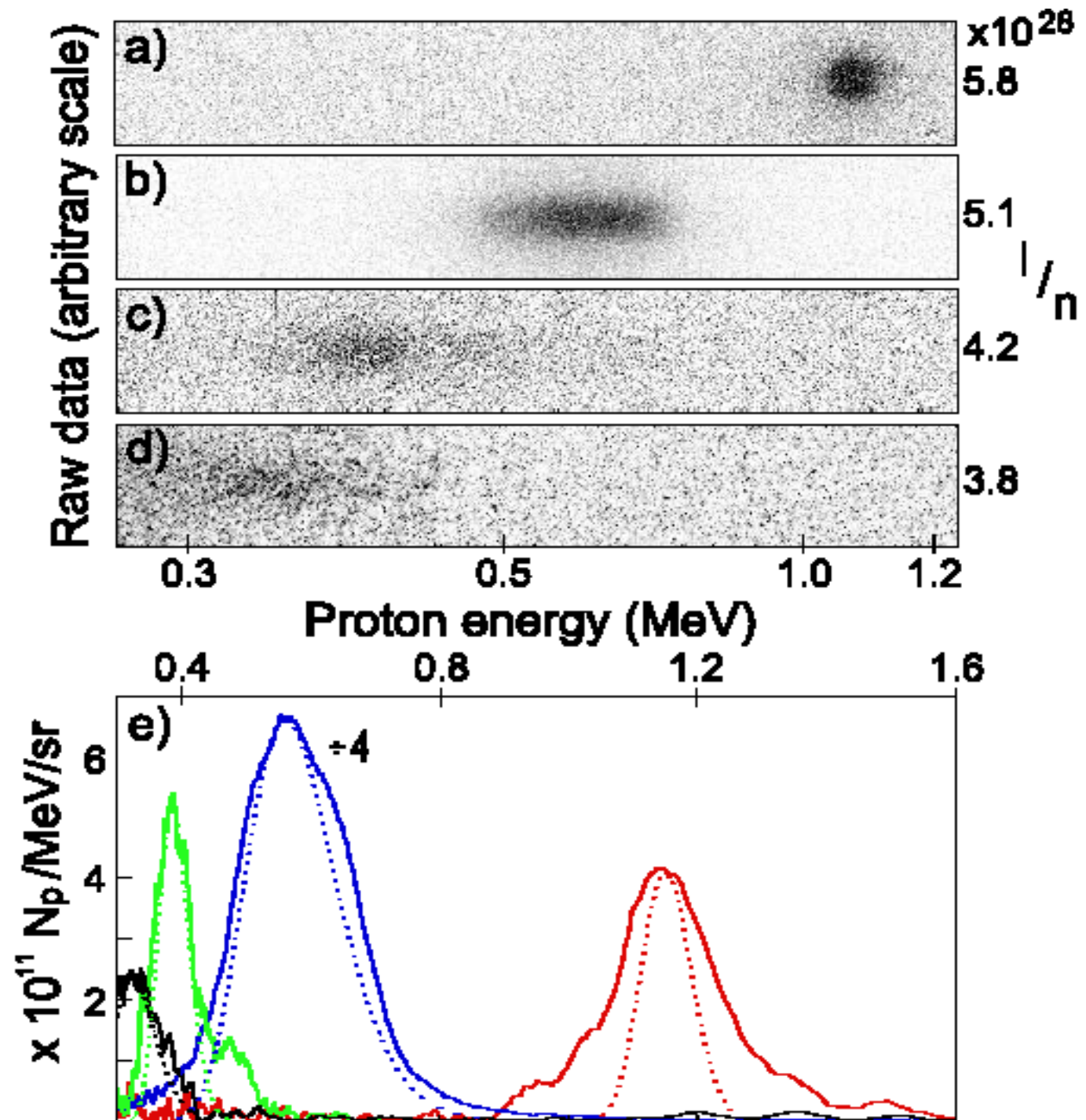
- CO_2 laser:
 - $\lambda = 10.6 \mu\text{m}$
 - Pulse energy $\sim 2\text{-}4 \text{ J}$
 - Pulse length $\lesssim 10 \text{ ps}$
 - **Pulse train with 25 ps separation.**
 - Focal spot diameter $\sim 60 \mu\text{m}$
- $I \sim 5 \times 10^{15} \text{ W/cm}^2$



hole-boring (ponderomotive) acceleration



- up to $\sim 10^9$ protons
 - 1000 brighter than previous modulated spectra.
- energy spread down to $\sim 4\%$
 - local emittance $\sim \text{nm}$



hole-boring (shock) acceleration

Simulation Conditions:

Laser:

