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Laser plasma interactions in the relativistic transparent regime

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Talk overview

- What is the relativistic transparent regime?
- Why is might it be relevant to fast ignition?
- Experiment
- Simulations
- Propagation model
- Summary

Relativistic Transparency Regime

The critical plasma density, n_c is when the laser frequency, ω_L, equals the plasma frequency, ω_p:

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = \omega_L$$

$$\longrightarrow n_c = \frac{m_e \varepsilon_0 \omega_L^2}{e^2}$$

Above this density the laser is unable to propagate.

However, for $a_0 > 1$, the electrons have relativistic motion so $m_e \to \langle\gamma\rangle m_e$ where $\langle\gamma\rangle = (1 + a_0^2/2)^{1/2}$ for linear polarisation.

Therefore there is a modification to the critical density:

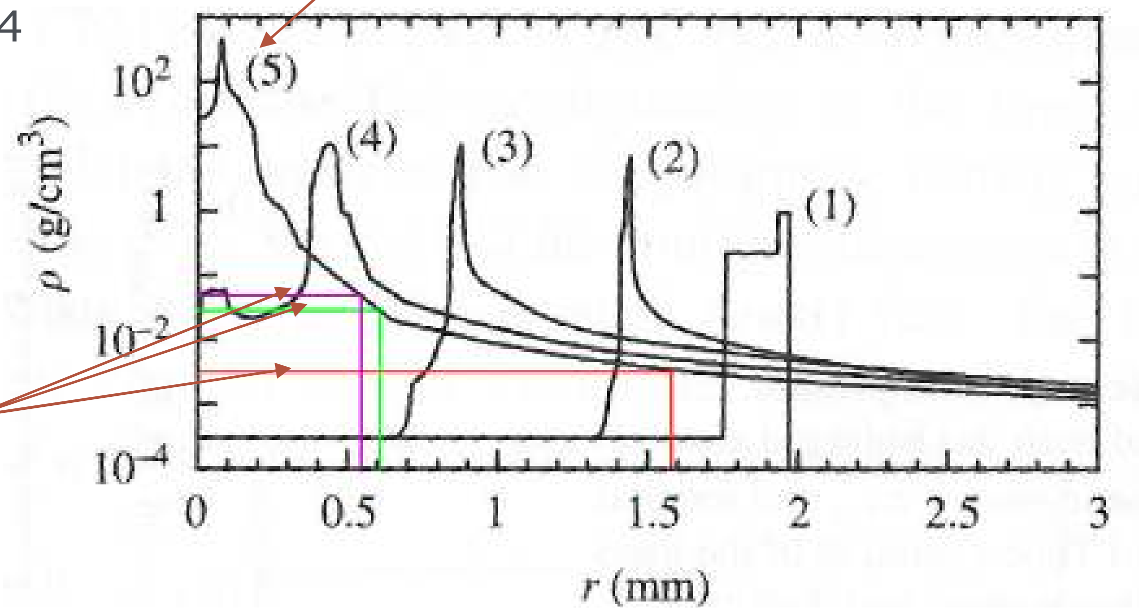
$$n_{c\gamma} = \frac{\langle\gamma\rangle m_e \varepsilon_0 \omega_L^2}{e^2} = \langle\gamma\rangle n_c$$

Consequence → the laser can propagate to higher densities.

Relevance of relativistic transparency to fast ignition

Distance from critical surface to dense core for different wavelengths

λ_L (nm)	n_c (cm^{-3})	ρ_c (gcm^{-3})
1053	1.01×10^{21}	~0.004
527	4.03×10^{21}	~0.02
351	9.08×10^{21}	~0.04



(5) About the time of ignition

Figure taken from "The Physics of Inertial Fusion" by S Atzeni and J Meyer-Ter-Vehn (2004) Page 57, figure 3.8

