Laser driven ion acceleration with near-critical targets

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BNL ion acceleration experiments

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I.V. Pogorelsky, O. Tresca, M.N. Polyanskiy

N. Cook, C. Maharjan, P. Shkolnikov

Why laser-plasma ion sources?

- What can laser-plasma sources offer?
  - High flux, low emittance, short bunch
  - High accelerating gradients - **compact source**
- Potential advantages
  - Lower cost
  - Flexible source
    - Different ion species, energy distributions...
    - Same laser for multiple applications

Targeted applications

Increased repetition rate/beam current

Increased source energy

Now: ~10s MeV, some spectral control, ~10^{12} particles per shot, ~1 Hz

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Cell irradiation radiobiology

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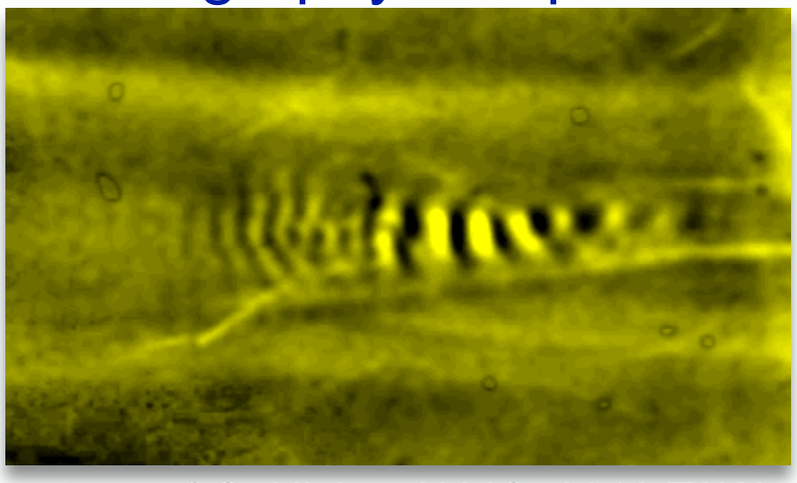
Cell irradiation
radiobiology

Plasma
radiography

Radiography of a plasma:



Courtesy of G. Hicks, JAI IC, 2012 TAW experiment

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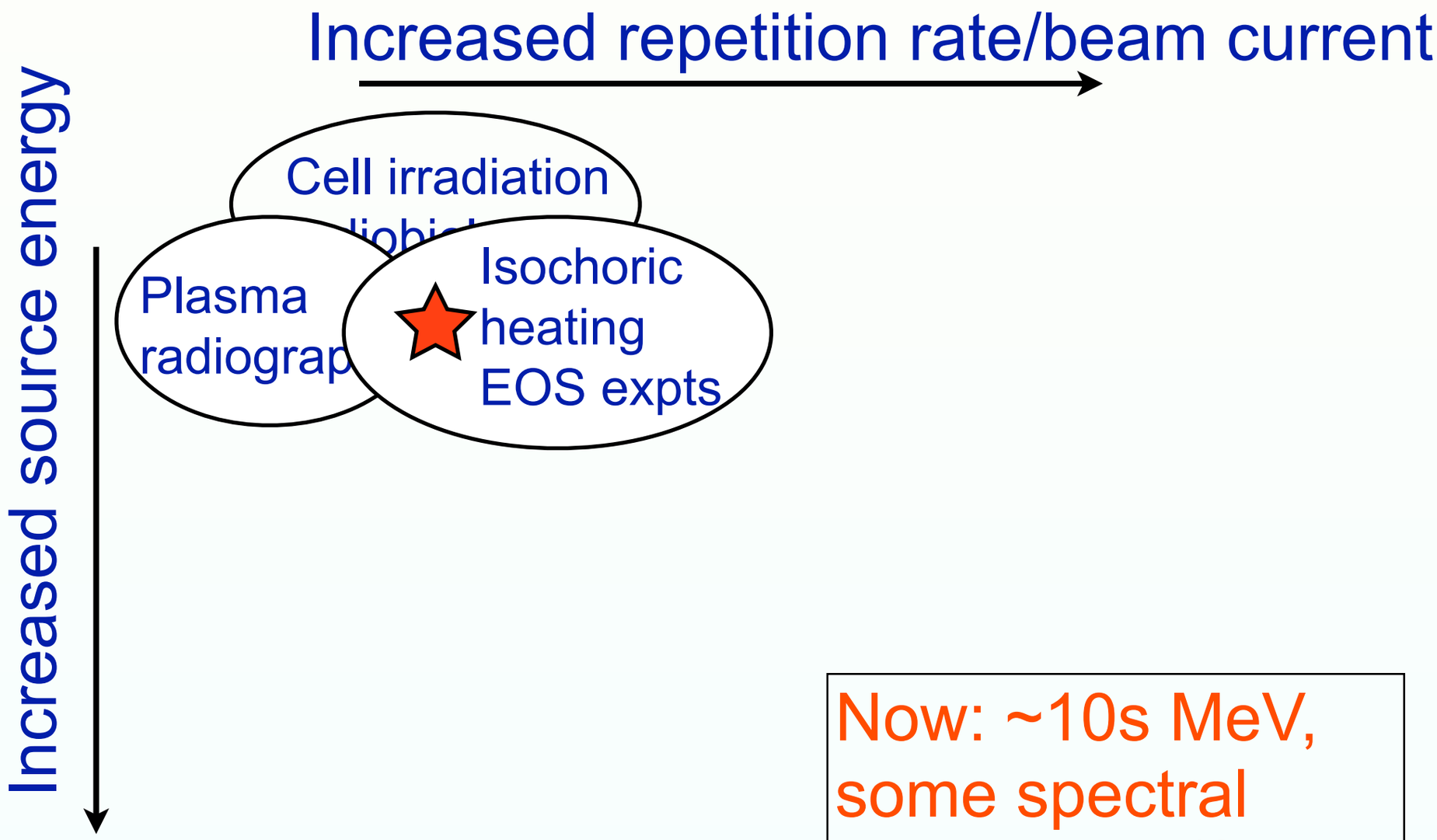

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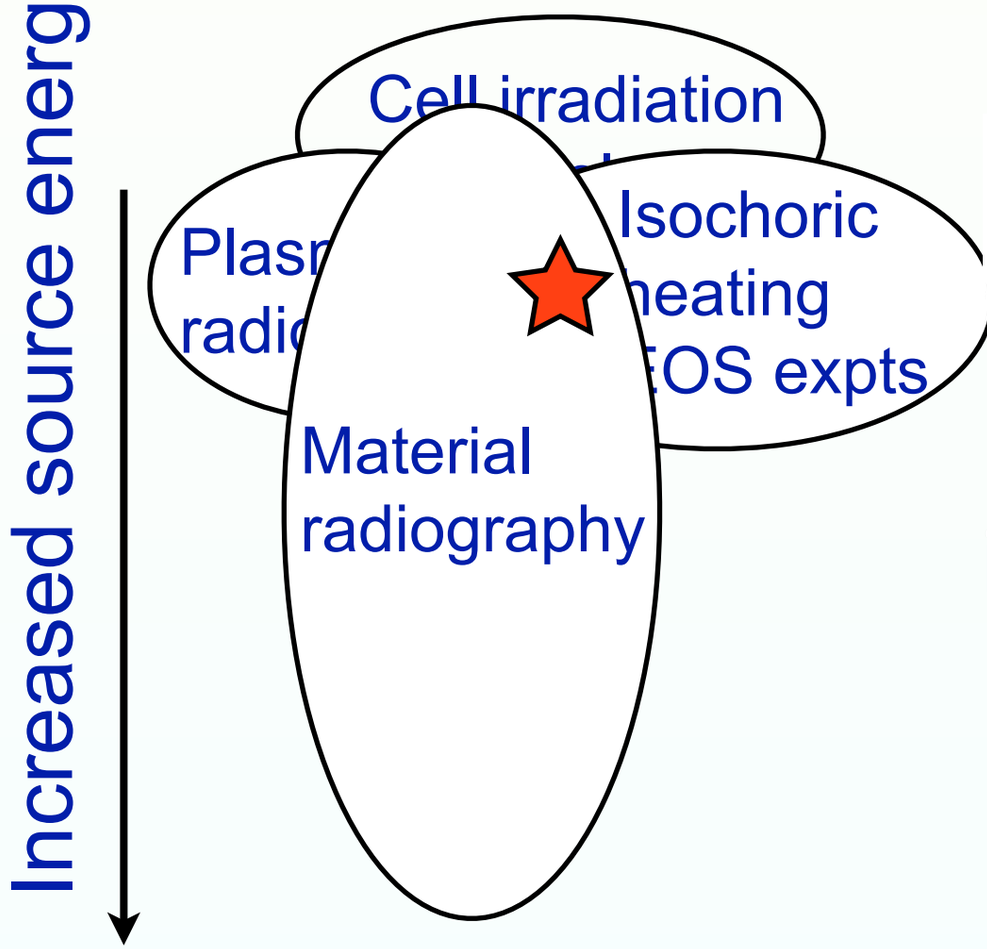
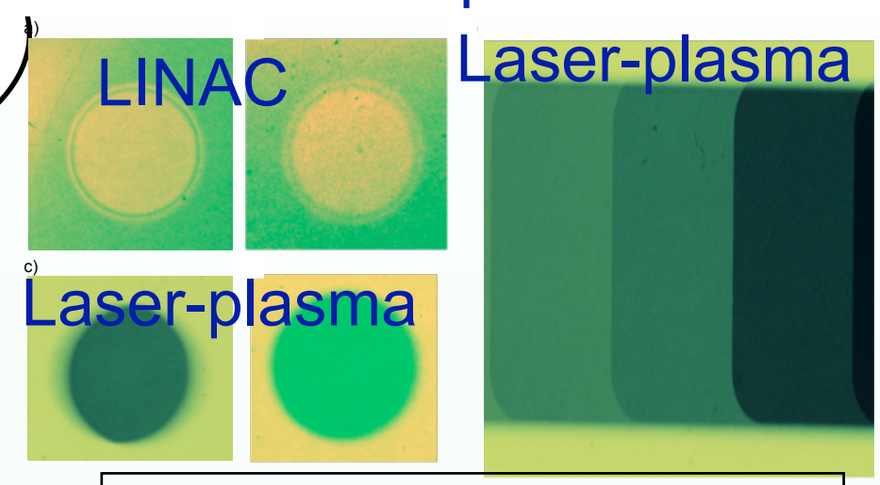


Radiography of phantom with LINAC & laser plasma source:



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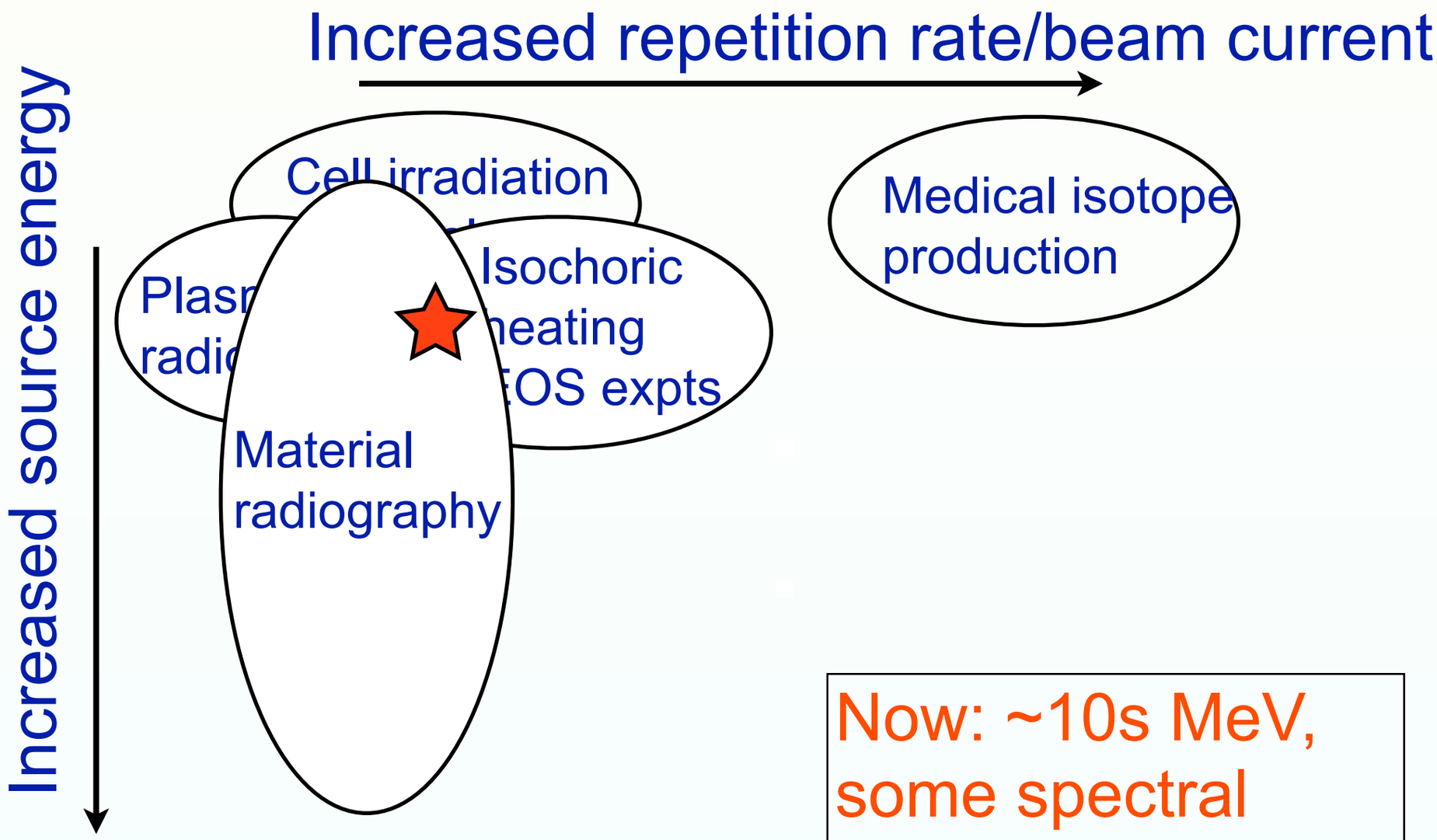
Targeted applications



Now: ~10s MeV, some spectral control, ~10^{12} particles per shot, ~1 Hz

Targeted applications

Increased repetition rate/beam current

Increased source energy

Cell irradiation

Plasma radiography

Isochoric heating EOS expts

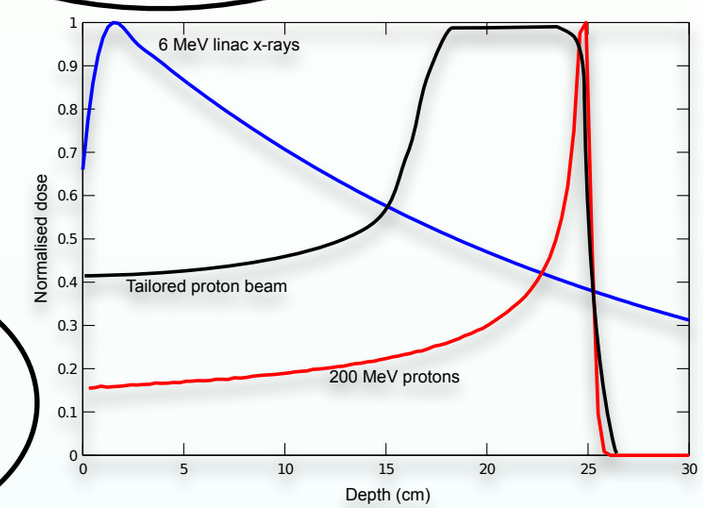
Material radiography

in vivo radiography

Medical isotope production

Particle therapy

> 250 MeV (protons)



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Laser radiotherapy

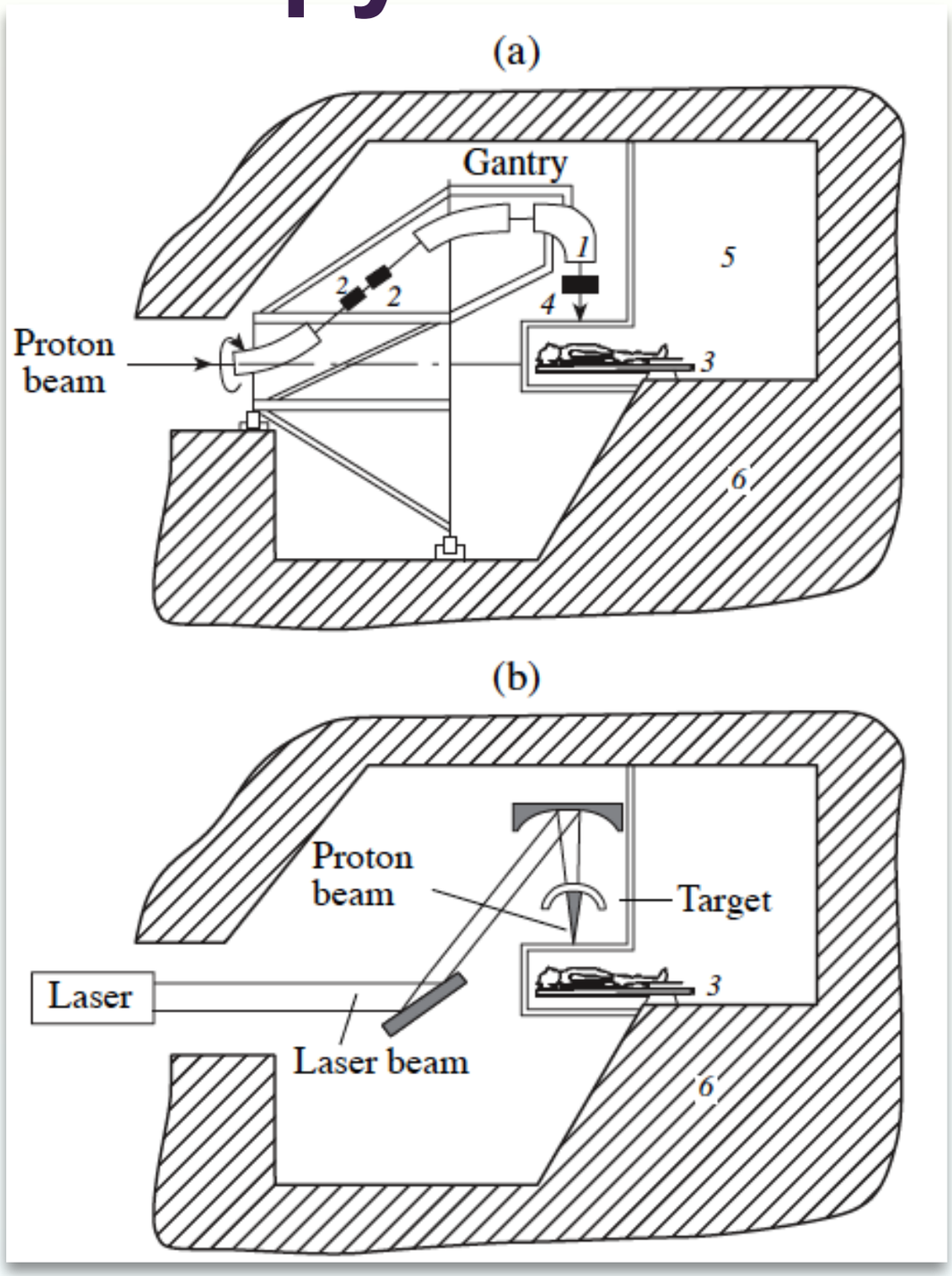
Advantages:

Compact

Less heavy
➠ (therefore cheaper)

Versatile
➠ (different ion species)
➠ (integrated imaging)

Plasma Physics Reports, Vol. 28, No. 5, 2002, pp. 453–456.
Translated from Fizika Plazmy, Vol. 28, No. 5, 2002, pp. 493–496.
Original Russian Text Copyright © 2002 by Bulanov, Khoroshkov.



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- Why
  - High flux, low emittance, short bunch
  - High accelerating gradients -
- Pros:
  - Lower cost
  - Flexible source
    - Different ion species, energy distributions...
    - Same laser for multiple applications
- Challenges:
  - Unwanted radiation production
  - Stability, reproducibility (ie. laser technology!)
  - For some applications, want higher energy, higher current, or both… in narrow energy spread

Radiation Pressure

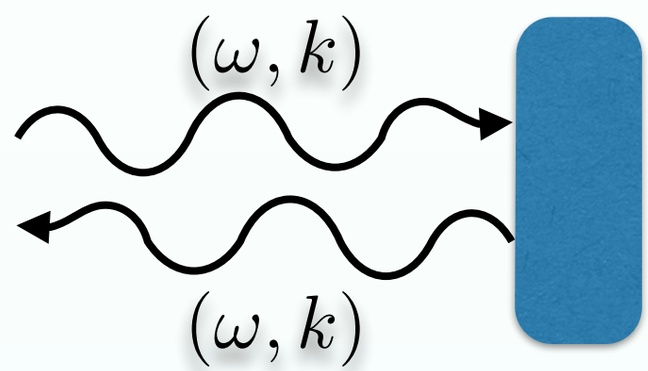
- **Thermal pressure: $P_R = n_e k_B T_e$ with:**

$$k_B T_e = mc^2 \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1 \right)$$

$$P_T \propto I^{1/2}$$

- **Radiation pressure:**

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



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

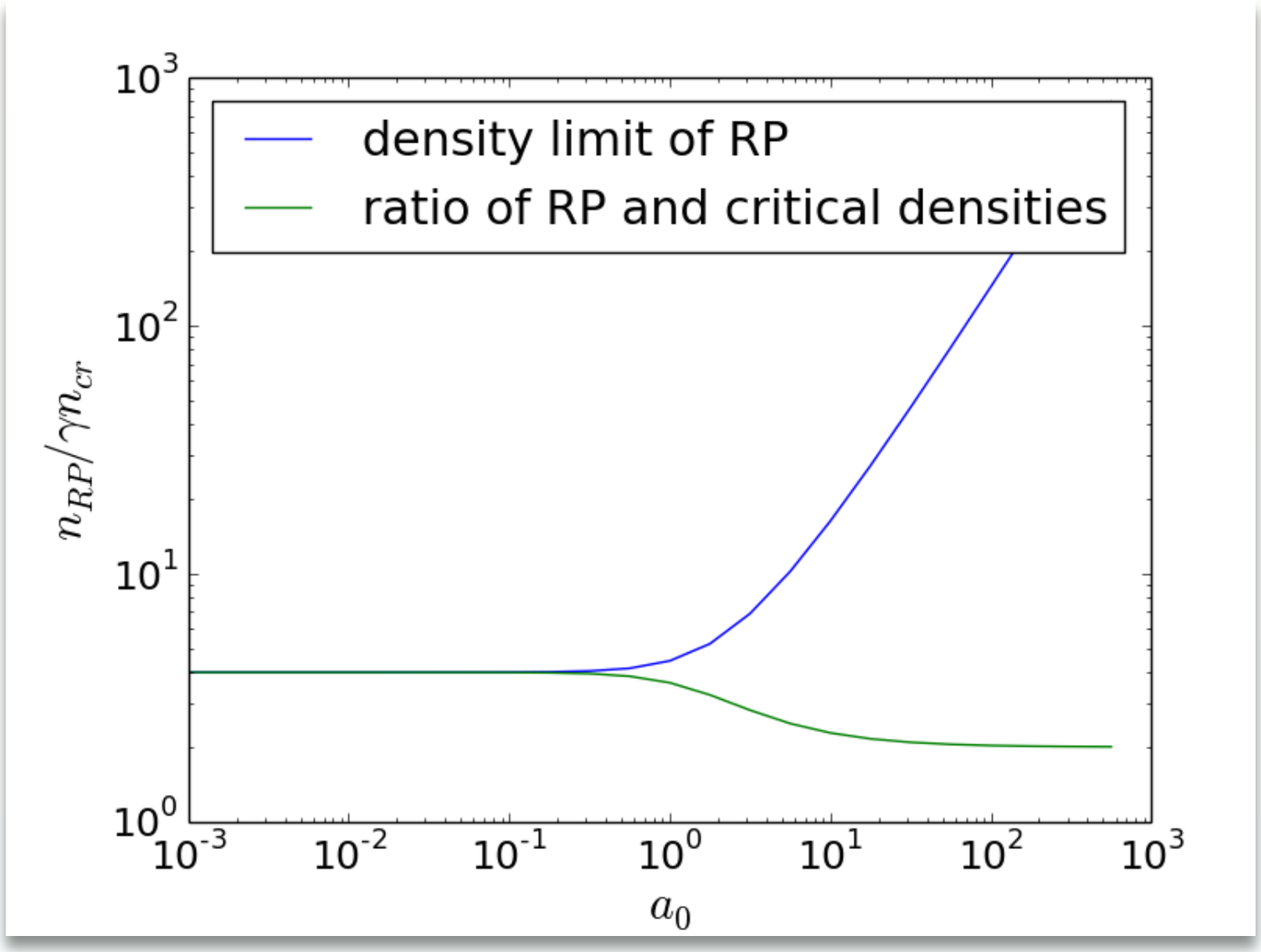
For ATF: 2 TW, w_0 ~ 60 μm, $I \approx 10^{16}$ Wcm^{-2} , P_R > 10 MBar