$a_0 = 0.9$

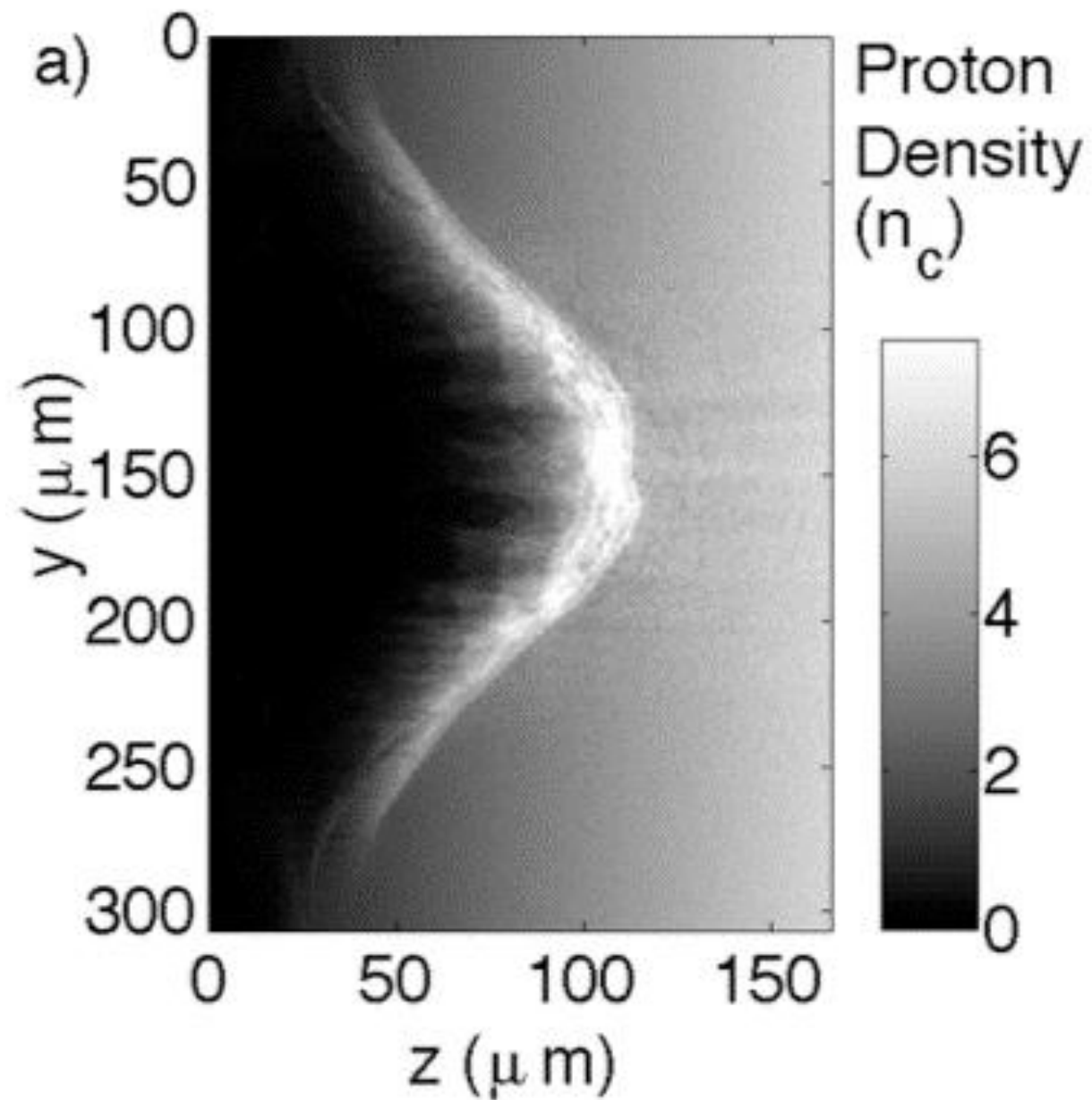
$\tau_L = 6\text{ps}$

Target:

Ionised H_2

Triangular density
profile

hole-boring (shock) acceleration



Simulation Conditions:

Laser:

$a_0 = 0.9$

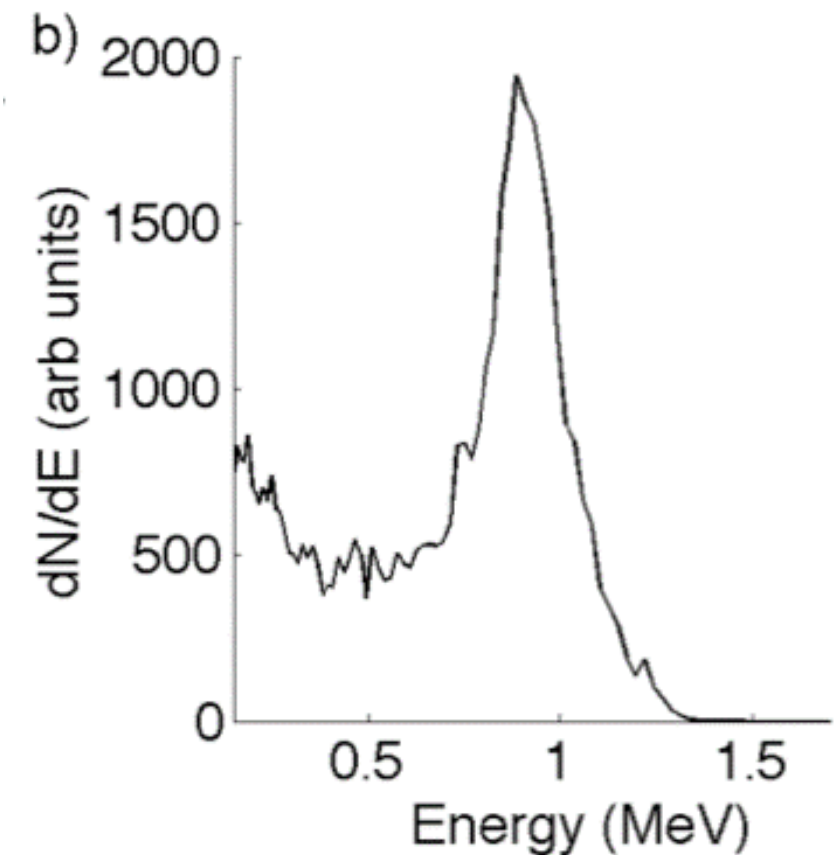
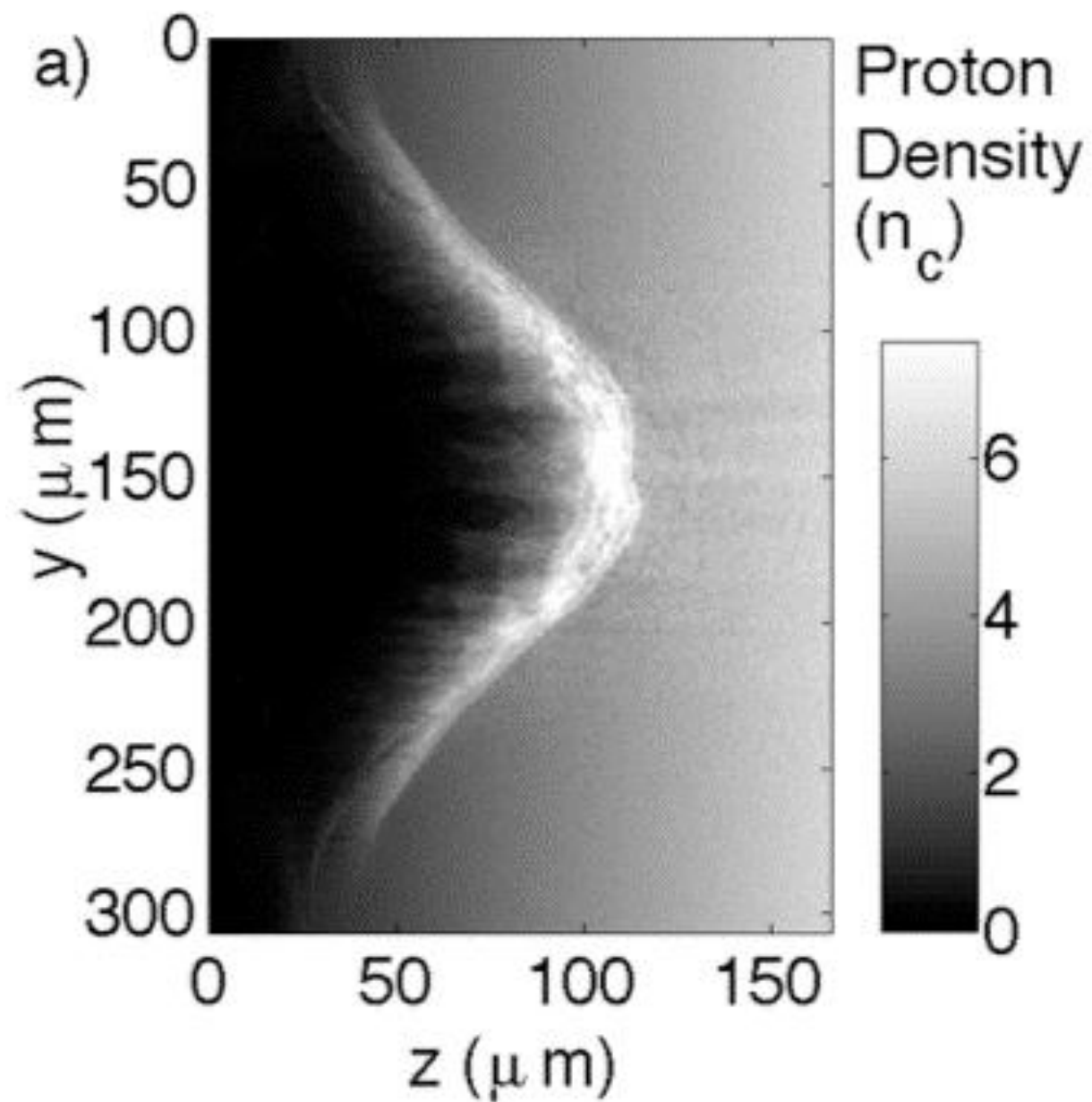
$\tau_L = 6\text{ps}$

Target:

Ionised H_2

Triangular density profile

hole-boring (shock) acceleration



Simulation Conditions:

Laser:

$a_0 = 0.9$

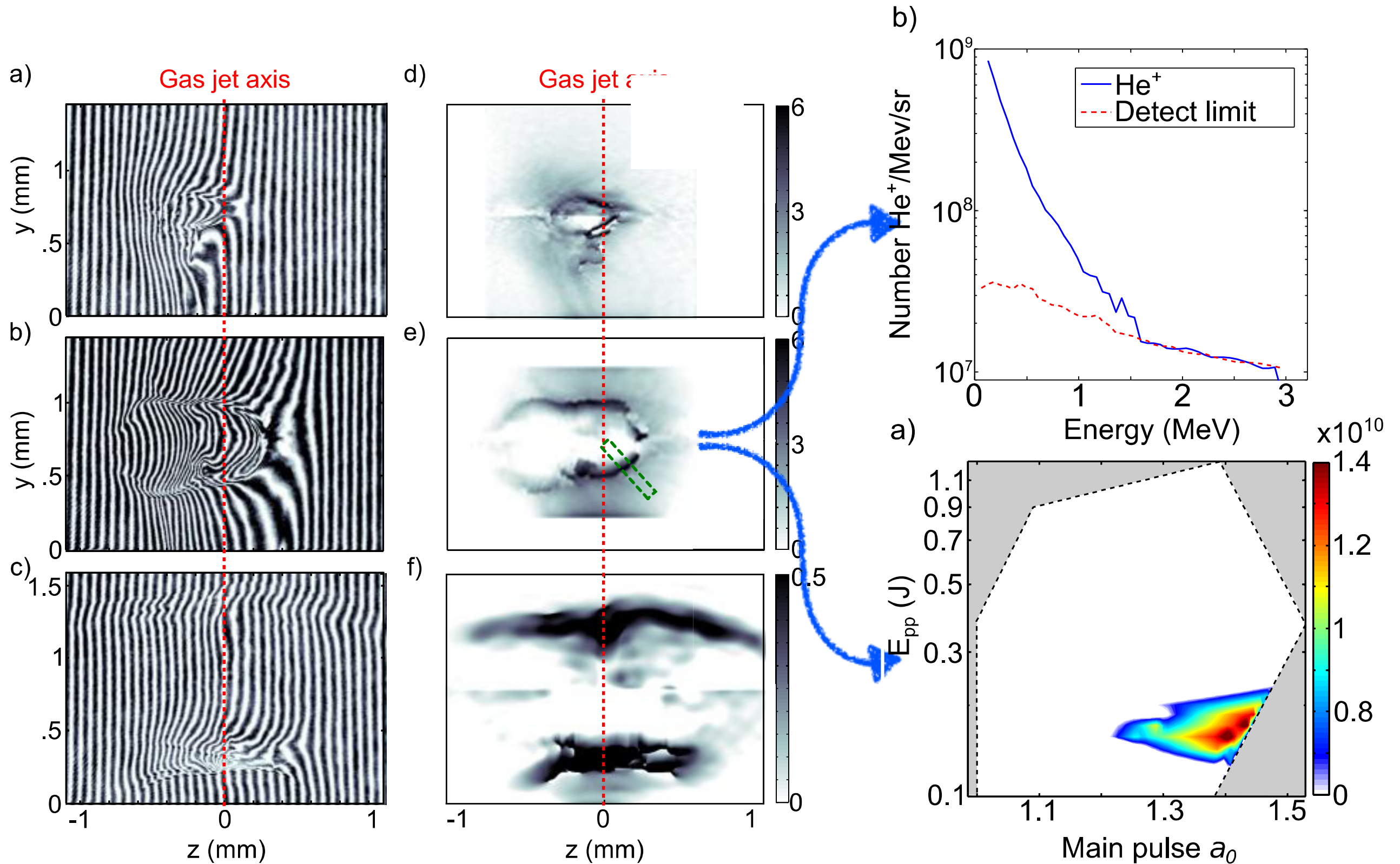
$\tau_L = 6\text{ps}$

Target:

Ionised H_2

Triangular density profile

scale-length manipulation



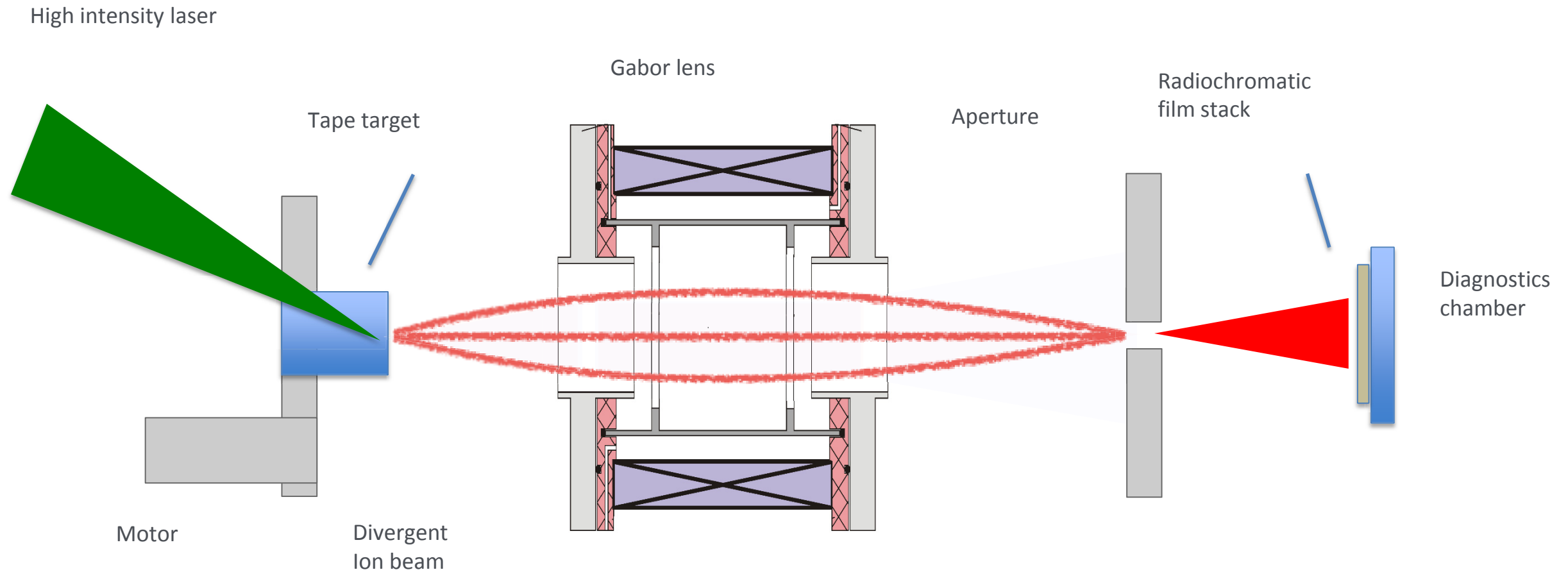
1. Tresca, O., et al, submitted Phys. Rev. Lett. (2014).

summary of mechanisms

Mechanism	Laser	Target	Ions	Energies	Pro	Con
Sheath	High intensity	Thin ($\sim\mu\text{m}$) foils	Protons (high-Z required target cleaning)	$\sim 50\text{ MeV}$ protons $\sim 200\text{ MeV}$ C	High number, short pulse length	Mixed species, low rep-rate, thermal beam, poor energy scaling
Light-sail	High intensity low prepulse	Ultrathin ($\sim\text{nm}$) foils	Protons (high-Z require cleaning)	$\sim 10\text{ MeV/u}$	High number, v. short pulse length, good emittance	poor beam quality, difficult target try
Hole-boring	Infra-red (adjustable prepulse)	Gas ($\sim\text{mm}$) ($\gtrsim n_{cr}$)	Any gaseous species	$\sim 1\text{ MeV/u}$	Good number, low energy spread, high rep-rate	No targets for optical lasers

Future Considerations

Beamline using laser generated ions



A Gabor lens used for both focussing and energy selection.

Gabor lens focuses both transverse dimensions simultaneously, thereby significantly reducing through-put.

