Laser driven shockwave acceleration of ions with optically shaped gas jets

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Octoberfest at JAI, Royal Holloway University of London
29th September 2014

http://www.adams-institute.ac.uk

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UNIVERSITY OF OXFORD

Royal Holloway University of London

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BNL ion acceleration experiments

John Adams Institute for Accelerator Science

Imperial College London

BROOKHAVEN NATIONAL LABORATORY

Accelerator Test Facility

Stony Brook University

N.P. Dover, G. Hicks, Z. Najmudin

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
- Significant challenges still exist!
  - Unwanted radiation production
  - Stability, reproducibility (ie. laser technology!)
  - For some applications, want higher energy, higher current, or both...

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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Targeted applications

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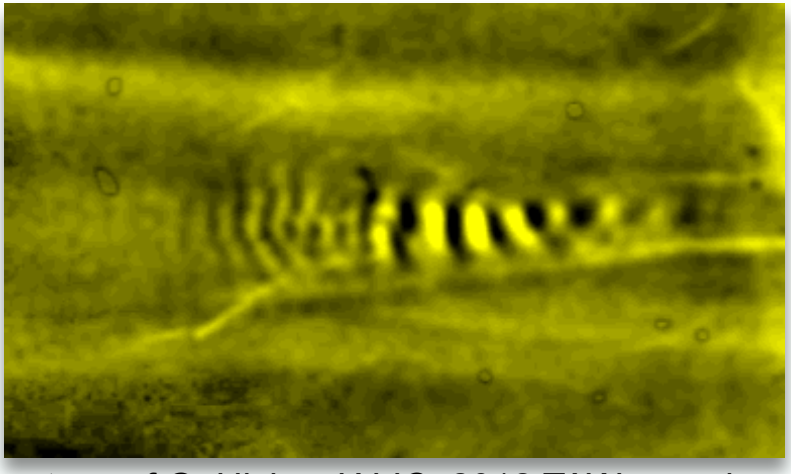
Cell irradiation
radiobiology

Plasma radiography

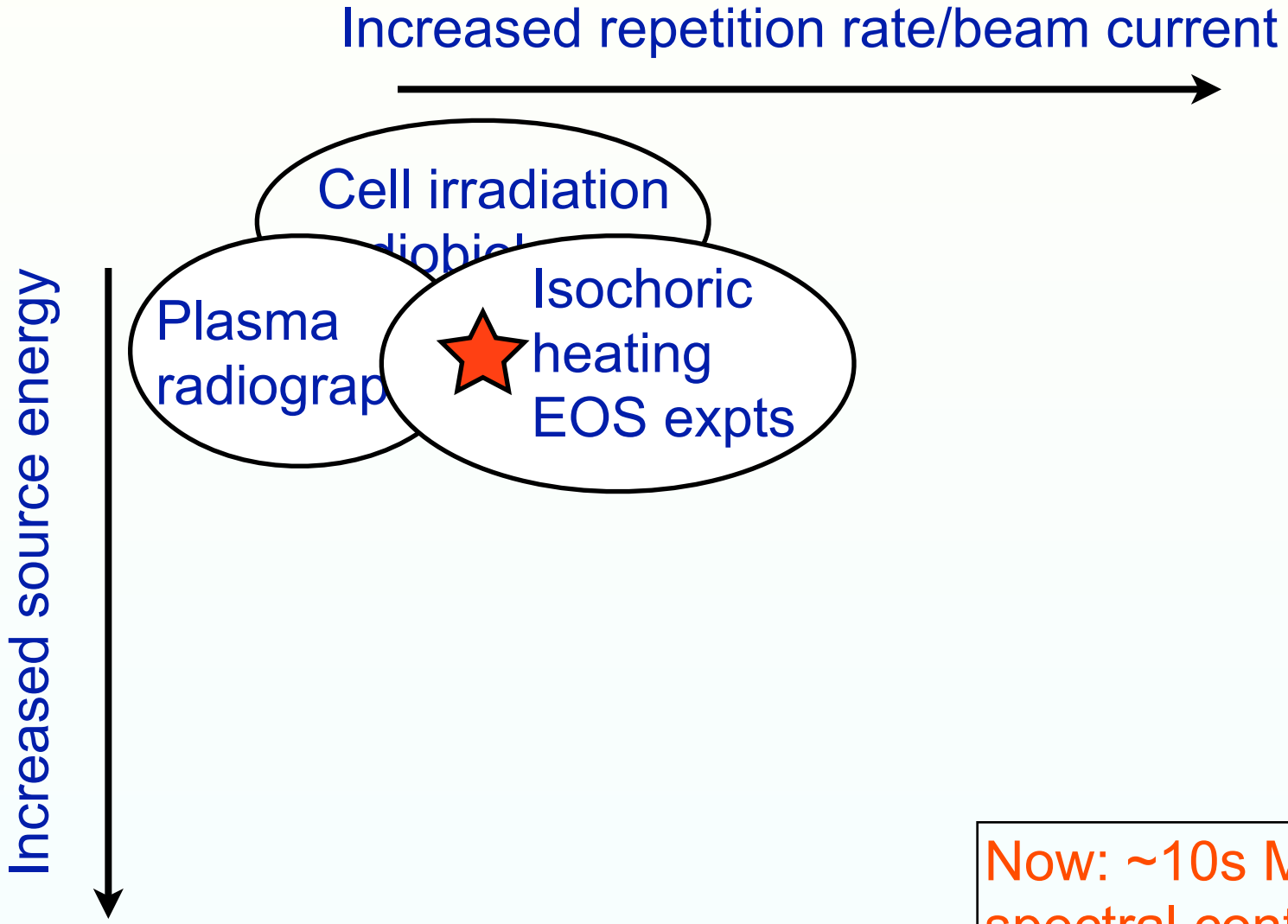
Radiography of a plasma:



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

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

Targeted applications



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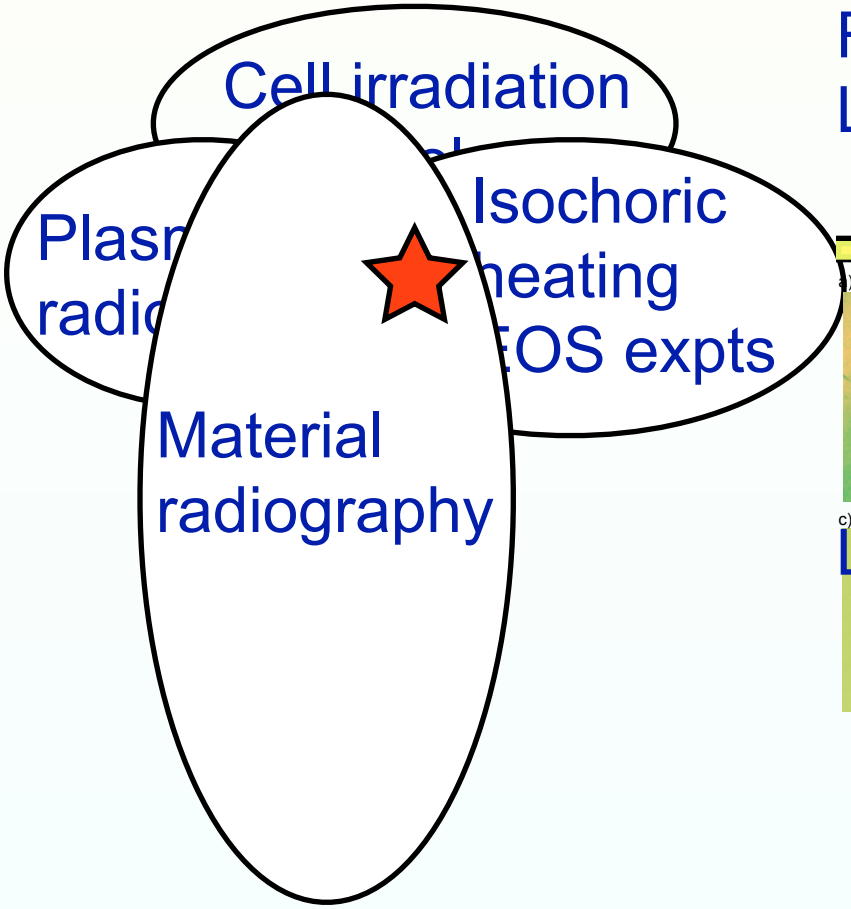
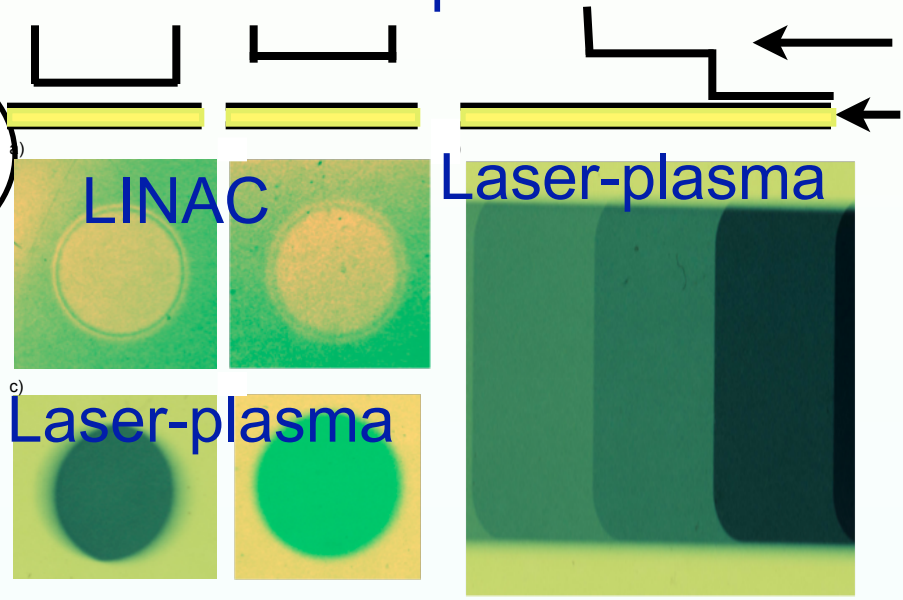


Radiography of phantom with LINAC & laser plasma source:



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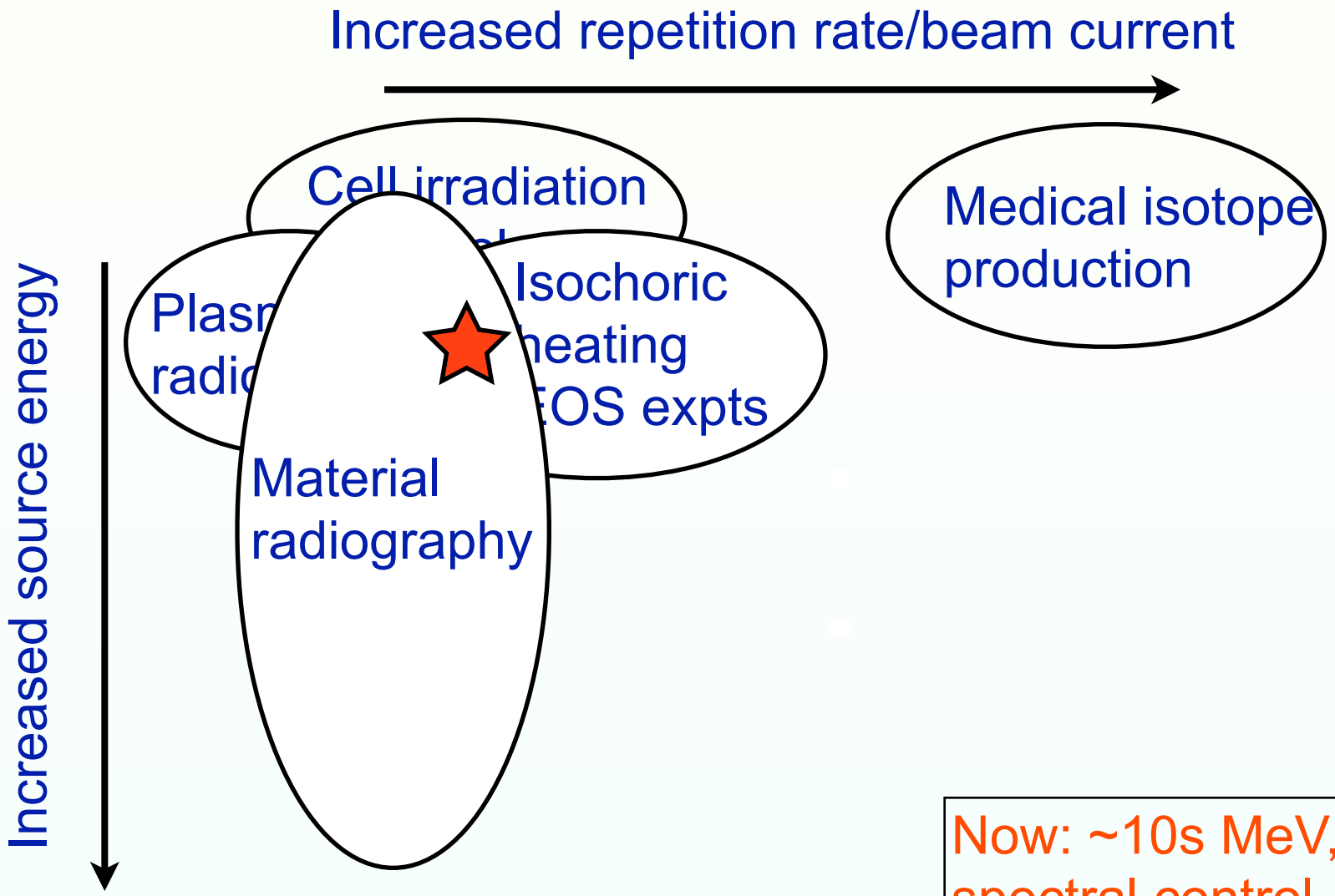

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Targeted applications

Increased repetition rate/beam current

Increased source energy

Cell irradiation

Plasma radiography

Isochoric heating EOS expts

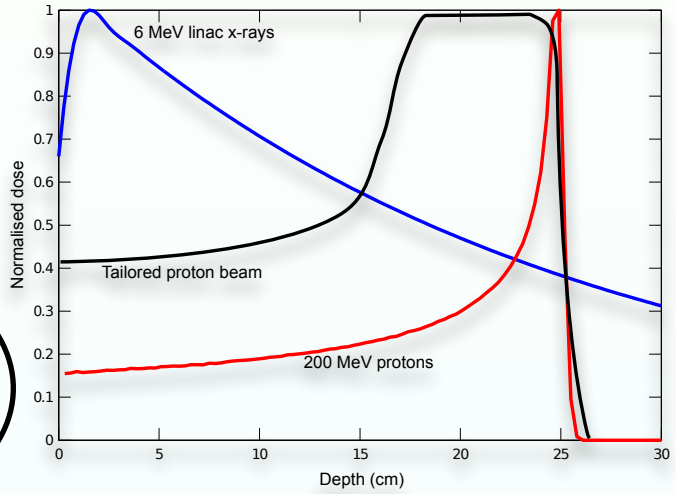
Material radiography

in vivo radiography

Medical isotope production

Particle therapy

> 250 MeV (protons)



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Can gas targetry help?

- Most research currently aimed at solid (nm-μm) targets & near-optical lasers (λ ~ 1 μm)
- What about gas targets?
  - Potentially less bremsstrahlung radiation
  - Easily scalable to high repetition rate
  - Change gas to change ion species
- Still want local heating to create giant electric fields - opaque 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**

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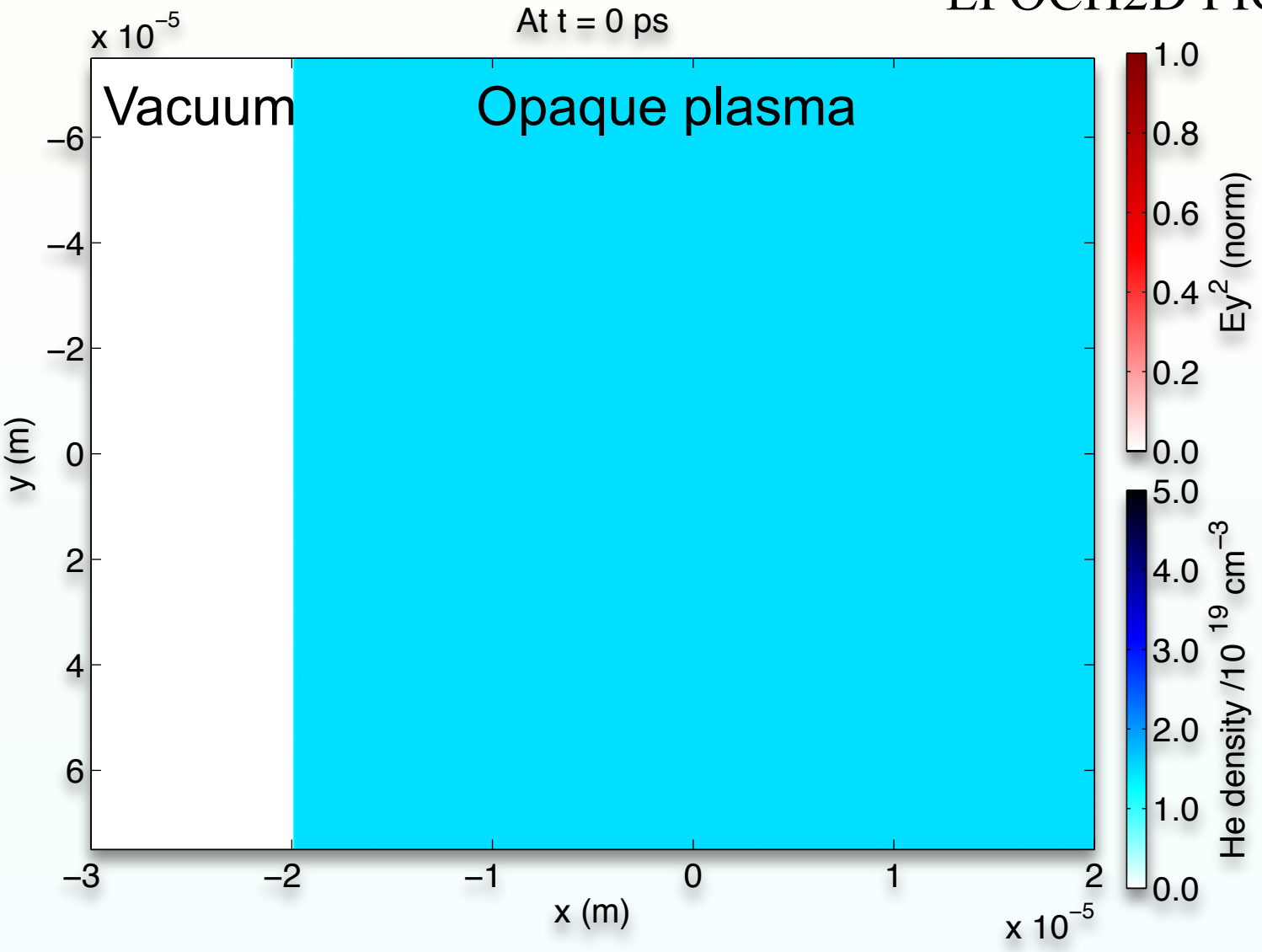
  - Achievable using pressurised **gas jets**

Ions accelerated from a moving shock

EPOCH2D PIC code



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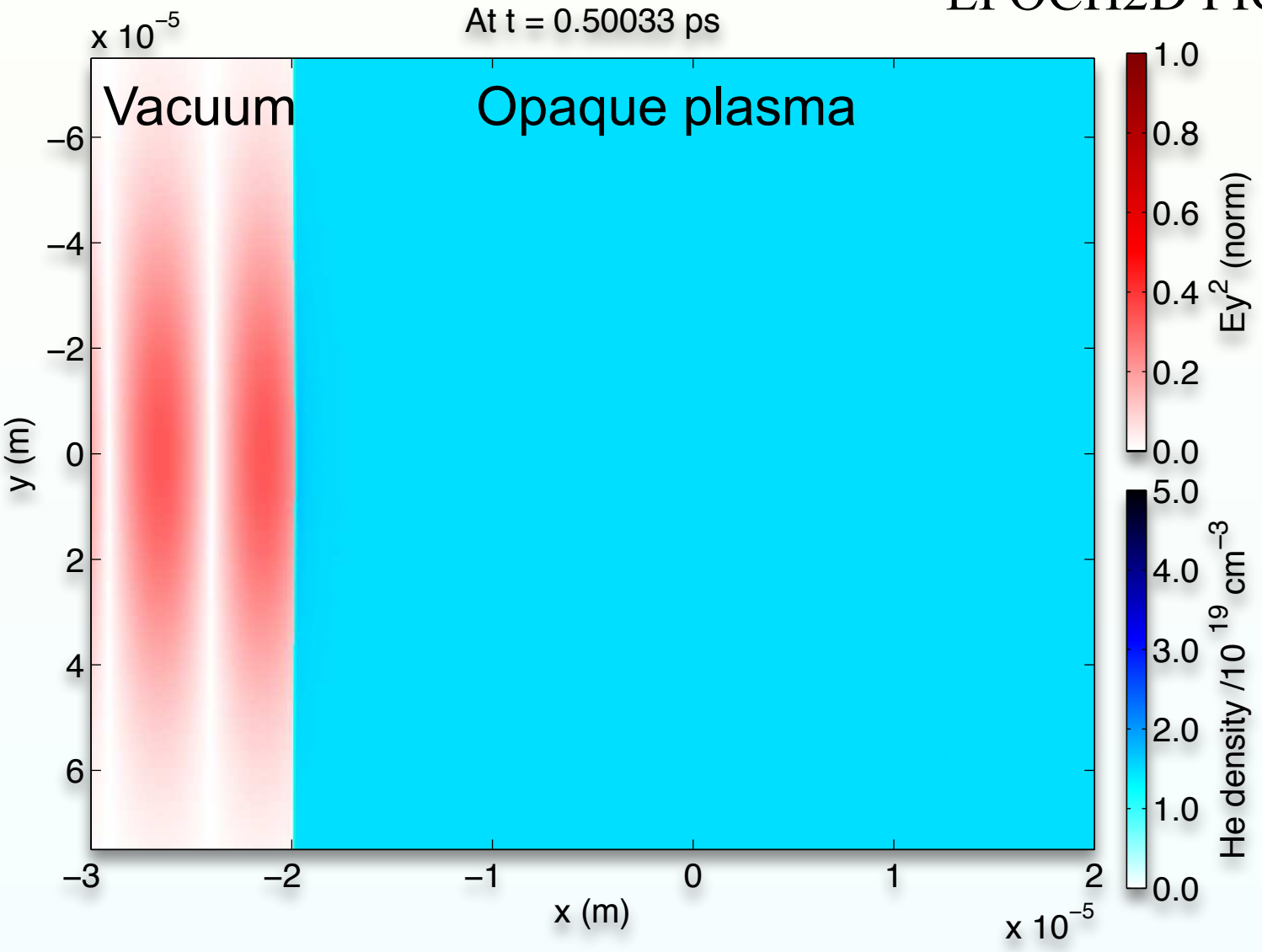

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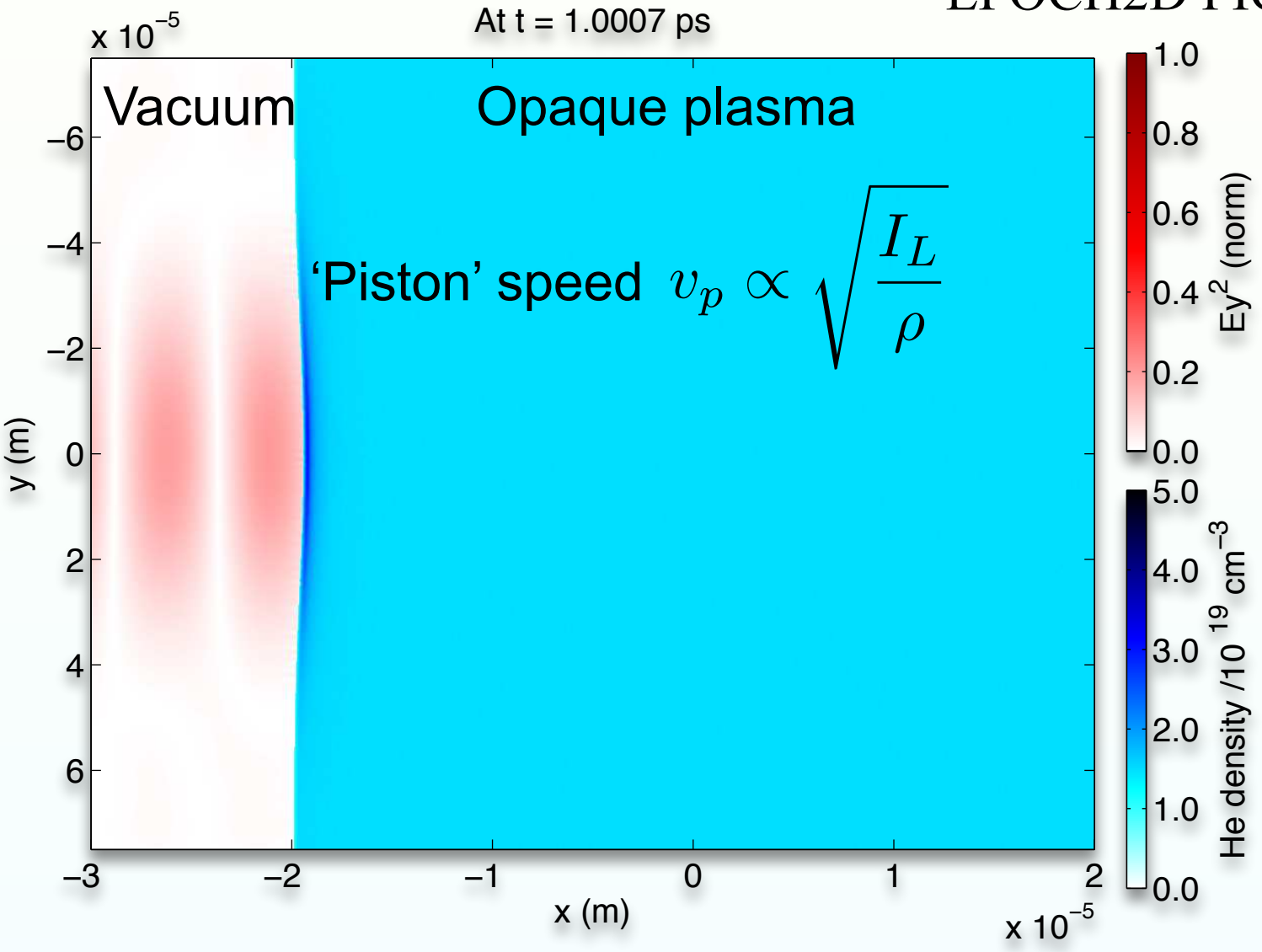