For ATFII: 100 TW, w_0 ~ 20 μm, $I \approx 10^{18}$ Wcm^{-2} , P_R > 1 GBar

Radiation pressure acceleration

- Writing $$I = \frac{1}{2}\epsilon_0 {E_0}^2 c = \frac{1}{2} n_{cr} m c^2 {a_0}^2 c$$
- and $$k_B T_e = mc^2 \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1 \right)$$
- then $$P_R > P_T \quad \rightarrow \quad (1+R)\left(\frac{I}{c}\right) > n_e k_B T_e$$
- or $$n_{cr} {a_0}^2 > n_e \left(\sqrt{1 + \frac{{a_0}^2}{2}} - 1 \right)$$

Radiation pressure



$$n_{cr}{a_0}^2 > n_e\left(\sqrt{1+\frac{{a_0}^2}{2}}-1\right)$$

- For dense targets need
  - extreme intensities or
  - cold targets (circular polarisation?)
  - and extreme care!
- But radiation pressure can become dominant at much lower intensities if lower densities used.
  - indeed for $n_e < 4\ n_{cr}$, P_R always dominates

Radiation pressure on thin foils

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

- But if too thin all electrons depleted from foil
- balance space charge and RP for **optimum thickness** $\mathbf{d_{opt}}$:

$$d_{opt} = \left(\frac{n_{cr}}{n_e}\right) a_0 \left(\frac{\lambda_0}{2\pi}\right)$$

- for λ=1 μm, $I \approx 10^{18}$ Wcm^{-2}, DLC
  - ➡ $d_{opt} \approx 5$ nm

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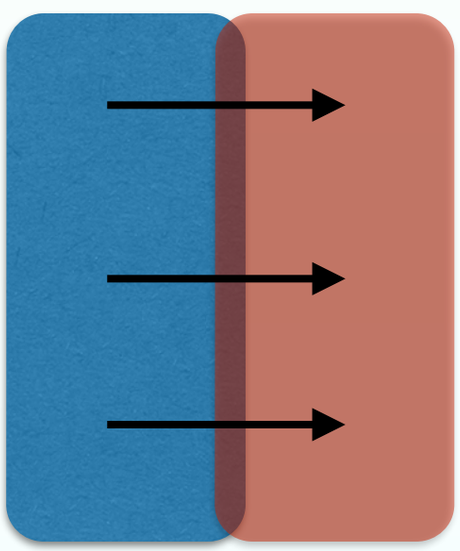
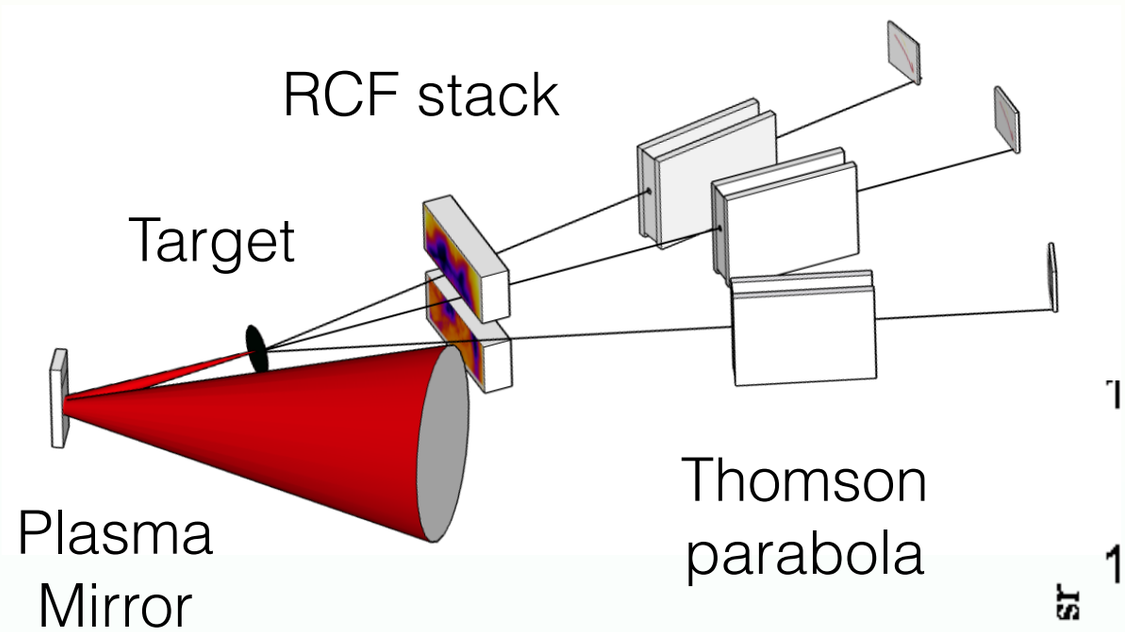


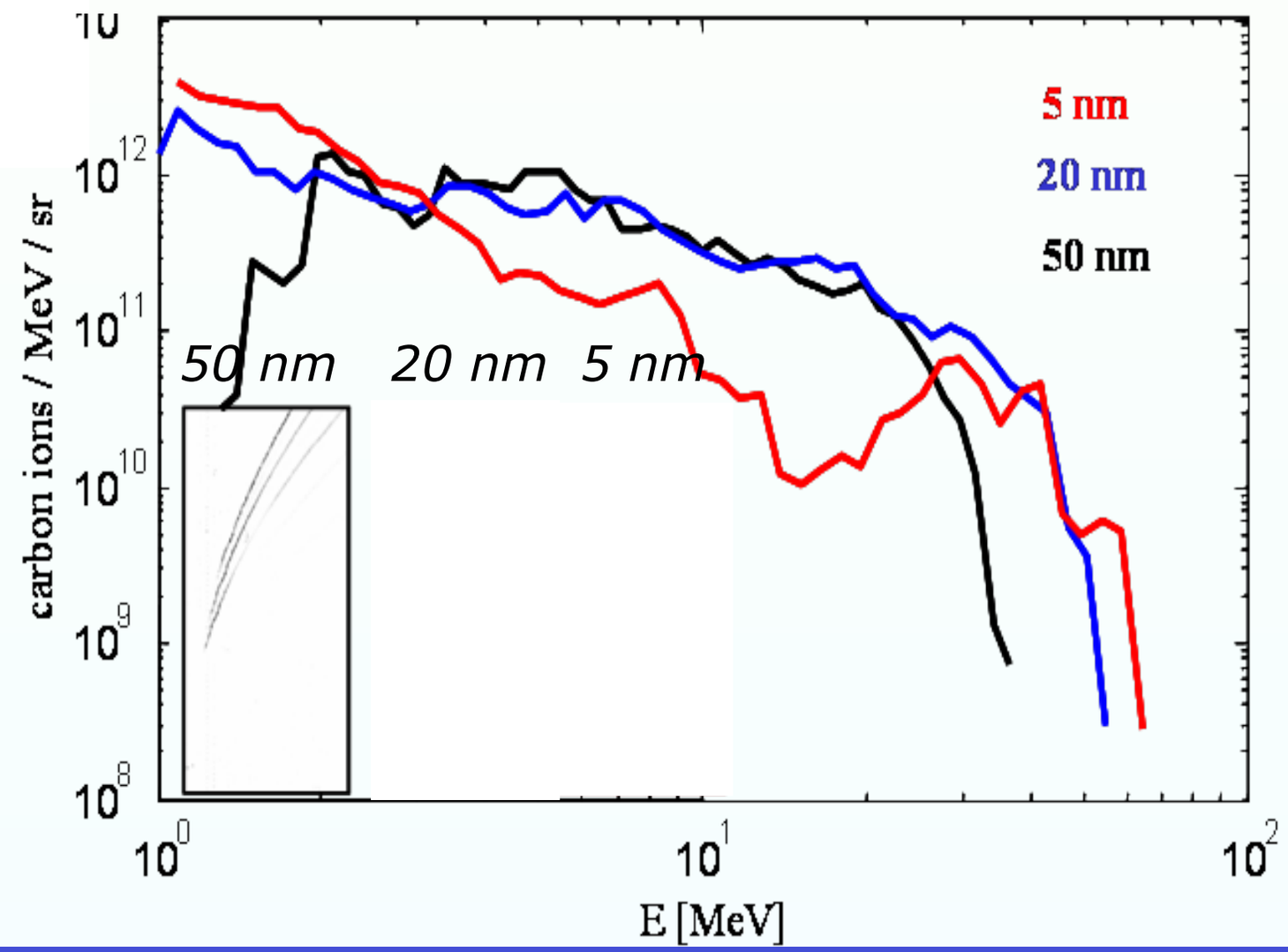
$E \sim 10^{11}\ \mathrm{Vm}^{-1}$

Thin foil interactions



Experiment Conditions:

Laser:	Target:
$I=10^{20}Wcm^{-2}$	d = 10nm
(a_0=10)	DLC target
τ_L= 600fs	C^{6+} $n_e=800n_c$



1. Palmer, C. A. J. et al. Phys. Rev. Lett. 108, 225002 (2012).

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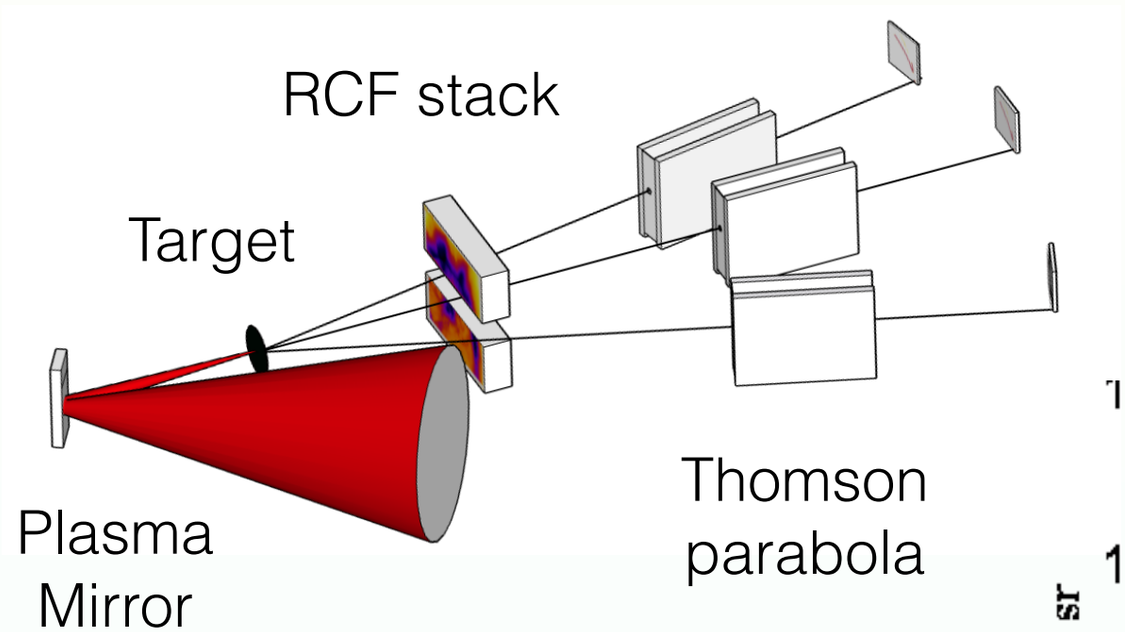

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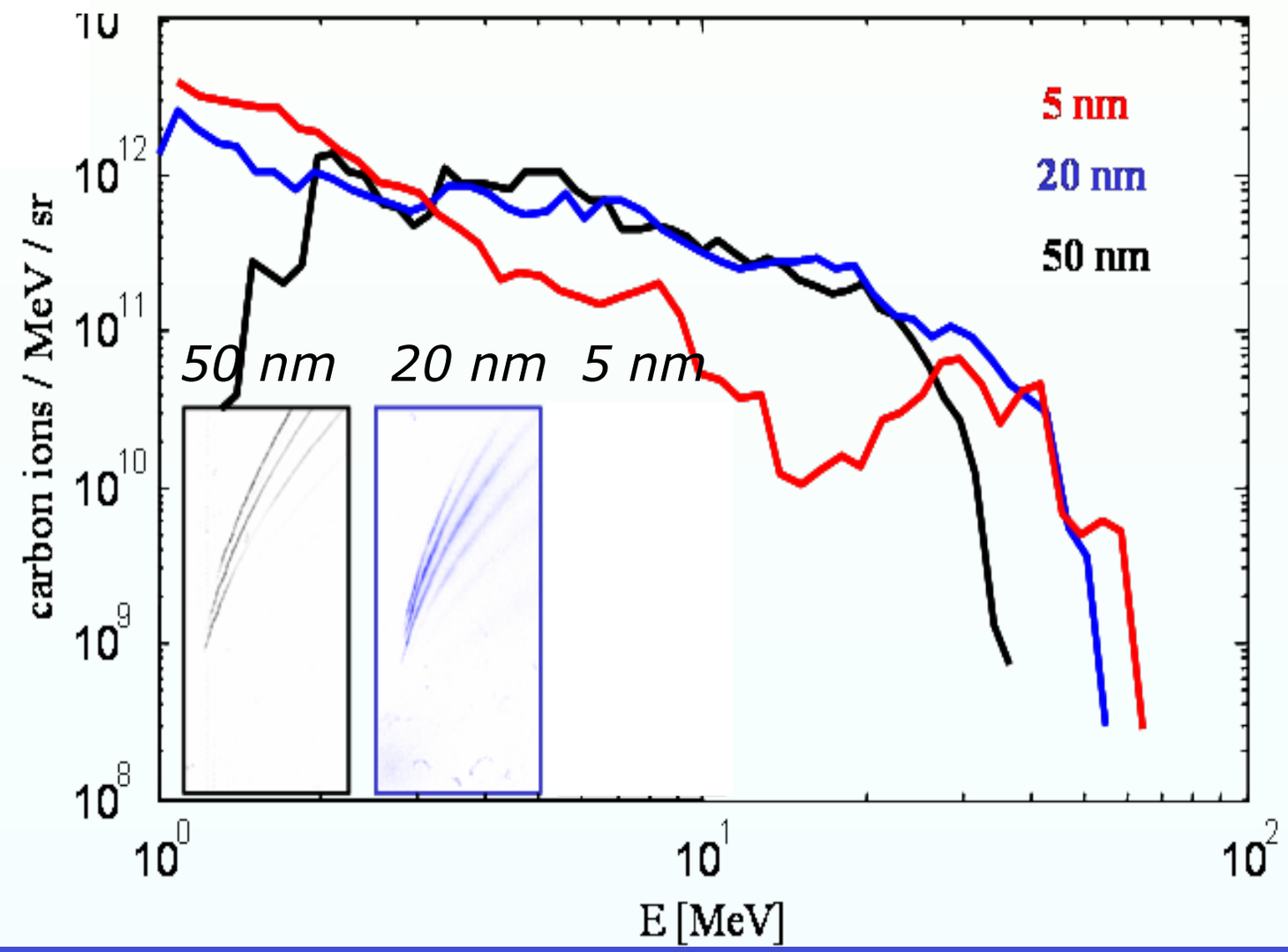

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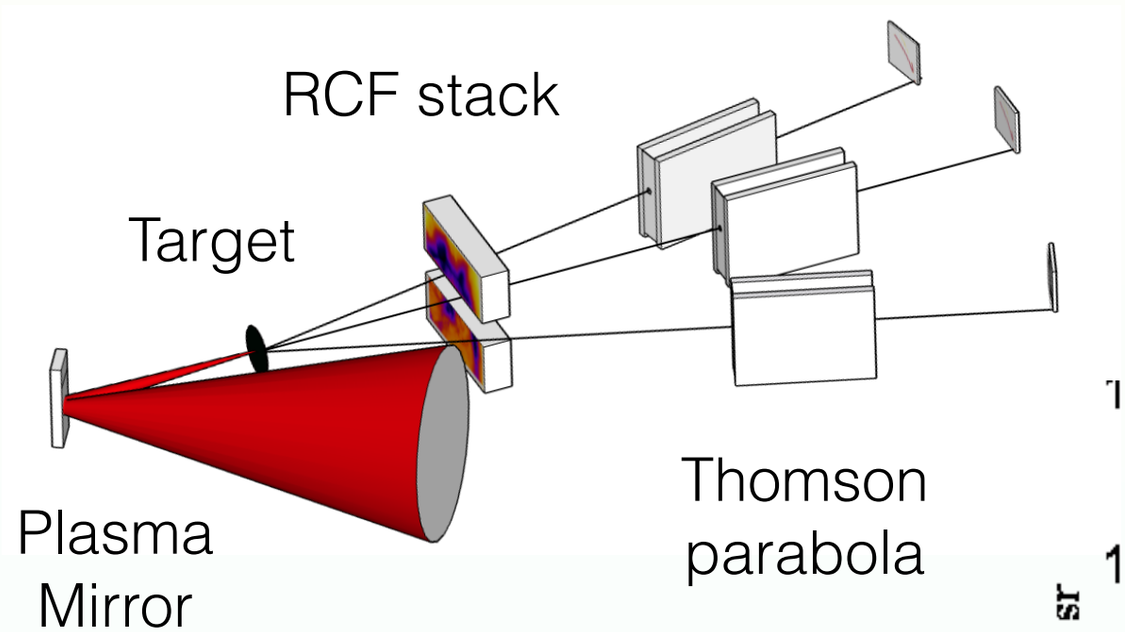

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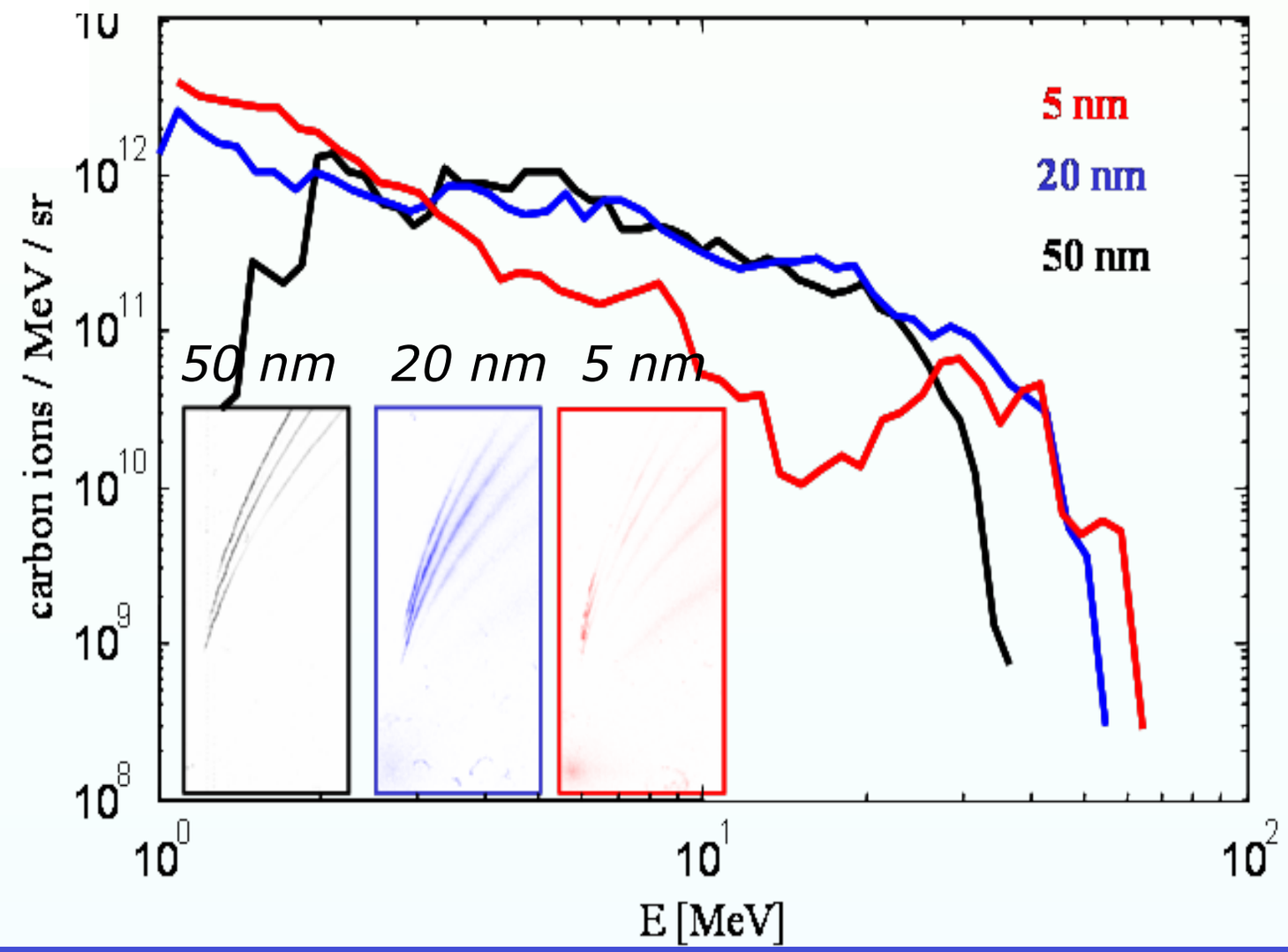

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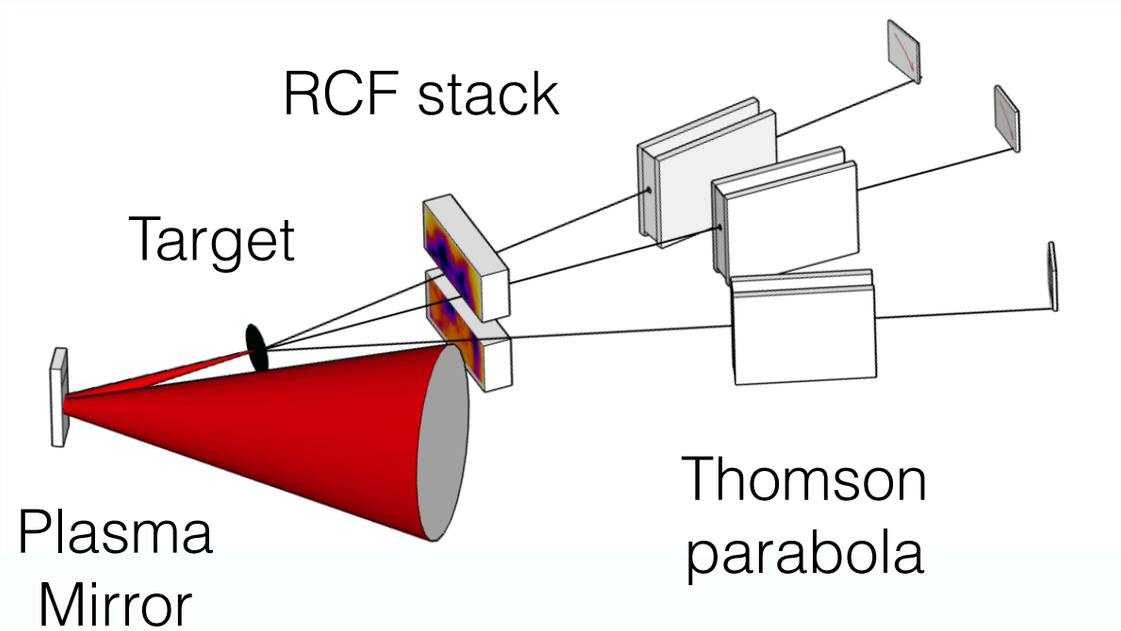
Rayleigh-Taylor Instability