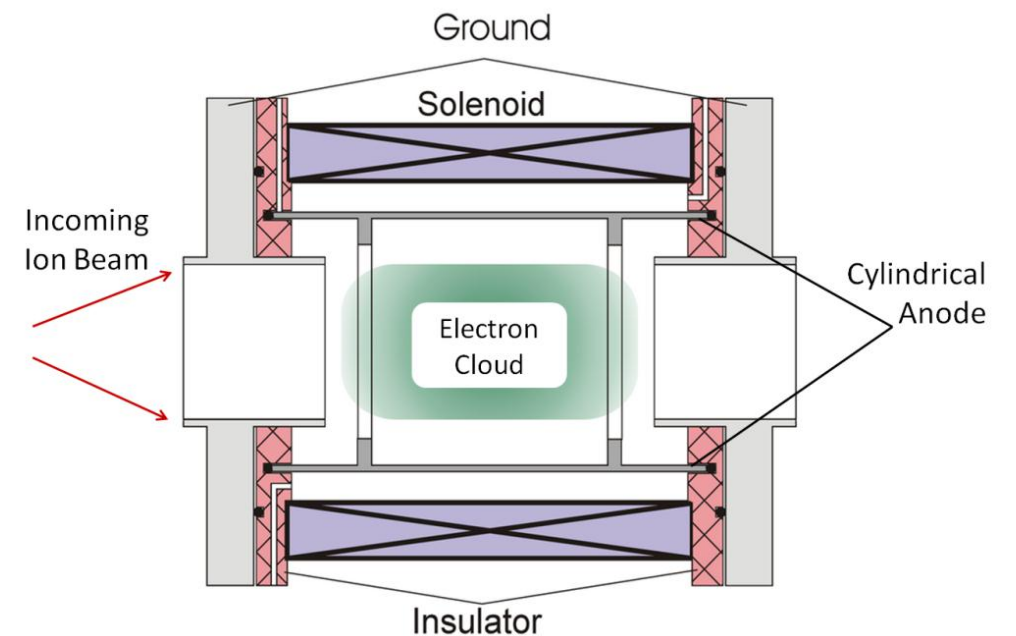
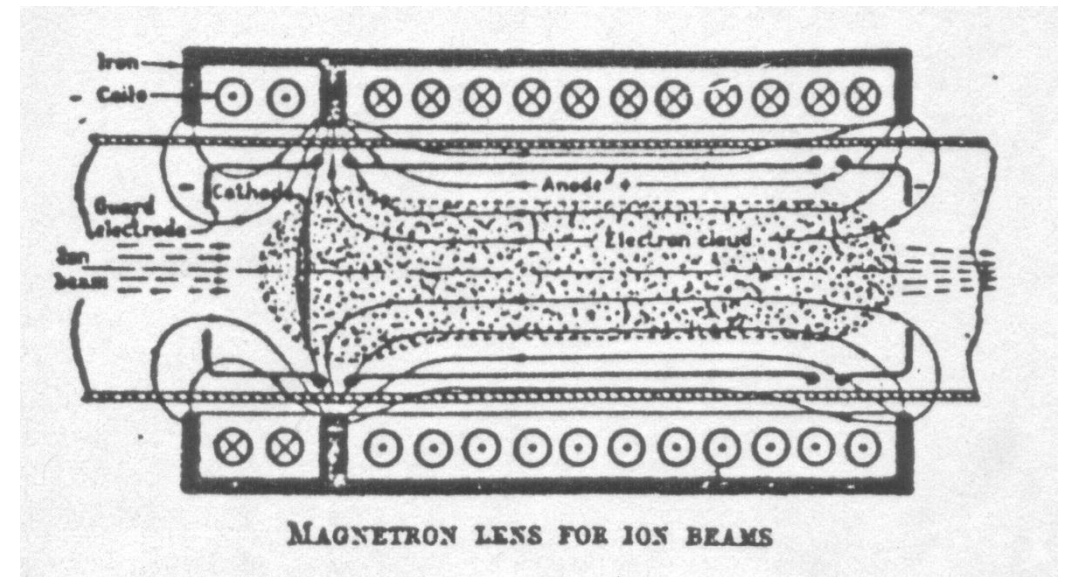
Gabor Lens

A Gabor lens is a space-charge lens first proposed in 1947.

Requires reduced magnetic field for focusing ions, compared to solenoids:

$$B_{GPL} = B_{sol} * \sqrt{\frac{m_e}{m_{ion}}} Z.$$

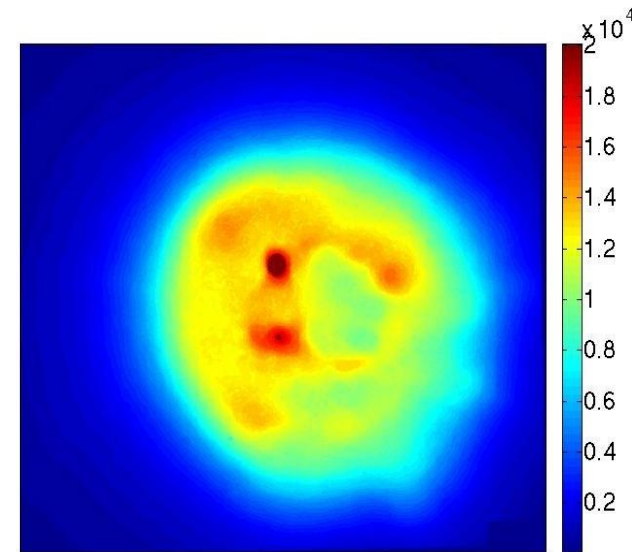
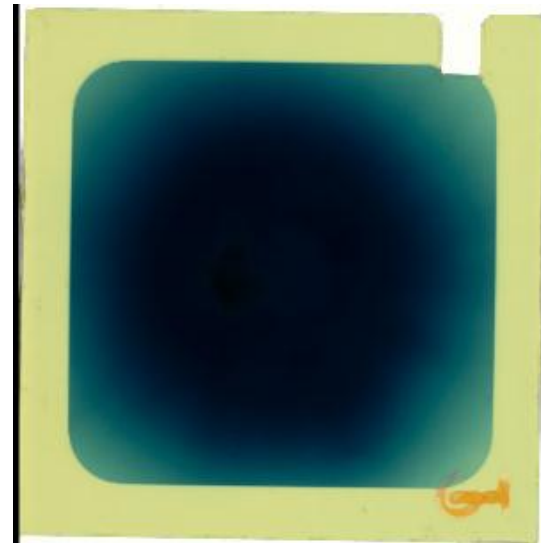
Has recently been considered for focussing laser generated ion beams.