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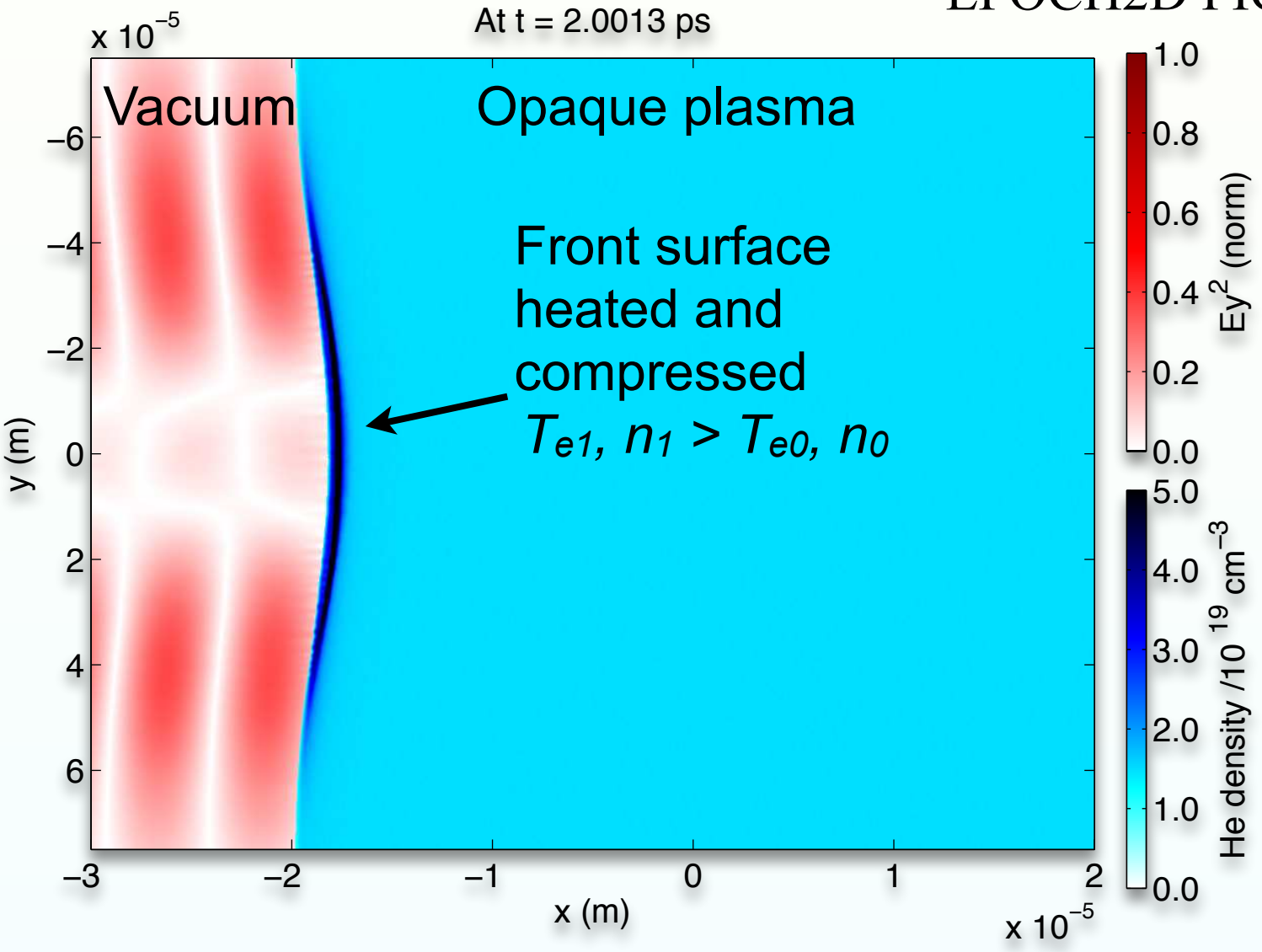

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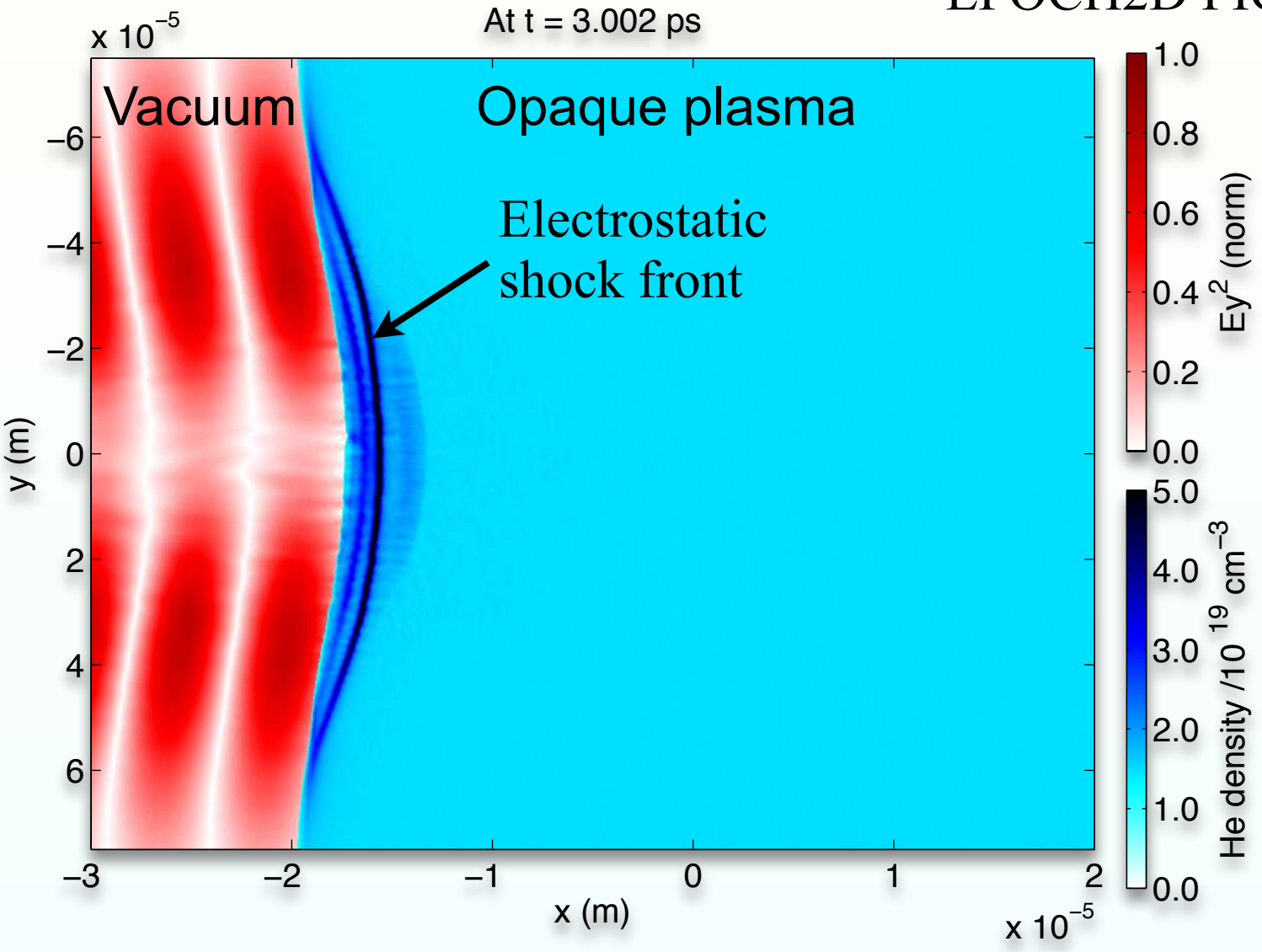

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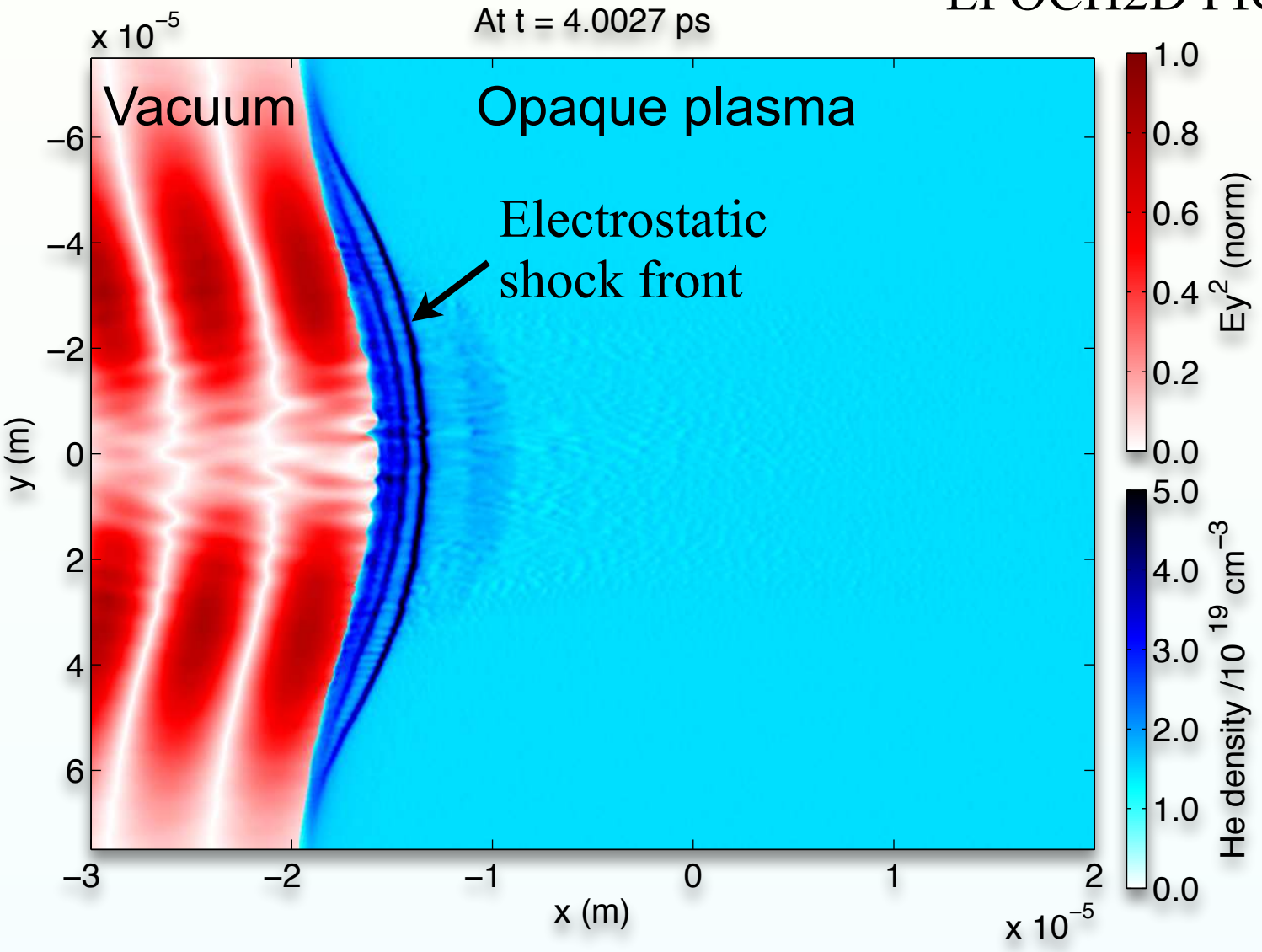

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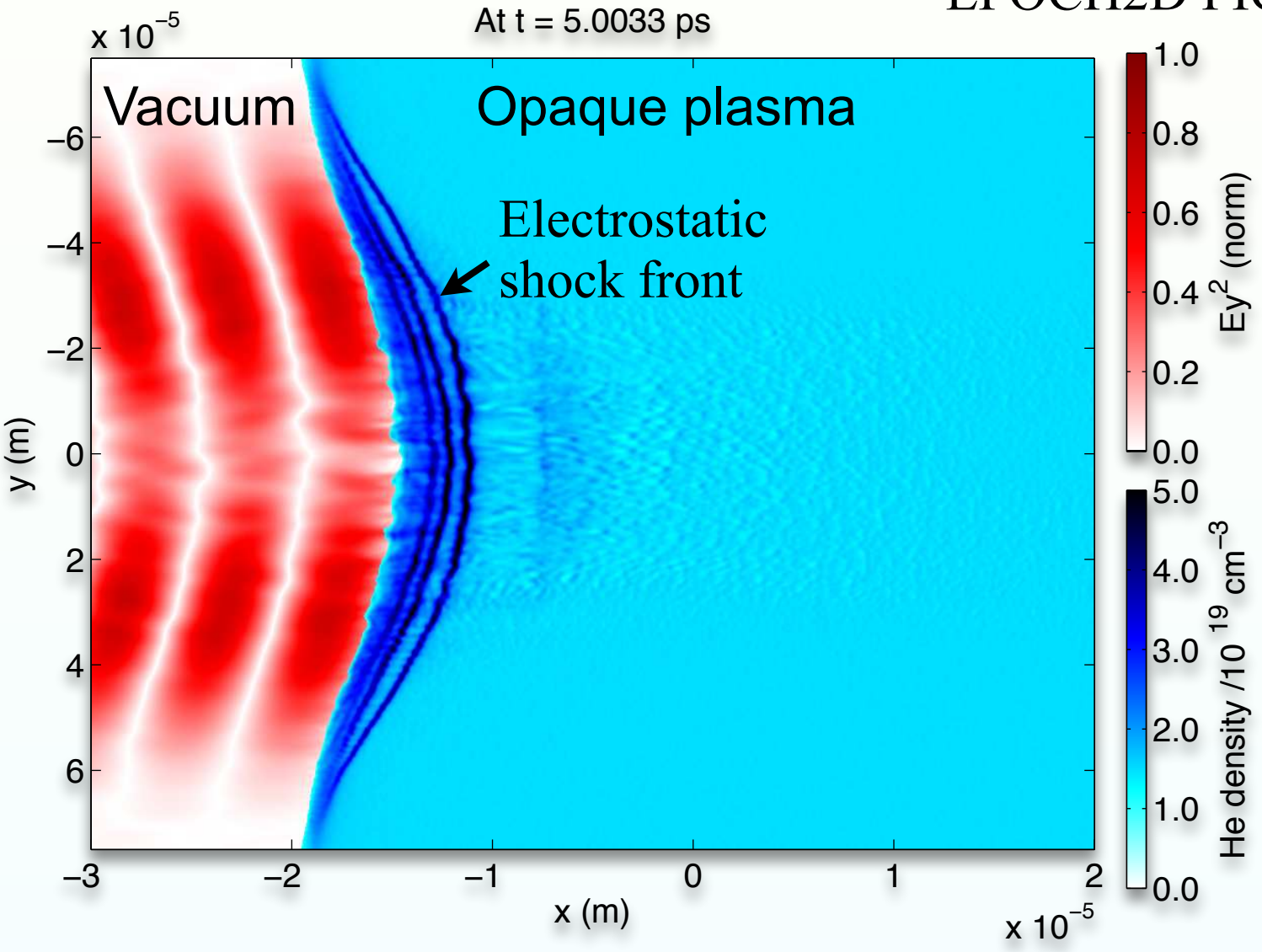

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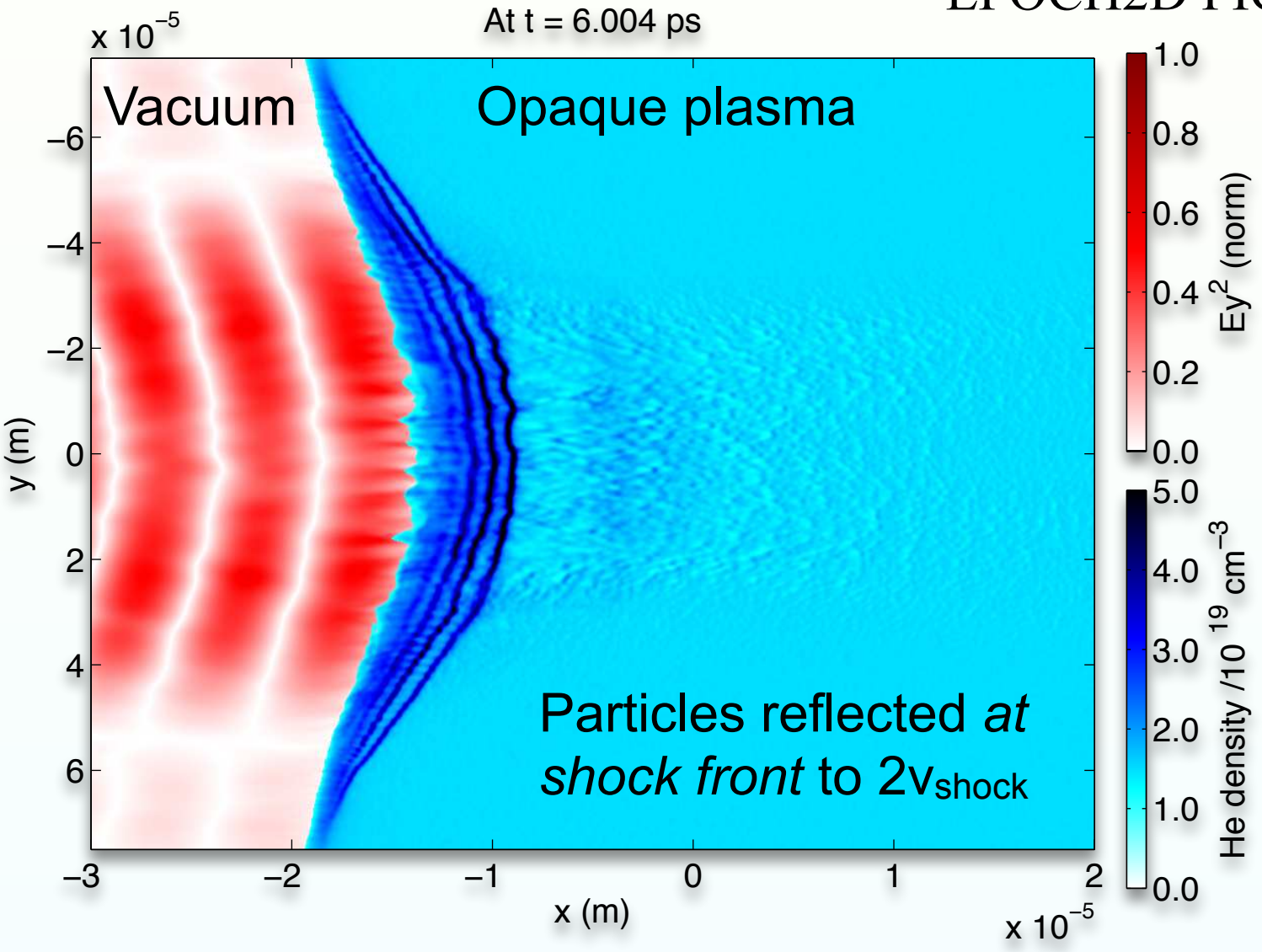

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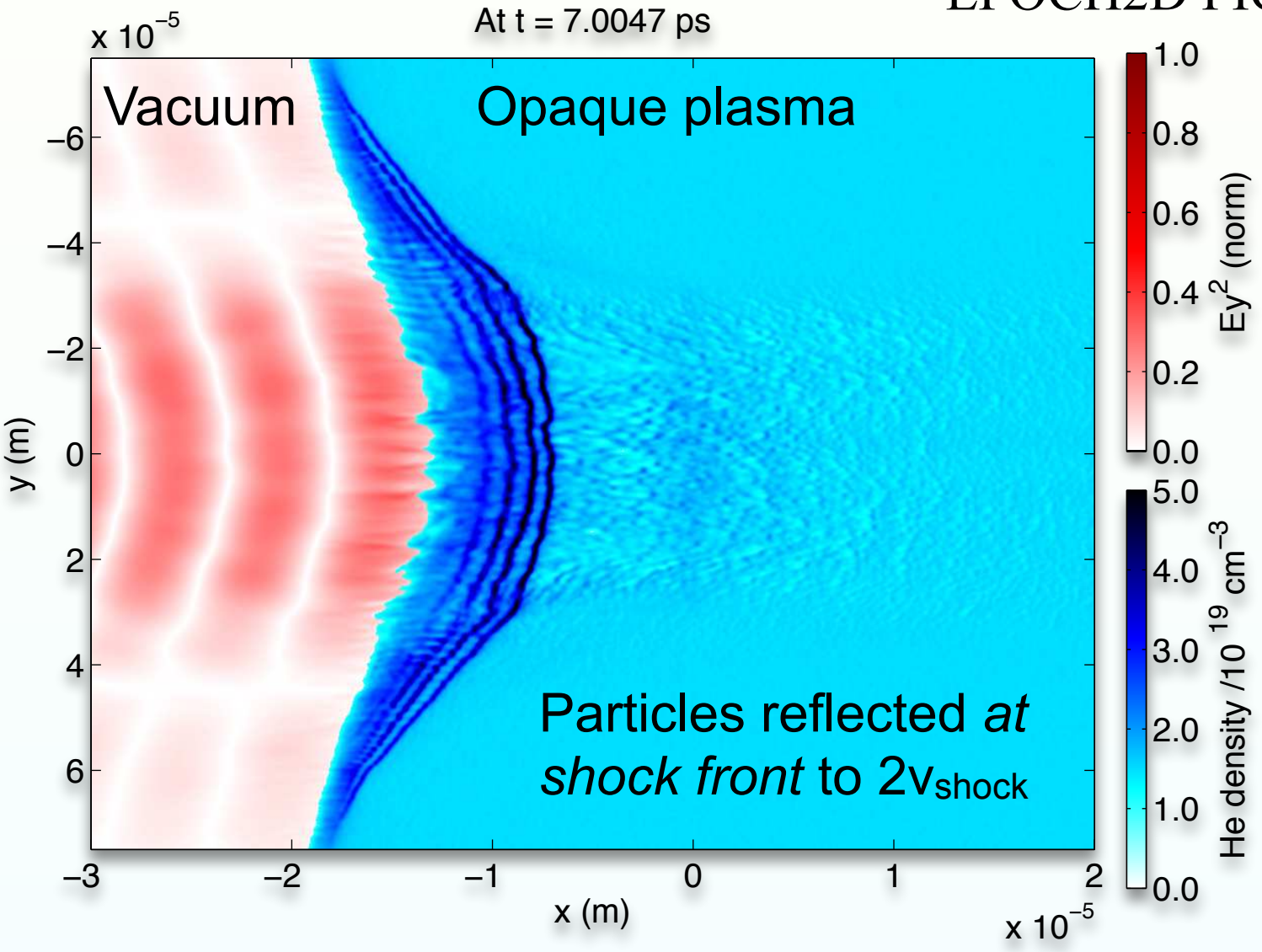

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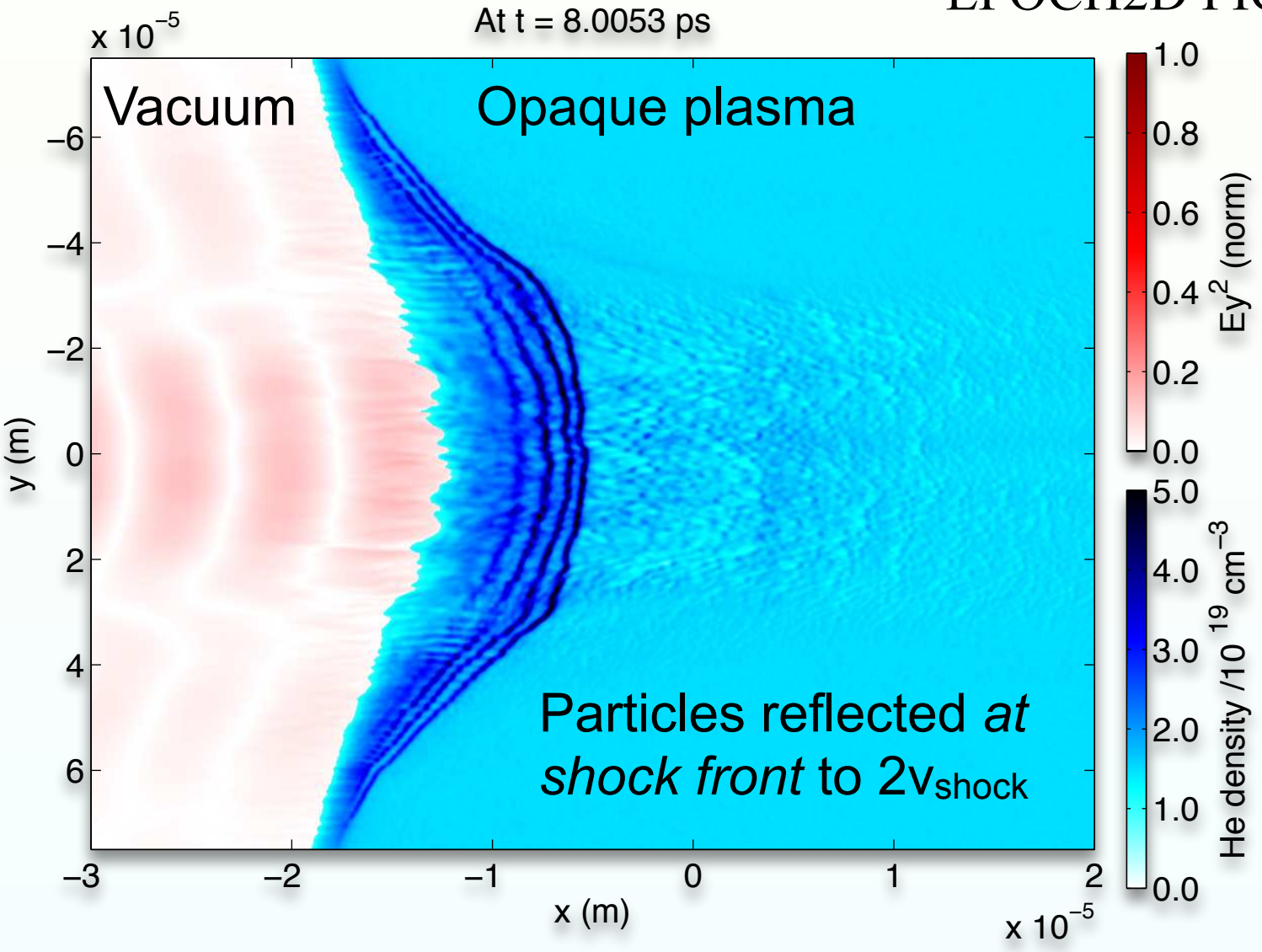