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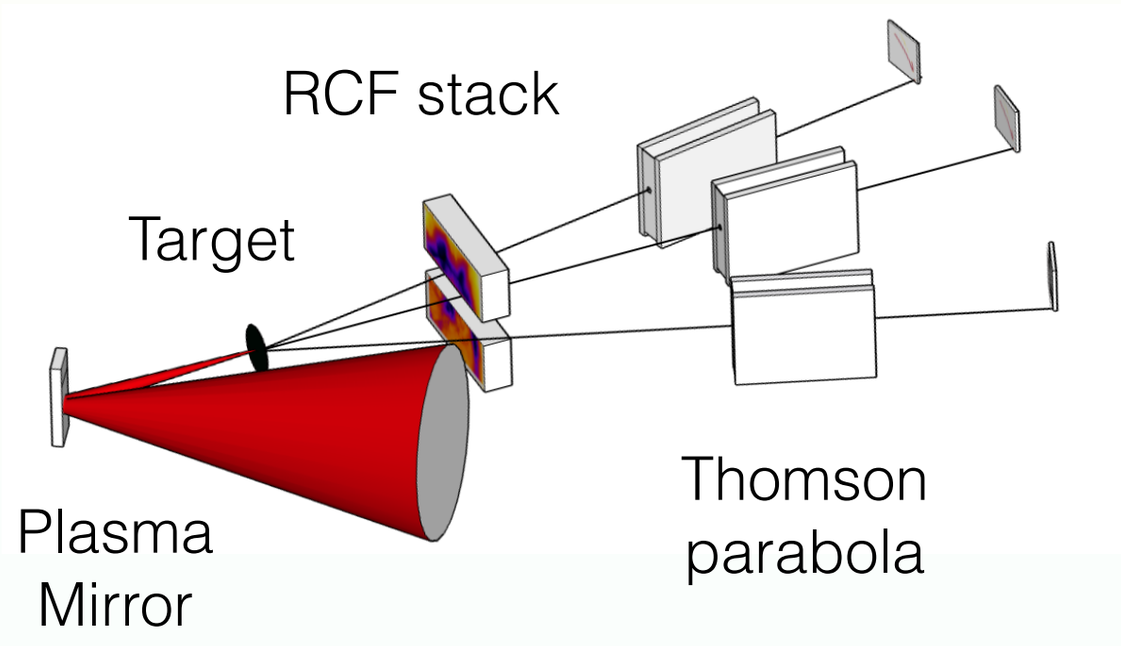

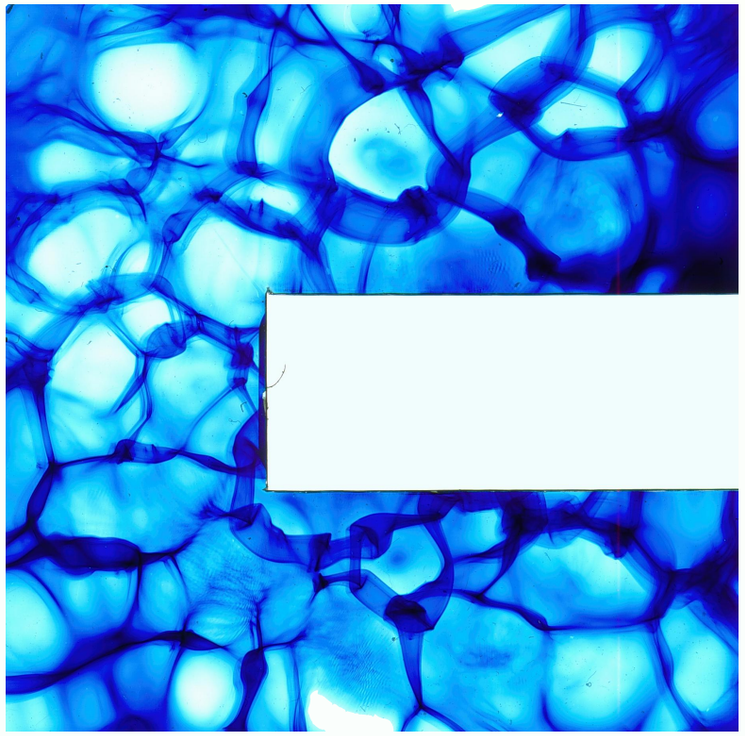

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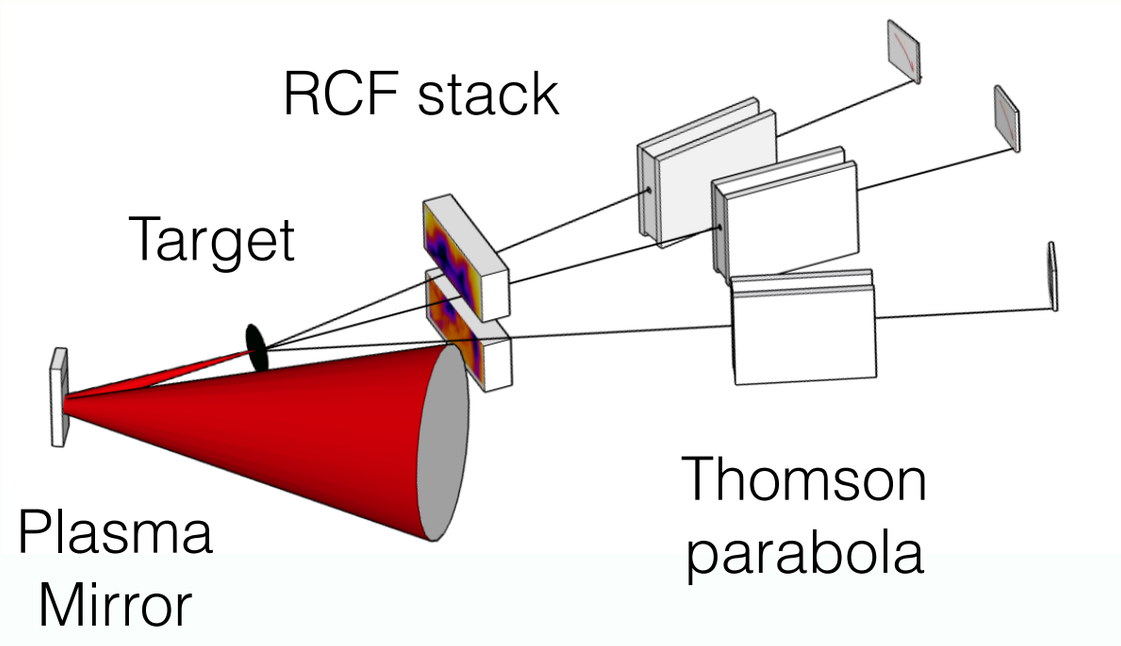

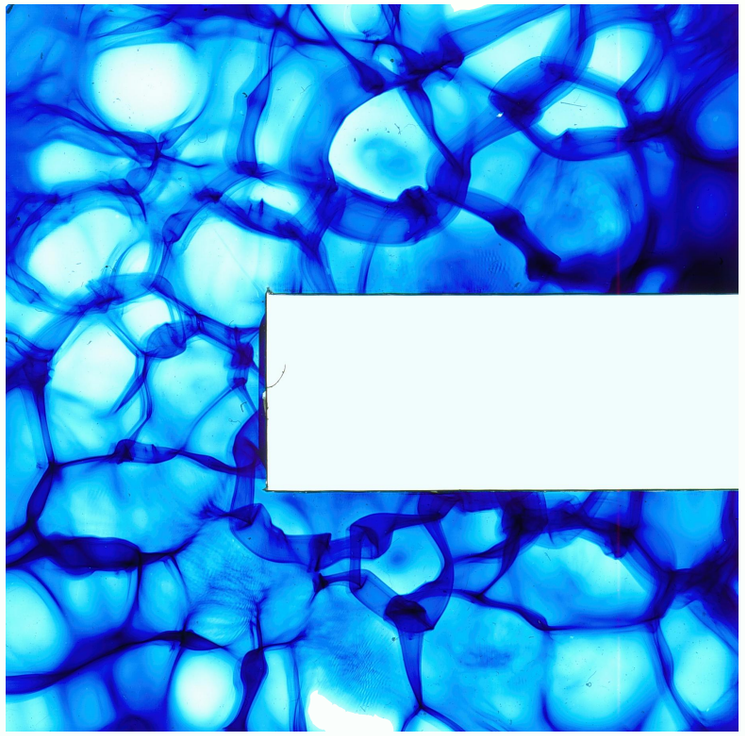

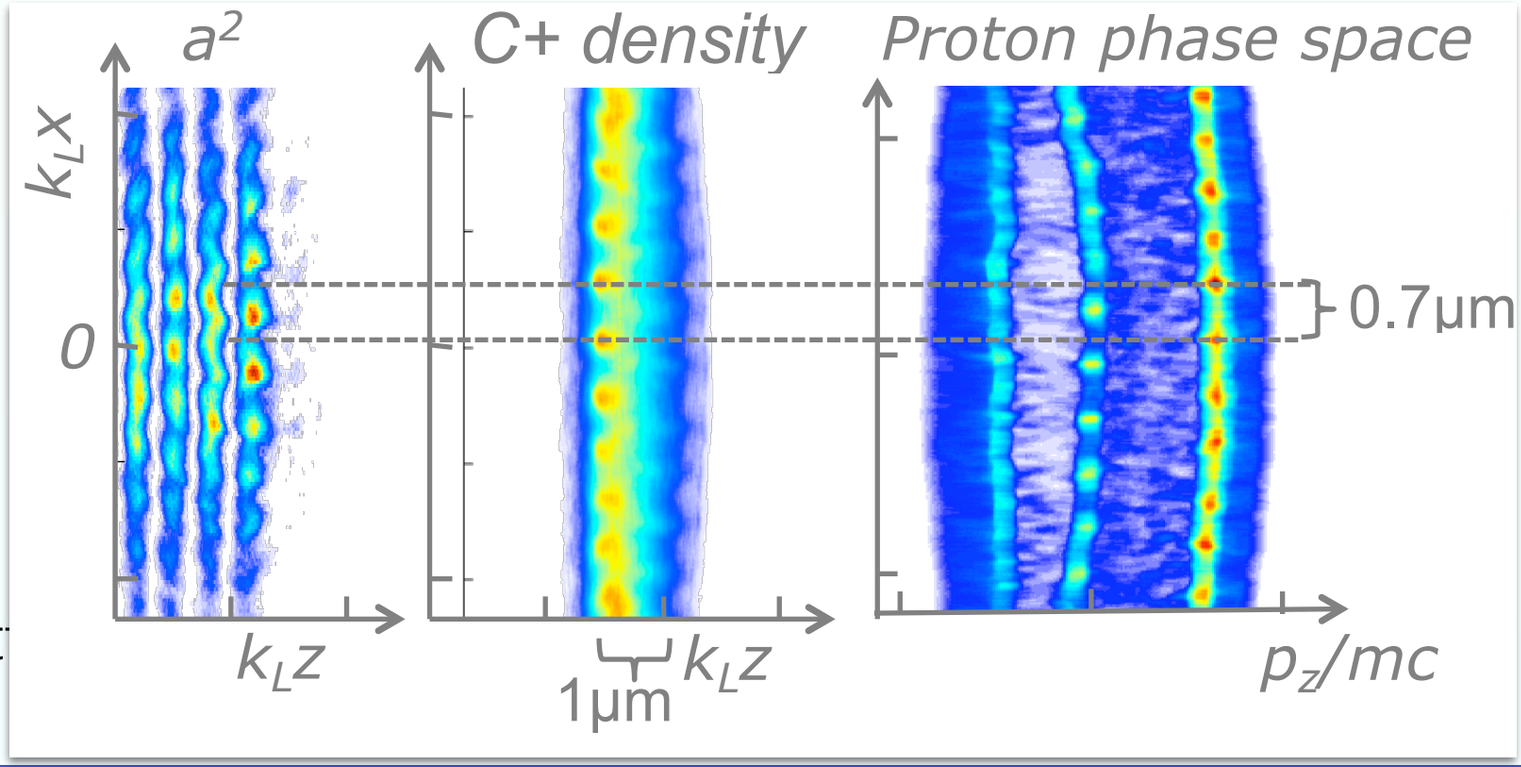

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$(a_0=10)$	carbon 6+
τ_L= 600fs	$n_e=800n_c$

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Can gas targetry help?

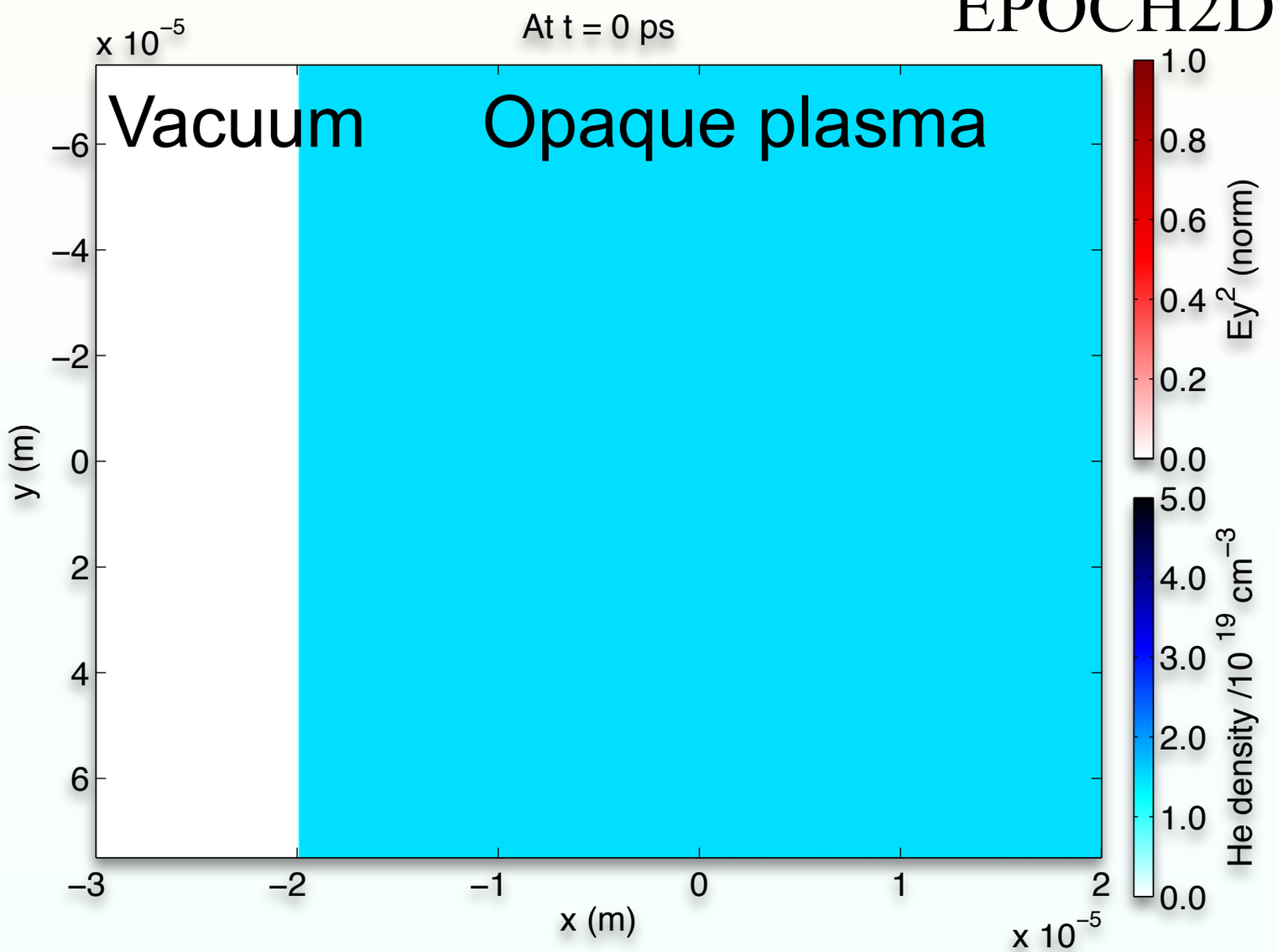
- What about gas targets?
  - less bremsstrahlung
  - Easily scalable to high repetition rate
  - Change gas to change ion species
- Still want overdense plasma:

$$n_c = \frac{1.1 \times 10^{21}}{\lambda_L^2\,(\mu\mathrm{m})}\mathrm{cm}^{-3}$$

- For λ~10 μm, $n_c = 10^{19}\,\mathrm{cm}^{-3}$
  - Achievable using pressurised **gas jets**

Ions accelerated from a moving shock

EPOCH2D PIC code



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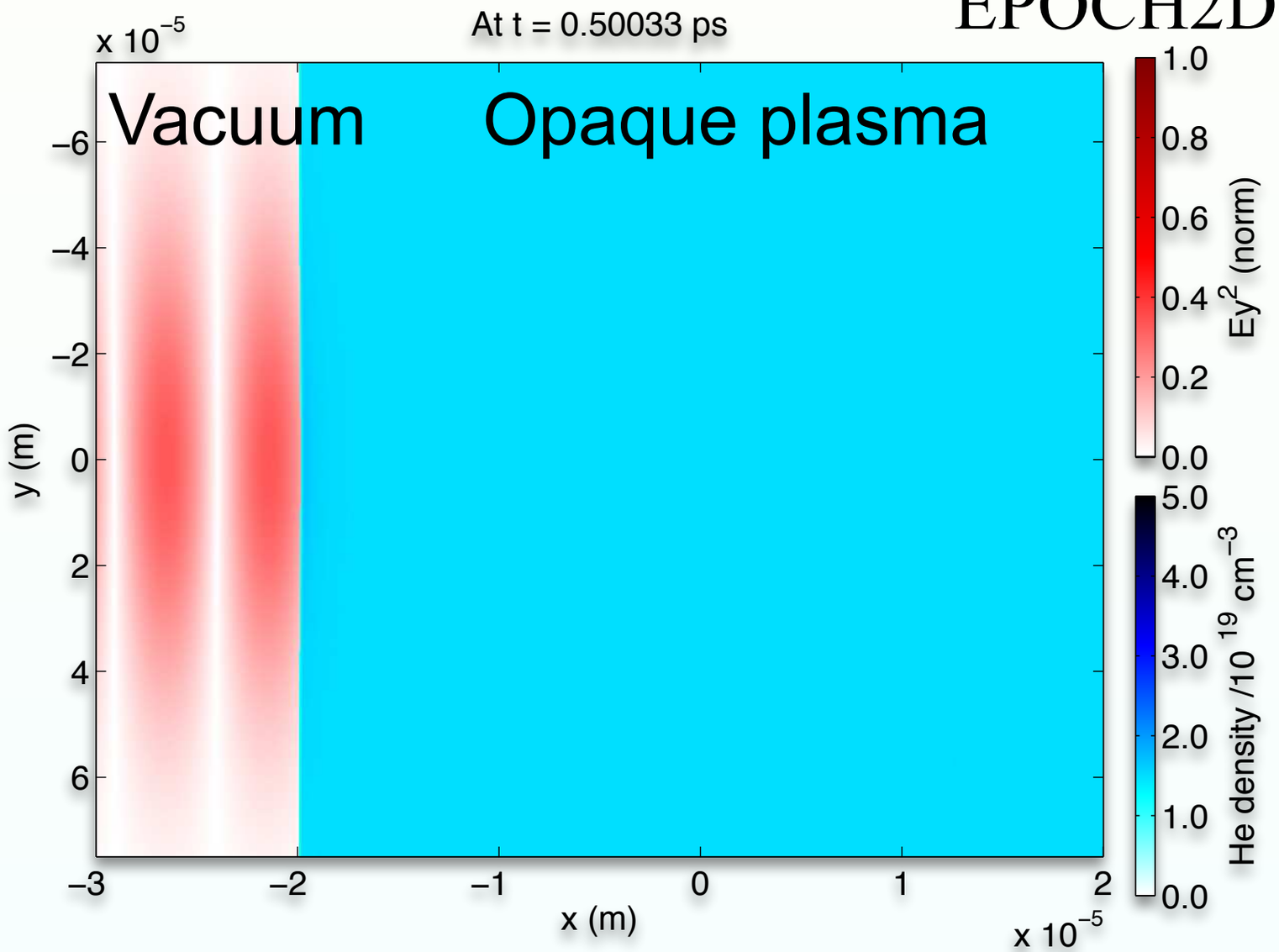

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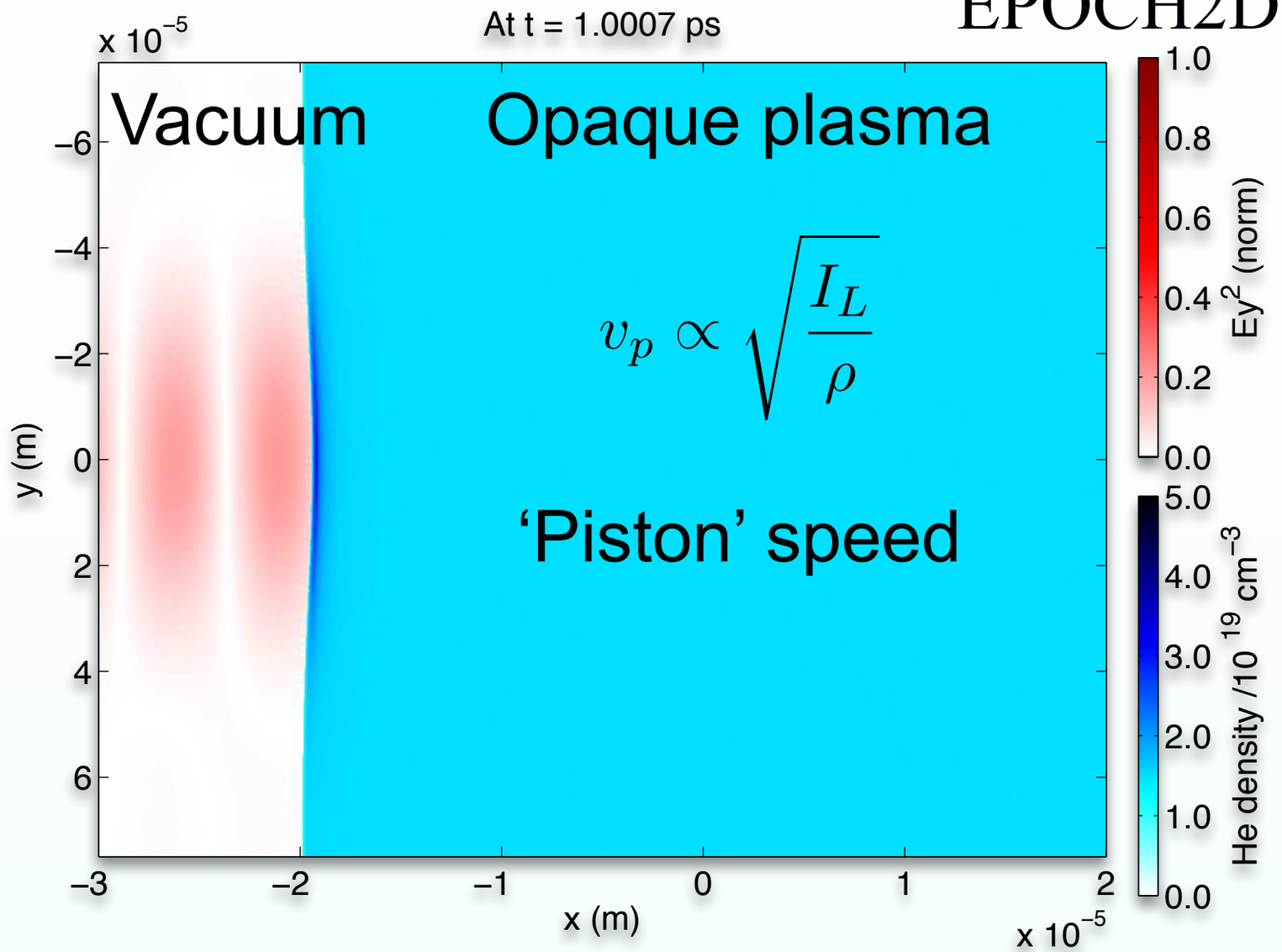