1. D. Gabor, Nature 159, 1947.
2. J. Pozimski and M. Aslaninejad, Laser and Particle Beams, 31, 2013

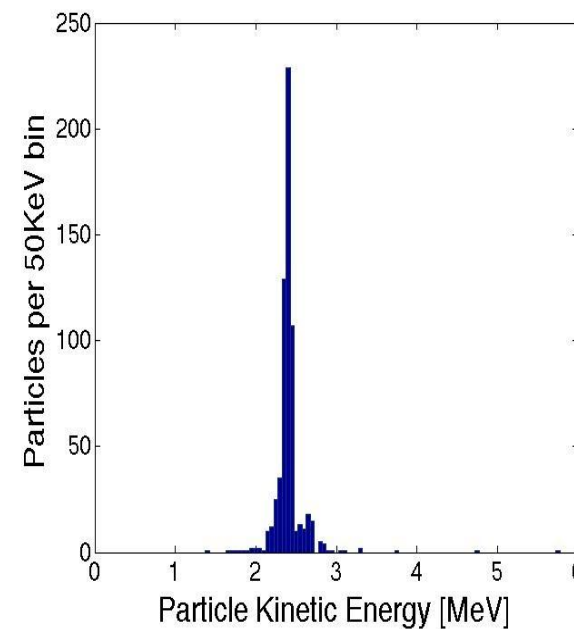
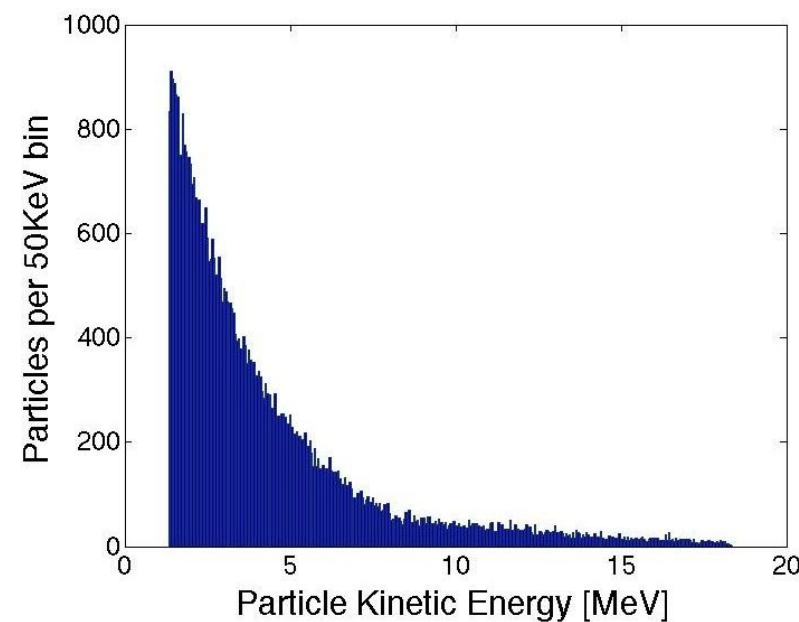
Beamline using laser generated ions