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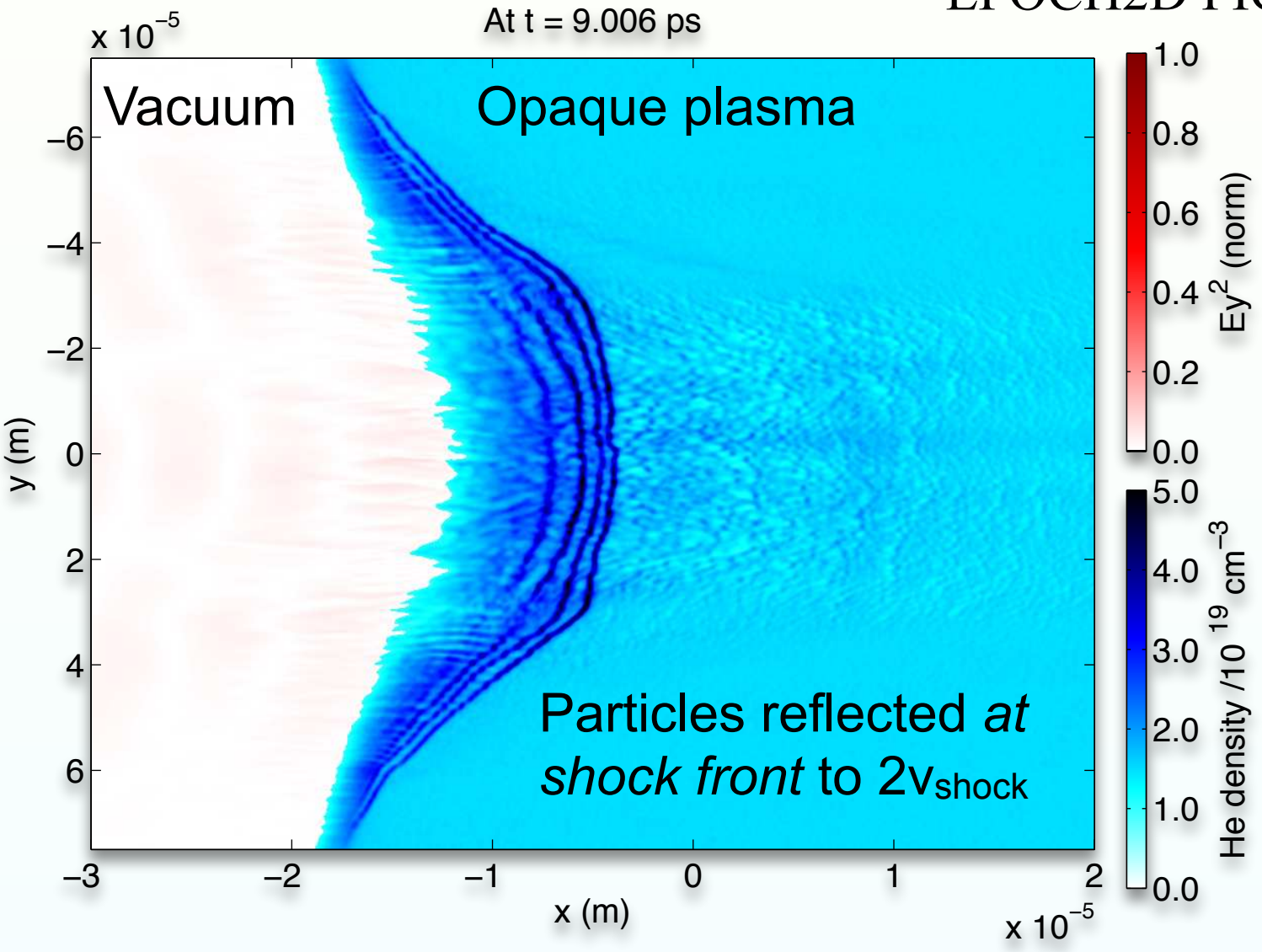

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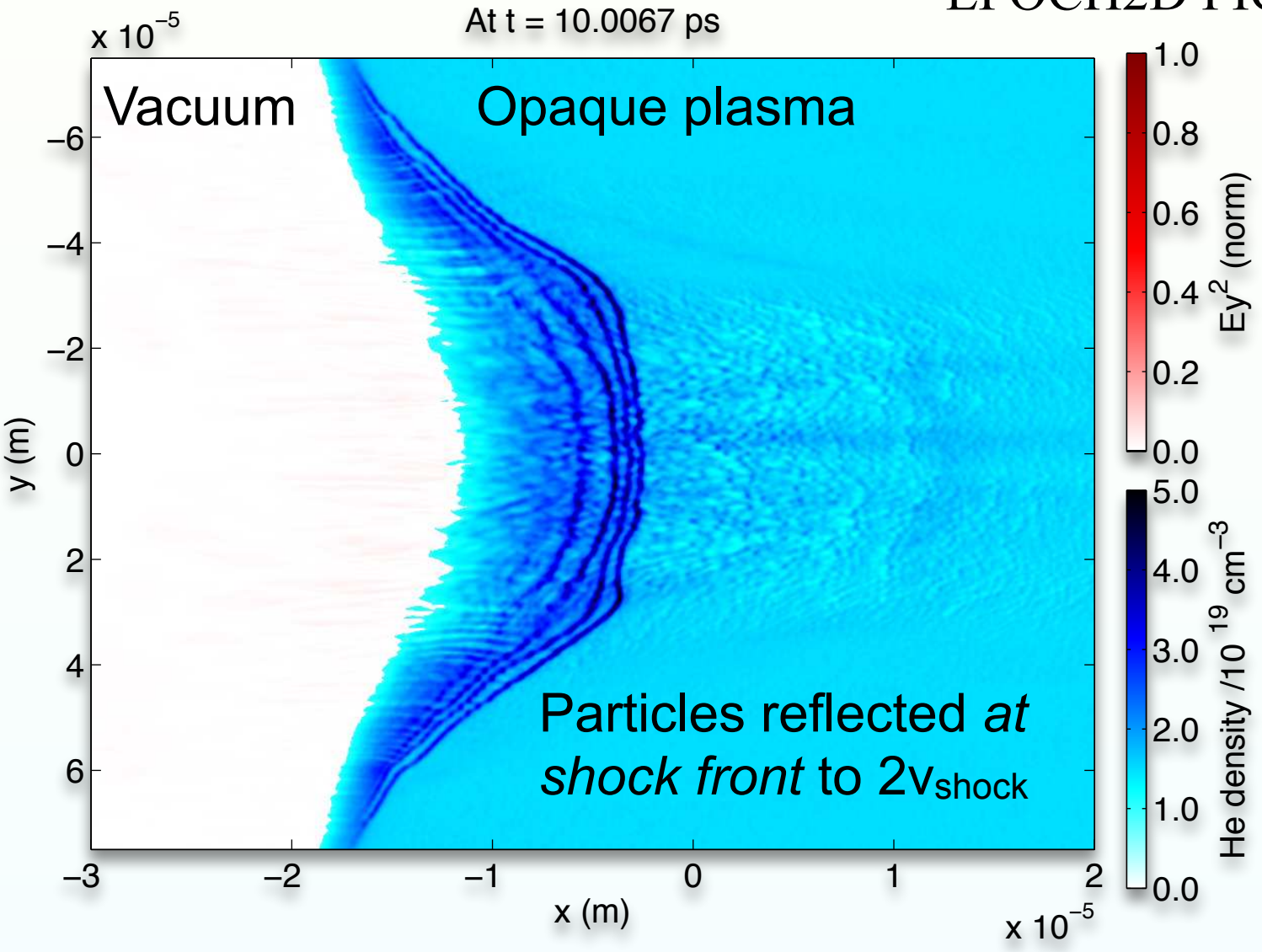

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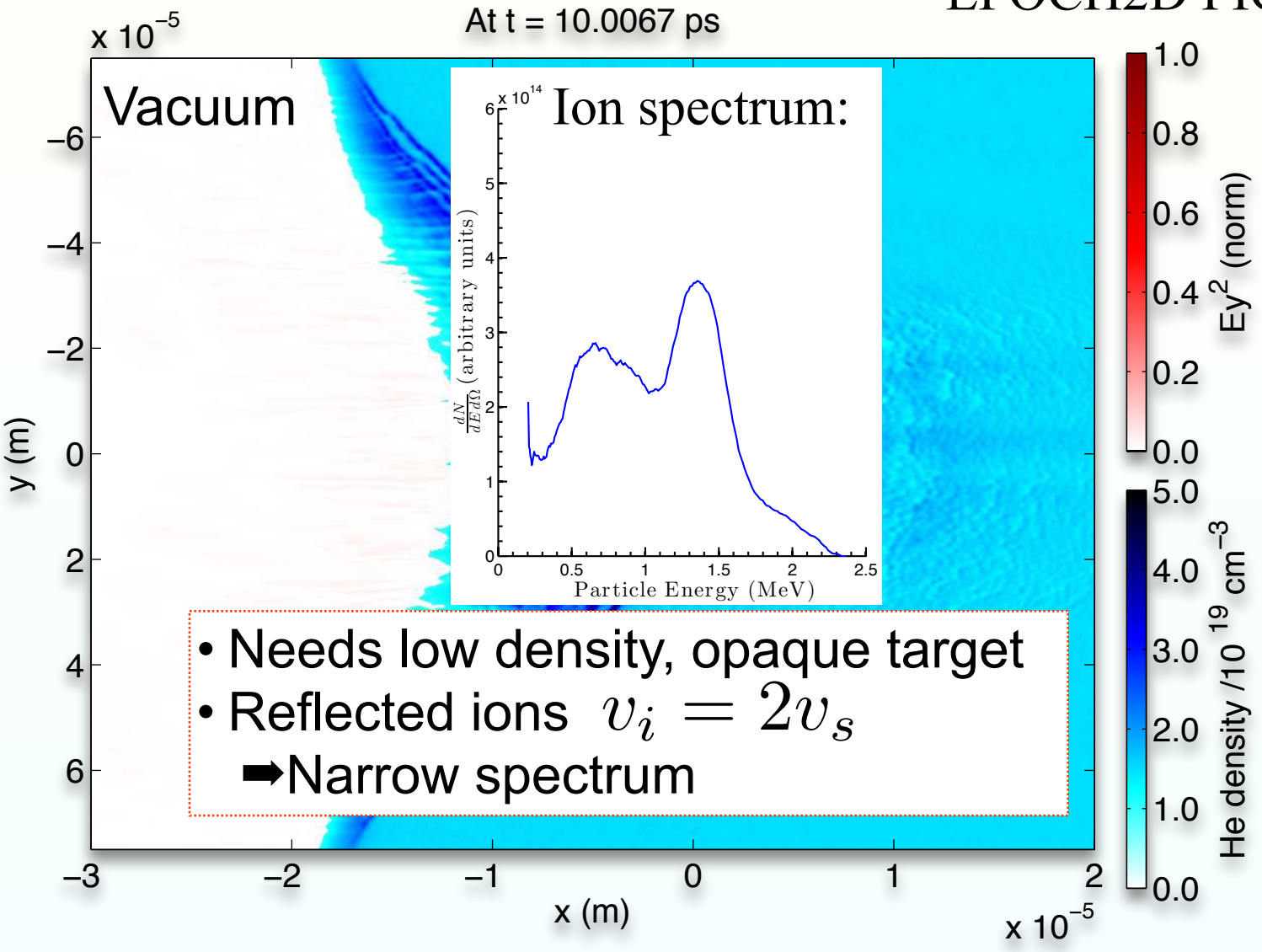
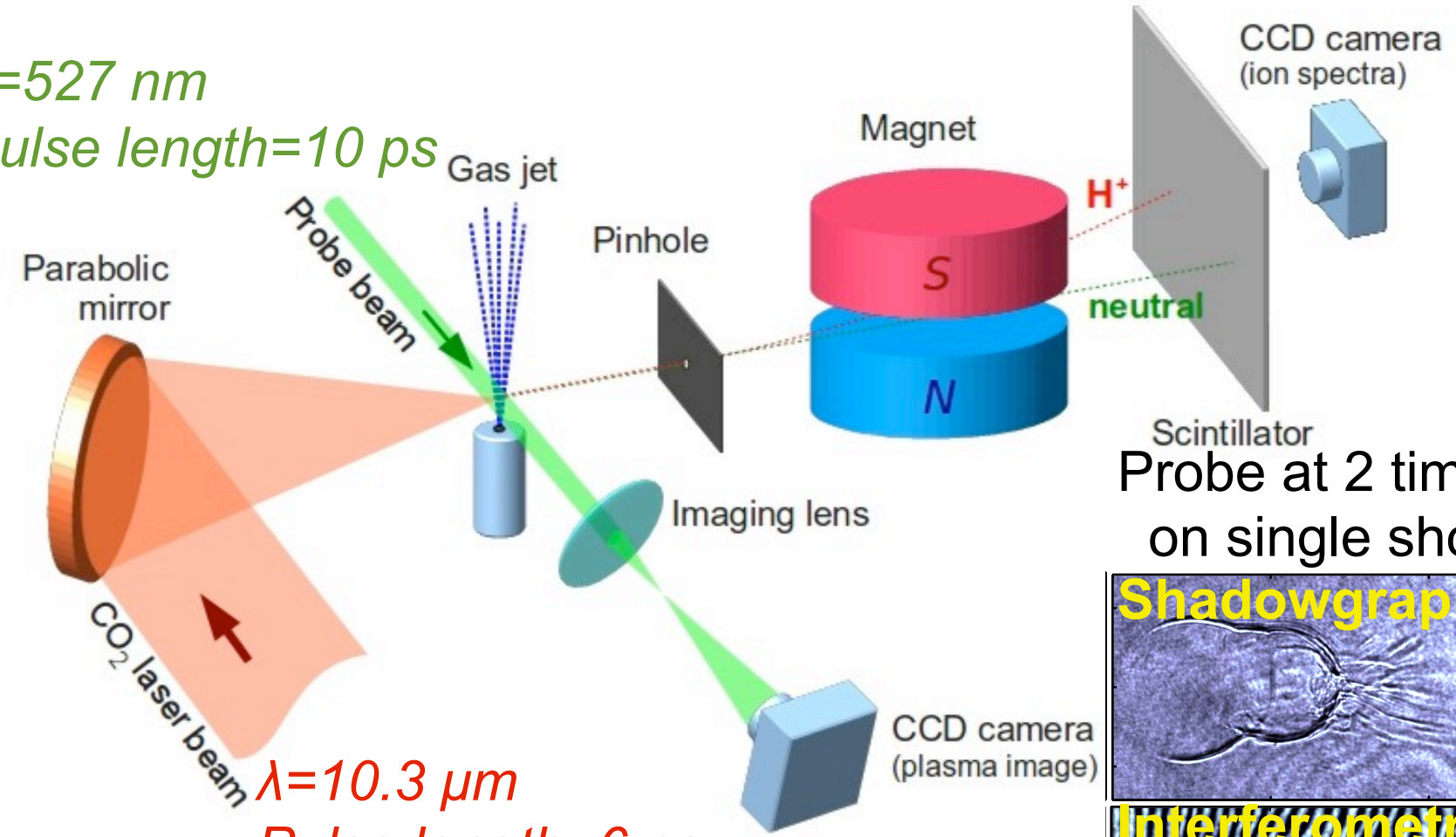


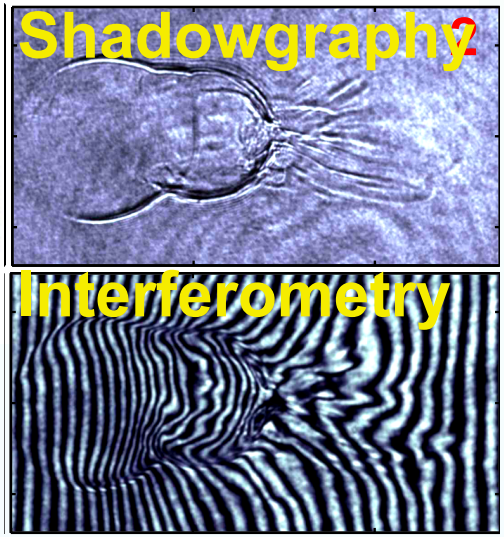
Typical experimental set-up

λ=527 nm
Pulse length=10 ps

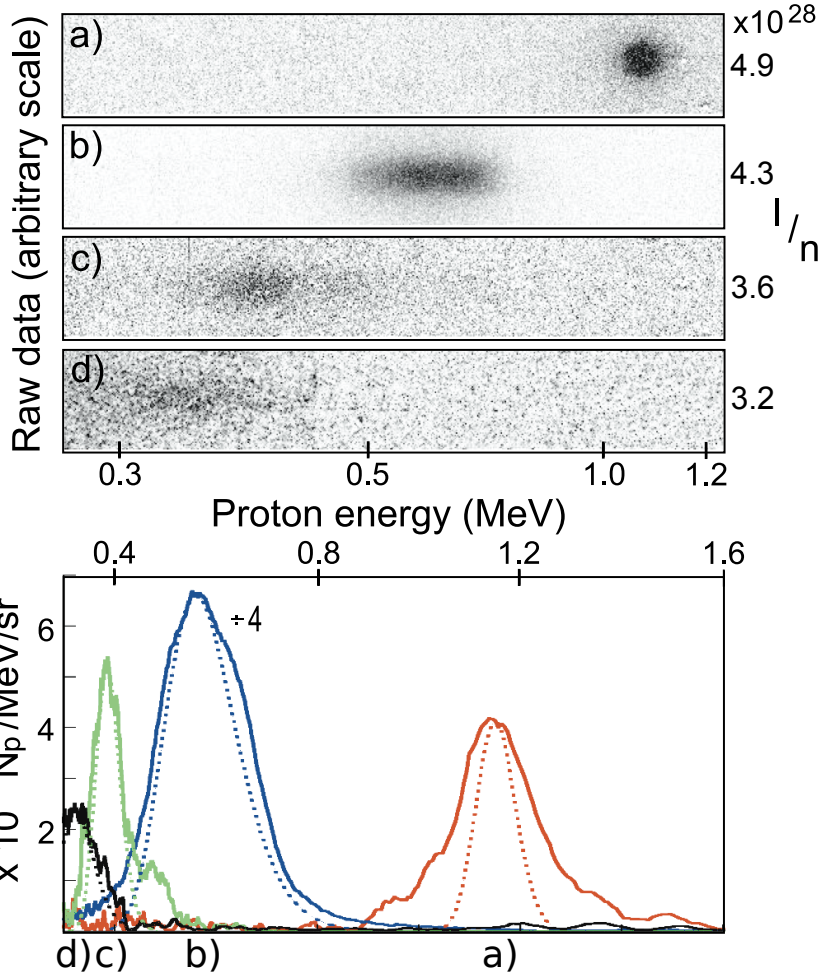


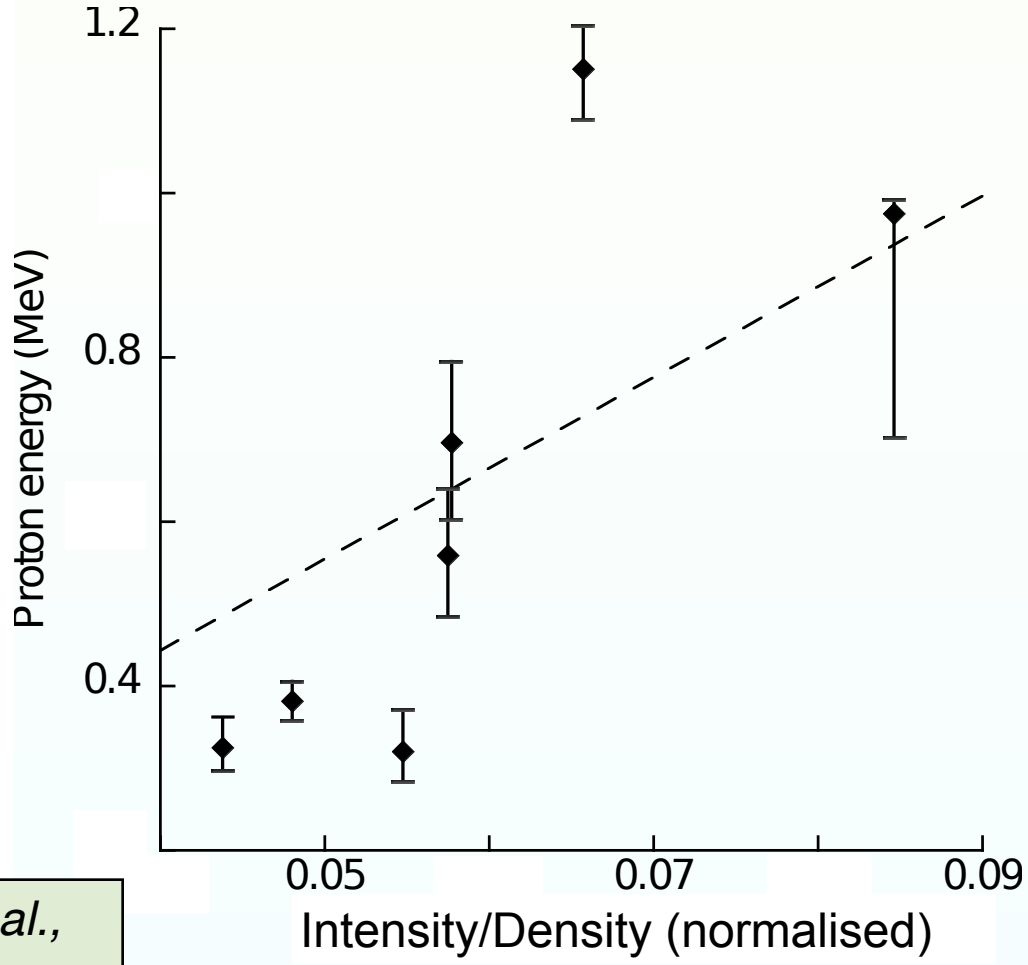
λ=10.3 μm
Pulse length=6 ps
Spot size = 70 μm
Intensity ~ 10^{16} W/cm^2