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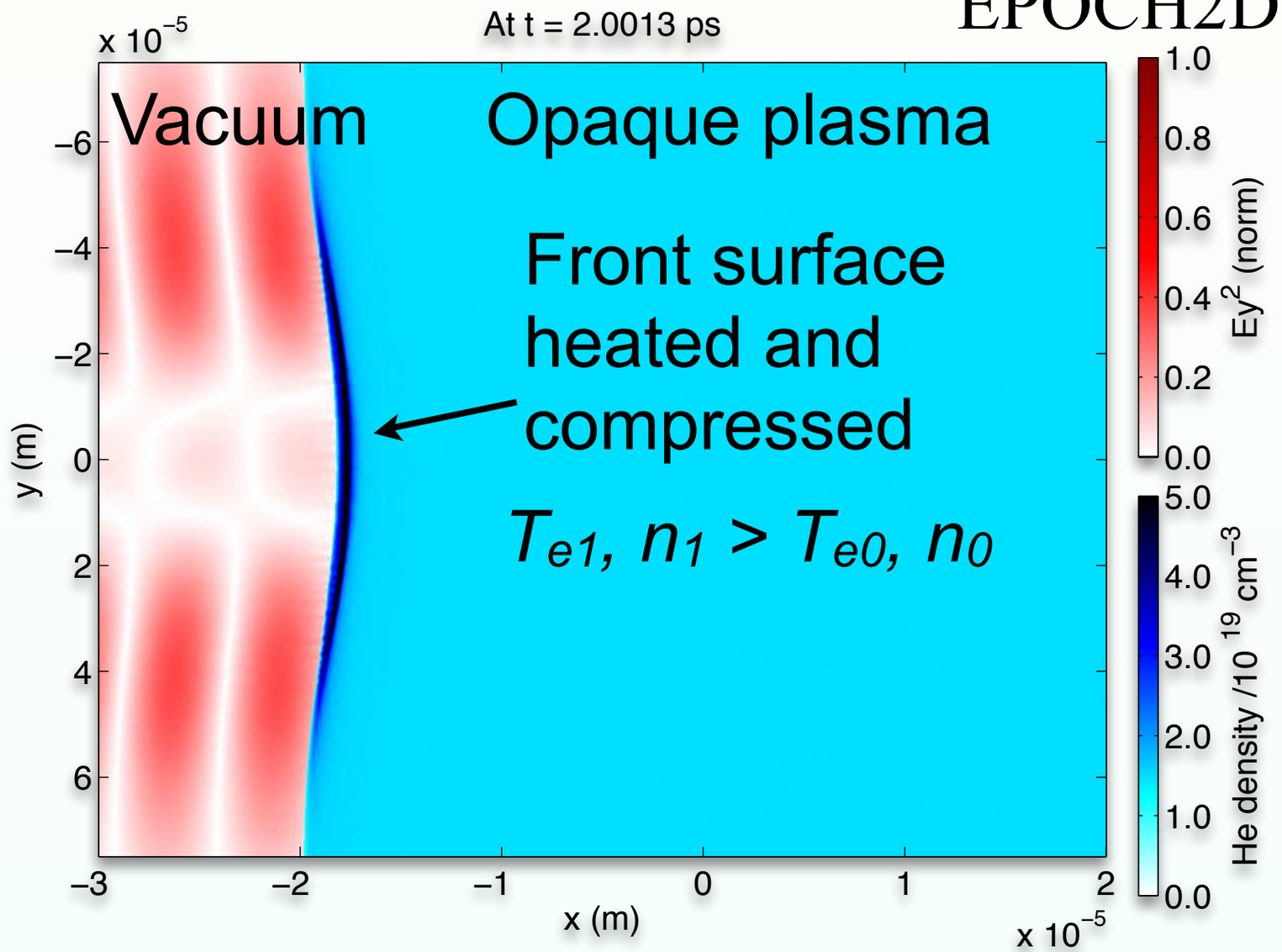

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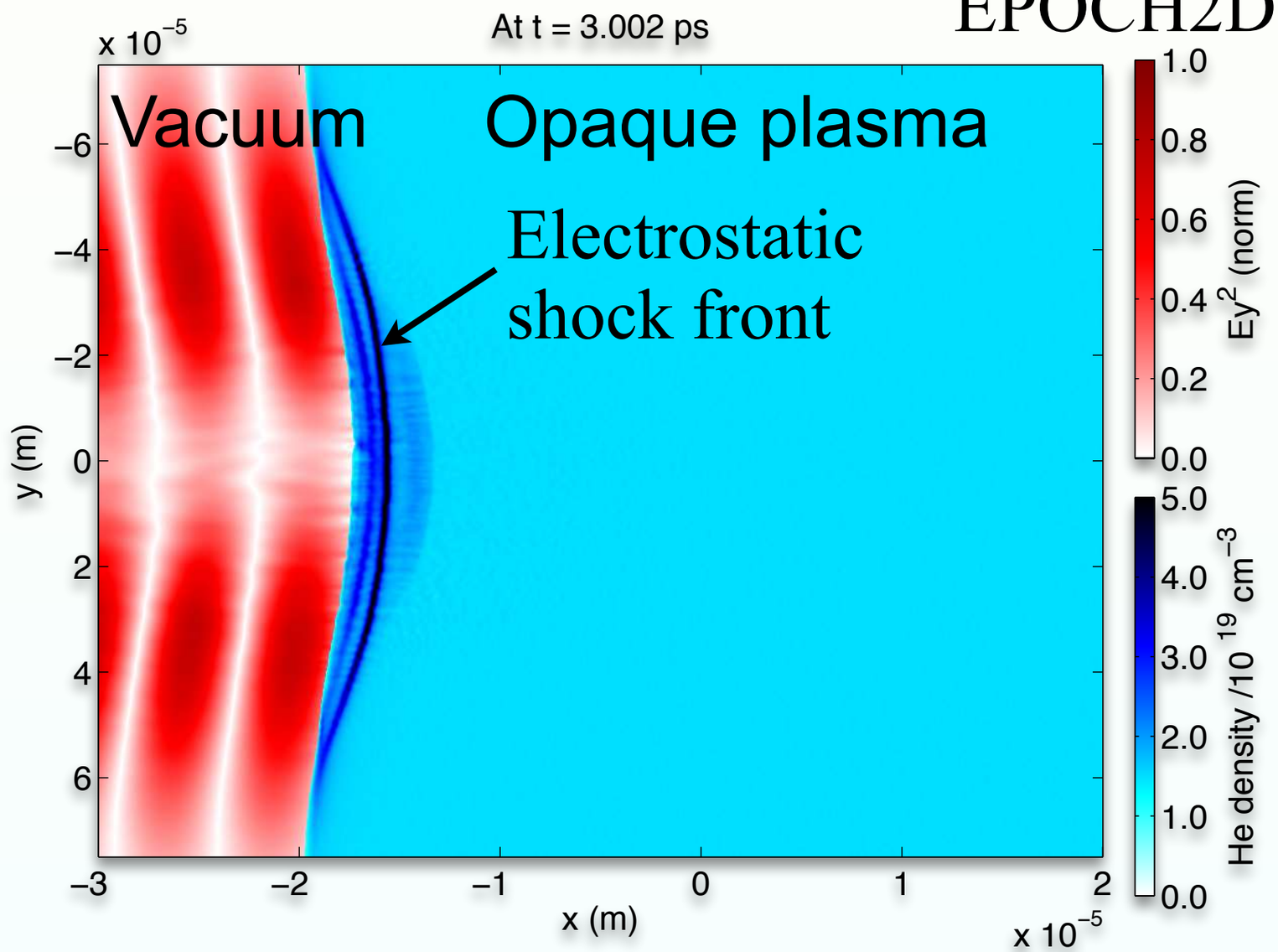

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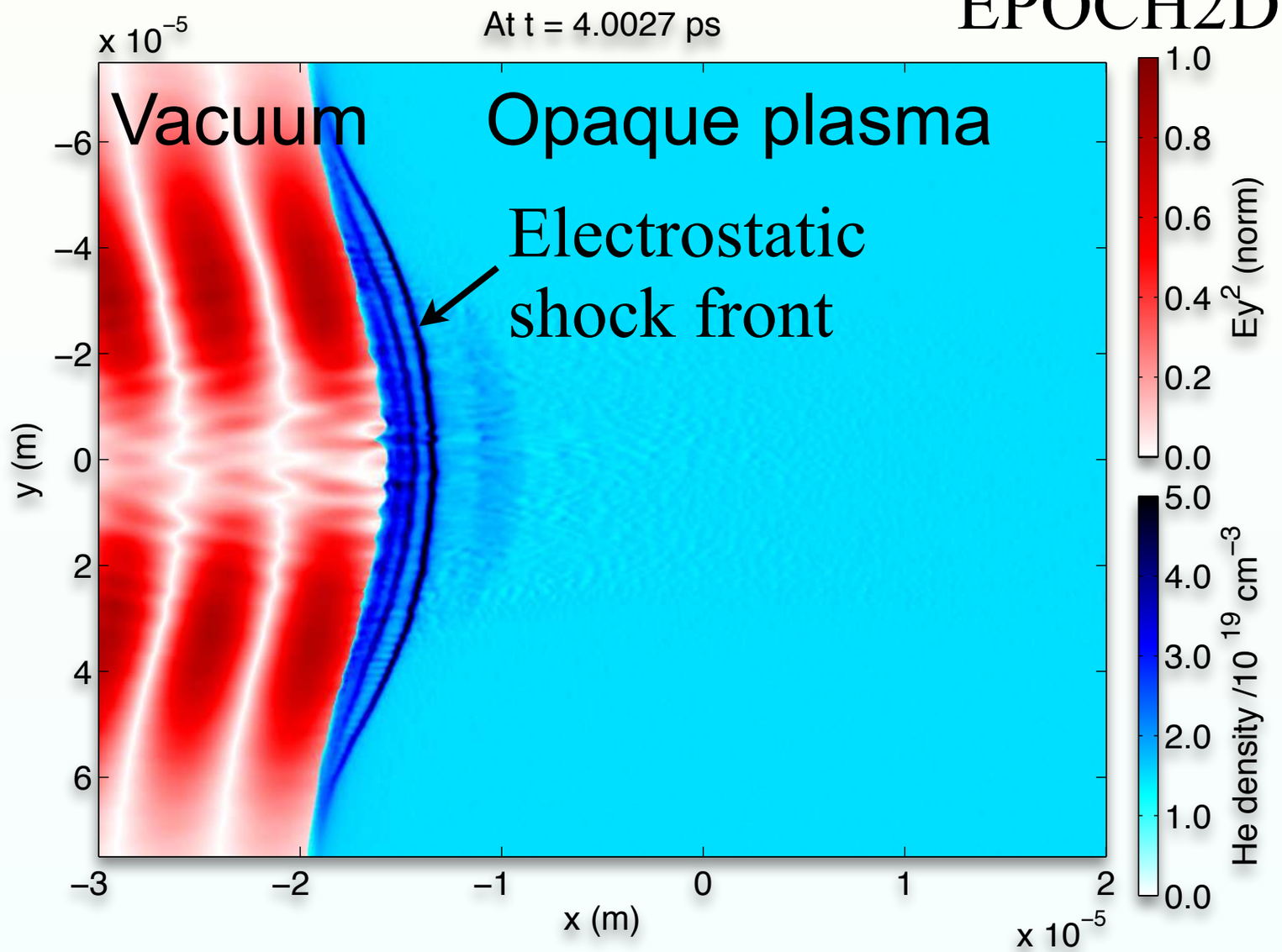

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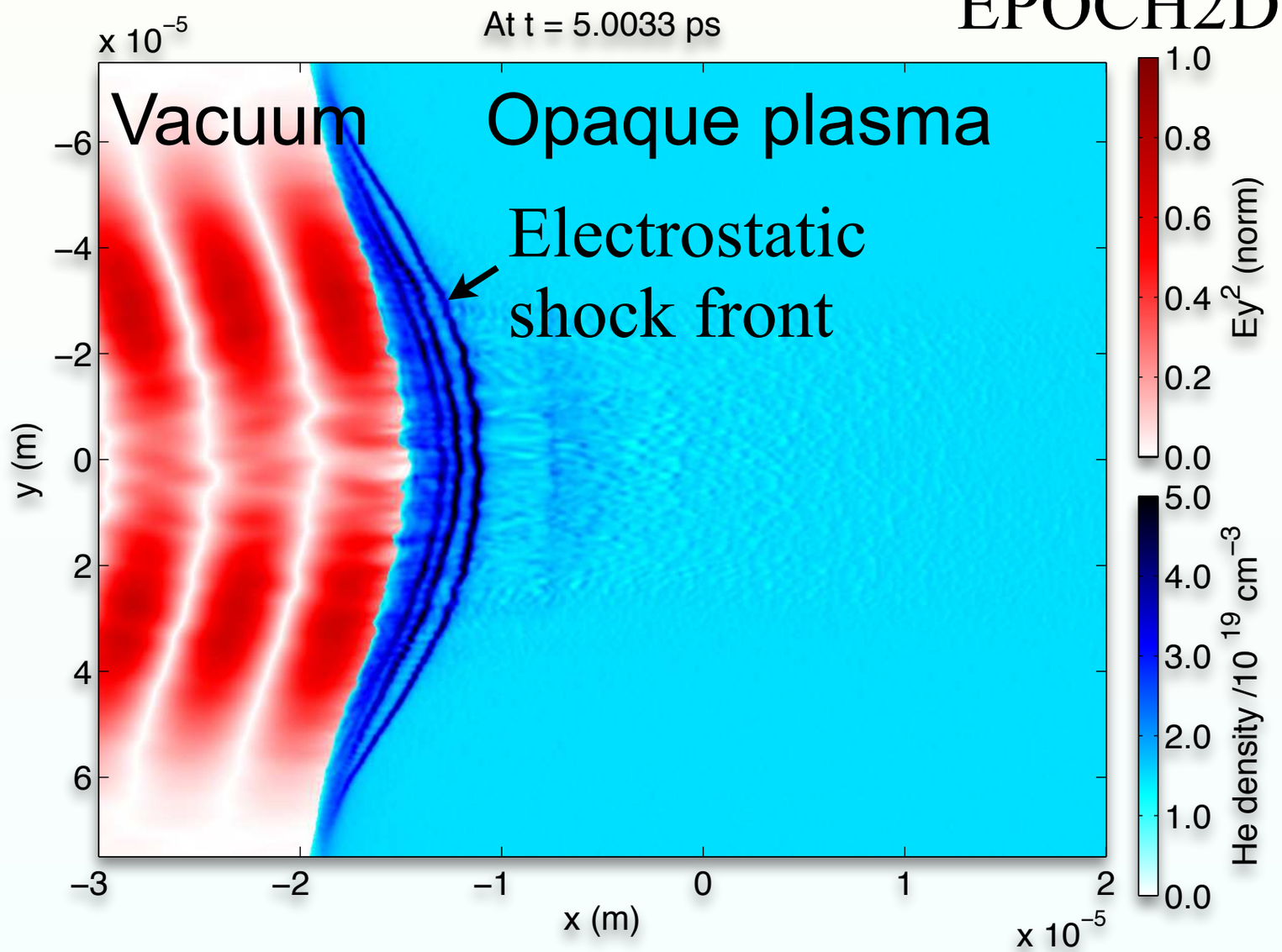

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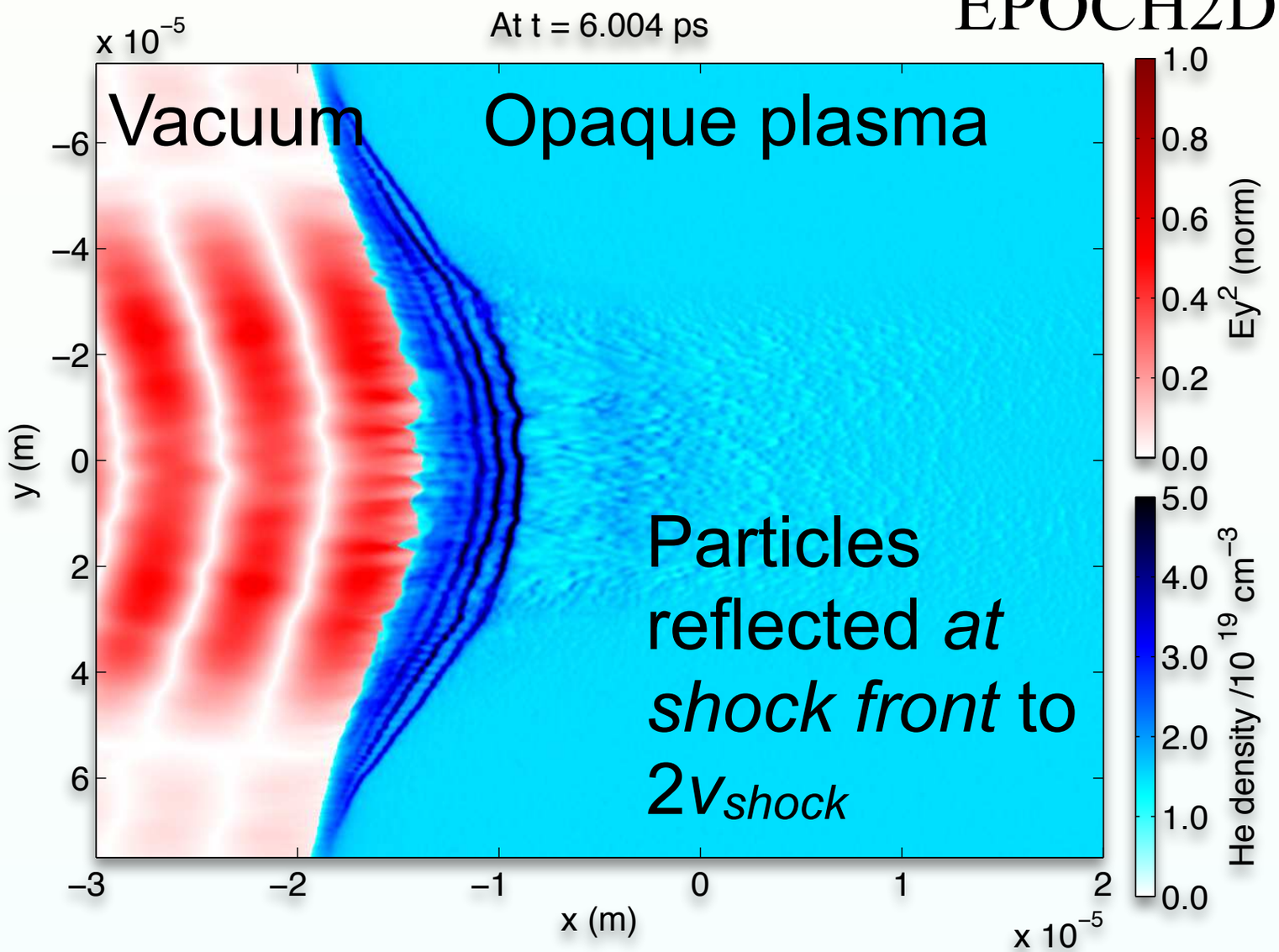

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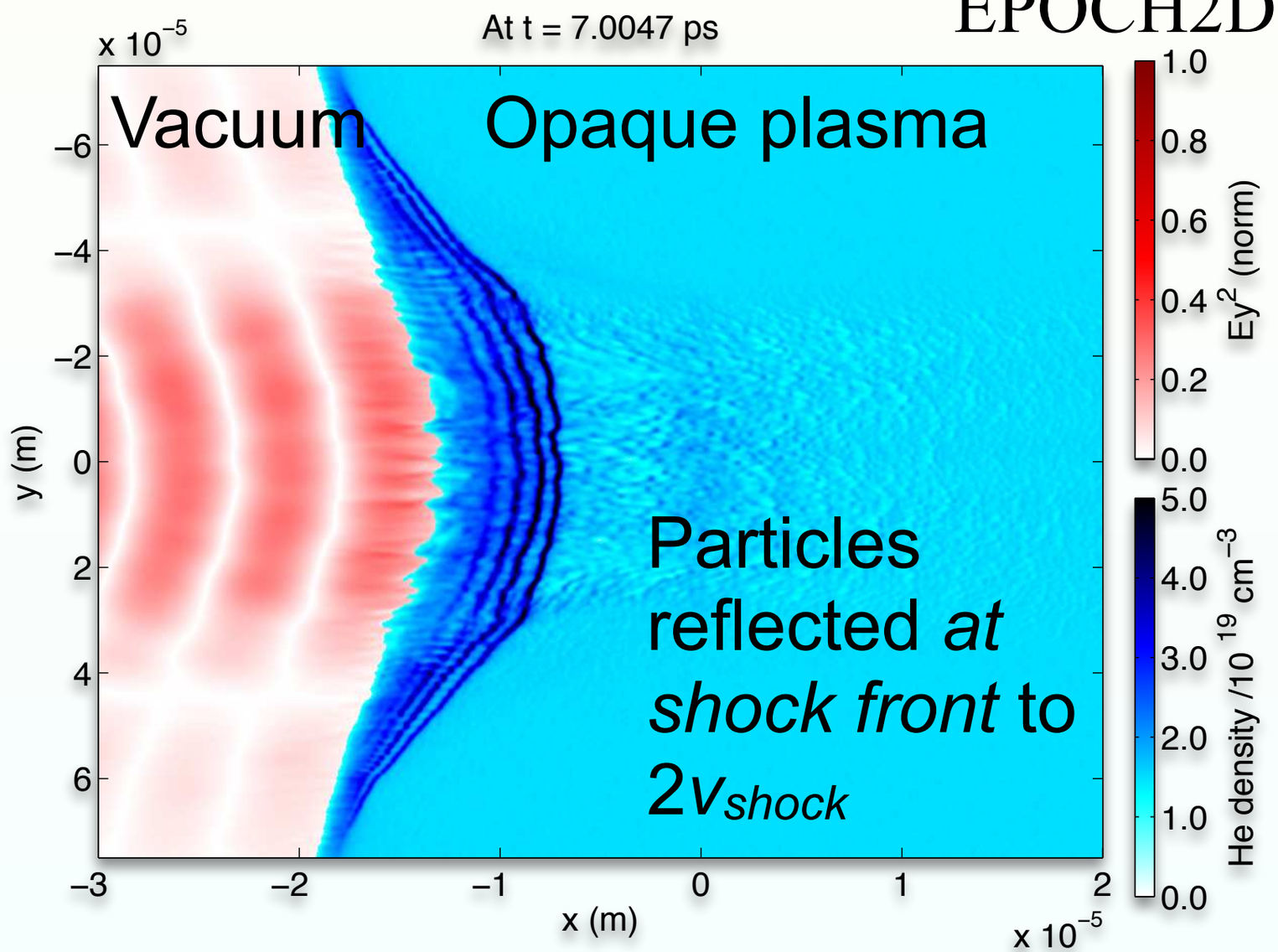