Scanned RCF
from Astra
Gemini
experiment



Dose map

Spectrum
Before lens

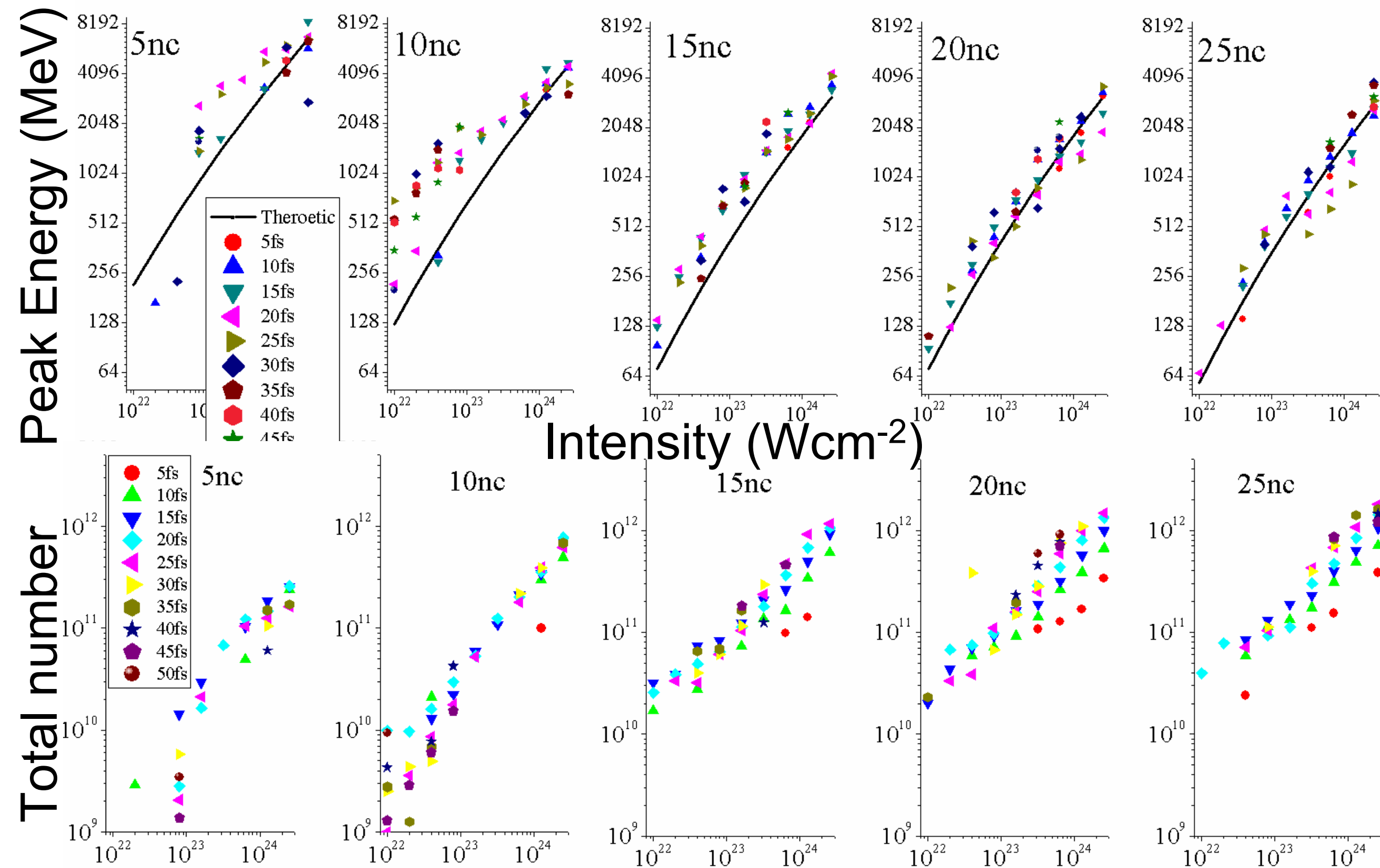


After lens and
aperture

Proposed Applications:

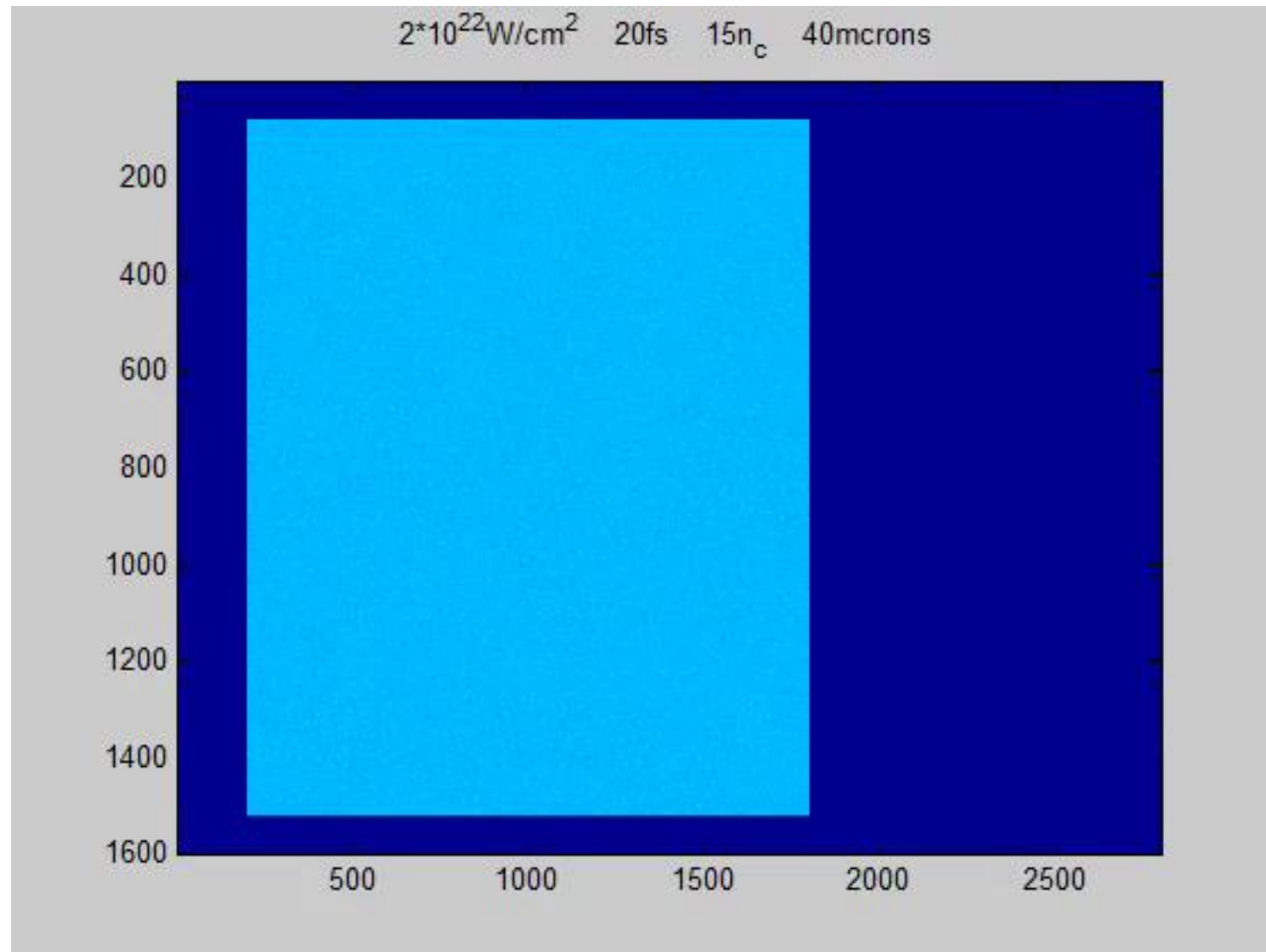
Radiobiology with varying ion species, Radio-isotope production