Probe at 2 times on single shot



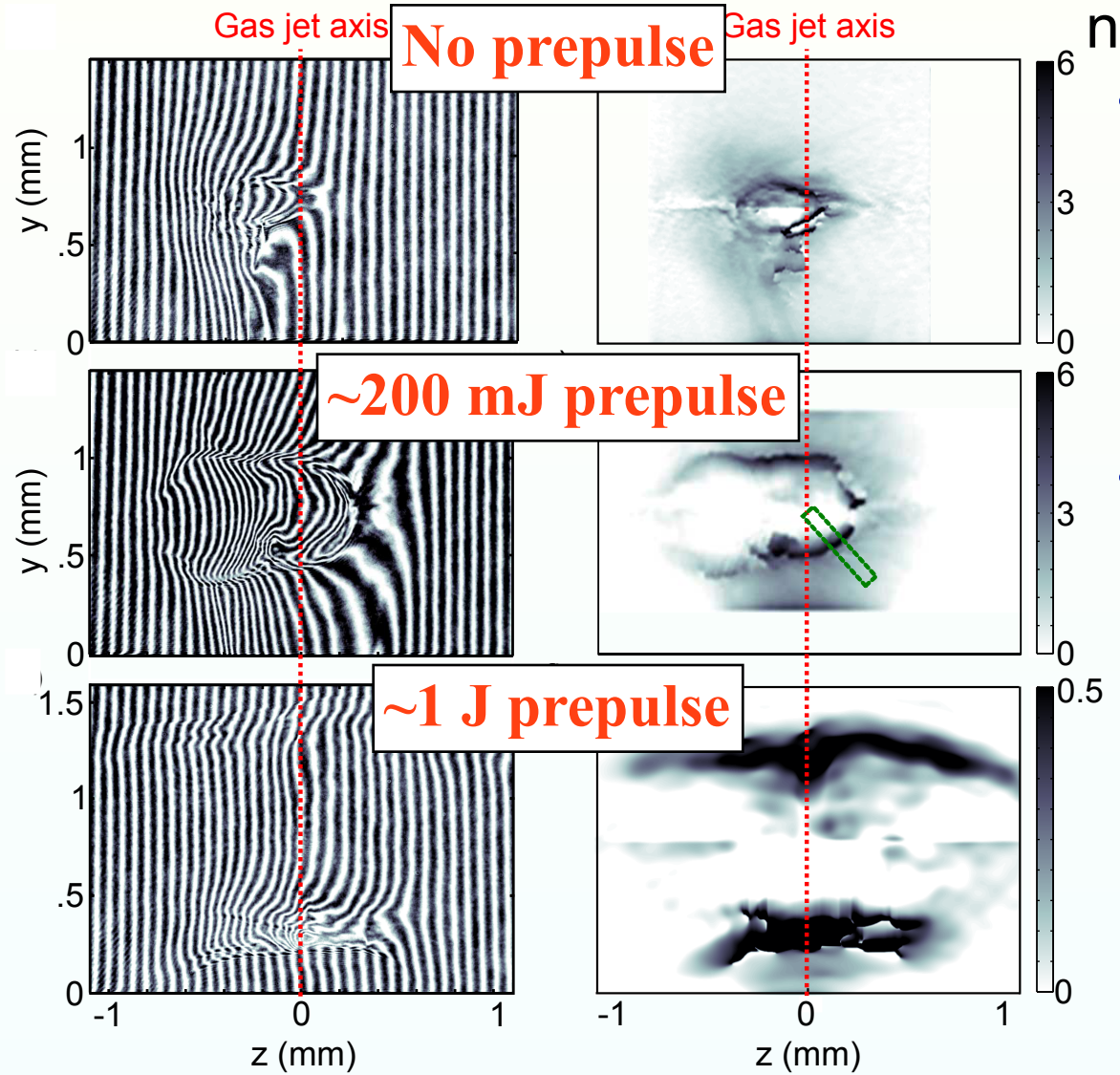
Generated monoenergetic proton beams





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

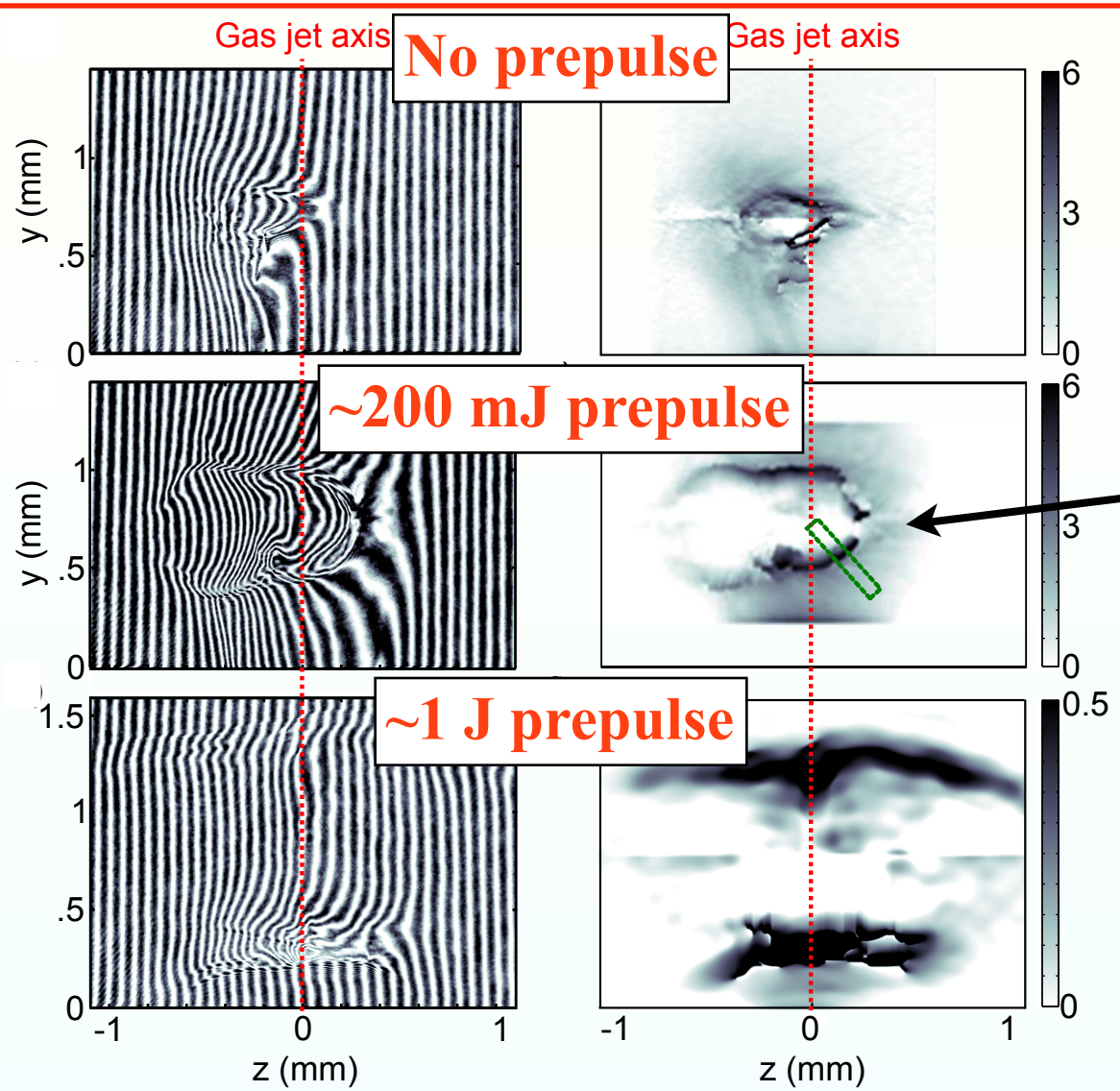
Varying prepulse changes ion beam properties

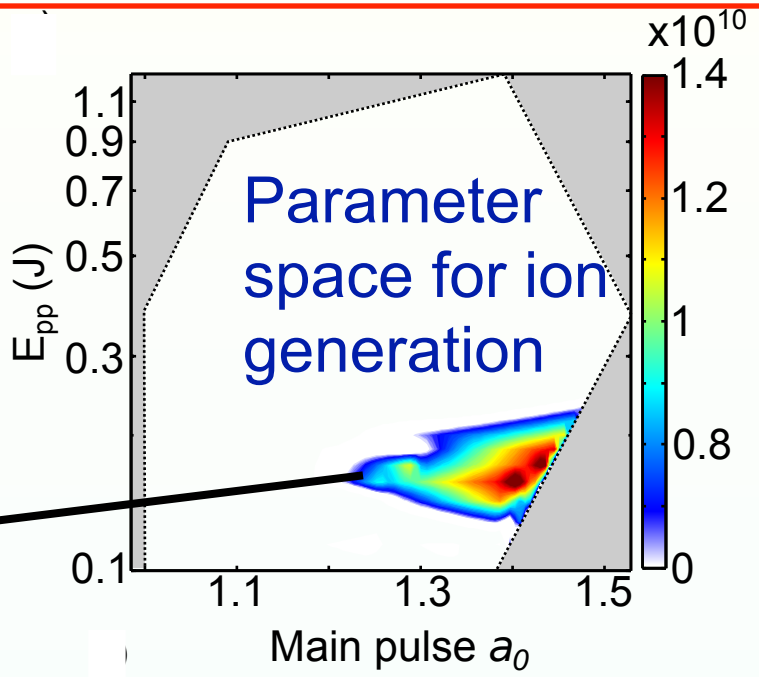


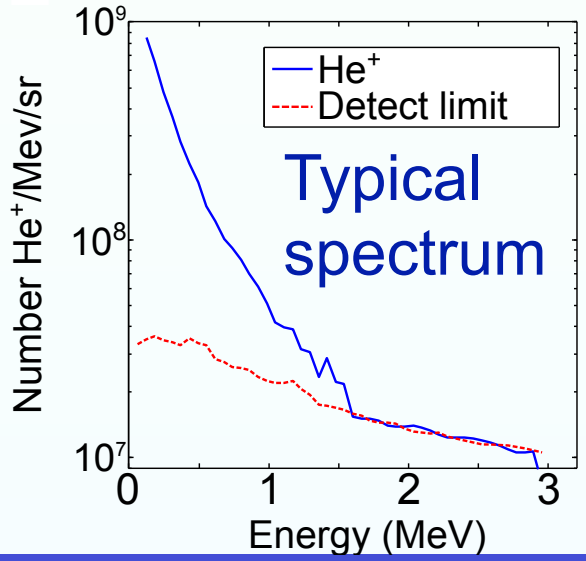
- Using ~100 mJ prepulse generates ~10λ density ramp for main pulse to interact with
- Sharp density ramp allows efficient *localised* heating & shock generation

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

Varying prepulse changes ion beam properties





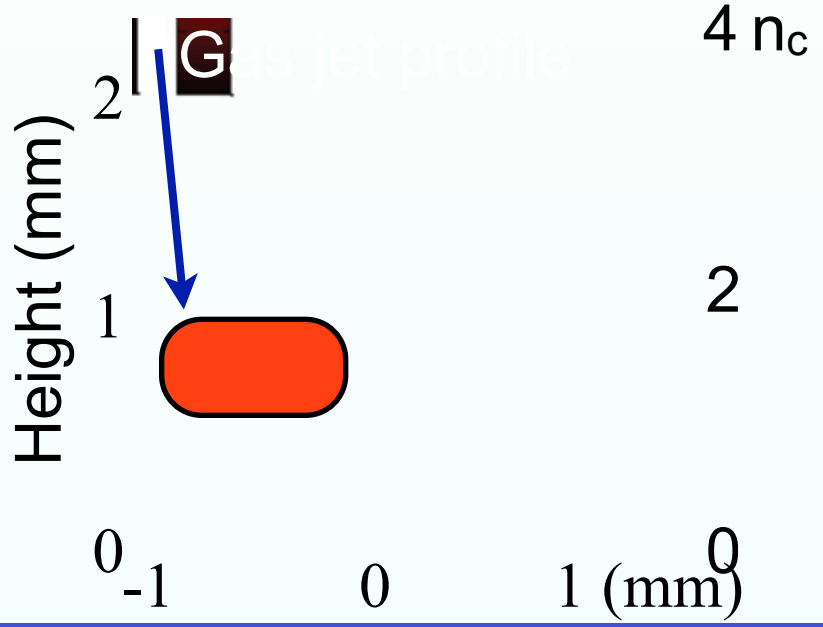


See: Tresca, Dover, Cook et al., Submitted 2014

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



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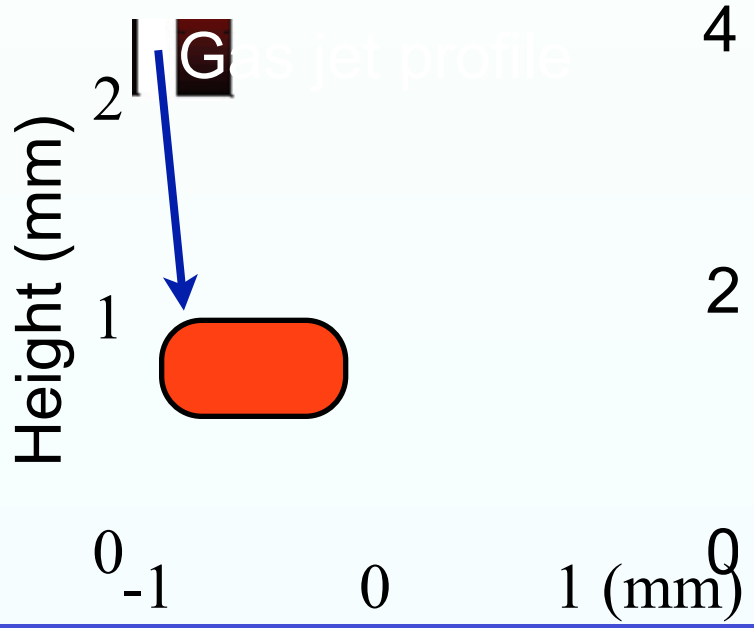
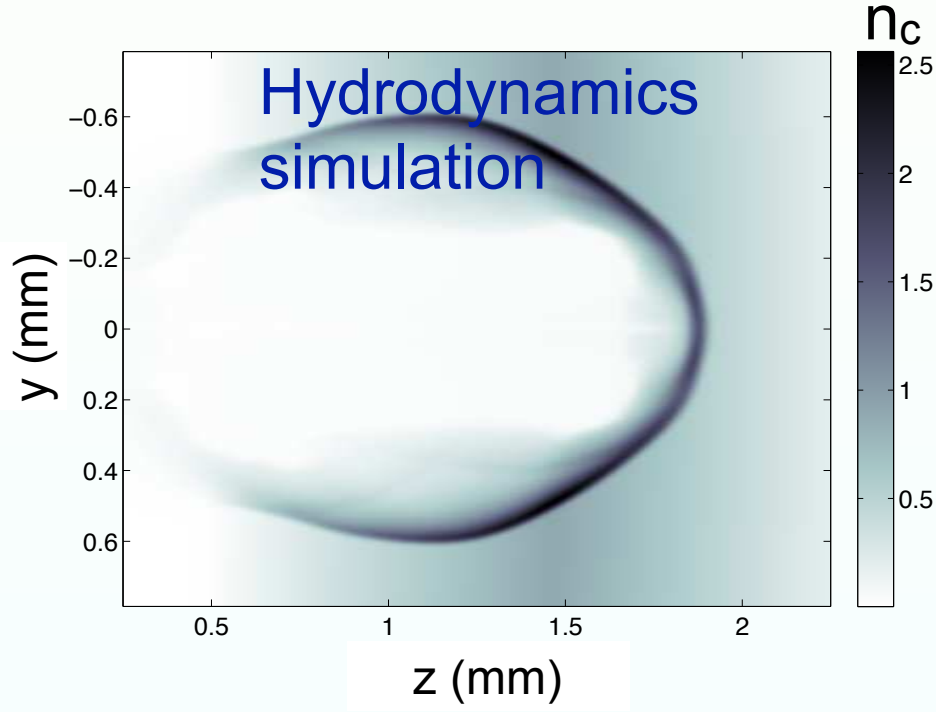
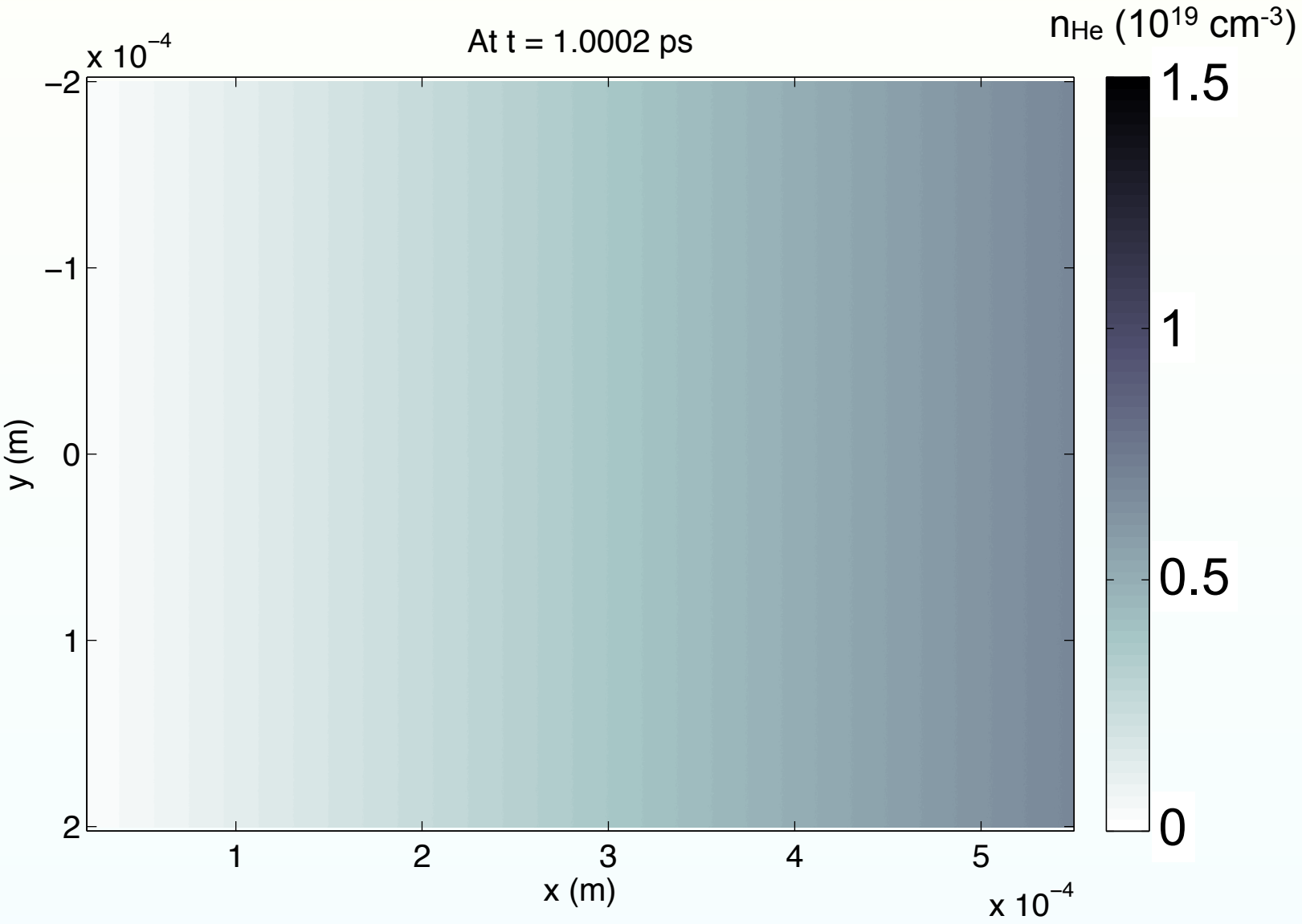




Main pulse interacts with steepened profile

2D PIC, no prepulse



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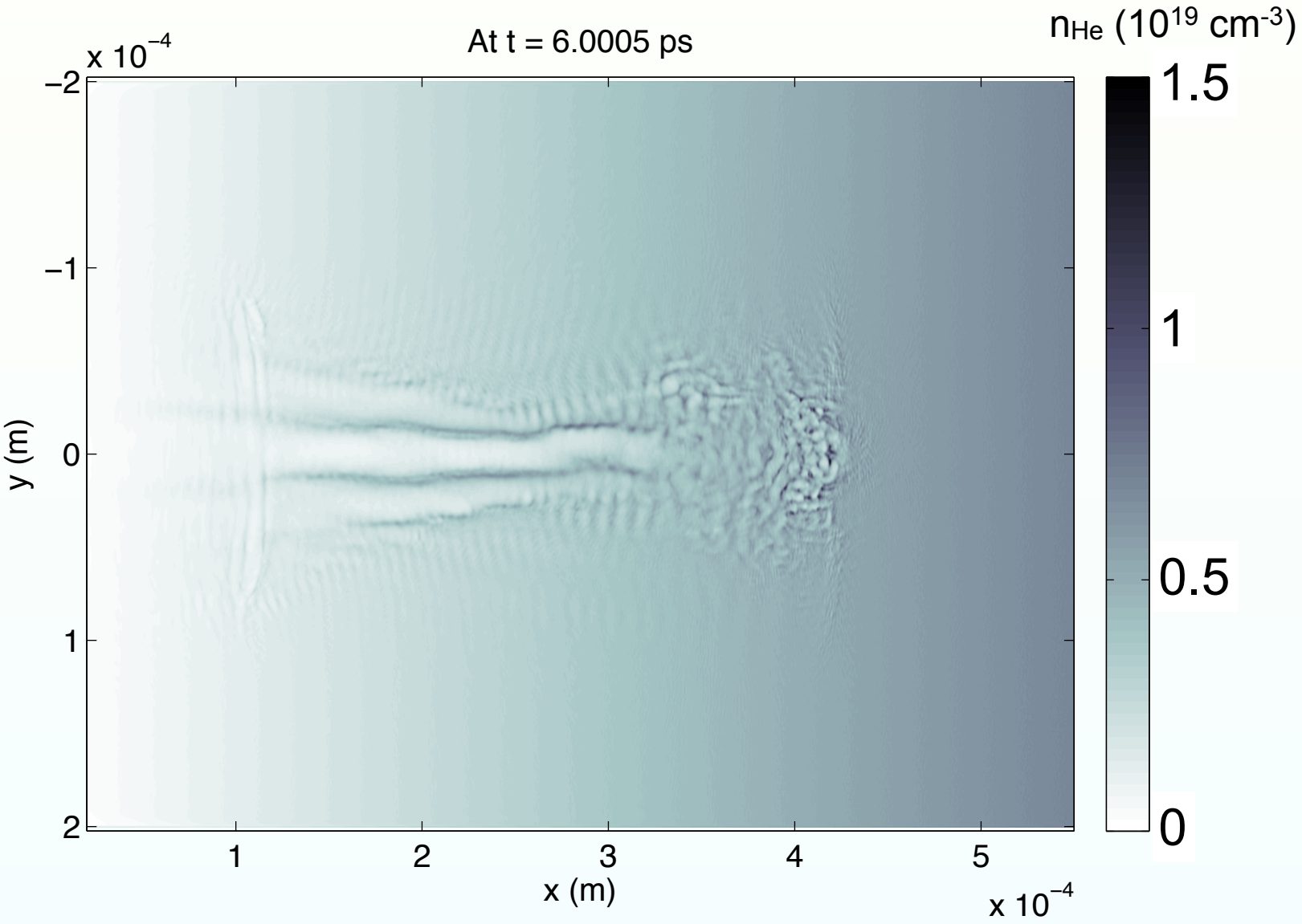

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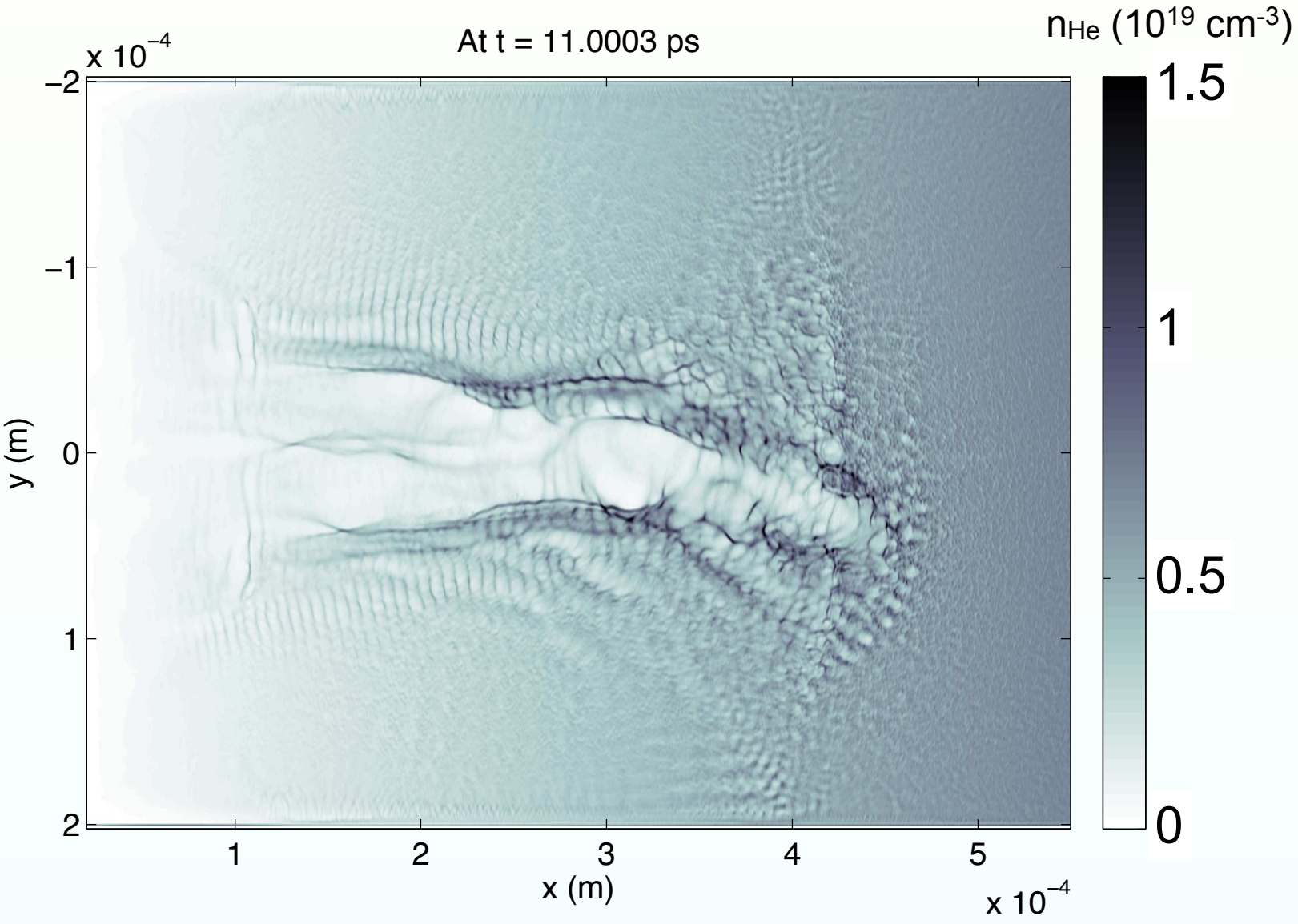

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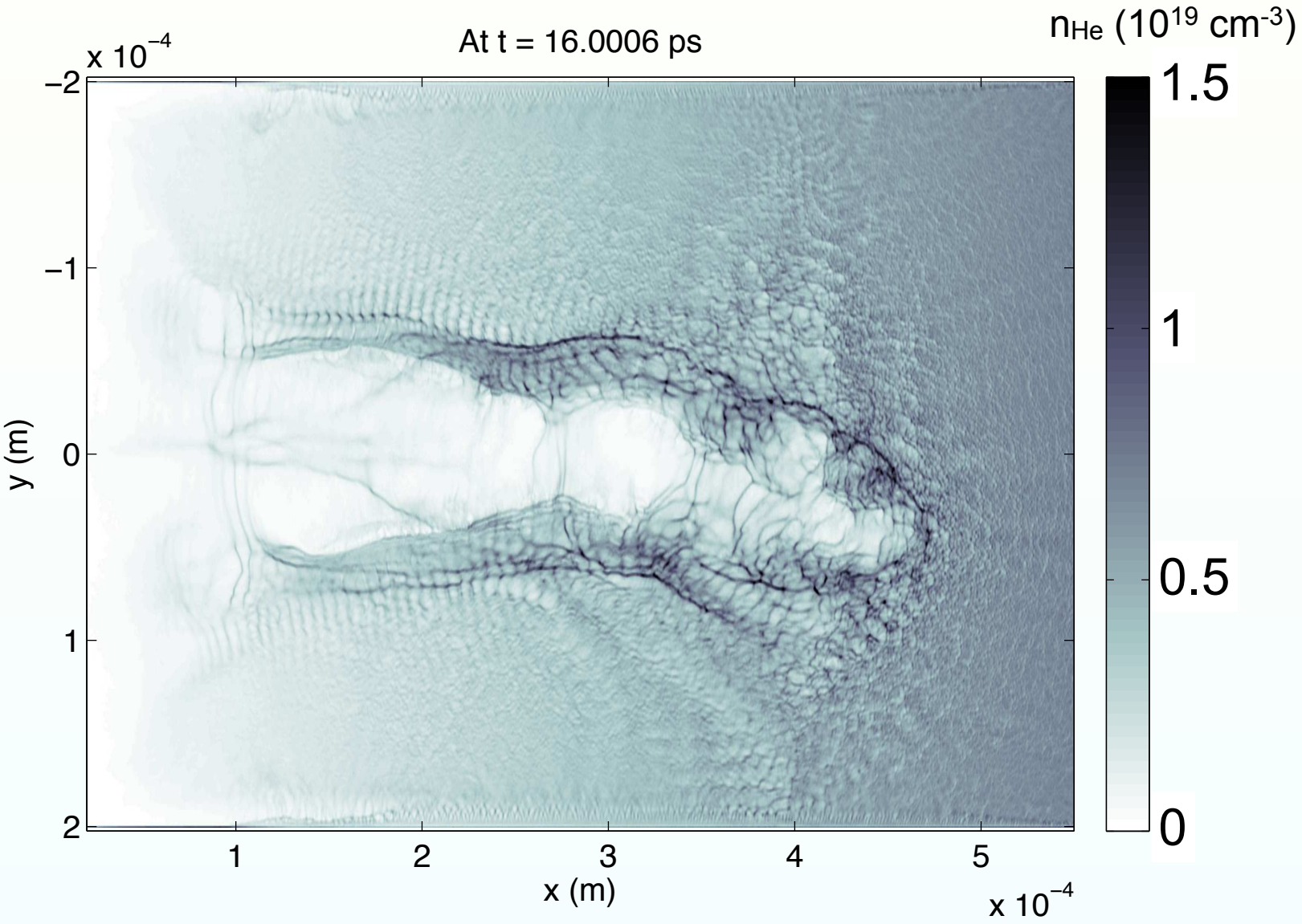