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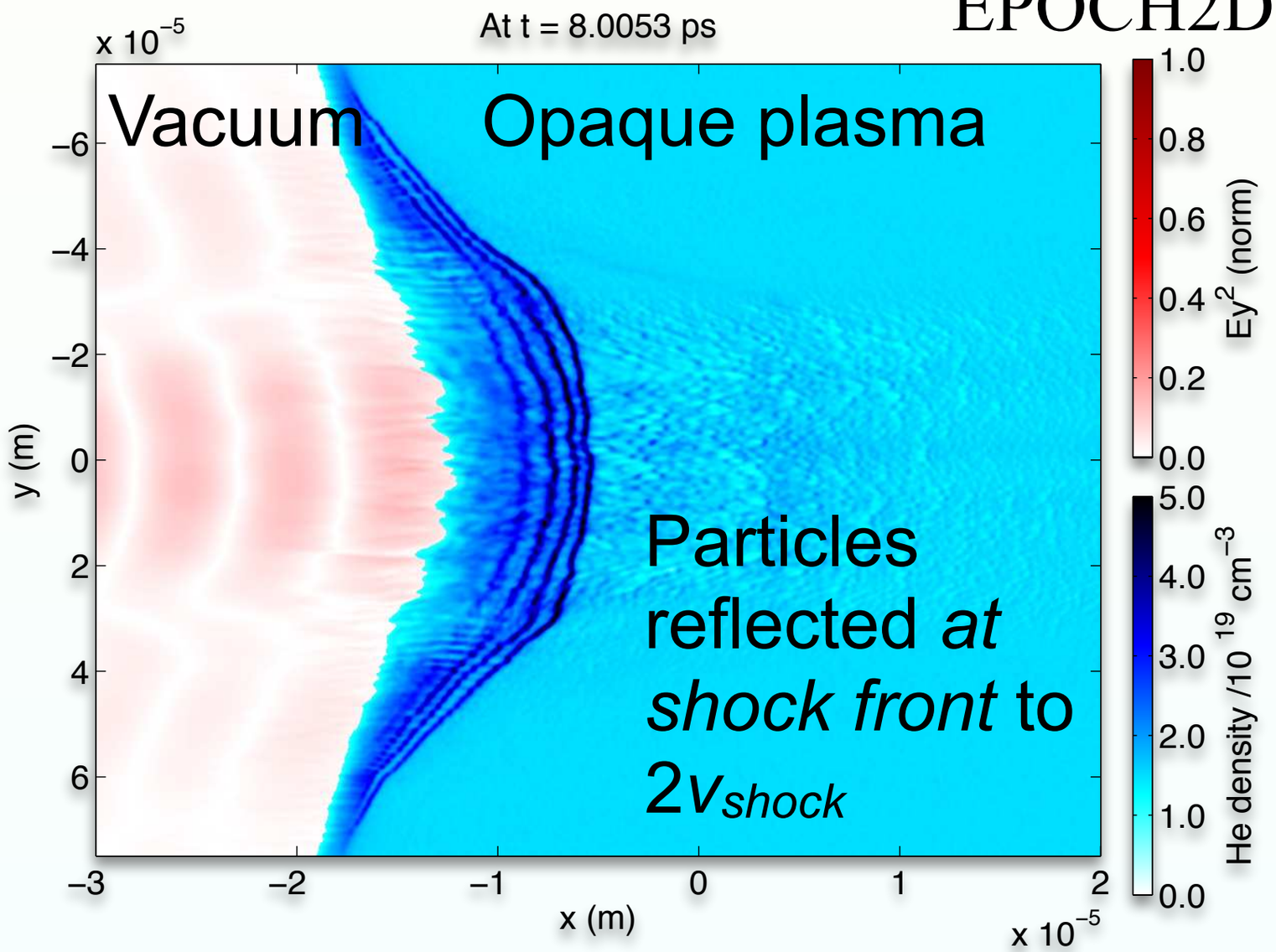

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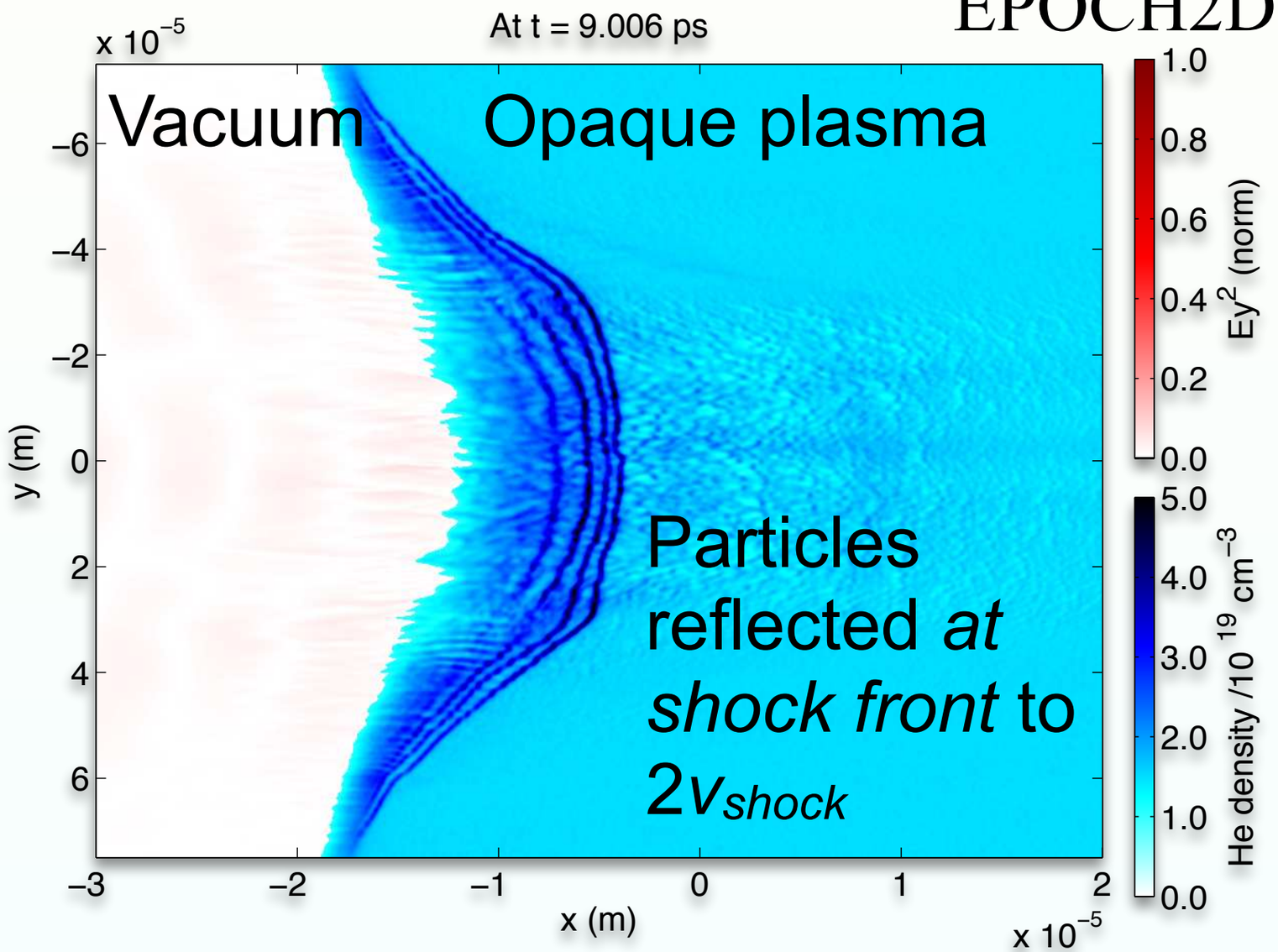

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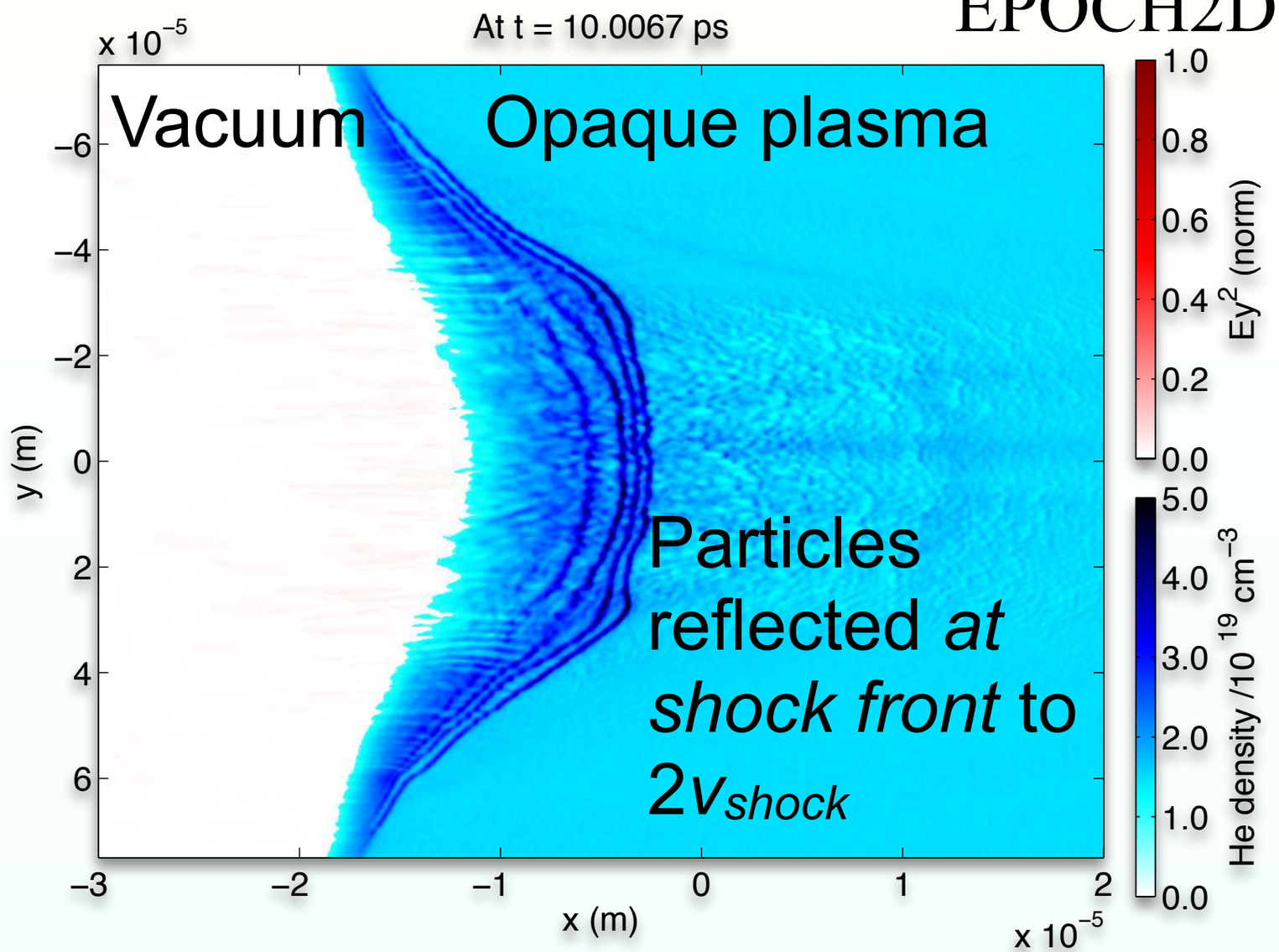

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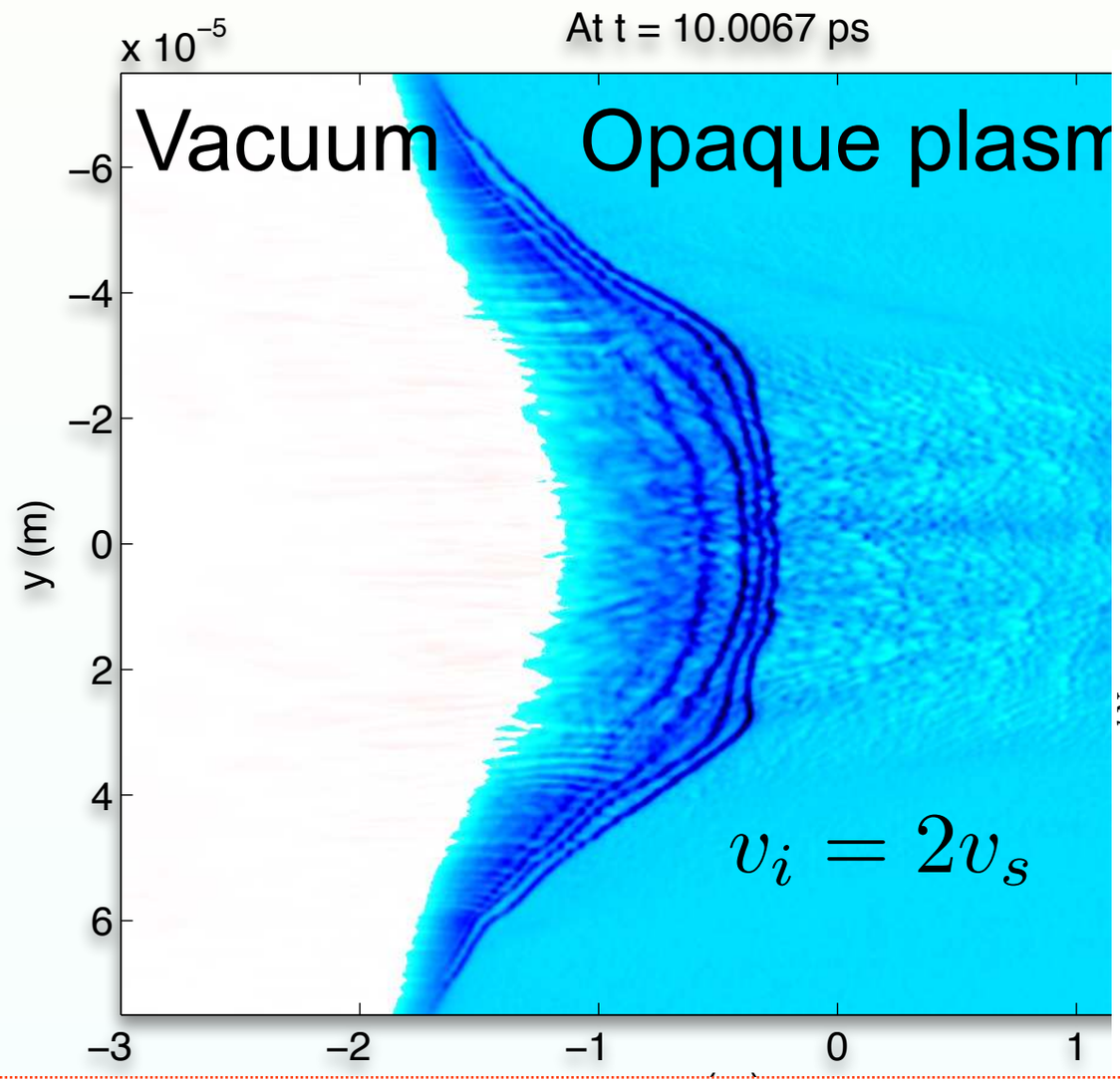

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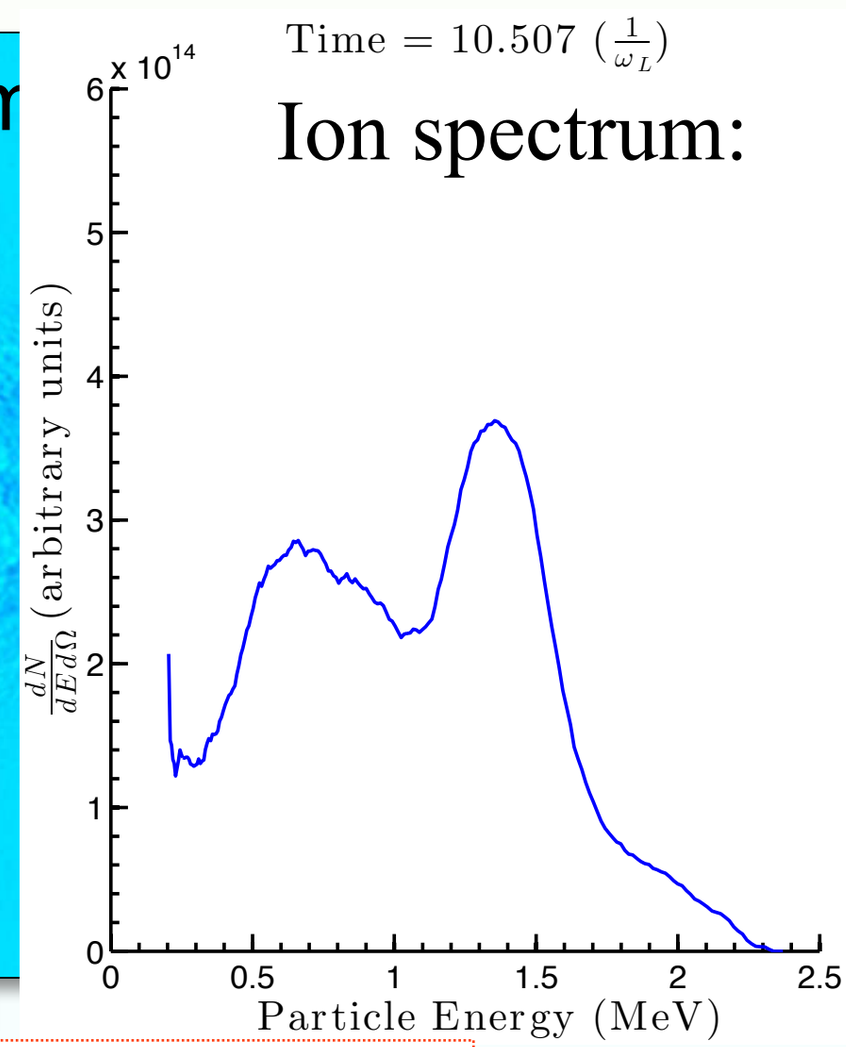
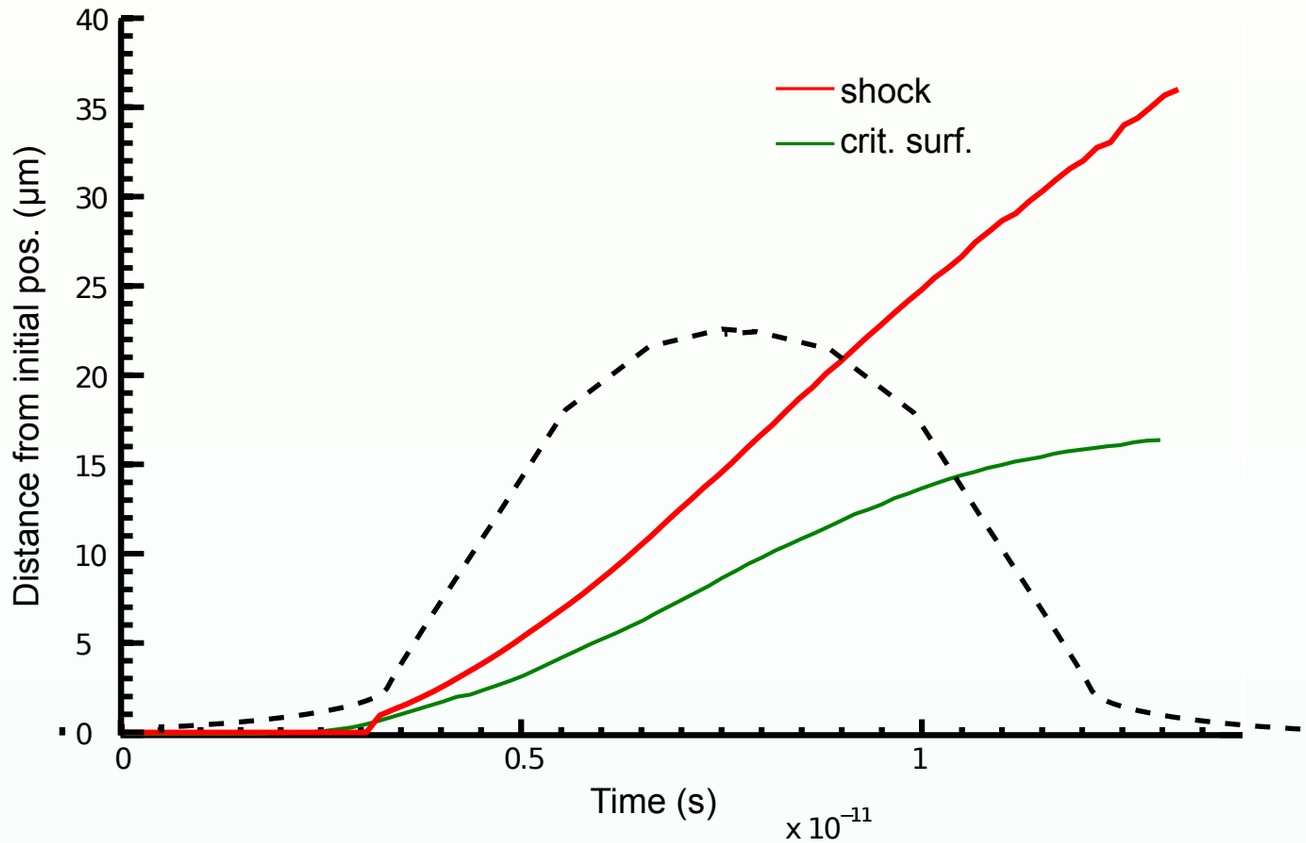


- Needs low density, opaque target
- Reflected ions ➠ Narrow spectrum

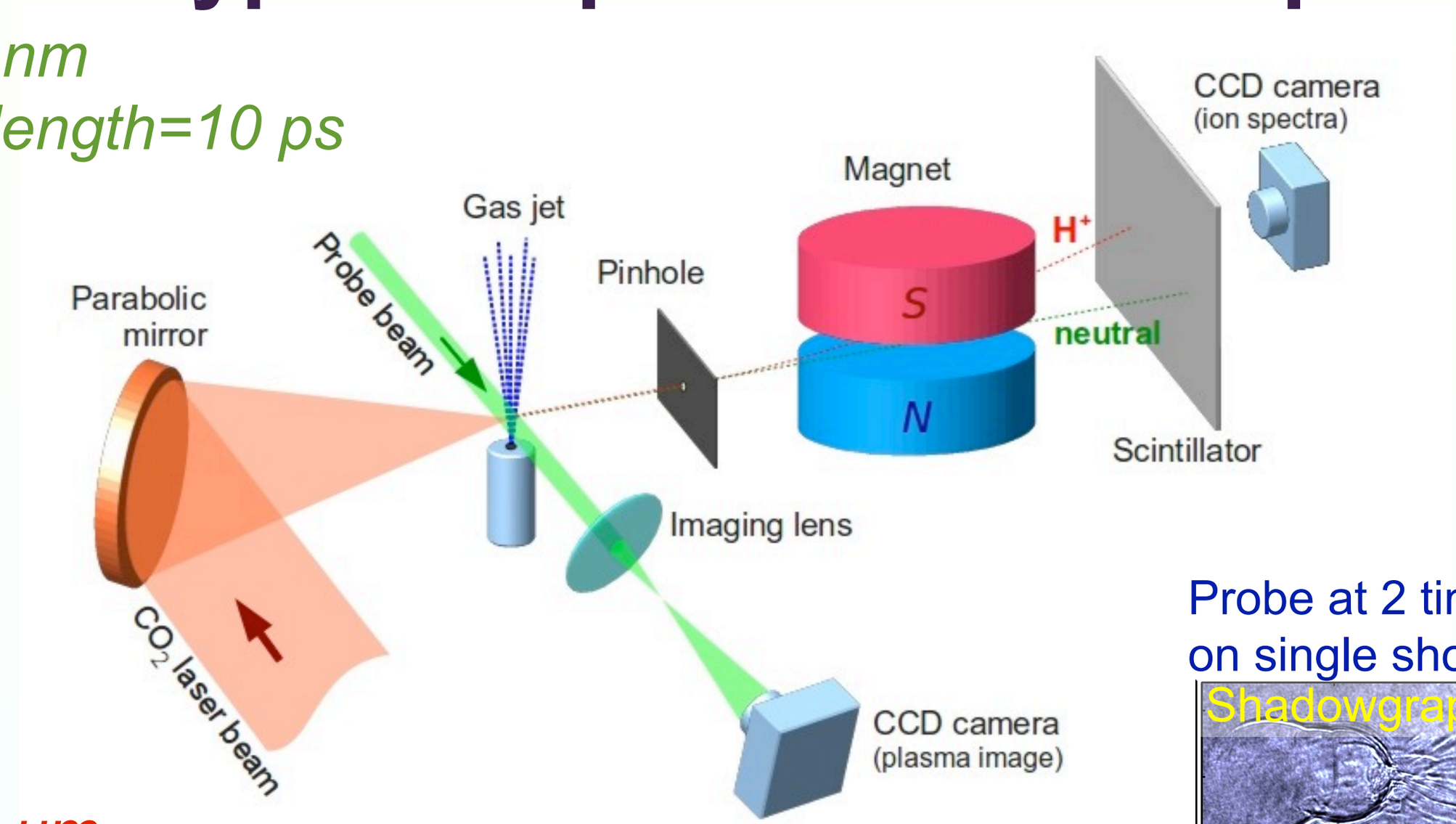
Numerical PIC simulations



- Shock moves ahead of hole-boring front
  - Reflected proton energies higher higher proton energies at lower intensities
- Consistent with moving wave seen on optical probing