Scaling of Hole-boring acceleration

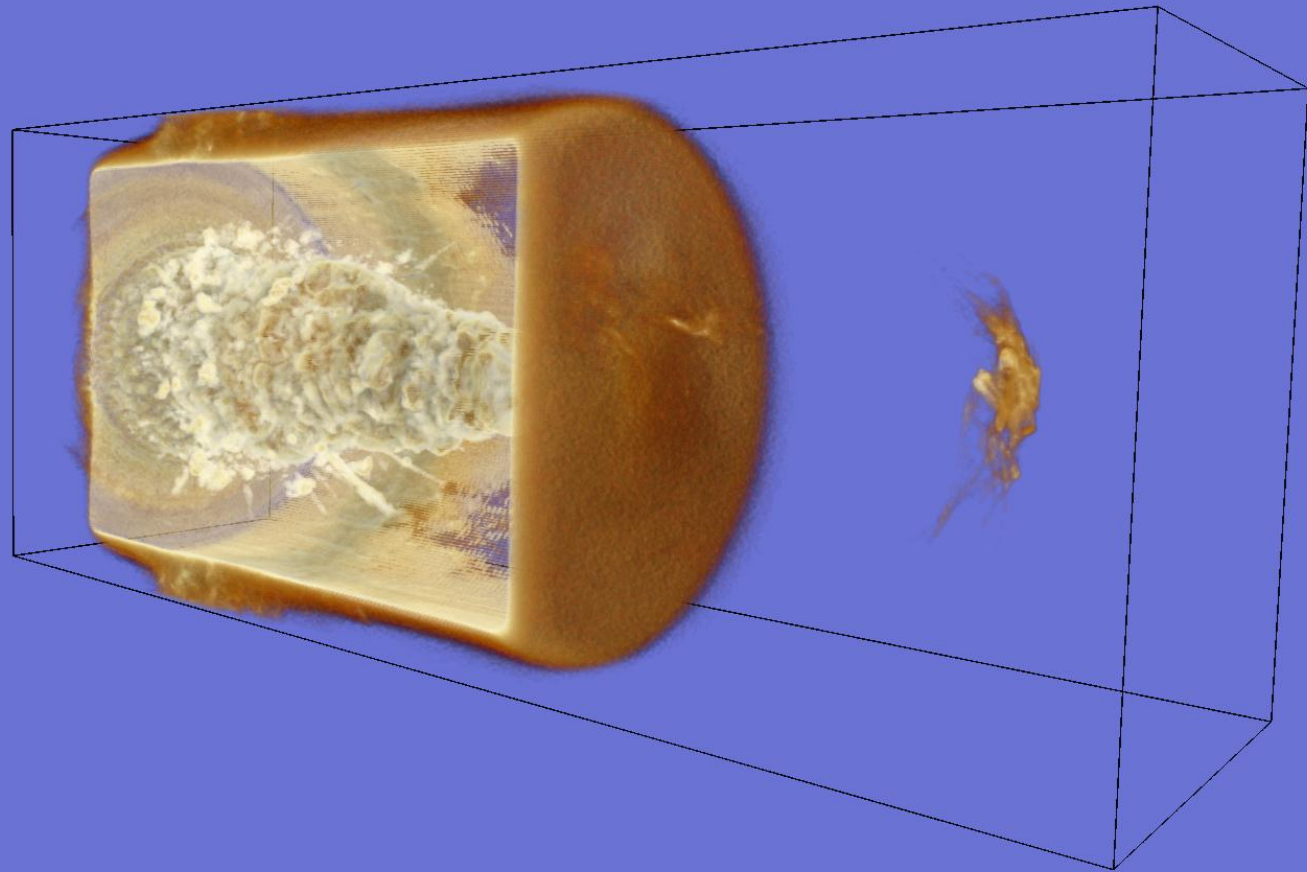


Scaling of Hole-boring acceleration

Scaling of Hole-boring acceleration



Scaling of Hole-boring acceleration



- Laser peak intensity: $4.0 \times 10^{22} \text{ Wcm}^{-2}$
- duration: 15fs
- Peak energy: 1.32GeV
- energy spread: 28%
- divergence: 9.2°
- total charge of bunch: 6.5nC
- spot size of the bunch: $2.9 \mu\text{m}$
- Laser spot size: $4 \mu\text{m}$

Collaborators

THIN FOIL EXPERIMENT:

JAI Imperial College London: **N.Dover, C. Palmer**, M. J. V. Streeter, C. Bellei, A.E. Dangor, S.R. Nagel, J. Schreiber.

Queens University Belfast: H. Ahmed, M. Borghesi, K. Kakolee, S. Kar, R. Prasad, M. Yeung and M. Zepf

LULI, École Polytechnique: B. Albertazzi, J. Fuchs, M. Nakatsutsumi

LMU München/ MPQ Garching: P. Hilz, D. Kiefer

Graduate School of Engineering, Osaka: R. Kodama, A. Kon, M. Tampo

SUPA, Strathclyde: D. A. MacLellan, P. McKenna, G. Scott

Central Laser Facility, RAL: D. C. Carroll, R. Heathcote, D. Neely, M. M. Notley

GAS JET EXPERIMENT:

JAI Imperial College London: **N. Dover, C. Palmer**, J. Schreiber

ATF, BNL: **O. Tresca, I. Pogorelsky**, M. Babzien, M. Ispiryan, M. N. Polyanskiy, V. Yakimenko.

Stony Brook University, USA: N. Cook, C. Maharjan, P. Shkolnikov.

BEAMLINER:

Imperial College London: **C. Hughes**, P. Posocco, J. Pozimski

JAI Imperial College London: G. Hicks, O. Ettlinger, N. Dover

SIMULATIONS:

JAI Imperial College London: **J. Yu**, N. Dover

Conclusions

- Buffering enhances proton acceleration from thin foils.
- Scale-length manipulation of gas profiles allows direct helium acceleration from gas targets
- Beam line based on Gabor lens simulated
- Hole-boring acceleration to GeV energy level simulated
- Time is ripe to marry laser and conventional techniques!