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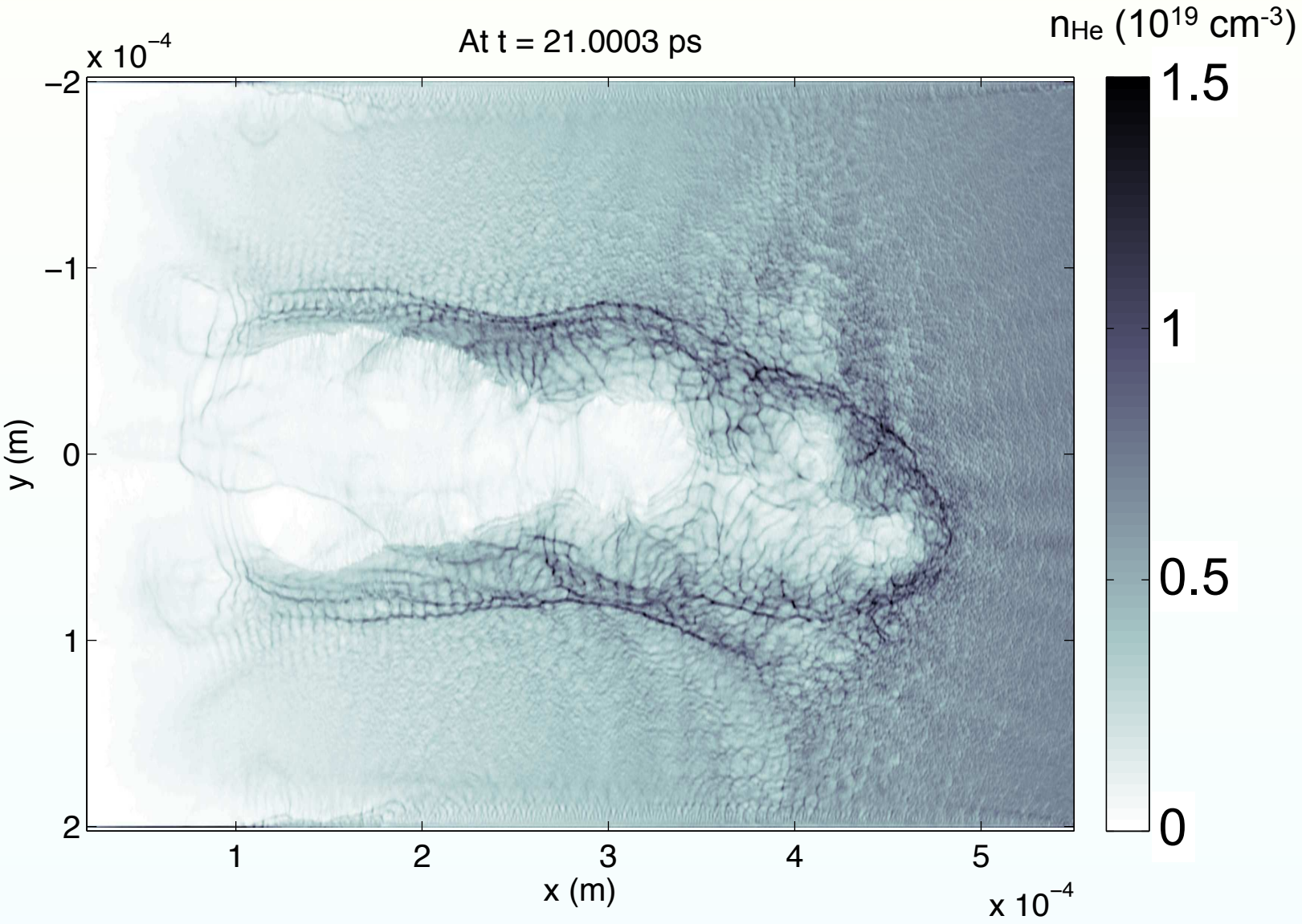

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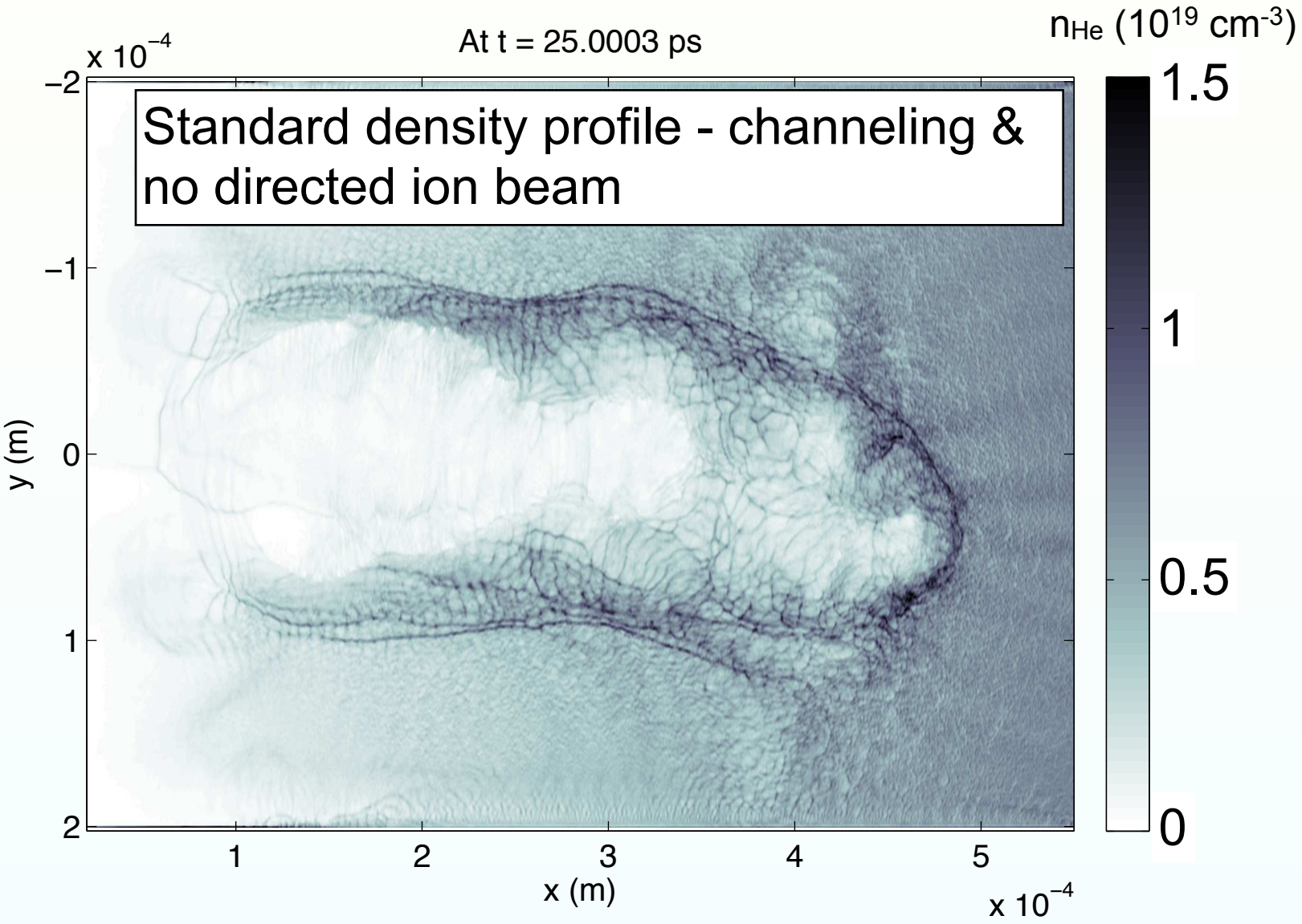
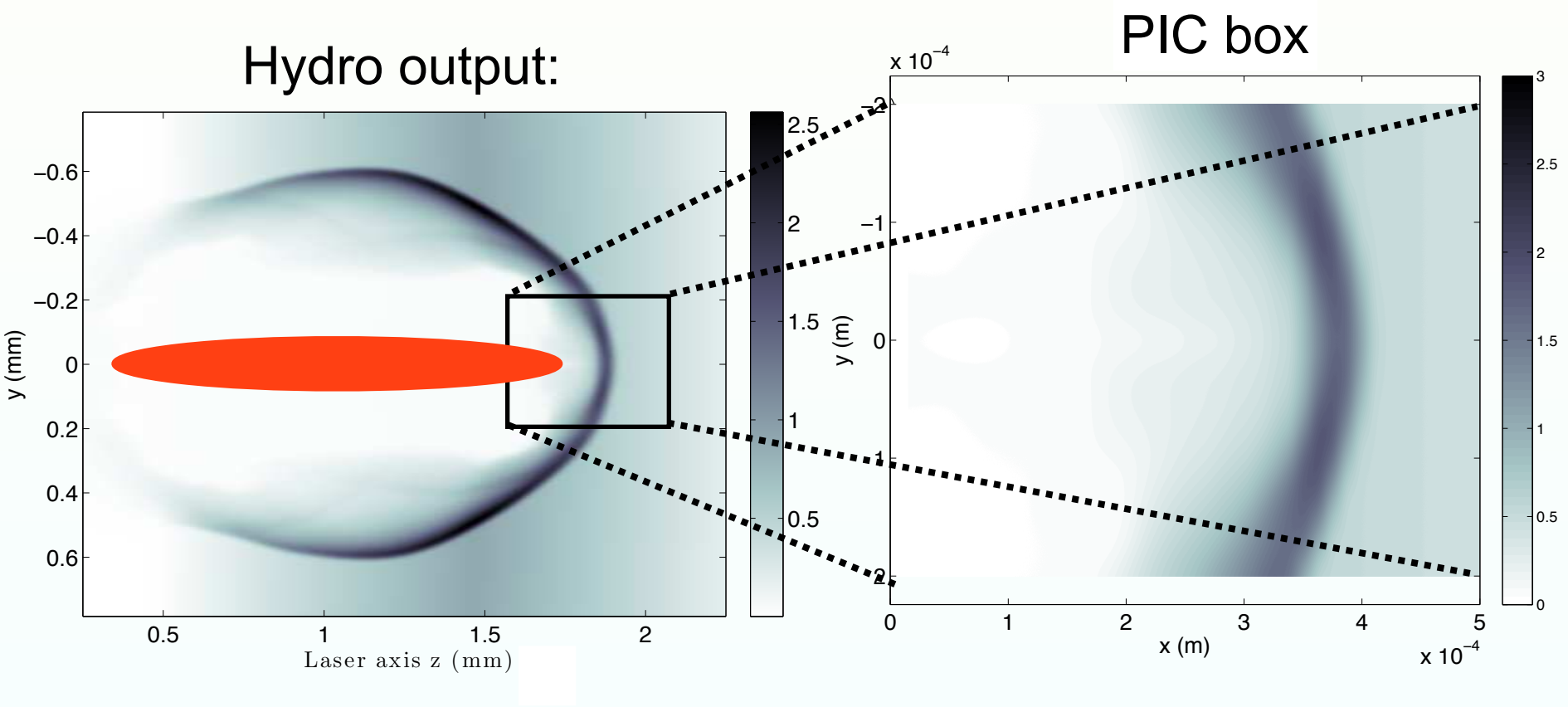


2D PIC with prepulse



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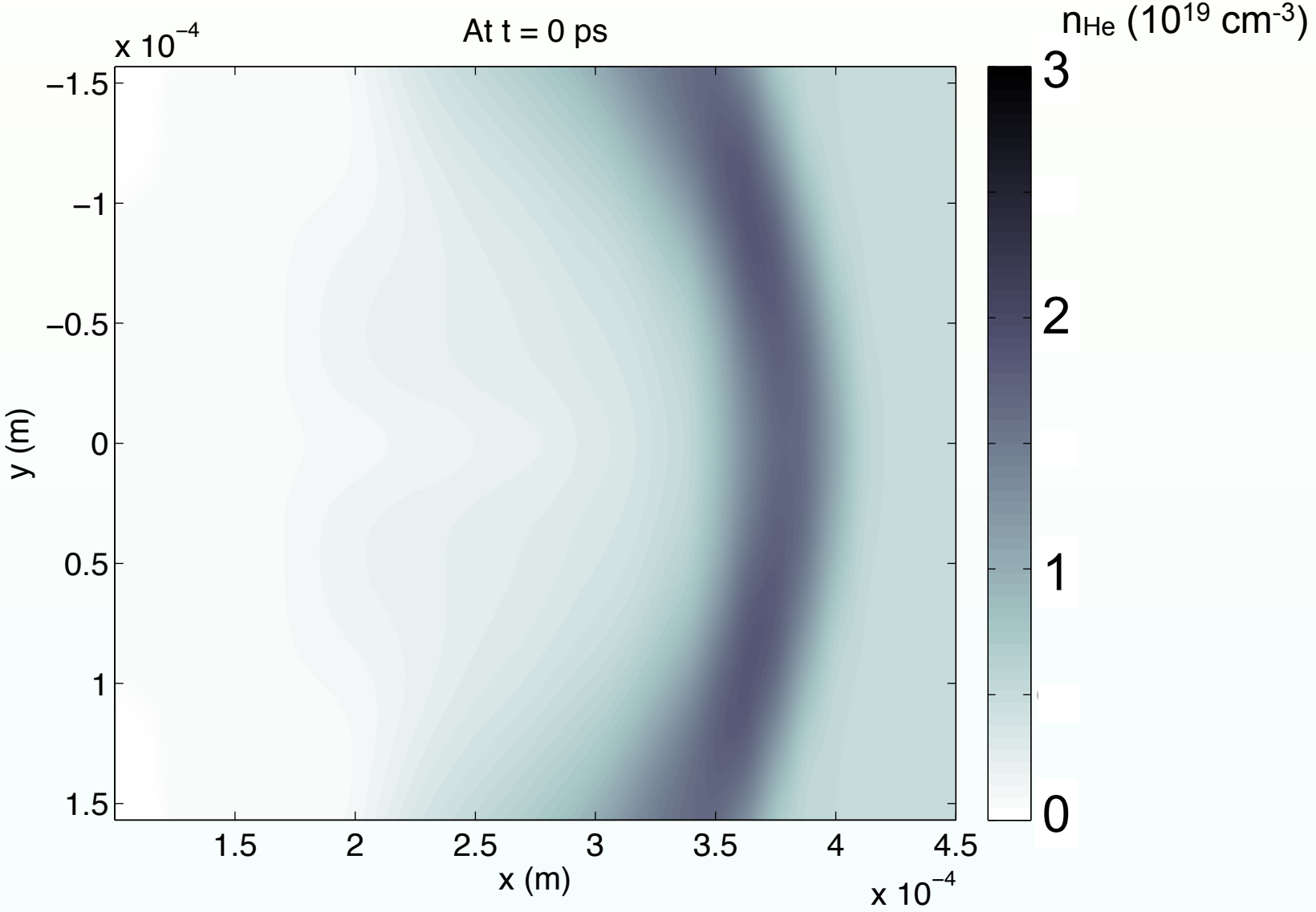

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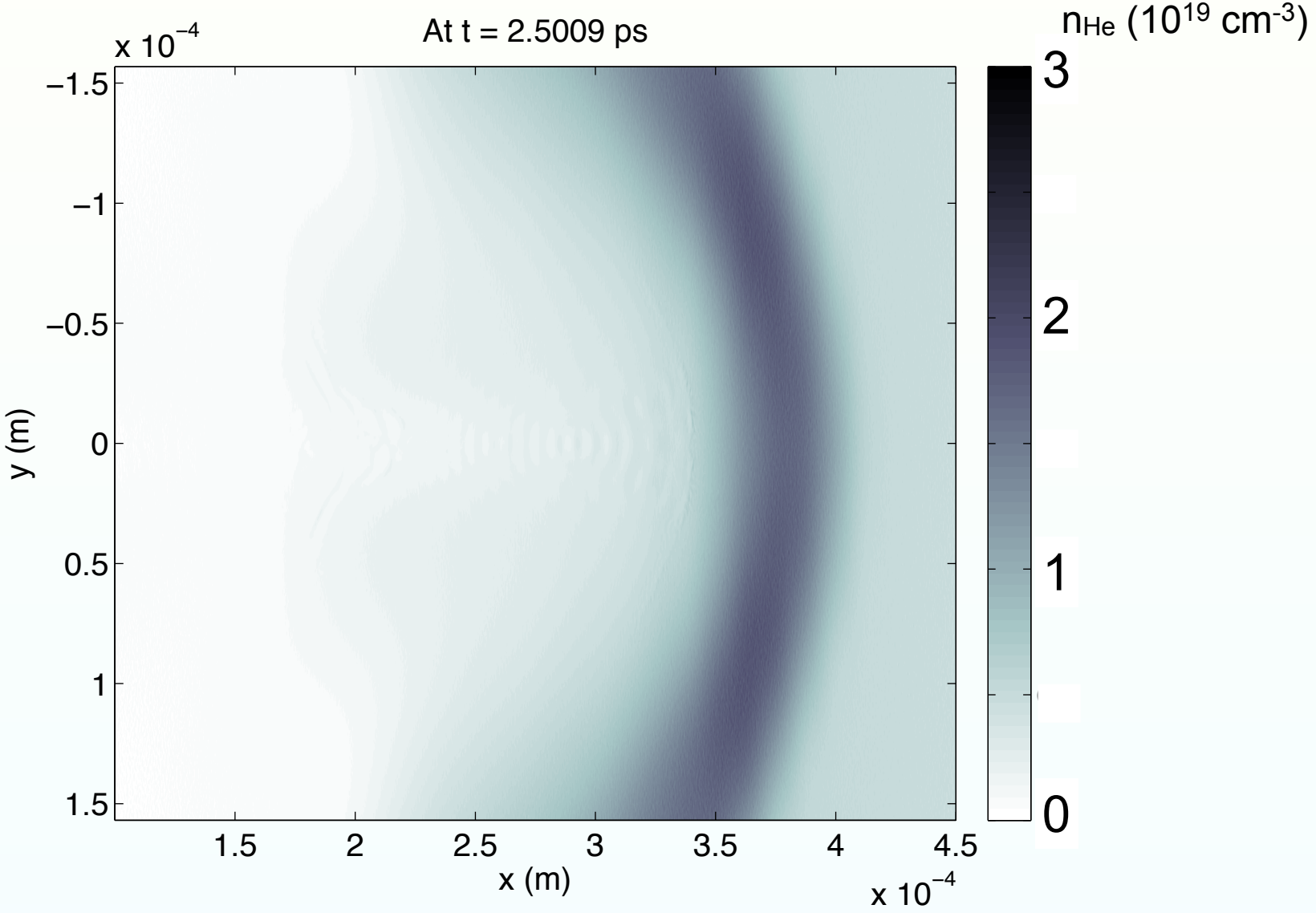

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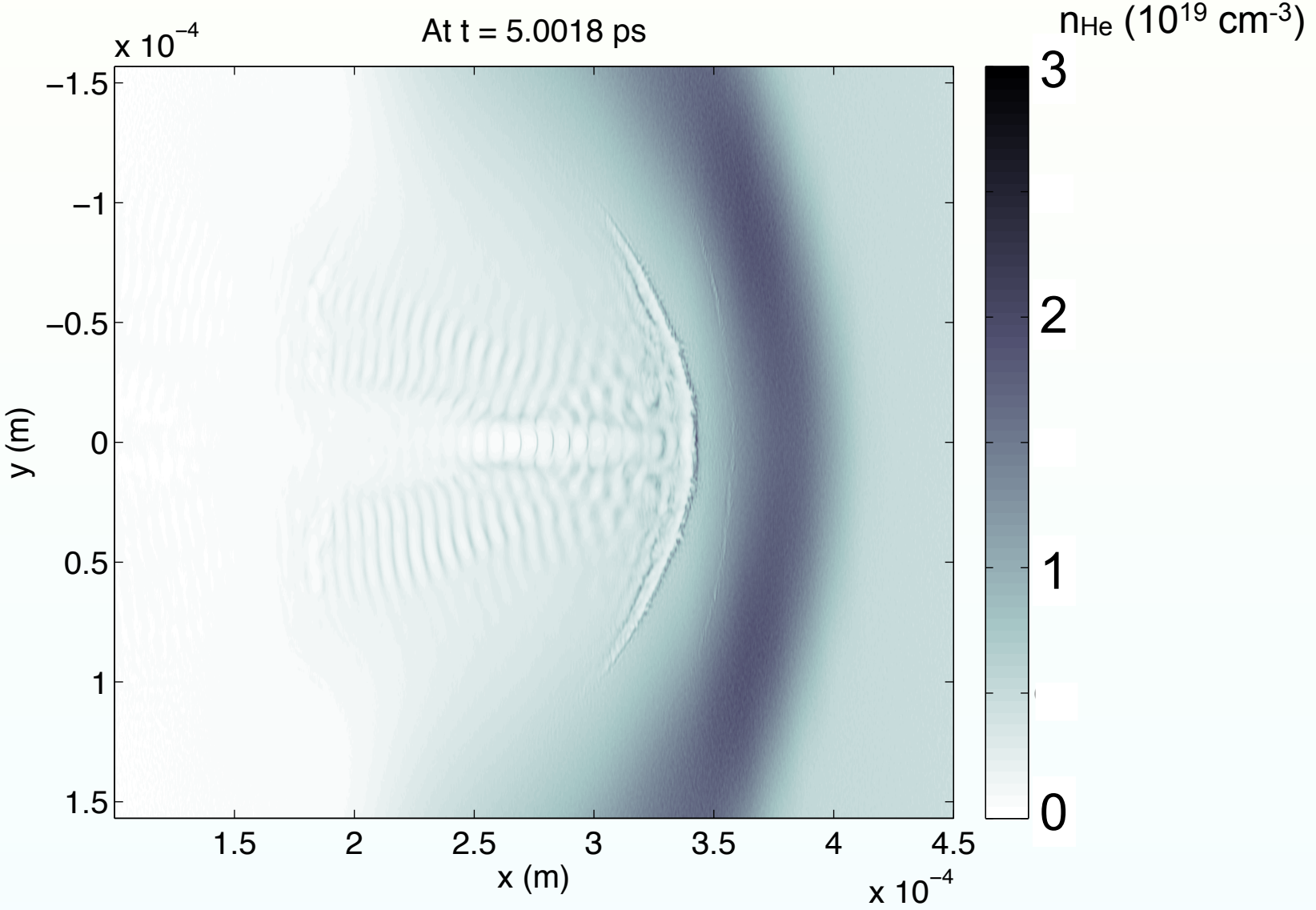

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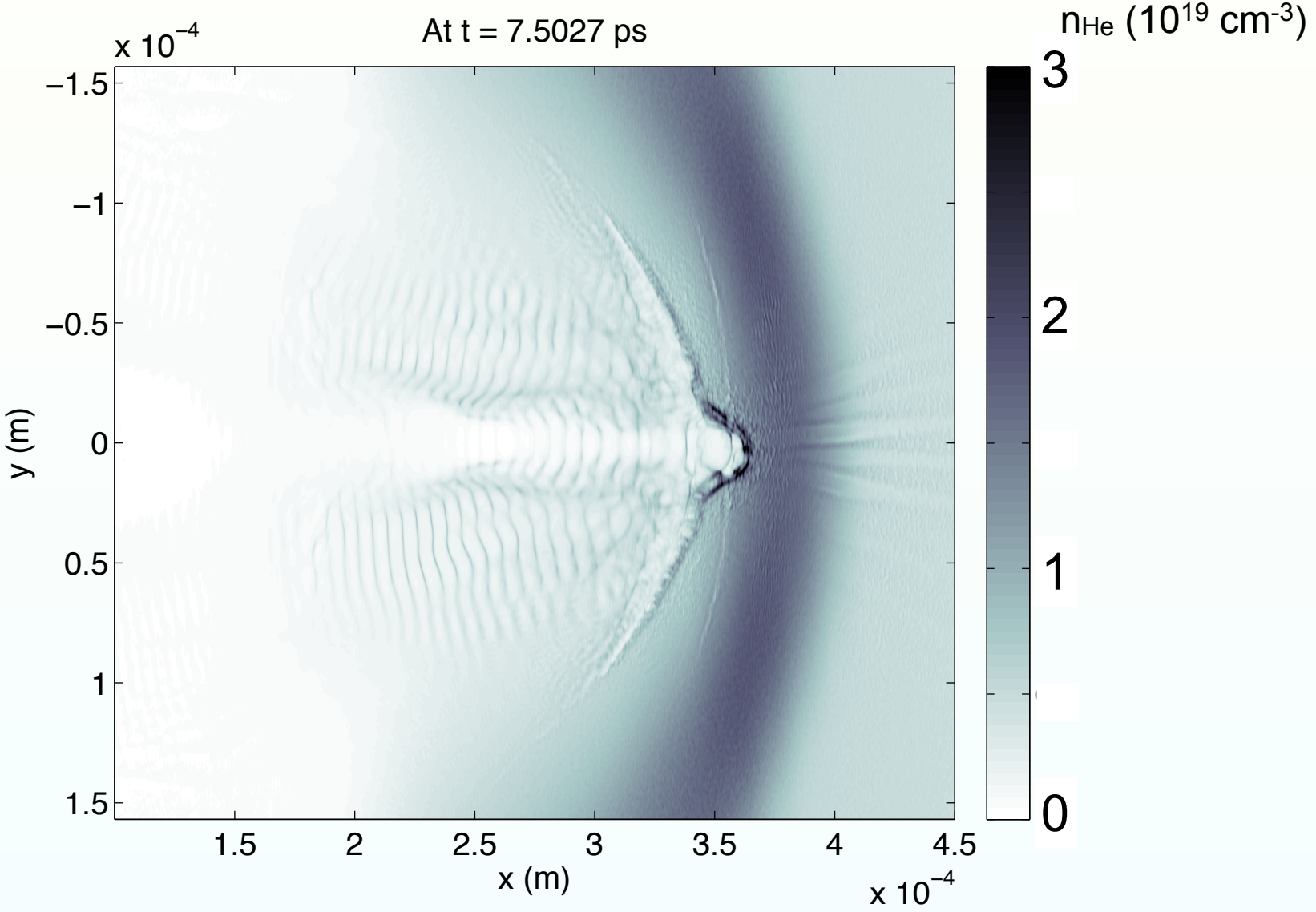