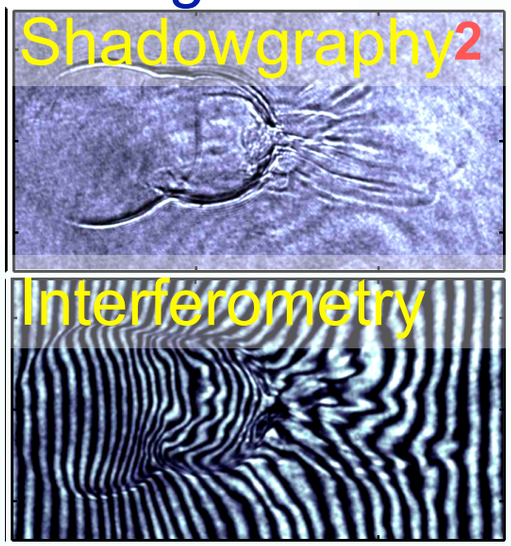
Typical experimental set-up

λ=527 nm
Pulse length=10 ps

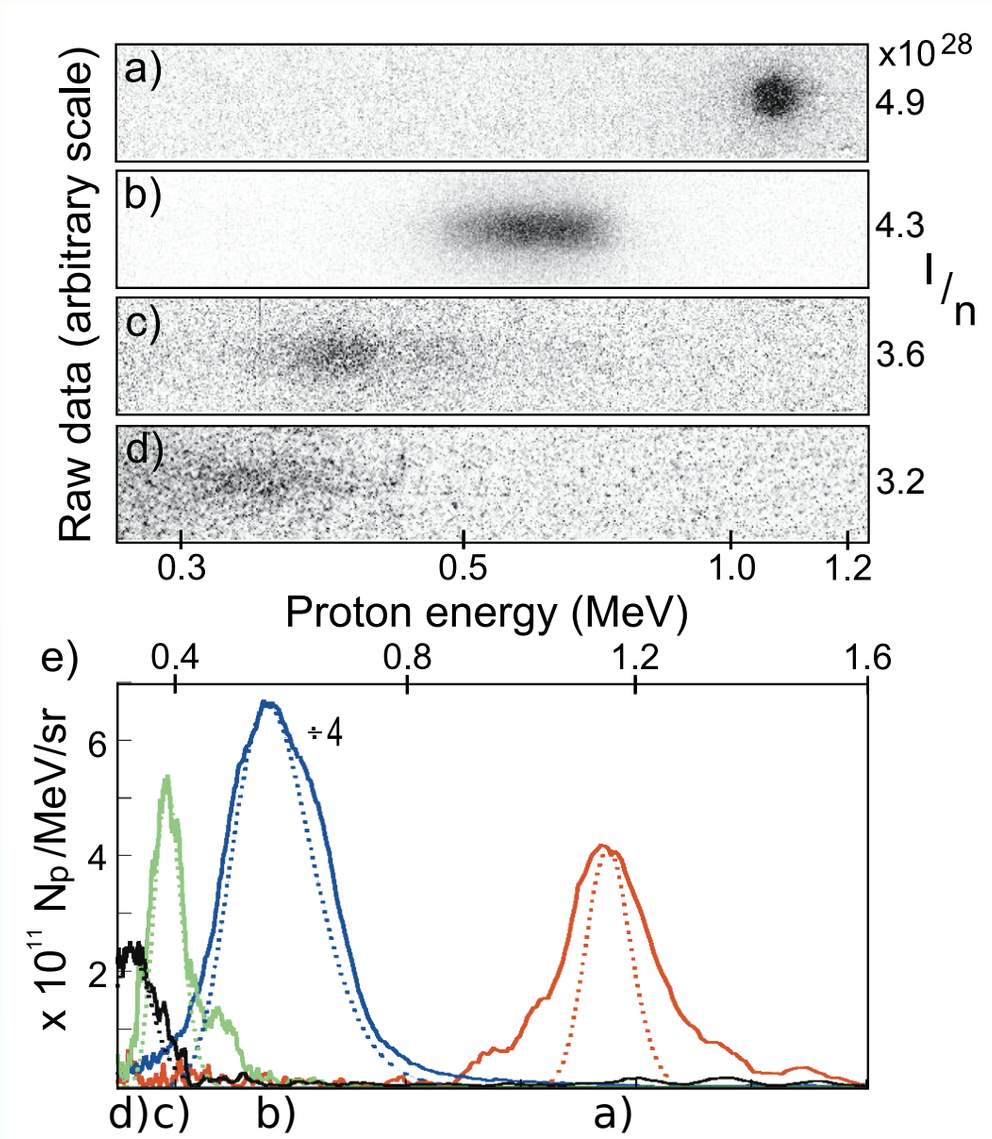


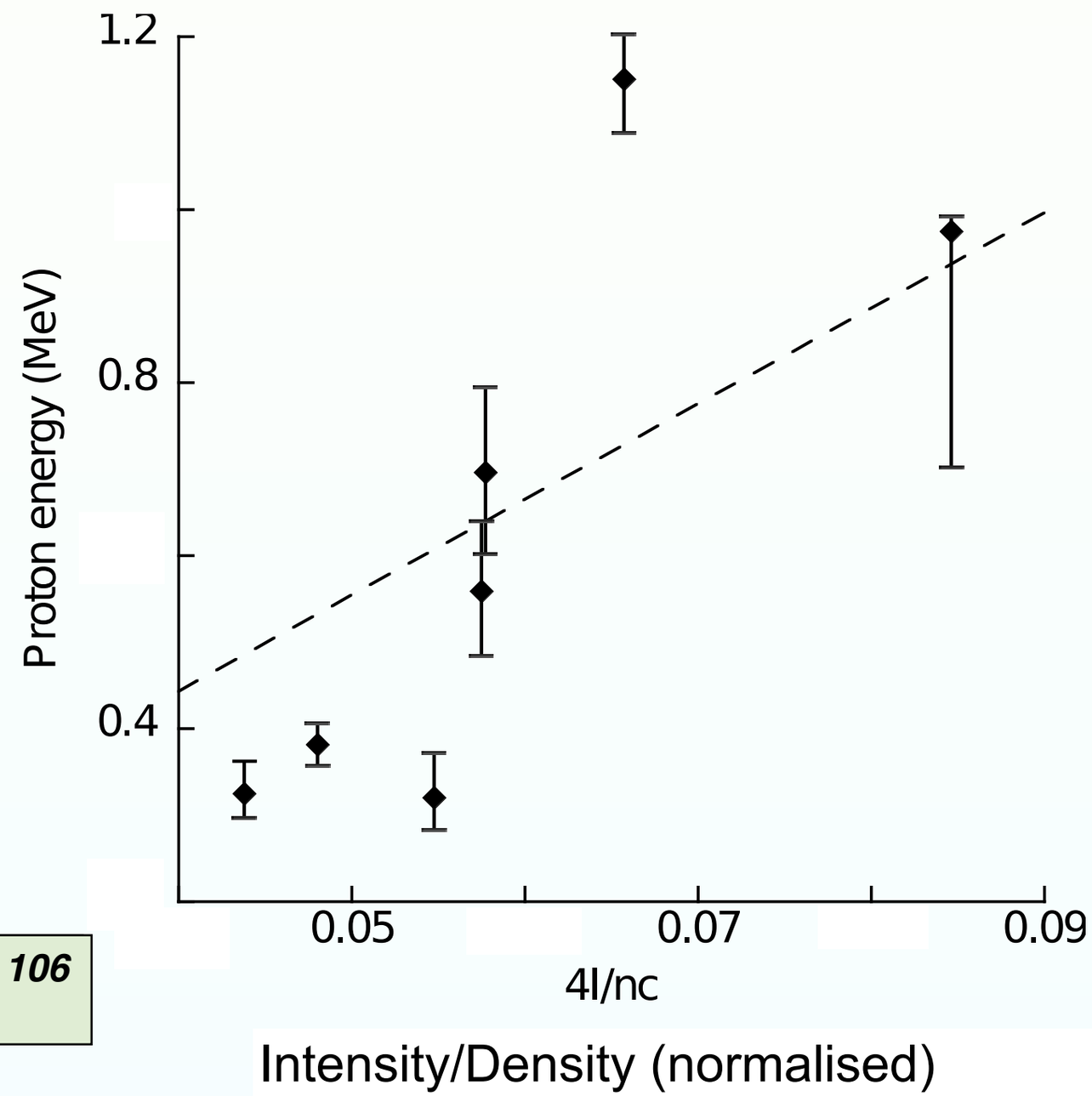
λ=10.3 μm
Pulse length=6 ps
Spot size = 70 μm
Intensity ~ 10^{16} W/cm^2

Probe at 2 times on single shot



Generated monoenergetic proton beams



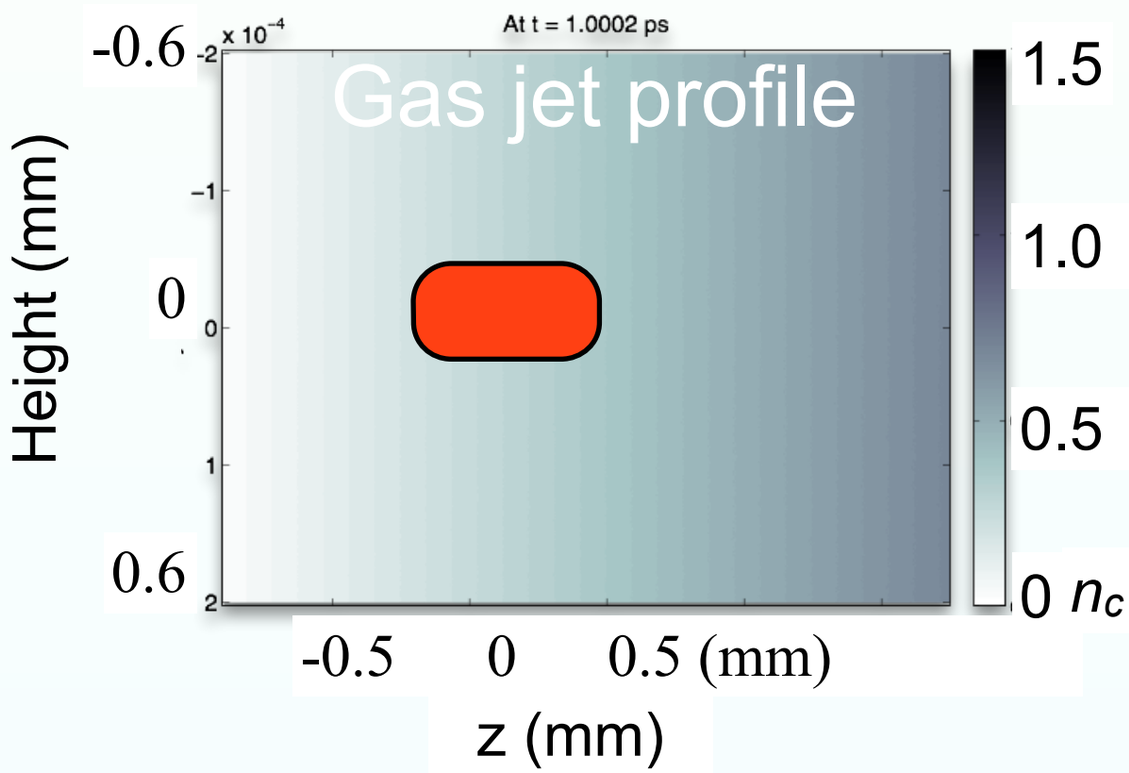


*See: Palmer, Dover, Pogorelsky et al., PRL, **106** (2011)*

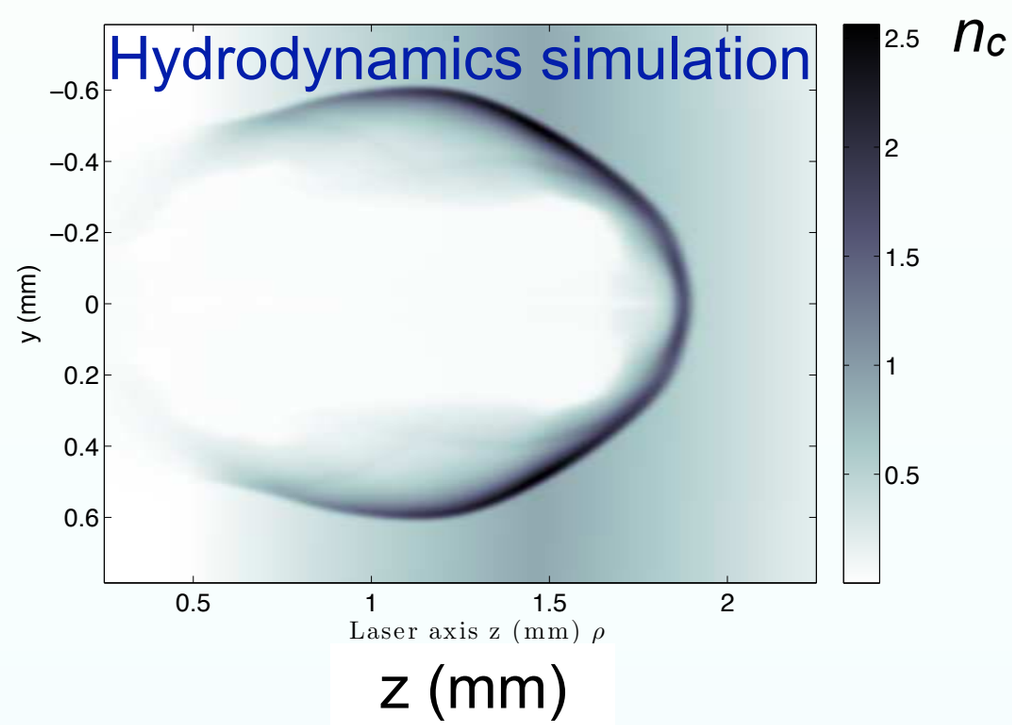
New technique: blast wave shaping

- *Single intense pulse* to drive acceleration controllably
- Prepulse 25 ns before main pulse to optically tailor density
- Helium gas to generate helium beams with shock acceleration

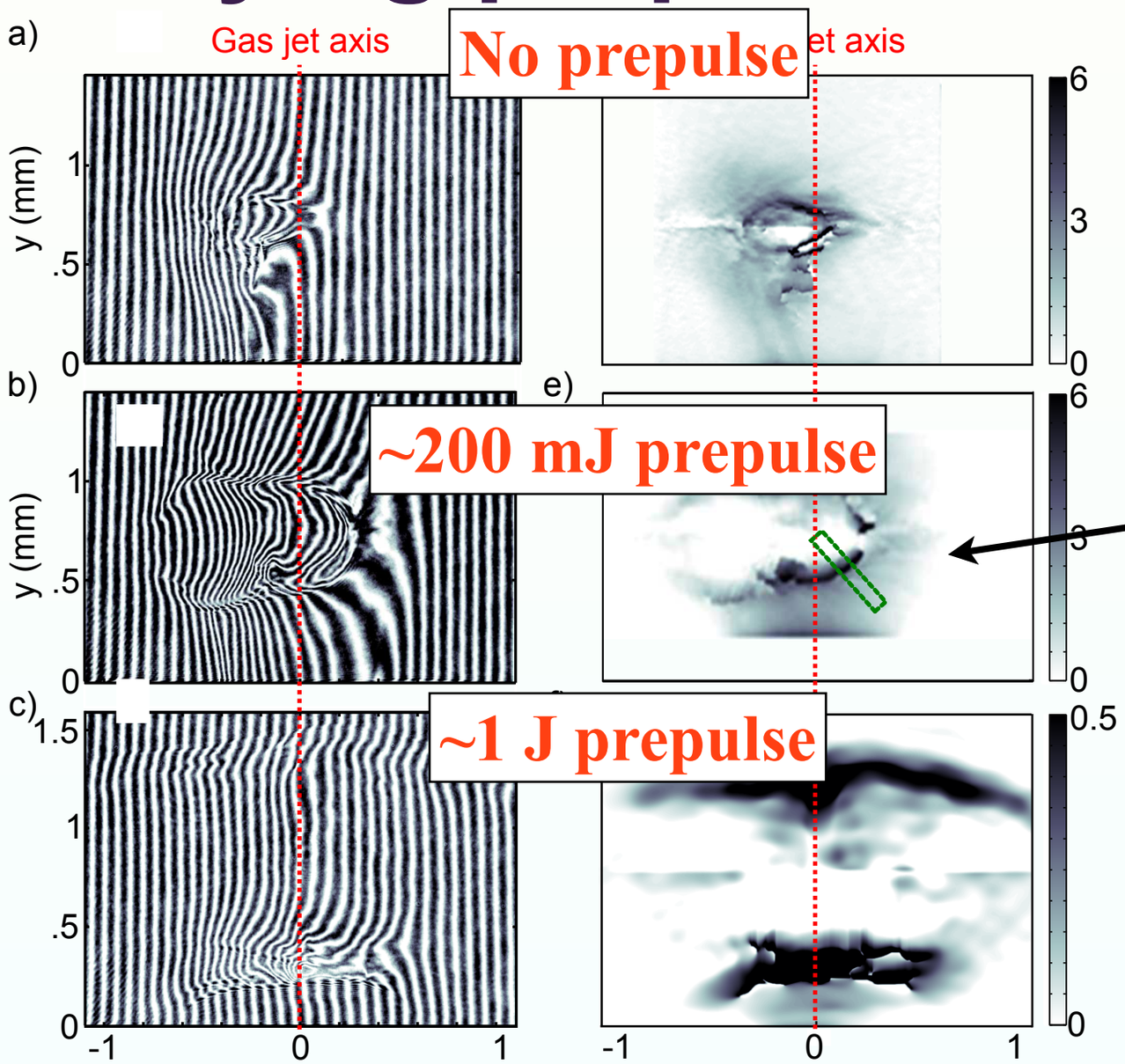
Prepulse deposits energy, gas expands and forms blast wave

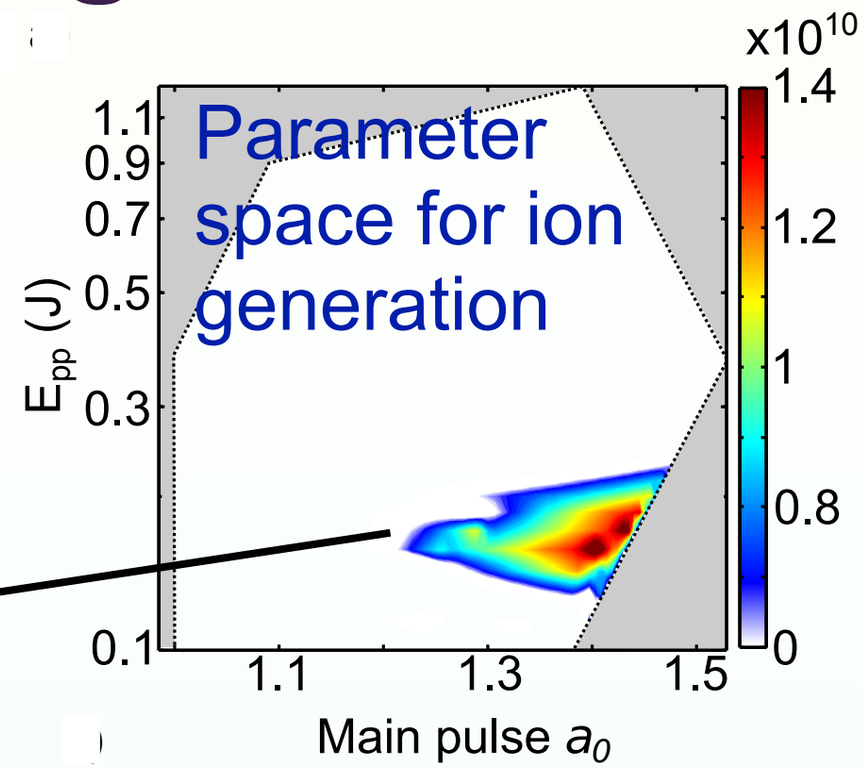


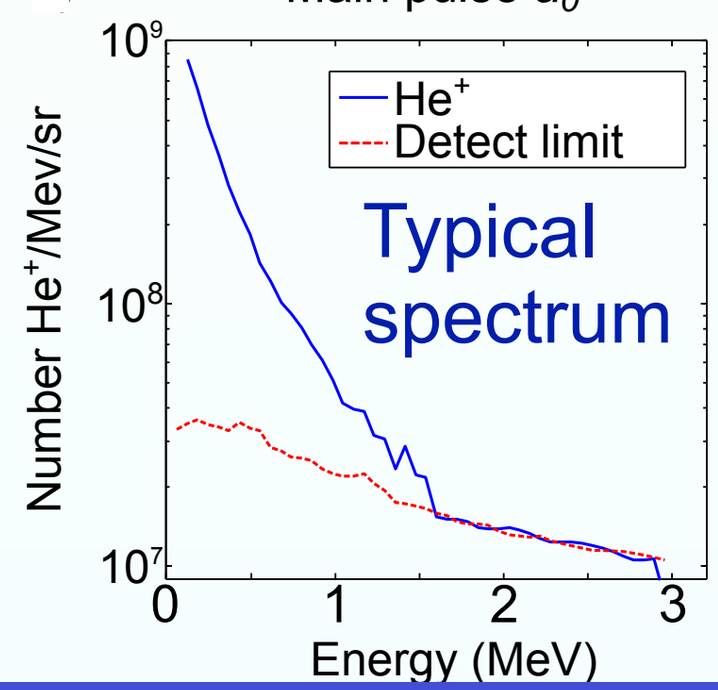
Main pulse interacts with steepened profile



Varying prepulse changes ion beam



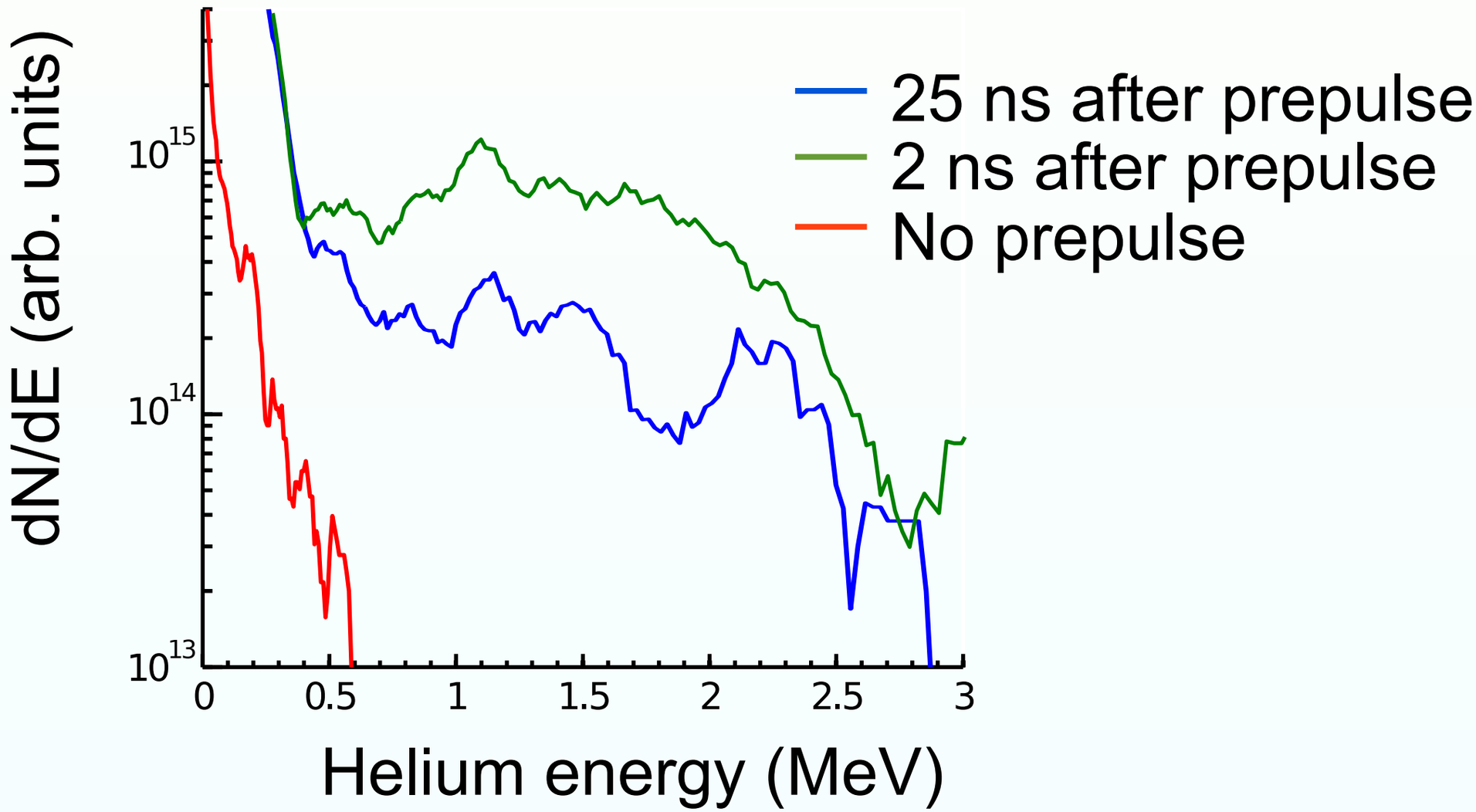




See: Tresca, Dover, Cook et al., Submitted 2014

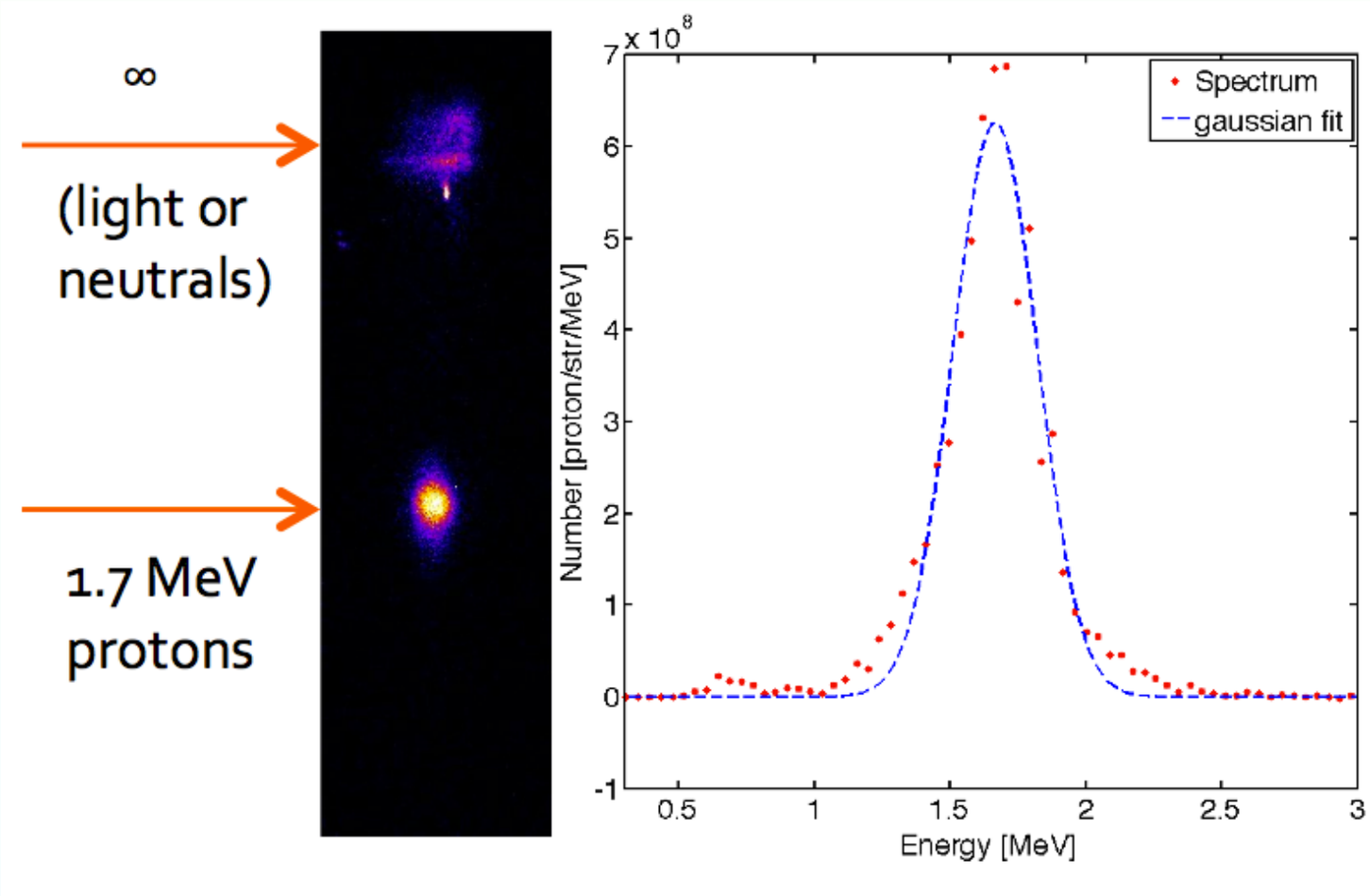
Can change beam by profile optimisation

Density profile optimisation to generate high energy, higher charge beams



Latest work on proton beams

- **Also appears to work for generation of proton beams - more mono-energetic beams & max energies up to ~3 MeV.**

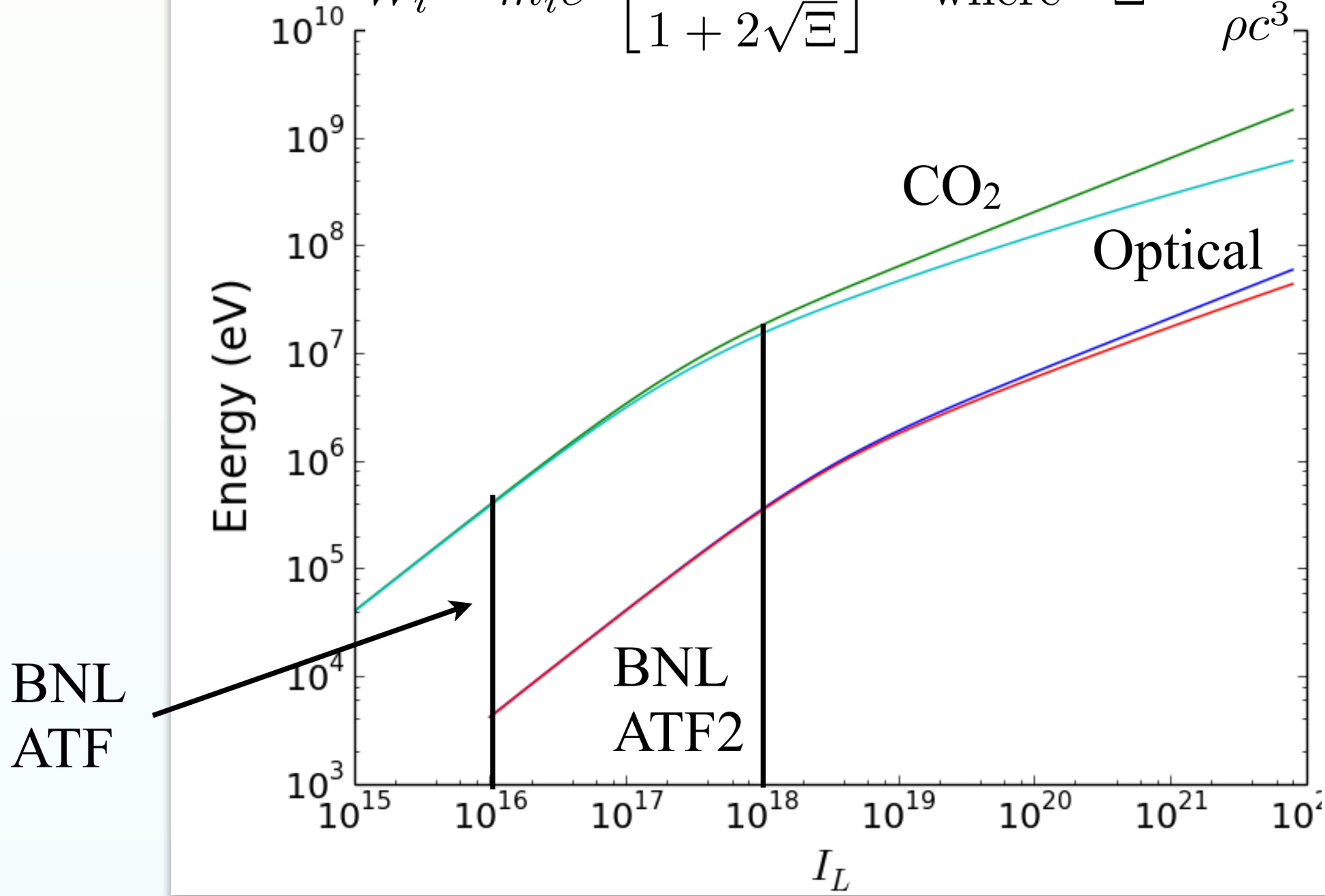


Future for shockwave acceleration

- Development of high power CO_2 lasers
  - '100 TW' CO_2 laser upgrade at ATF2:
    - Completed: Solid state OPA front end
      - 10 J in < 2 ps
    - Funded: New amplifier chain, CPA & frequency chirping:
      - higher energy output (>35 J),
      - higher repetition rate (10 Hz)
      - 500 fs pulse length
  - Investigate energy scaling and stability of acceleration from gas jet target

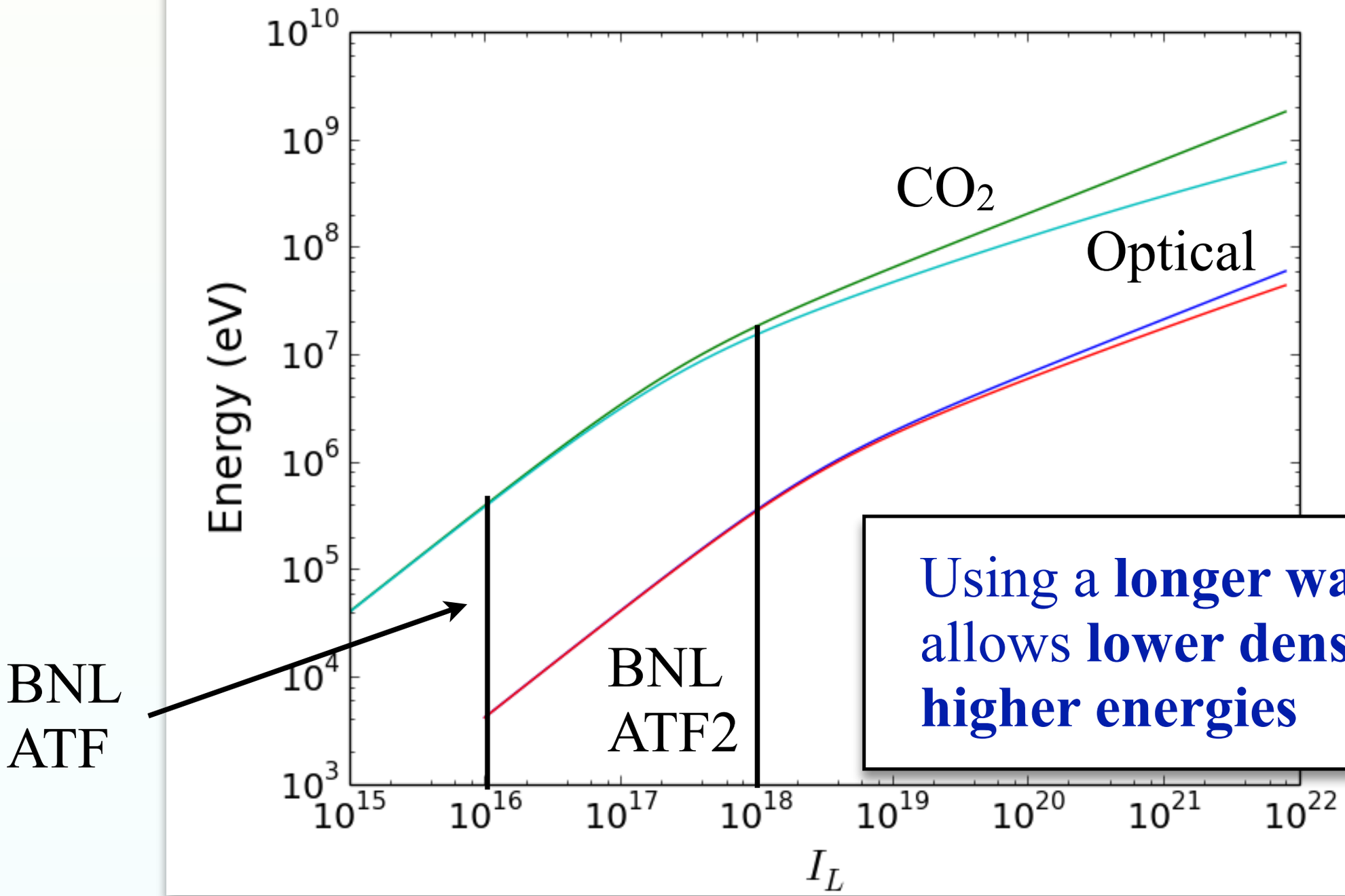
Hole-boring scaling

$$W_i = m_i c^2 \left[\frac{2\Xi}{1 + 2\sqrt{\Xi}} \right] \quad \text{where} \quad \Xi = \frac{I}{\rho c^3}$$



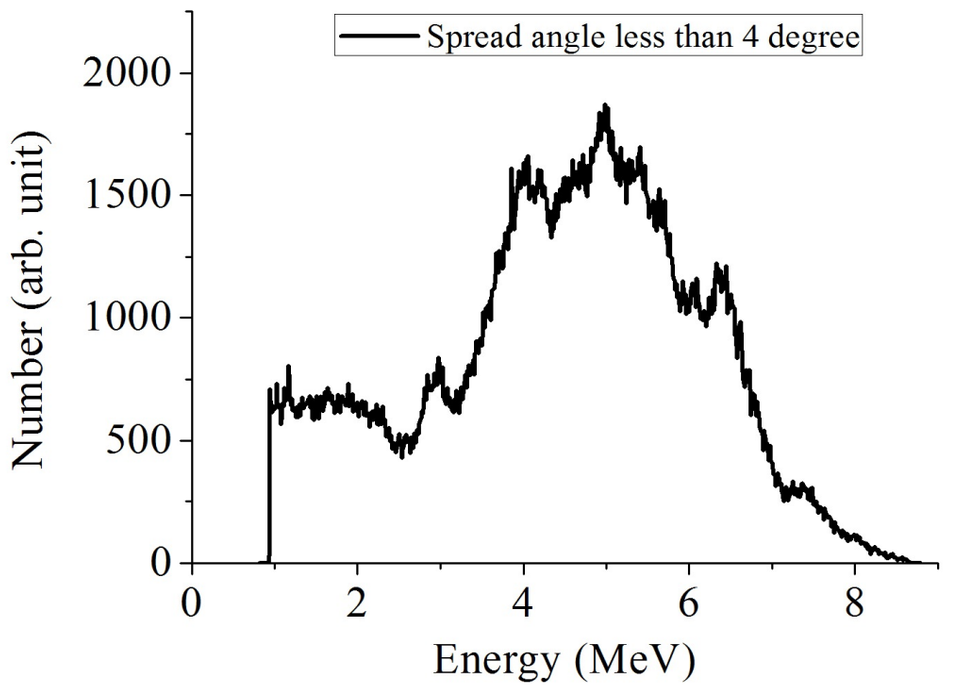
Robinson, A.P.L. et al., 2012. Hole-boring radiation pressure acceleration as a basis for producing high-energy proton bunches. Plasma Physics and Controlled Fusion, 54(11).

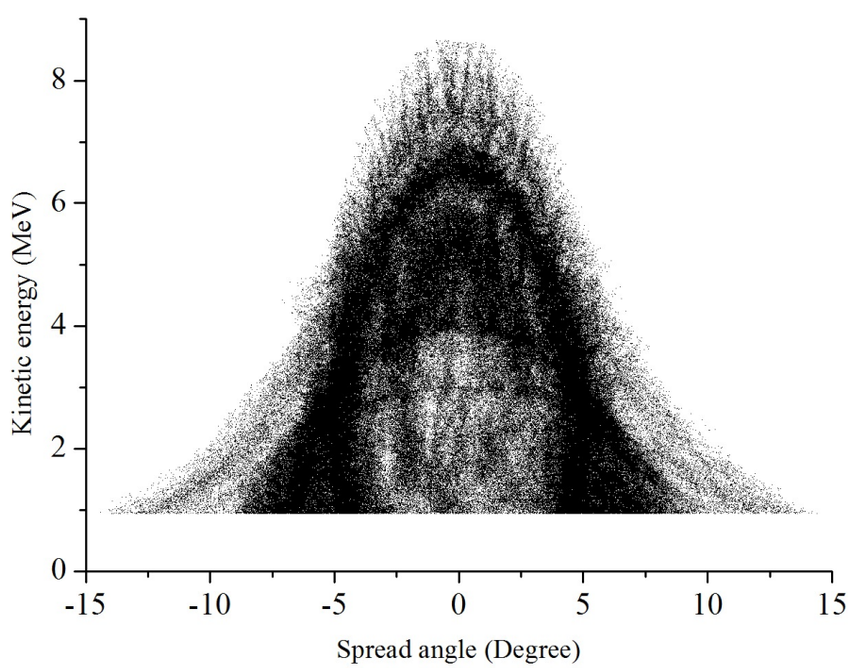
Hole-boring scaling

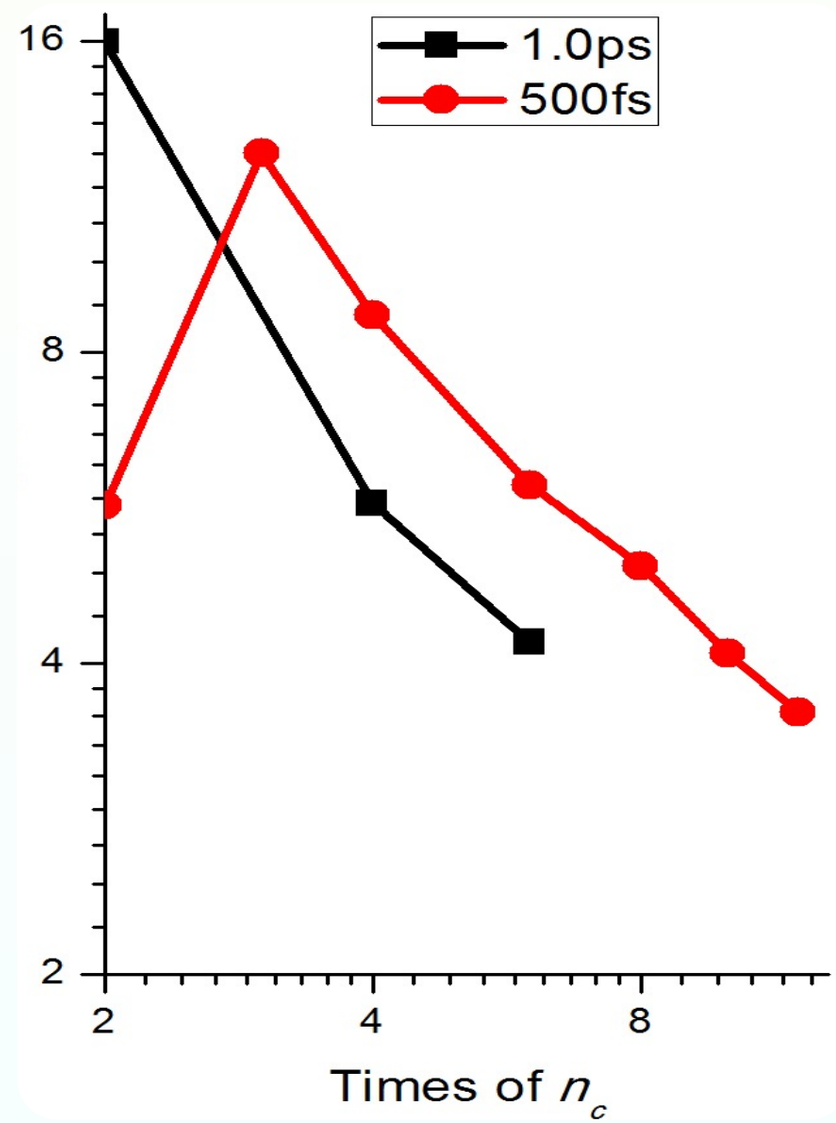


Using a **longer wavelength** allows **lower densities** and **higher energies**

Hole-boring scaling







Radiation pressure on thin foils

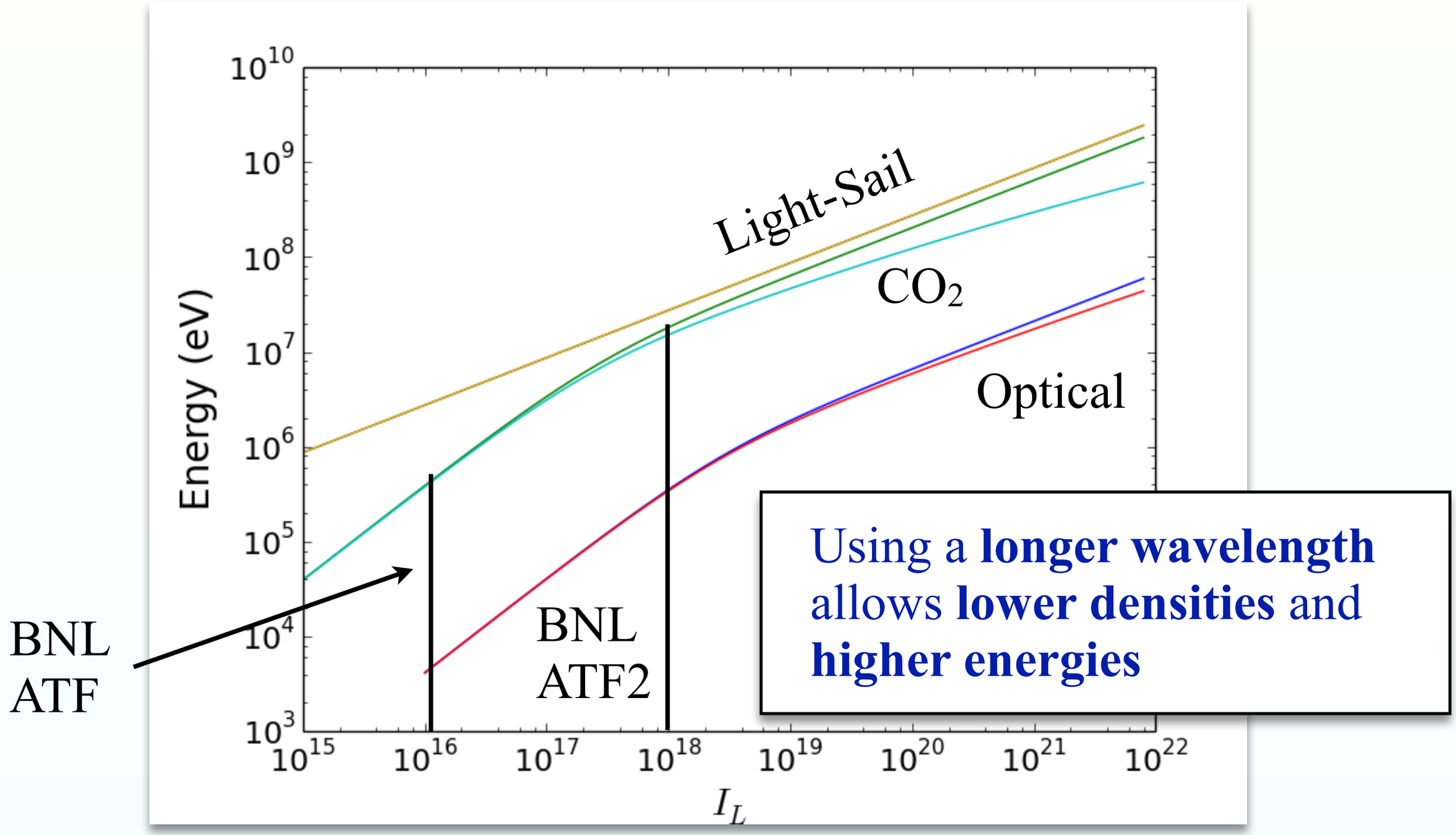
- optimum thickness d_{opt}:

$$d_{opt} = \left(\frac{n_{cr}}{n_e}\right) a_0 \left(\frac{\lambda_0}{2\pi}\right)$$