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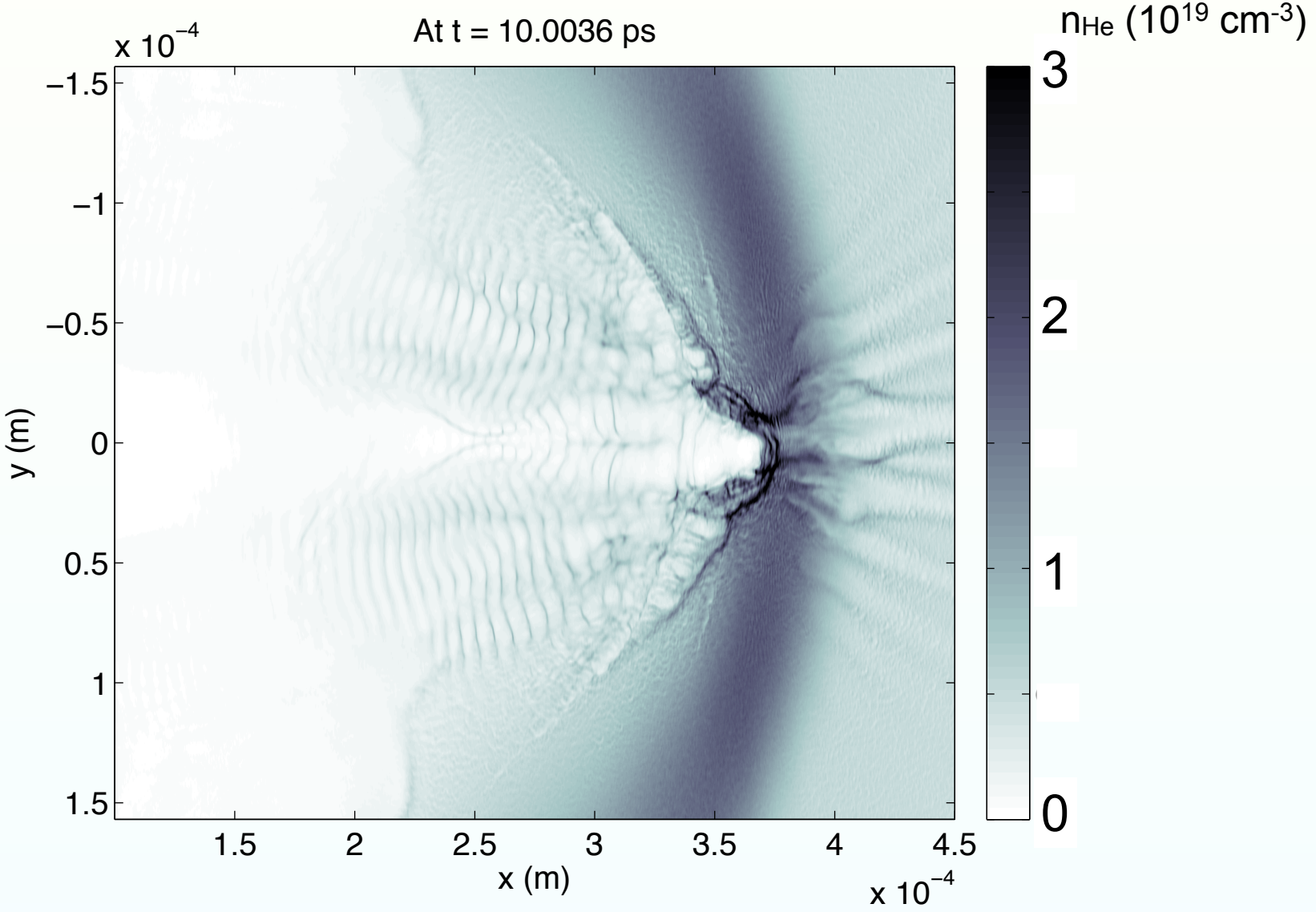

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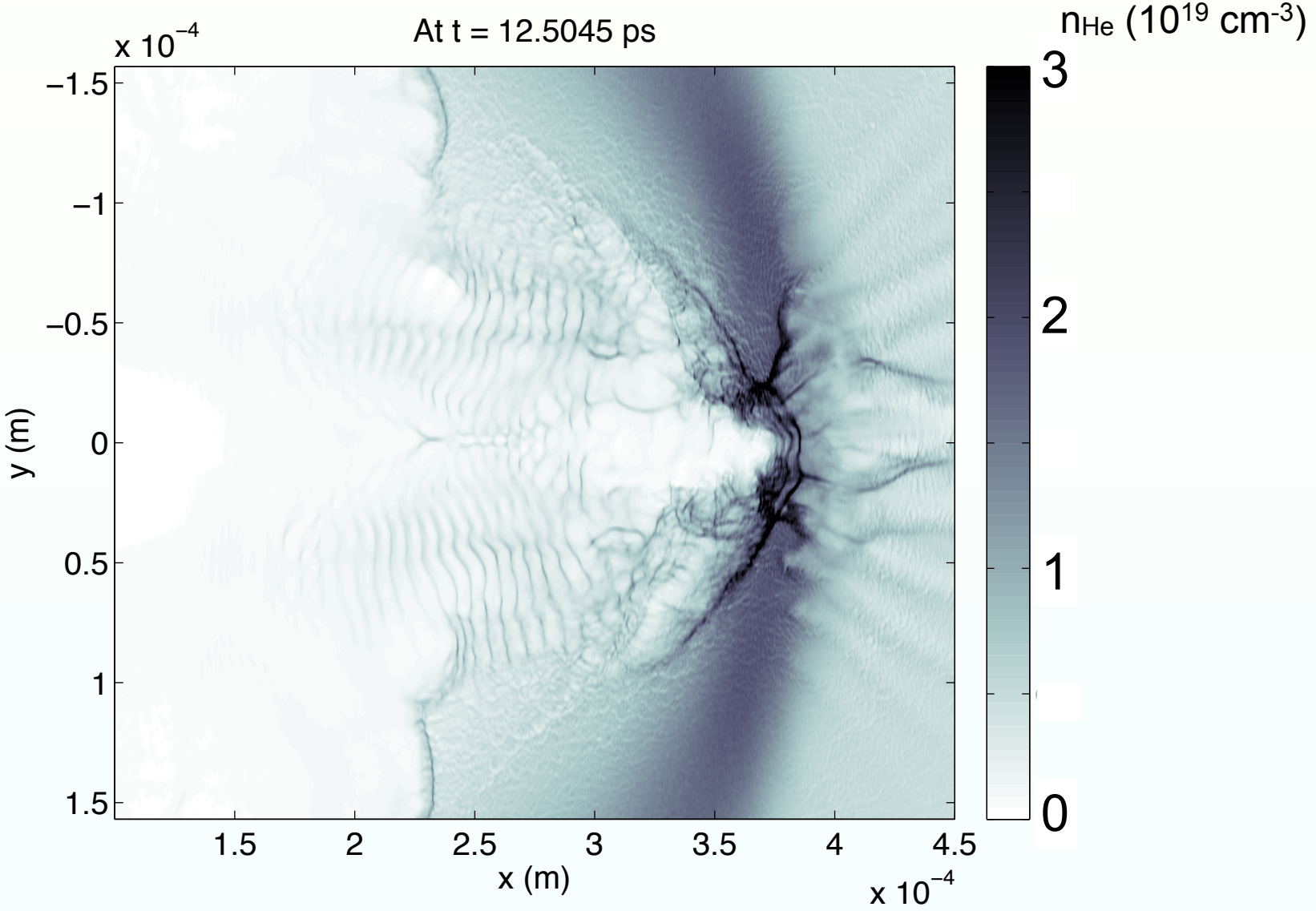

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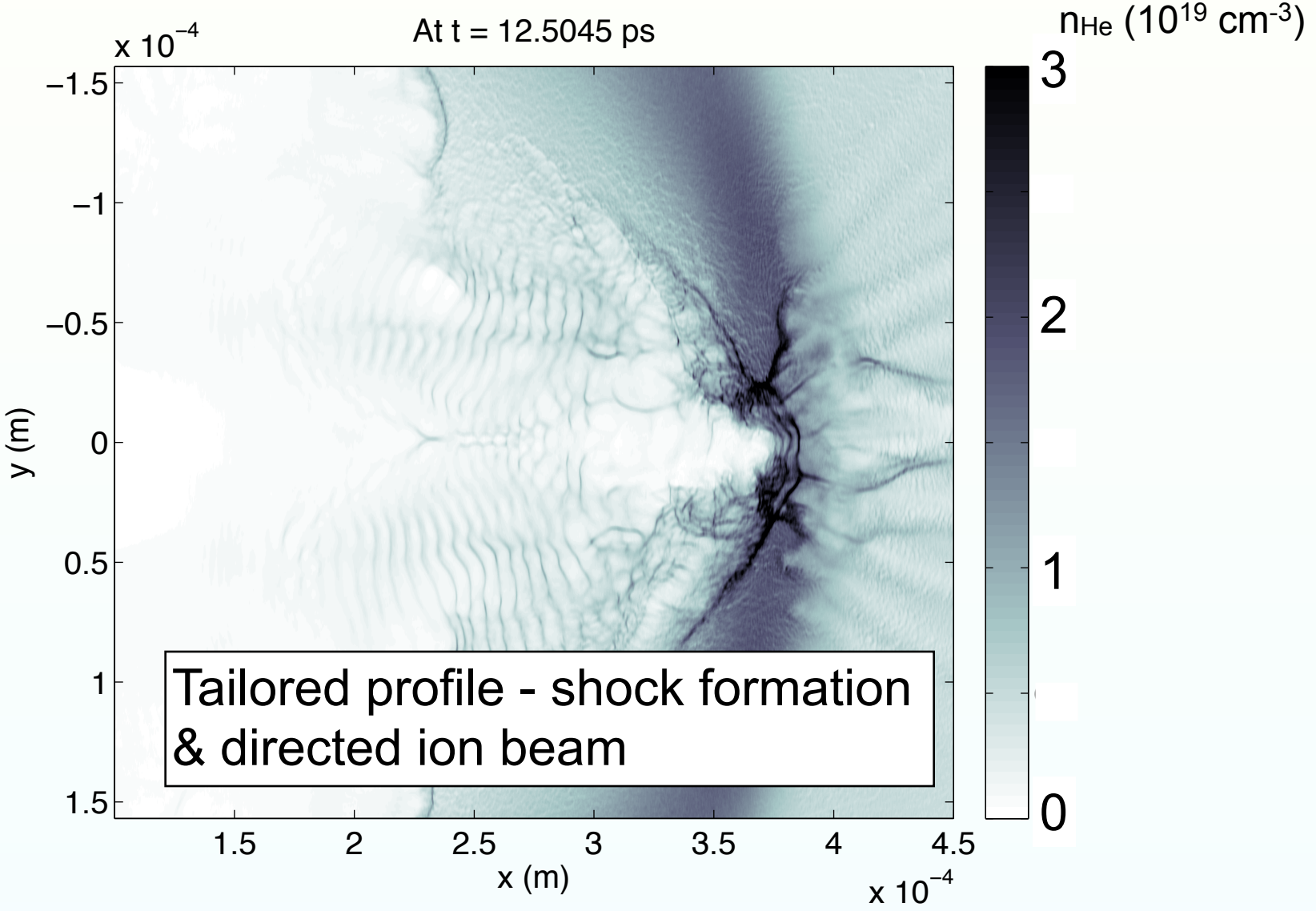
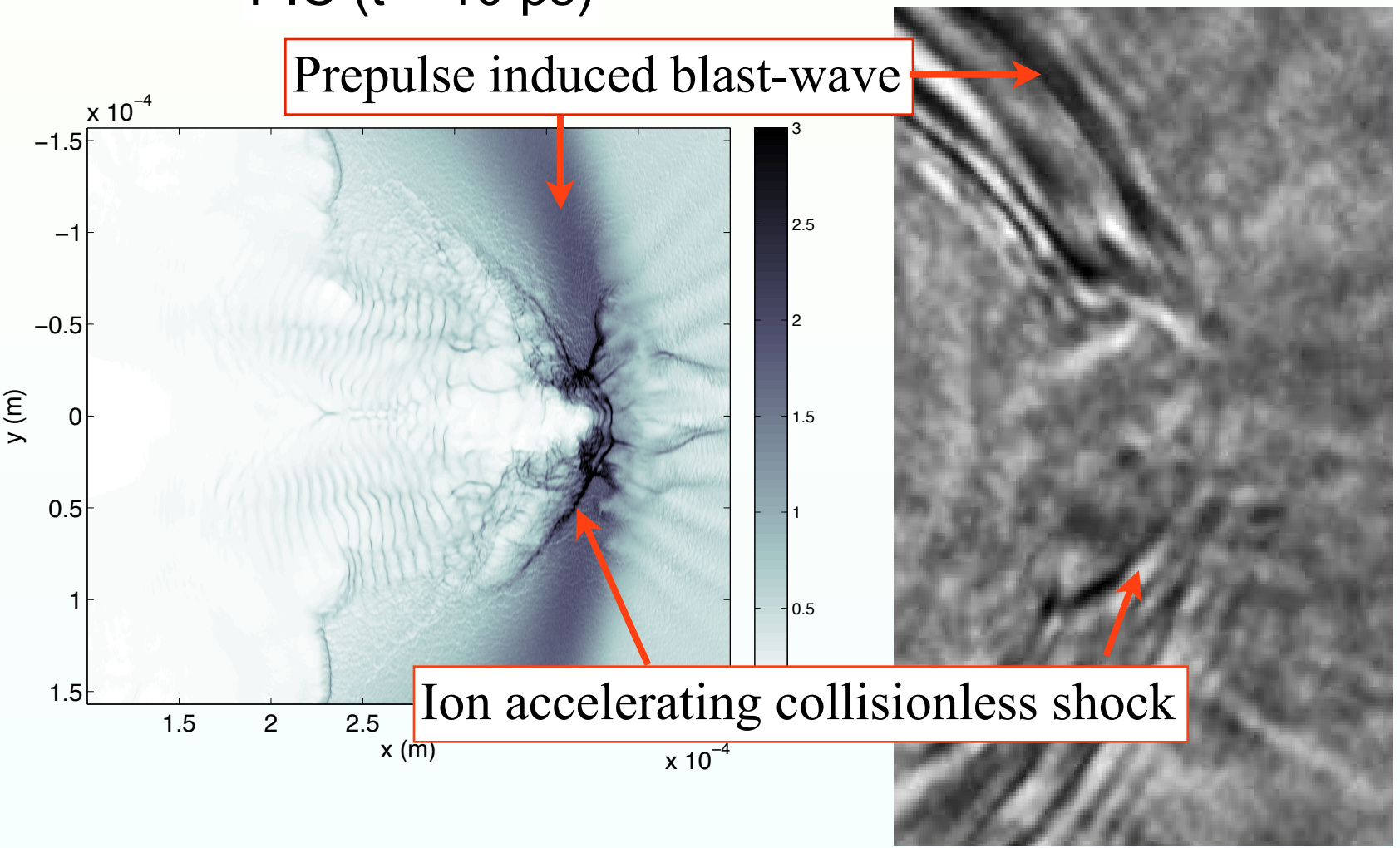


PIC shows agrees with experiment

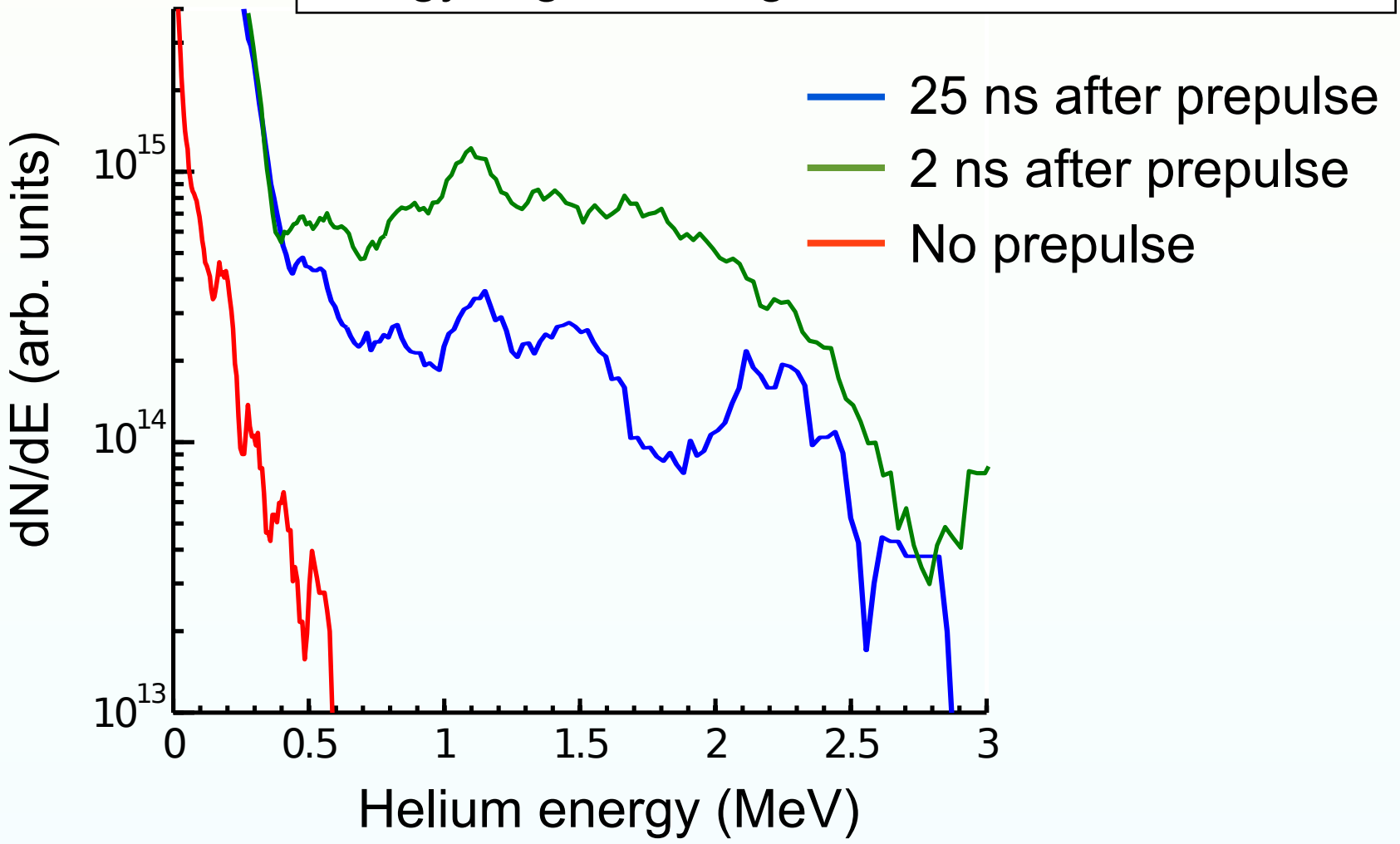
PIC (t ~ 10 ps)

Experiment (t ~ 100 ps)



Can change beam by profile optimisation

Density profile optimisation to generate high energy, higher charge beams



Future for shockwave acceleration

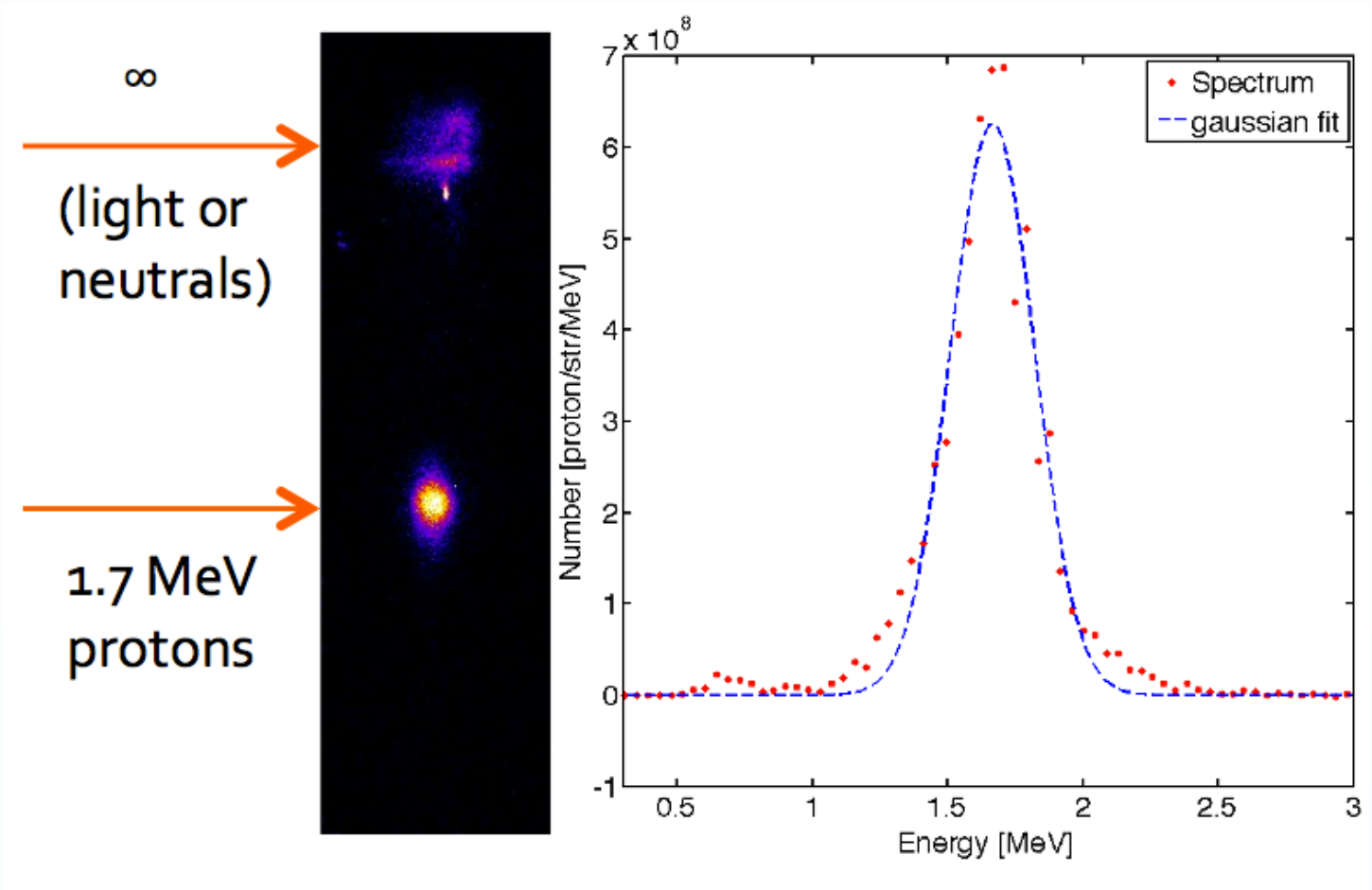
- Development of high power CO_2 lasers
  - '100 TW' CO_2 laser upgrade at ATF2:
    - Completed: Solid state OPA front end
      - 10 J in < 2 ps
    - Funded: New amplifier chain, CPA & frequency chirping:
      - higher energy output (>35 J),
      - higher repetition rate (10 Hz)
      - 500 fs pulse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

Summary

- Experimental demonstration of proton and helium beams from shock acceleration in gas jet targets
- Novel technique of all-optical shaping of overdense gas target using secondary pulse
- Optimising density profiles *essential* for ion generation