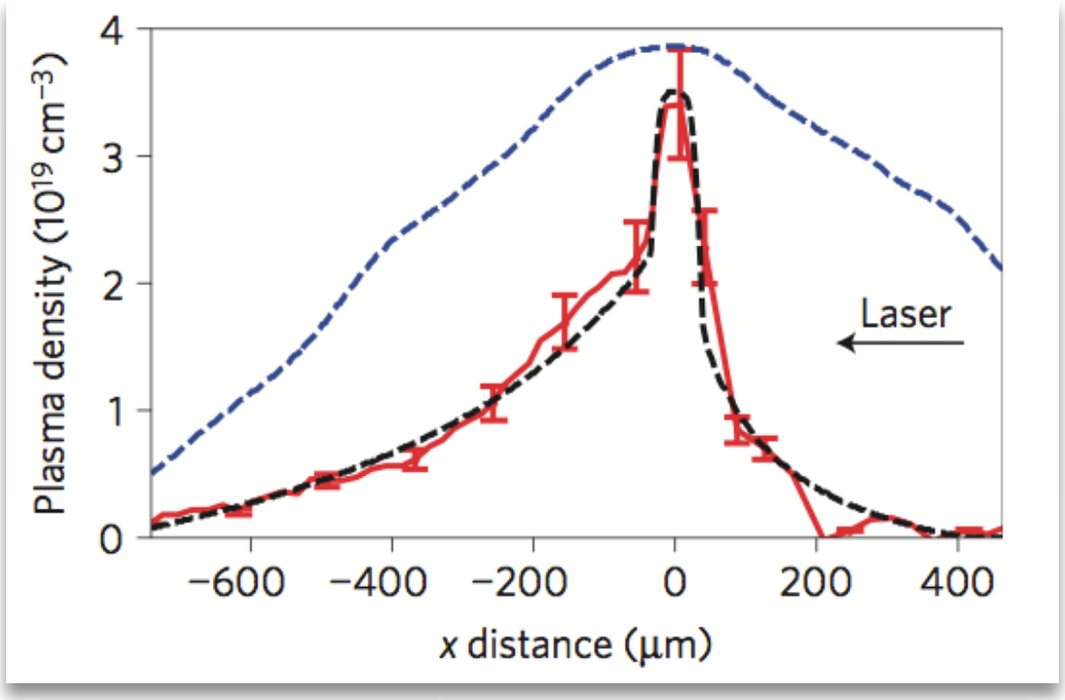
- for λ=10 μm, $I \approx 10^{18}$ Wcm^{-2}, H_2
  - ➡ $d_{opt} \approx 1.6$ μm

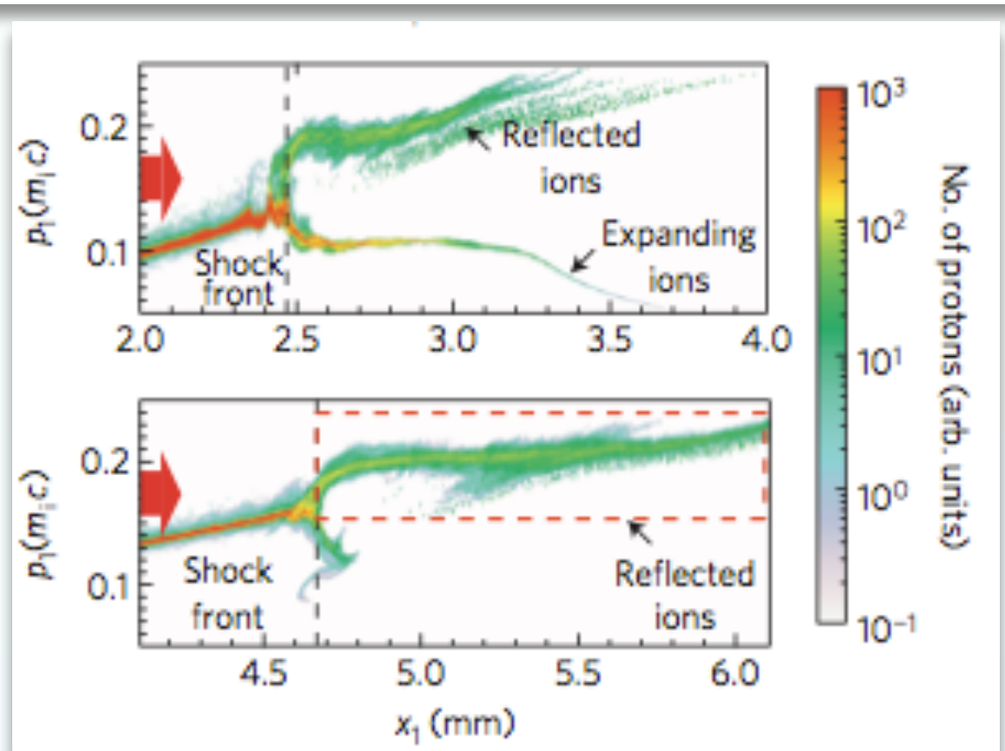
$$v_i = \frac{(1+R)\tau}{m_i n_i d}\frac{I_L}{c} \qquad W_i = \frac{1}{2}\left(\frac{m_e}{m_i}\right) m_e c^2 {a_0}^2 (\omega_0 t)^2$$

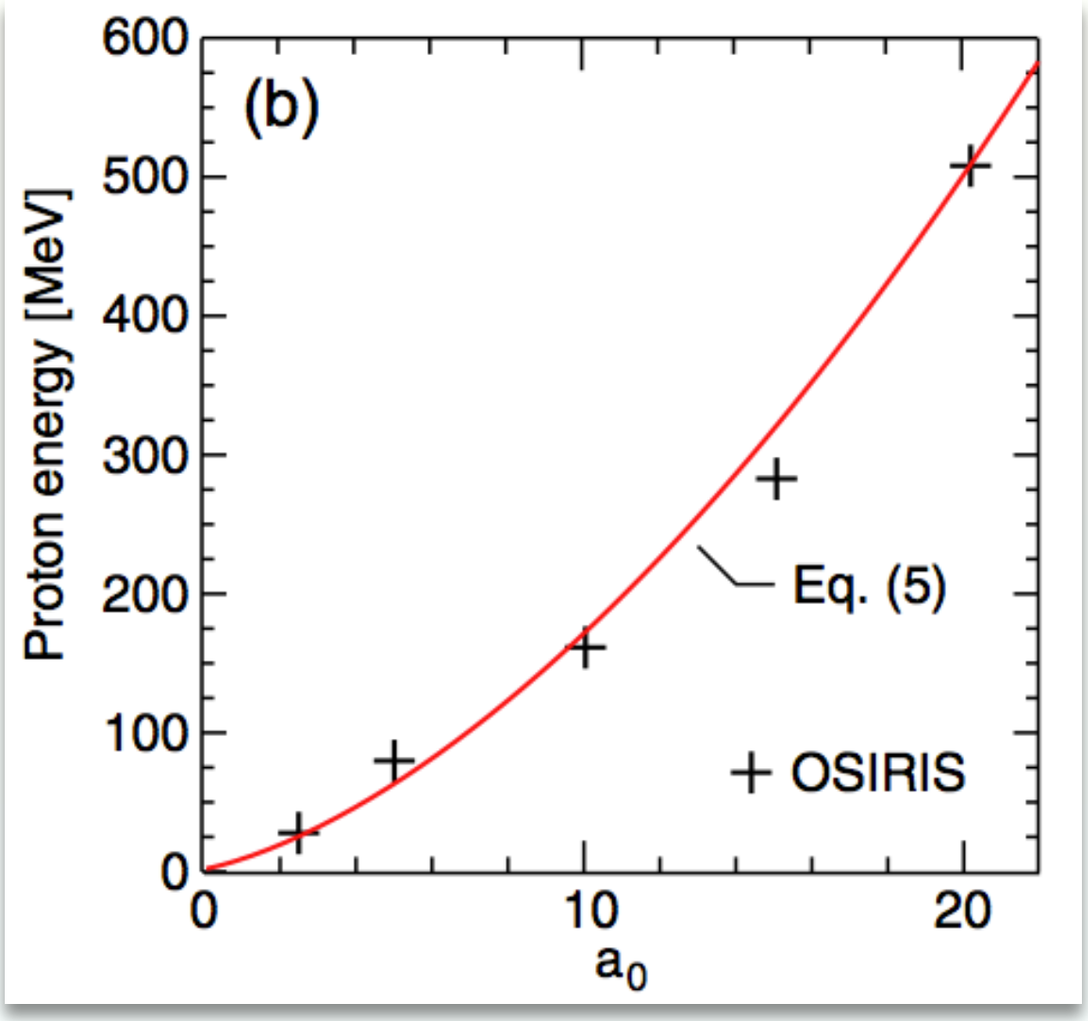
Hole-boring scaling



Prospects for thin targets

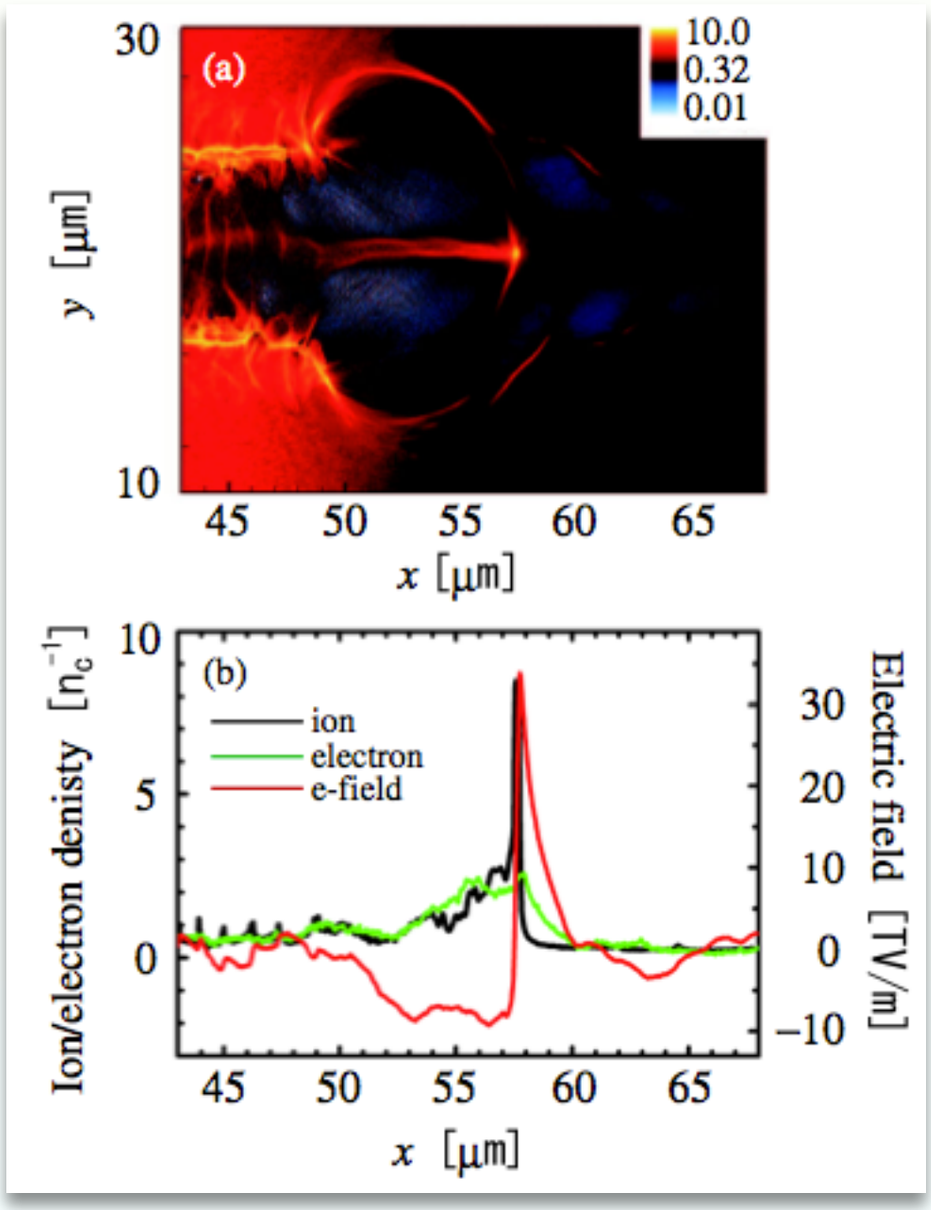


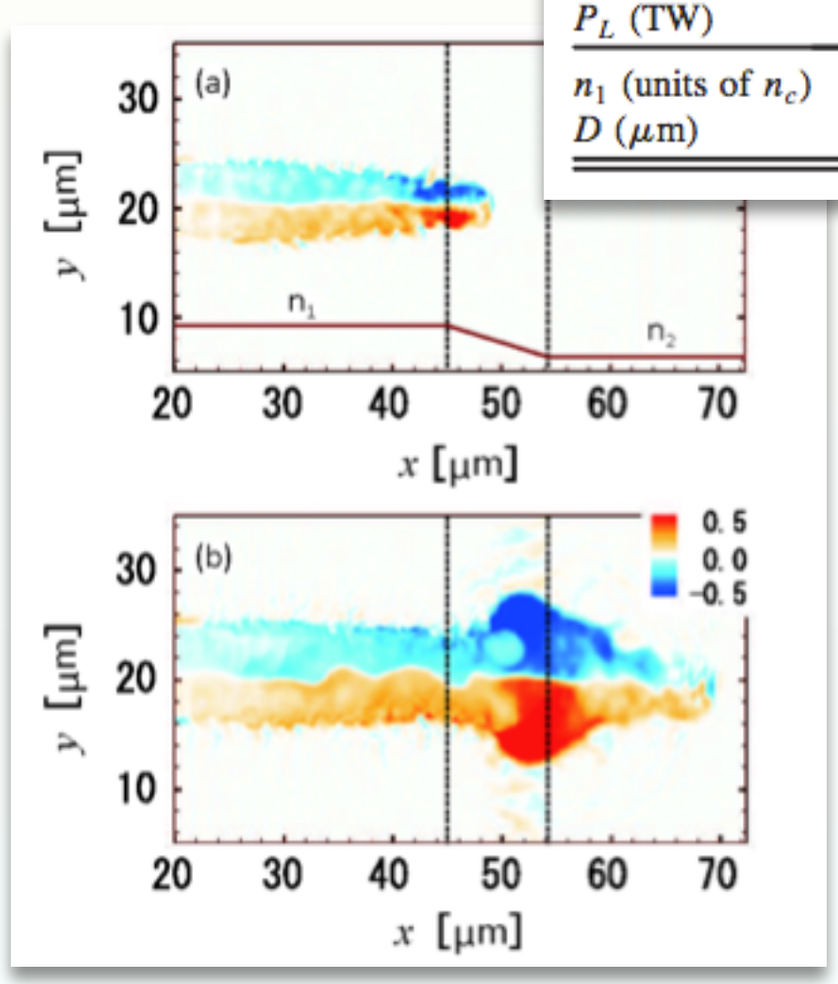




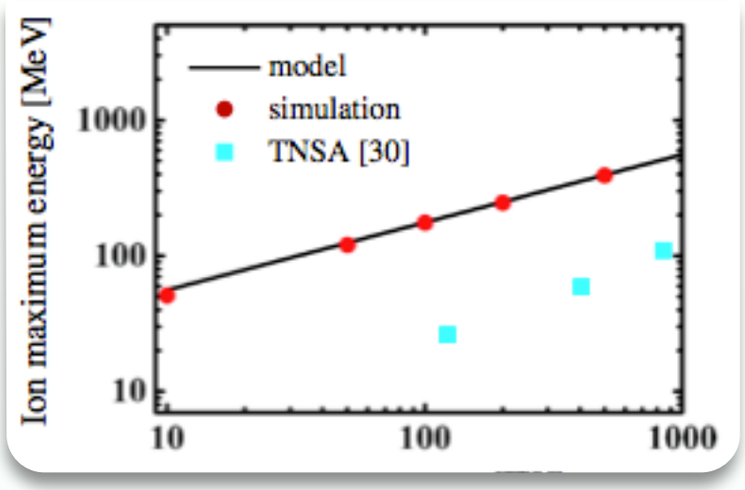
Haberberger, D. et al., 2011. Collisionless shocks in laser-produced plasma generate monoenergetic high-energy proton beams. Nature Physics, 8(1), pp.95–99.

Prospects for thin targets



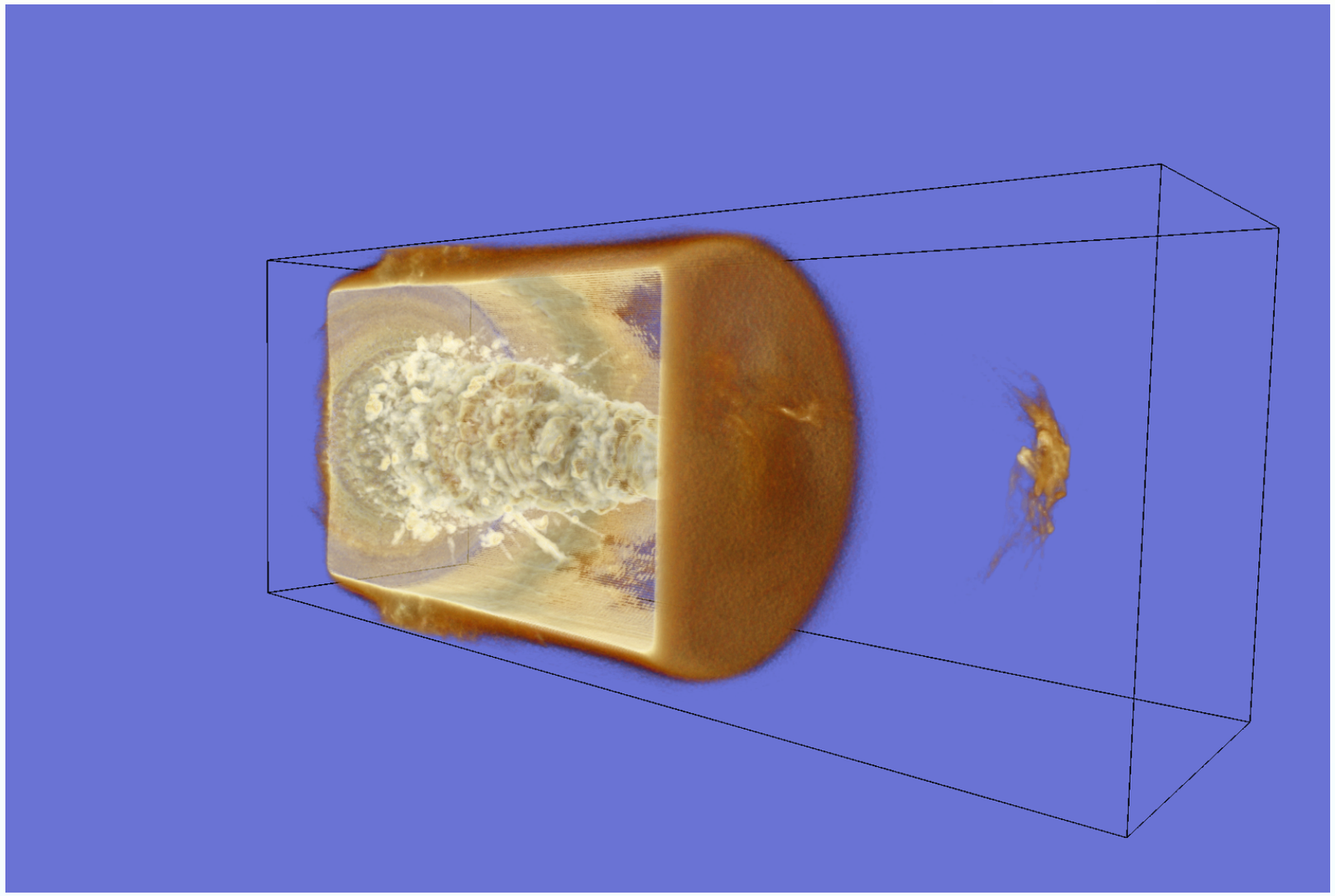


P_L (TW)	10	50	100	200	500
n_1 (units of n_c)	0.7	1.5	2.0	3.0	5.0
D (μm)	20.0	23.0	25.0	23.0	22.0



Nakamura, T. et al., 2010. High-Energy Ions from Near-Critical Density Plasmas via Magnetic Vortex Acceleration. Physical Review Letters, 105(13), p. 135002.

Scaling of Hole-boring acceleration



- Laser peak intensity: 2.0×10^{20} Wcm^{-2}
- duration: 187fs
- Peak energy: 1.32GeV
- energy spread: 28%
- divergence: 9.2°
- total charge of bunch: 6.5nC
- spot size of the bunch: 36.2 μm
- Laser spot size: 50 μm

1. Yu. J. in preparation (2014)

Summary

- Experimental demonstration of proton and helium beams from shock acceleration in gas jet targets
- Optimising density profiles should lead to ~100 MeV proton beams with 100 TW ATF II