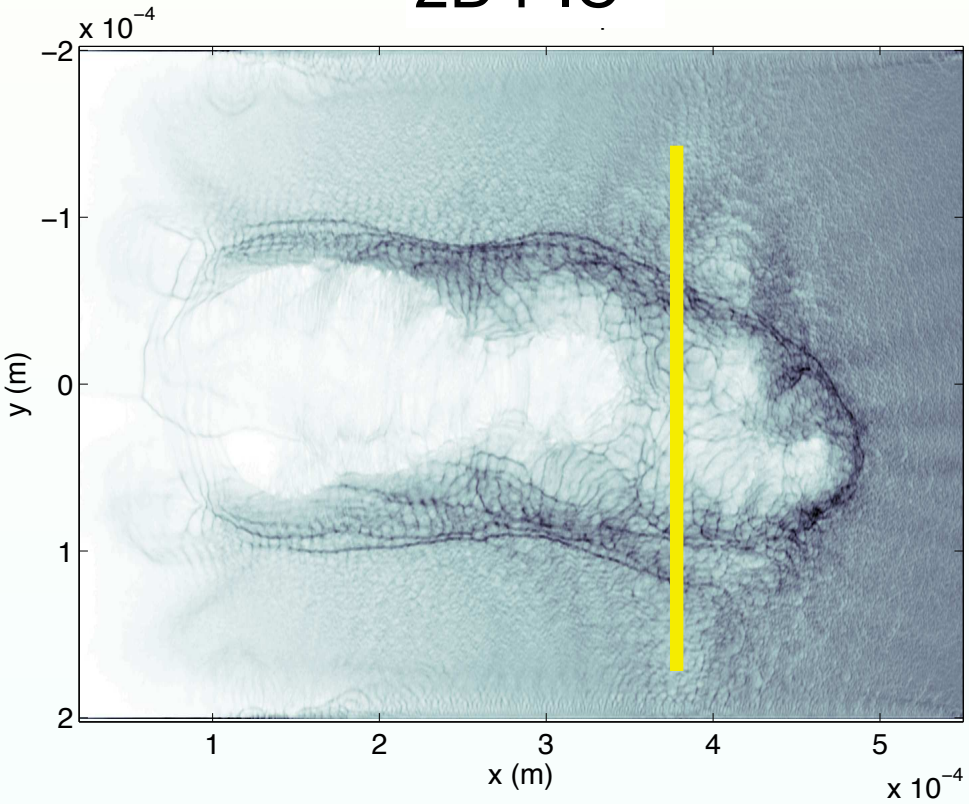
Further work on proton beams

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

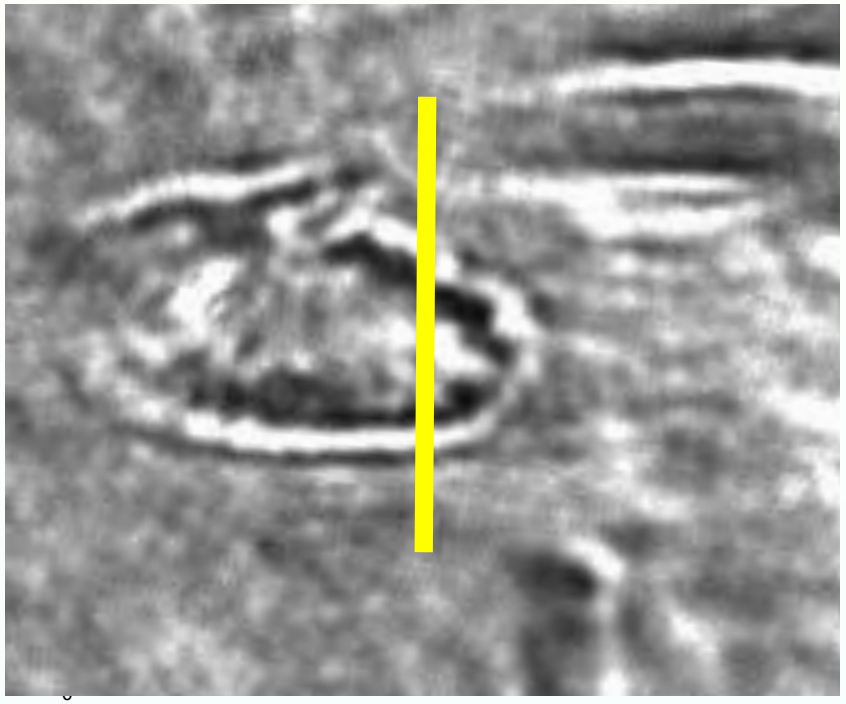


2D PIC, no prepulse

2D PIC

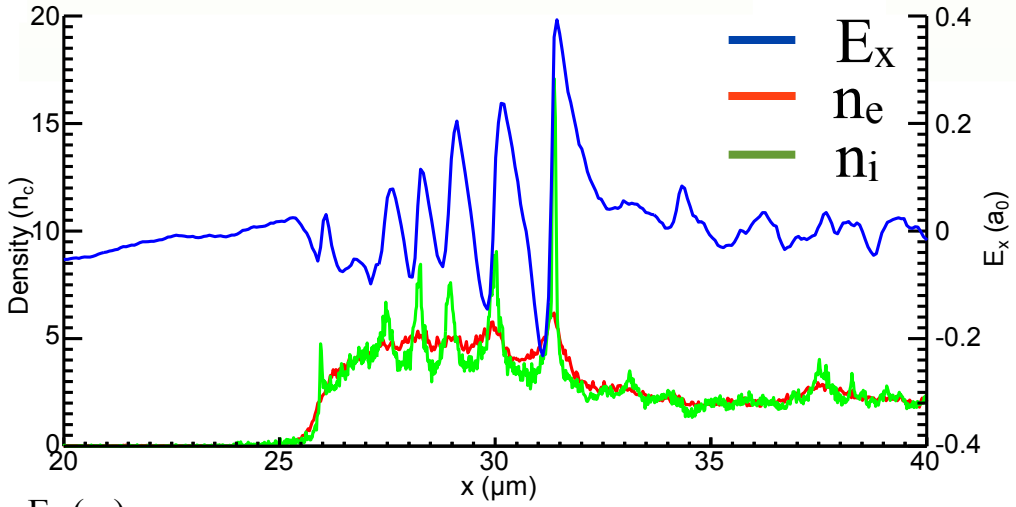


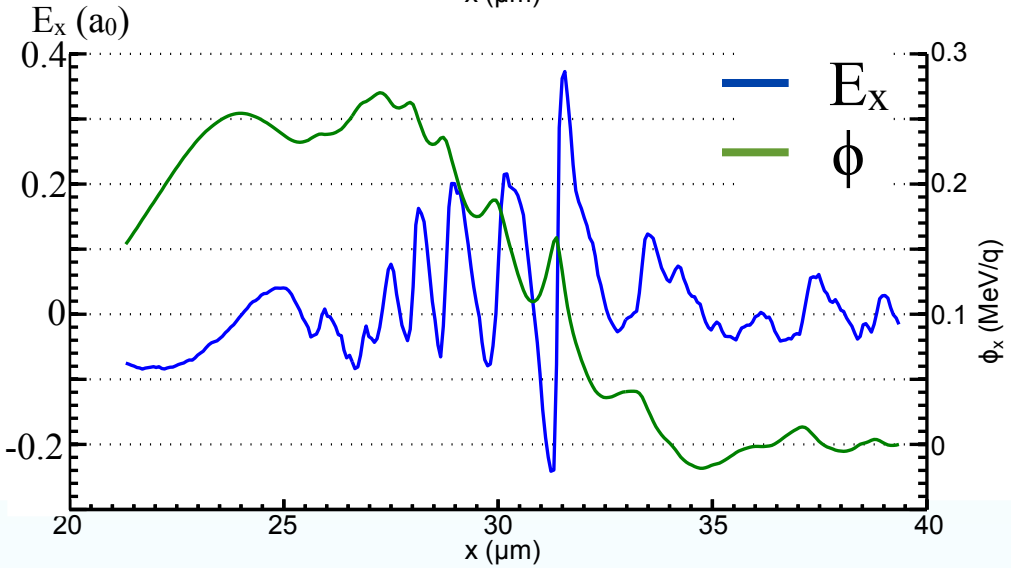
Experiment



Numerical PIC simulations

- Lineouts through centre of box

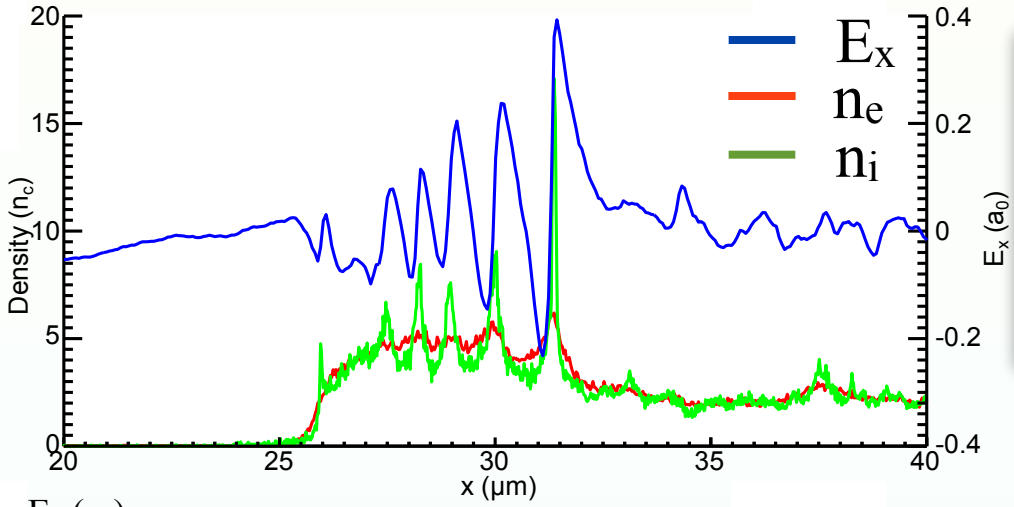


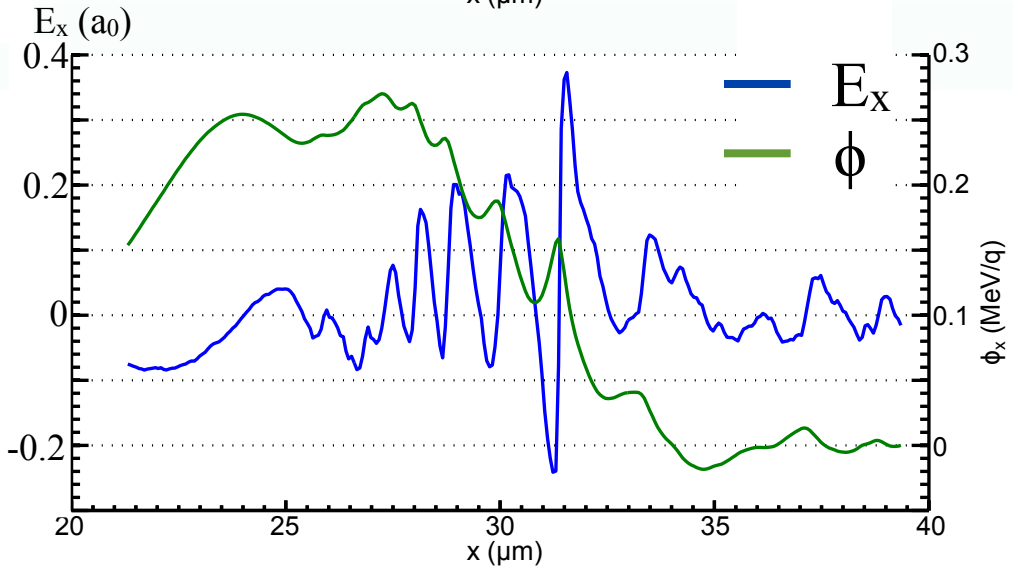


c)

Numerical PIC simulations

- Lineouts through centre of box



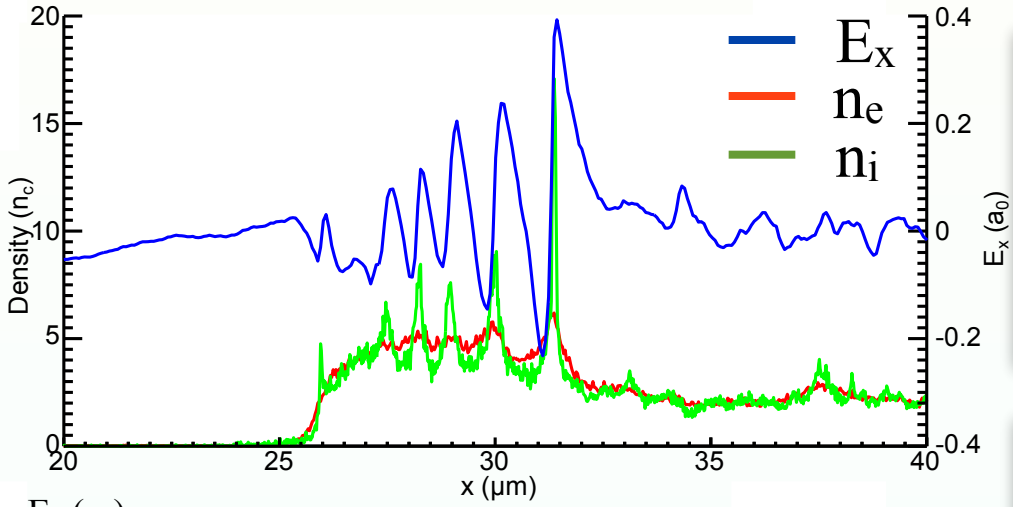


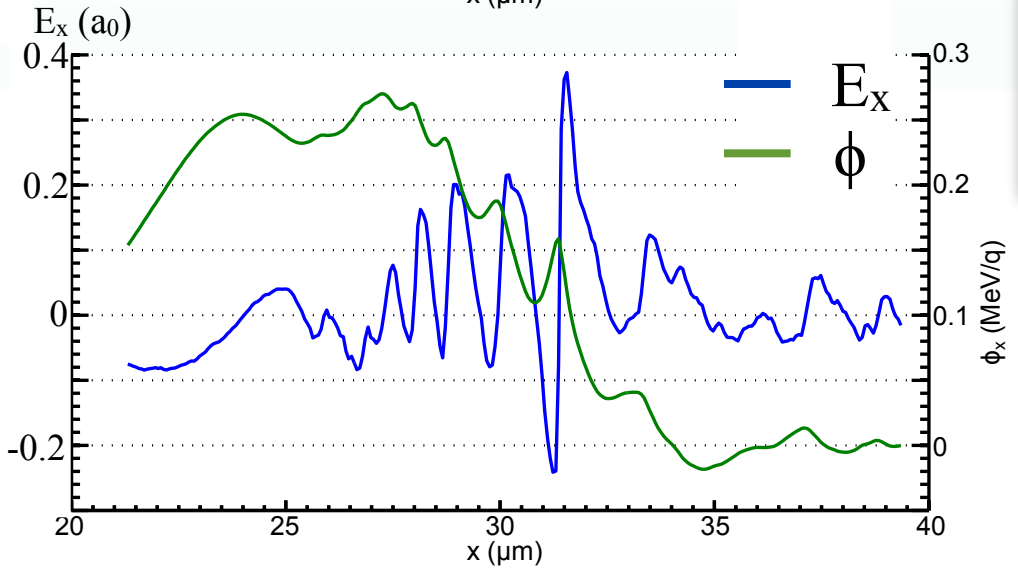
c)

Typical of **electrostatic collisionless shock** - a plasma shock driven by non-linear sound waves in hot plasma

Numerical PIC simulations

- Lineouts through centre of box





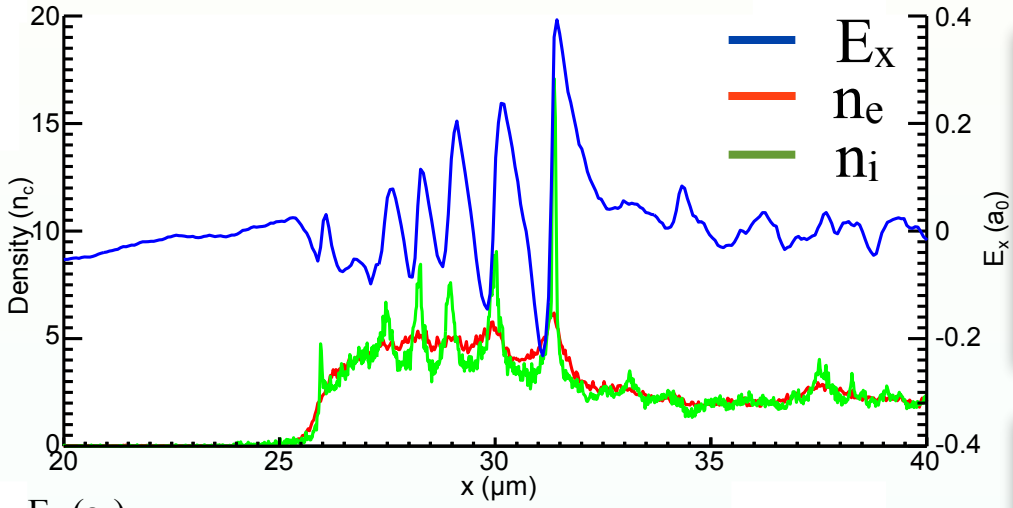
c)

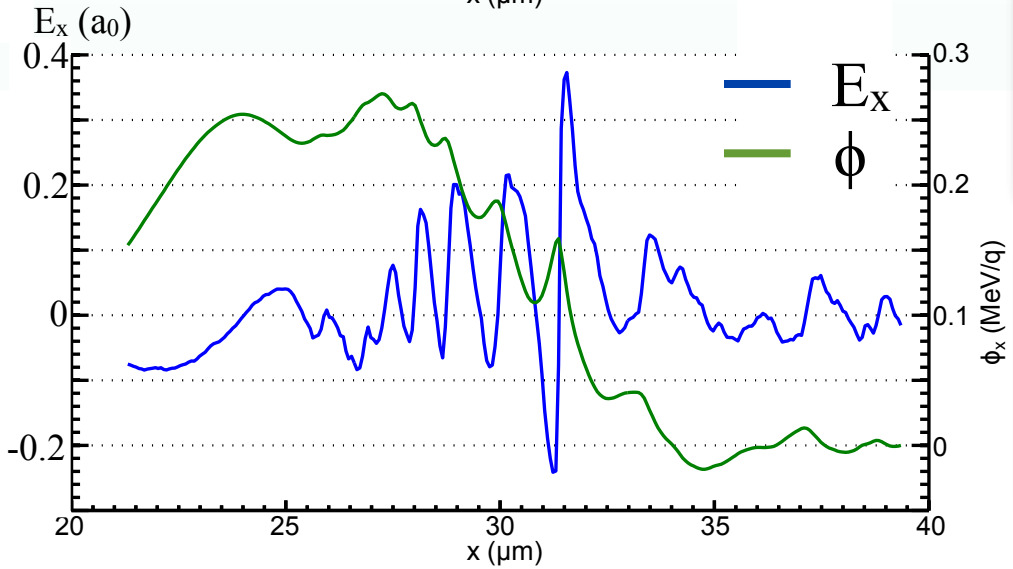
Typical of **electrostatic collisionless shock** - a plasma shock driven by non-linear sound waves in hot plasma

Hole-boring acts as piston driving **electrostatic collisionless shock wave**

Numerical PIC simulations

- Lineouts through centre of box





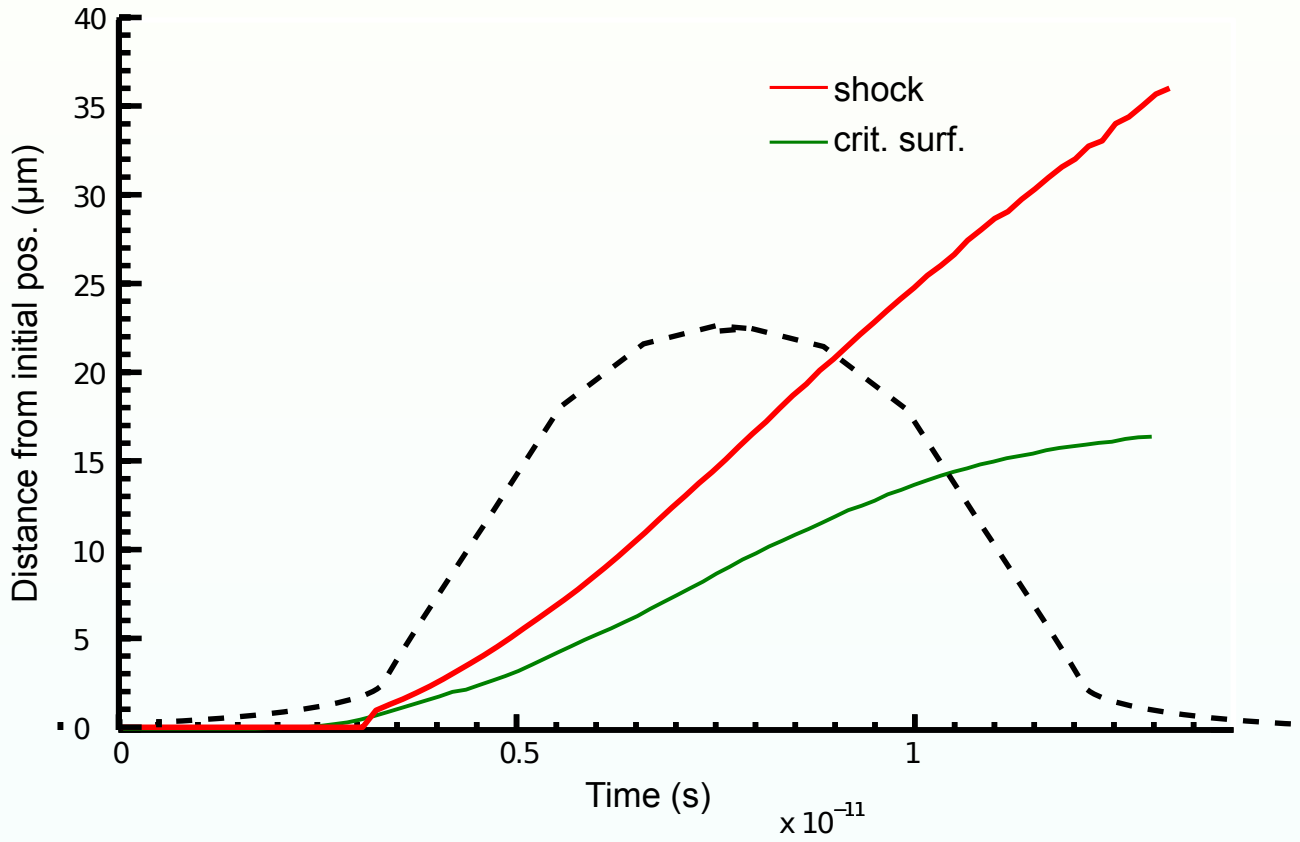
c)

Typical of **electrostatic collisionless shock** - a plasma shock driven by non-linear sound waves in hot plasma

Hole-boring acts as piston driving **electrostatic collisionless shock wave**

Protons are being accelerated by **reflection** at electrostatic **potential in shock**

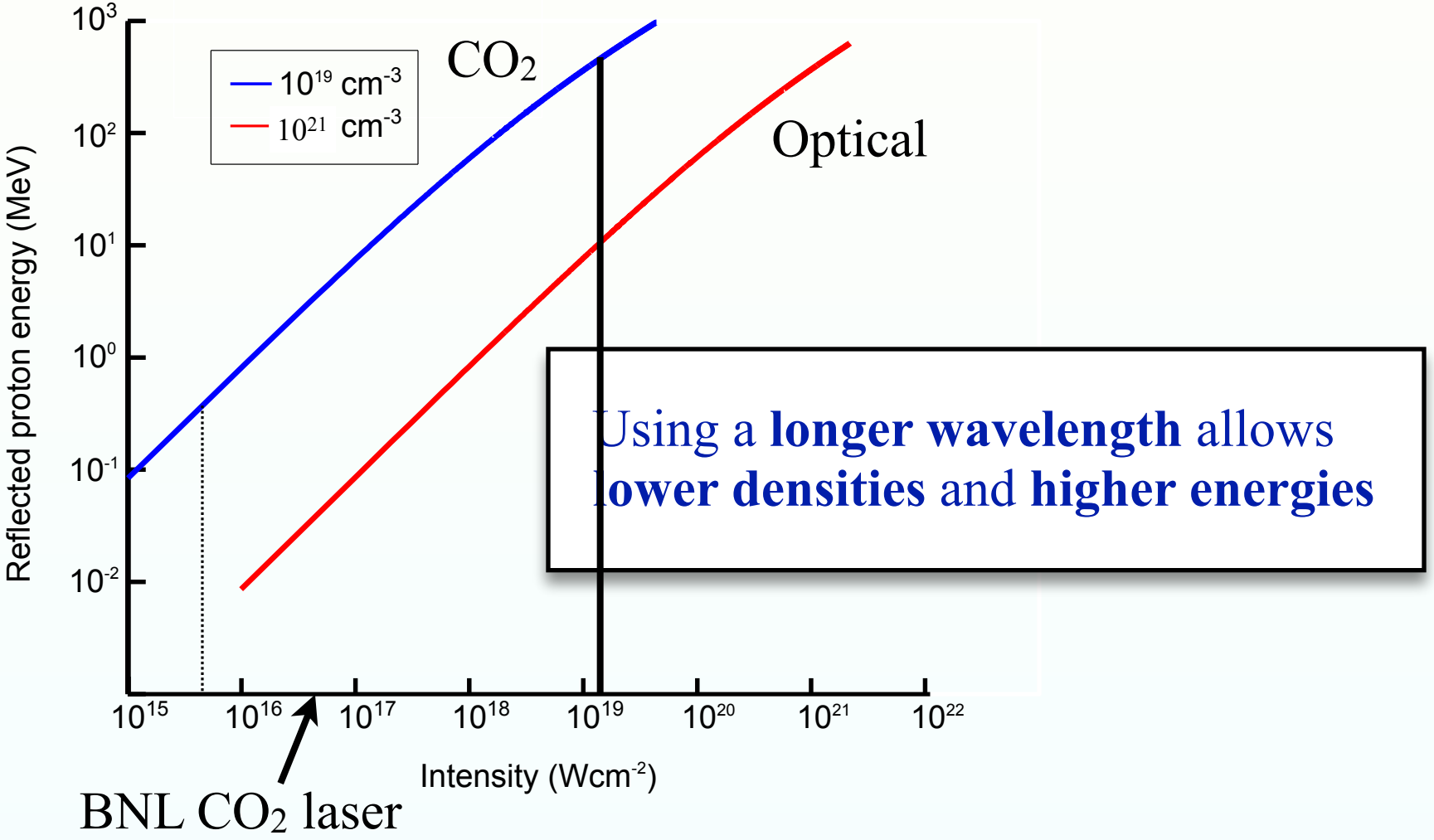
Numerical PIC simulations



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

Hole-boring scaling

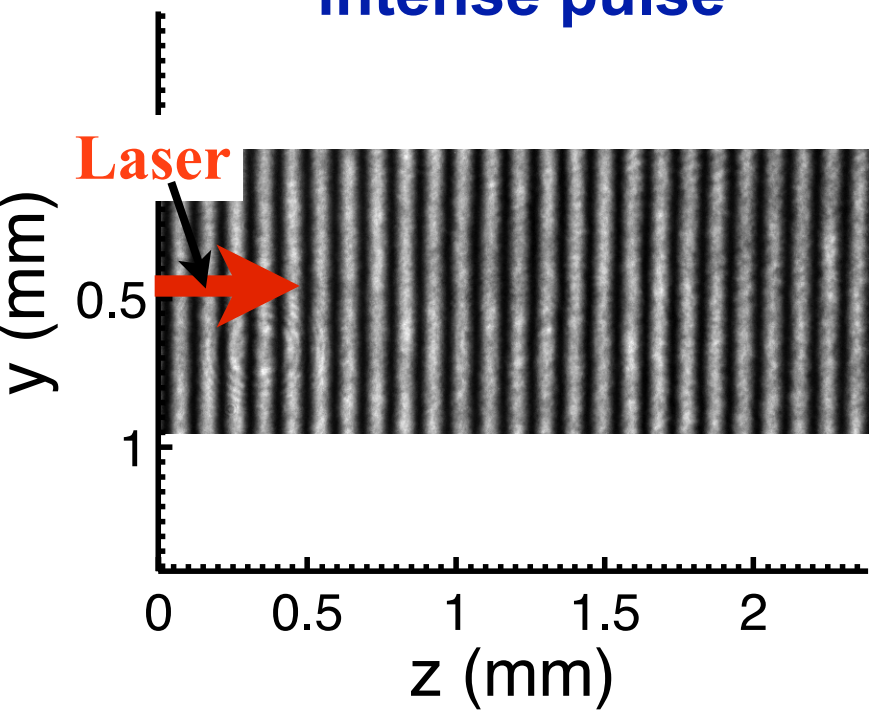
- Proton energy scaling with intensity



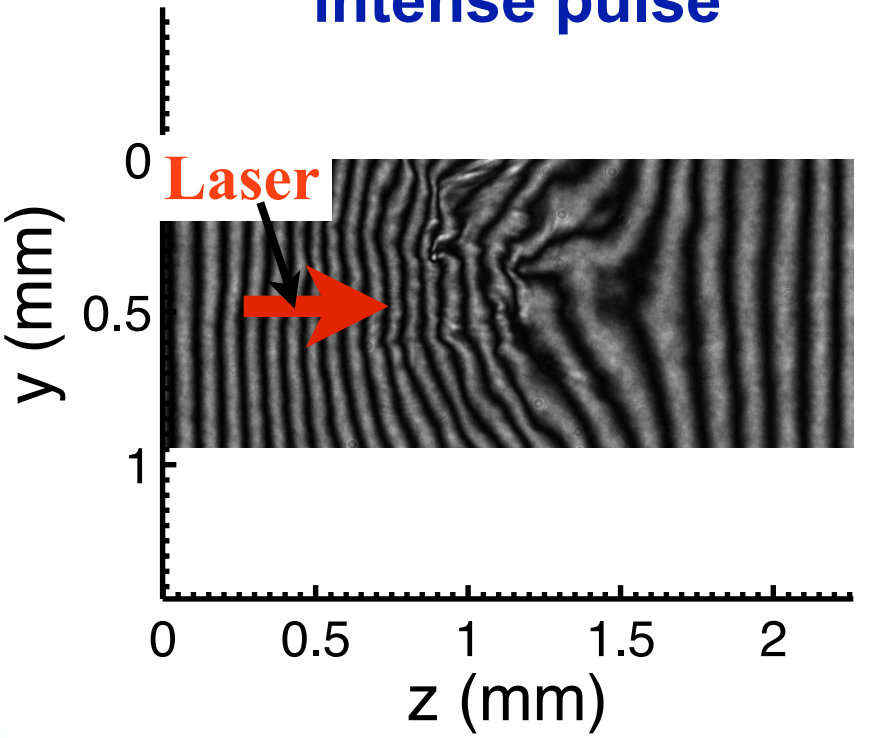
Using a **longer wavelength** allows **lower densities** and **higher energies**

Varying prepulse changes initial conditions

400 ps before intense pulse

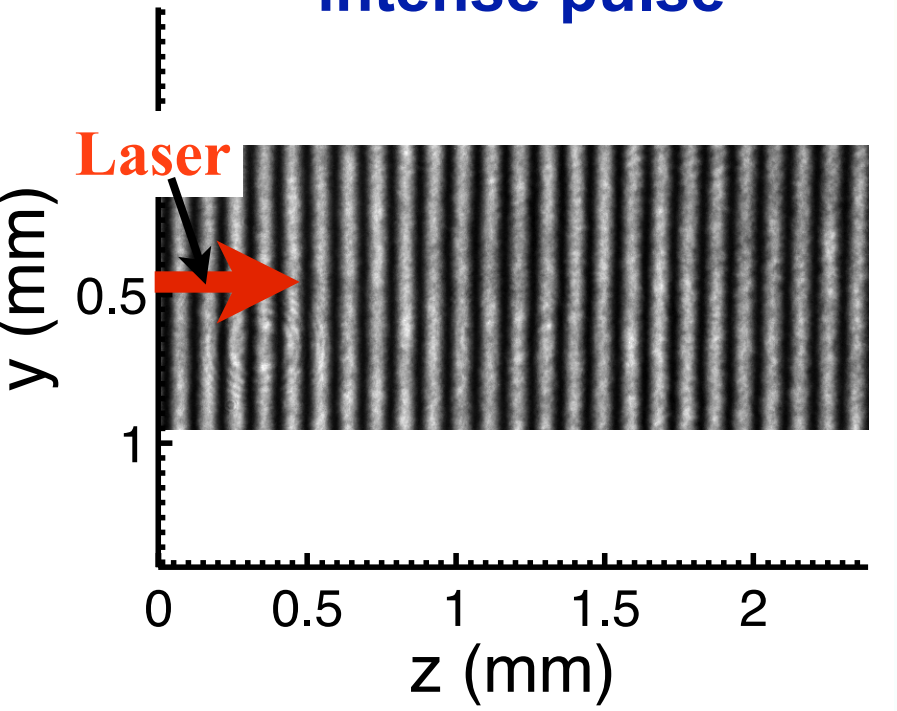


100 ps after intense pulse

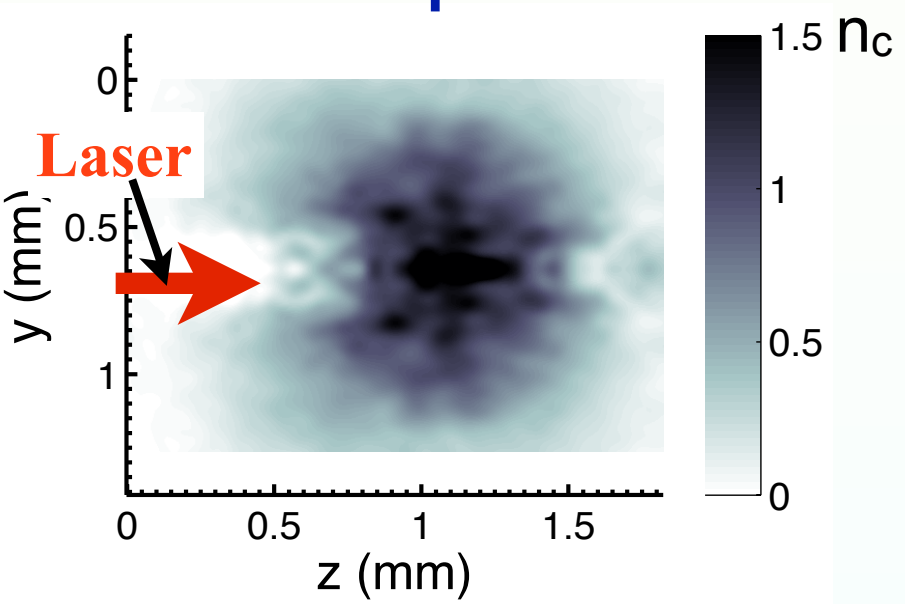


Varying prepulse changes initial conditions

400 ps before intense pulse



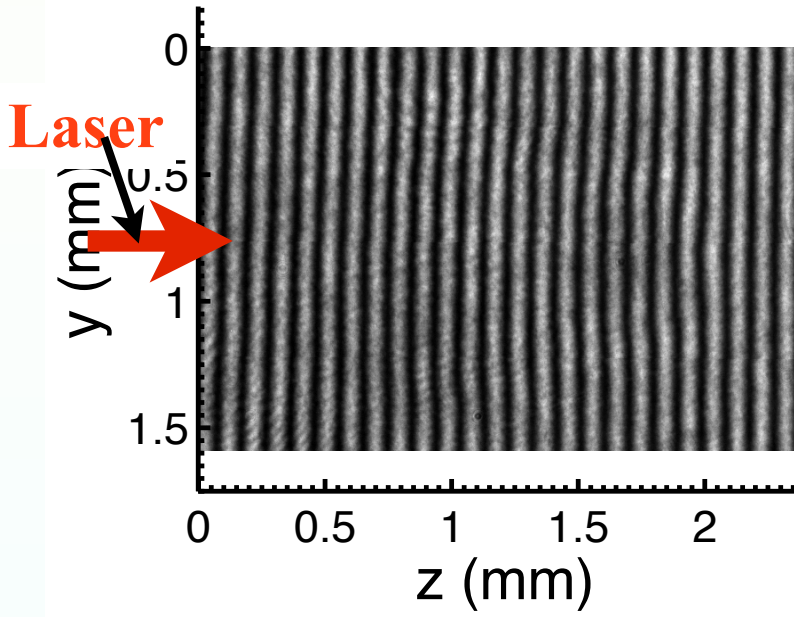
100 ps after intense pulse



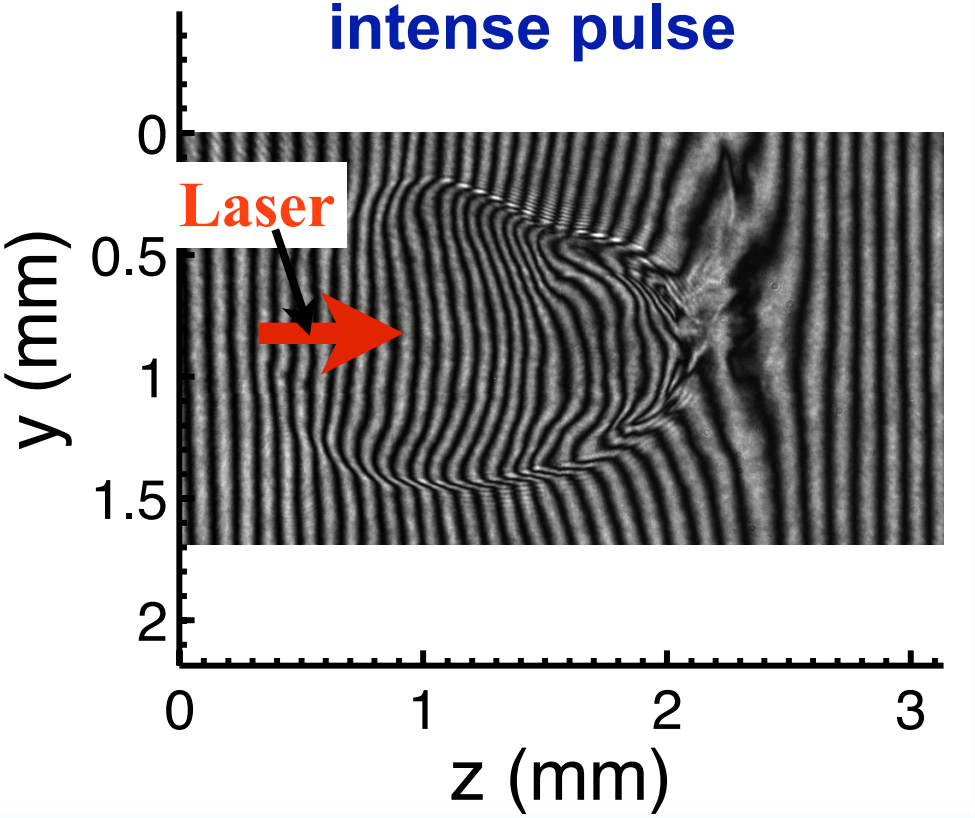
- No prepulse: intense pulse expends energy channeling up density ramp
  - **No ion acceleration!**

Varying prepulse changes initial conditions

400 ps before intense pulse

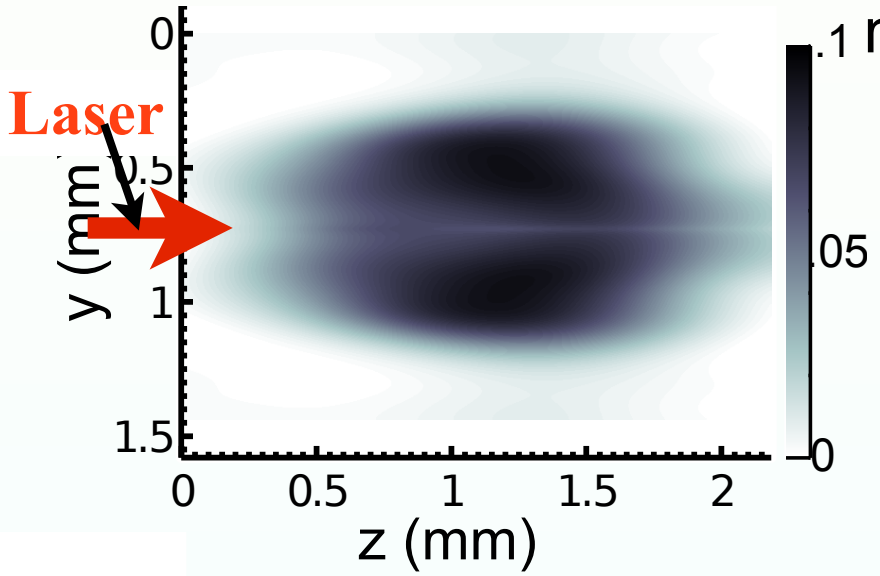


100 ps after intense pulse

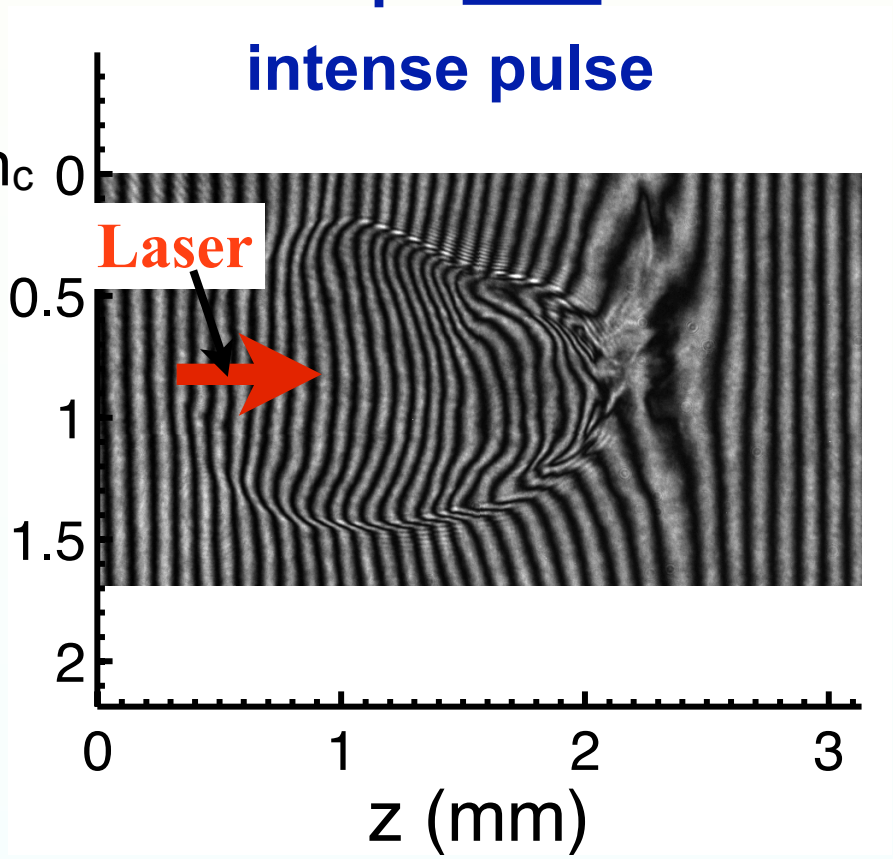


Varying prepulse changes initial conditions

400 ps before intense pulse

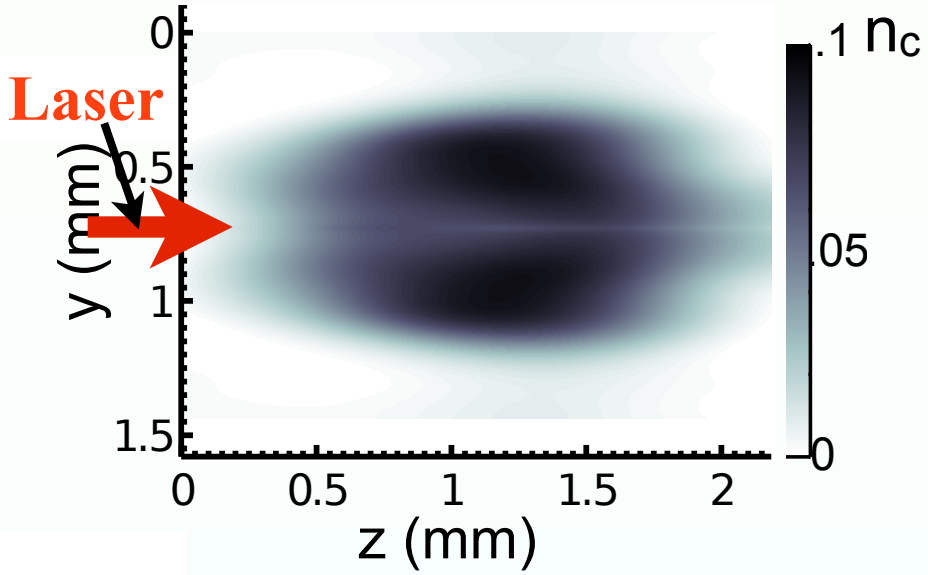


100 ps after intense pulse

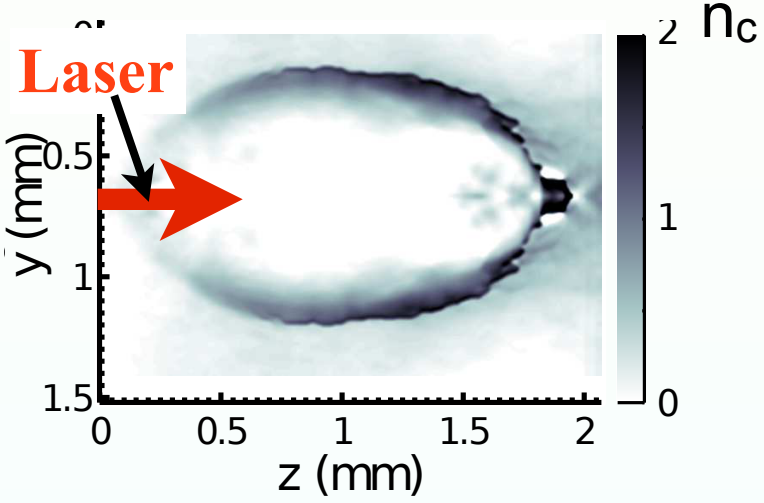


Varying prepulse changes initial conditions

400 ps before intense pulse



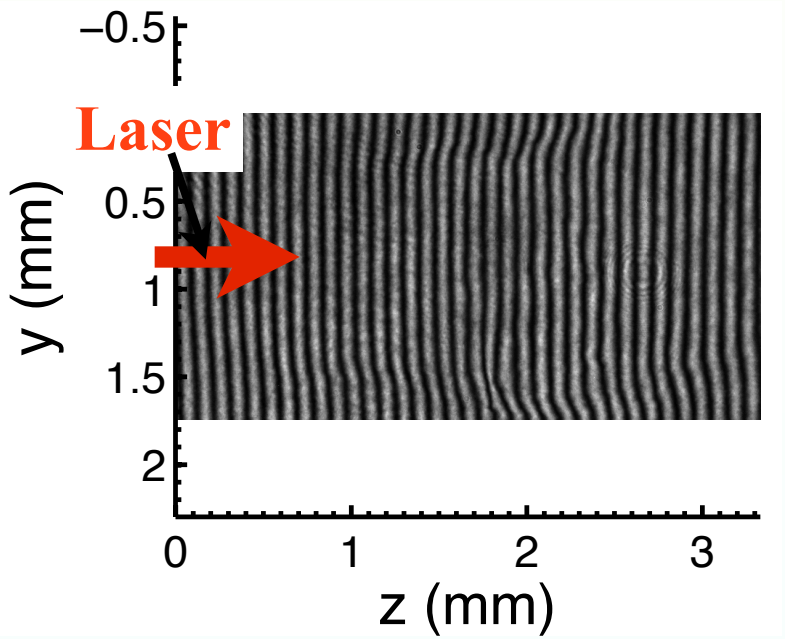
100 ps after intense pulse



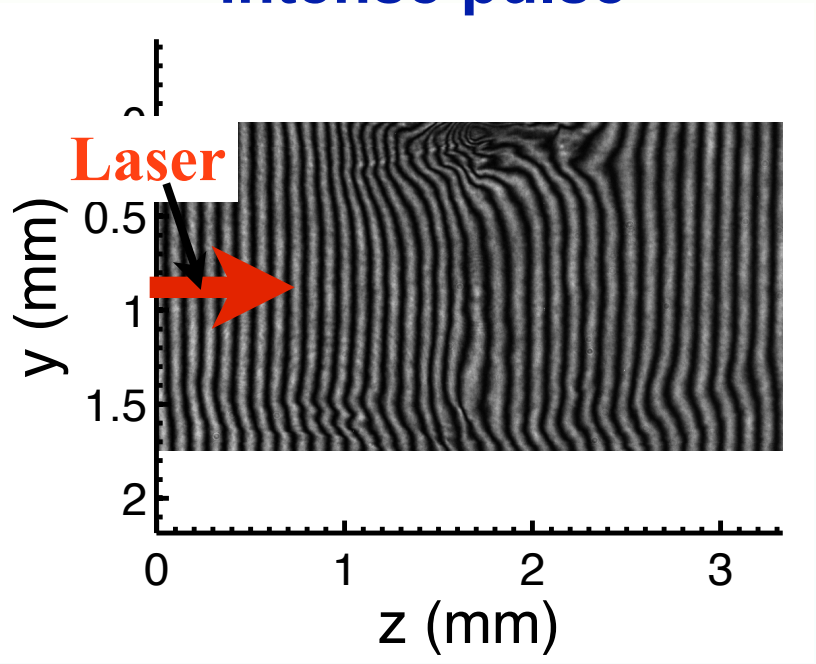
- "50 mJ" prepulse: significant preionisation prior to the interaction, indicative of optical tailoring of gas jet
  - **First observation of energetic helium ions from shockwave acceleration in overdense gas-jets**

Varying prepulse changes initial conditions

400 ps before intense pulse

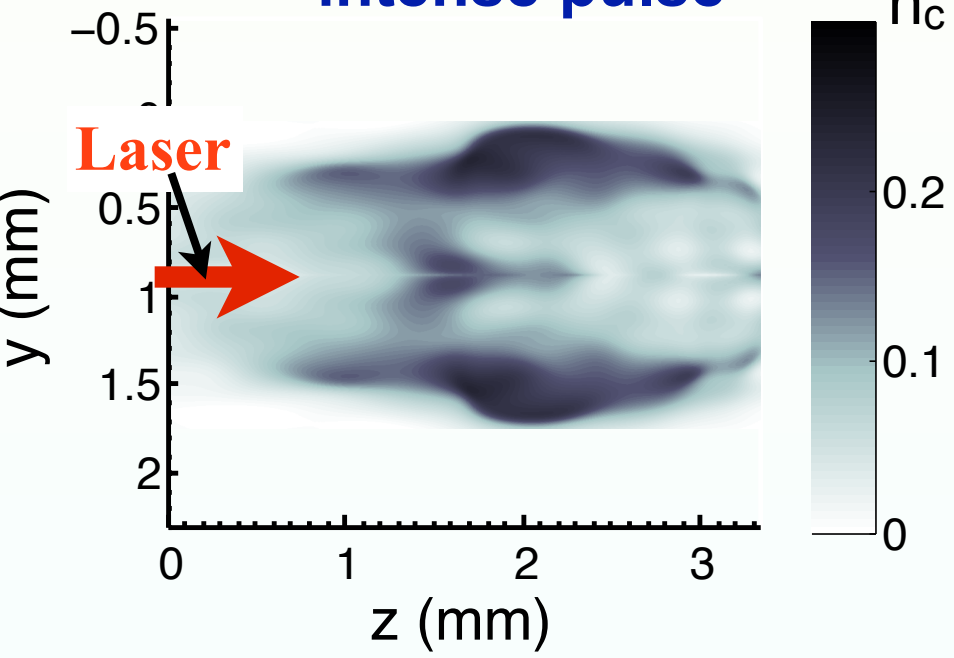


100 ps after intense pulse

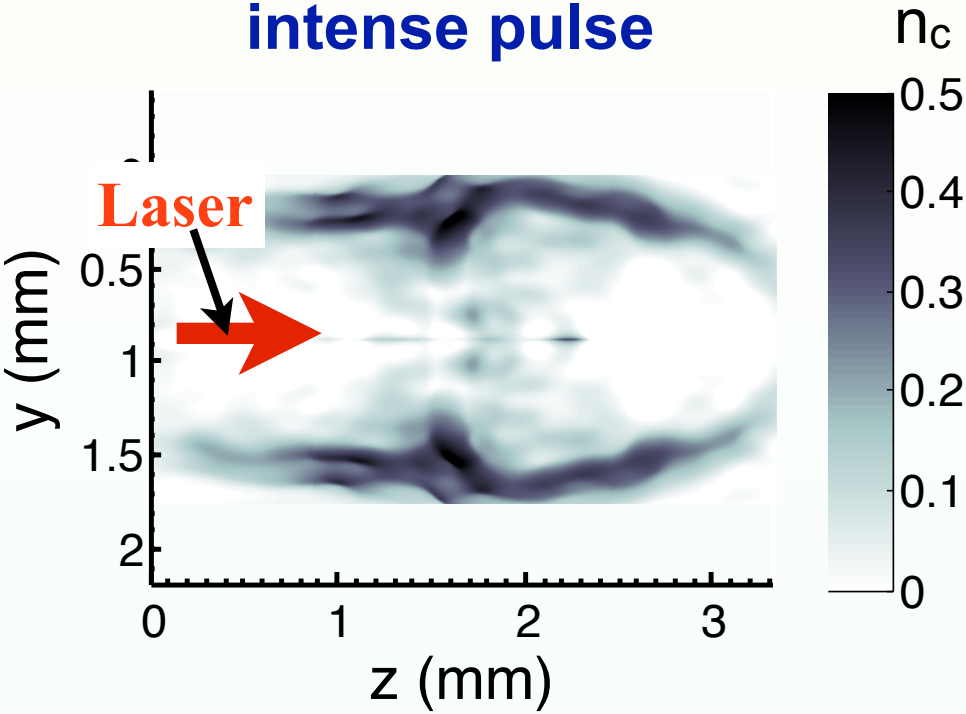


Varying prepulse changes initial conditions

400 ps before intense pulse



100 ps after intense pulse



- "100+ mJ" prepulse: prepulse heats filament which expands too much, causing intense pulse to go straight through gas jet
  - **No ion beams generated**