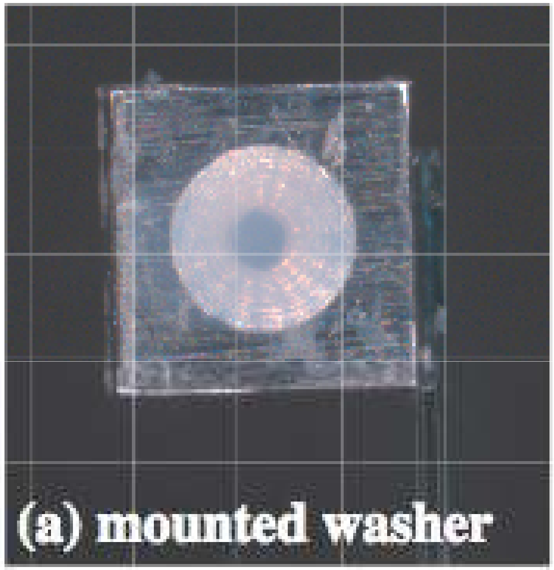
Critical density for each λ_L

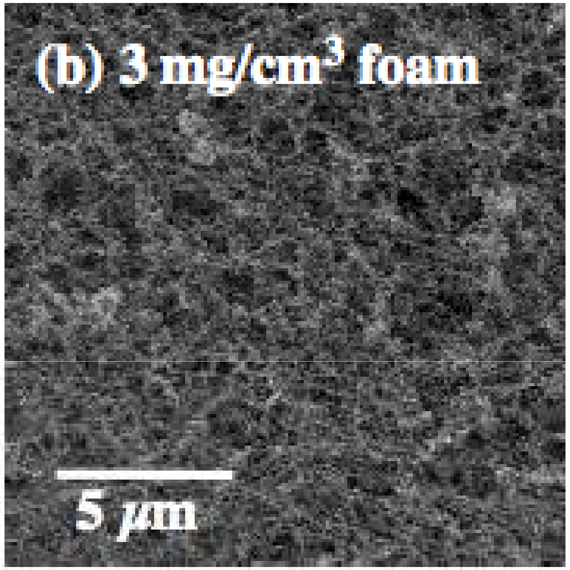
Distance that fast electrons have to travel from the critical surface is quite far considering the large divergence observed in electron beams.

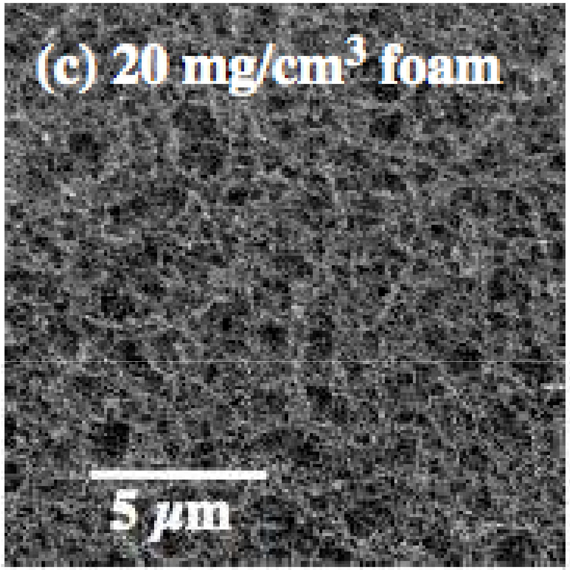
Maybe can use relativistic transparency in hole boring scheme to get closer to core?

Near critical density experiment
Foam targets

Images taken by C Spindloe







- Wigen Nazarov produced these CHO foam targets
- Assuming full ionisation, electron plasma densities of $0.9n_c$ to $30n_c$ were shot

Relativistic laser pulse
The Vulcan Petawatt laser system

1 Petawatt = 500 J / 500 fs

1.054 μm → $n_c = 1.0 \times 10^{21}$ cm^{-3}

For our experiment:

Energy = 255 ± 70 J

Pulse length = 550 ± 150 fs

Focal spot = 5.0 ± 0.5 μm

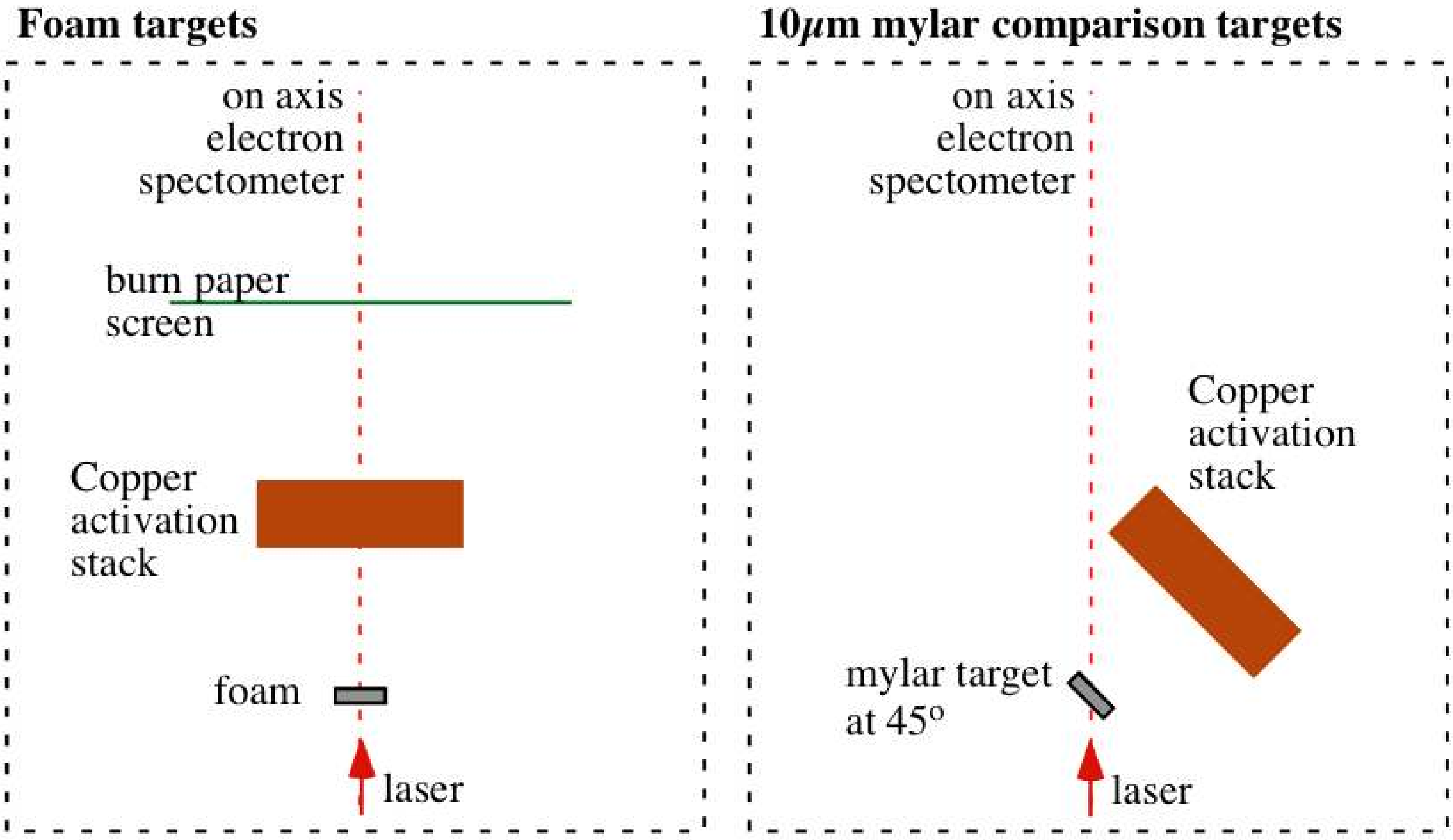
Peak intensity = $(7.7 \pm 3.4) \times 10^{20}$ Wcm^{-2}

Peak $a_0 \approx 35$

$n_{c\gamma} = 25\, n_c$

Contrast ratio ~ 10^{-7}

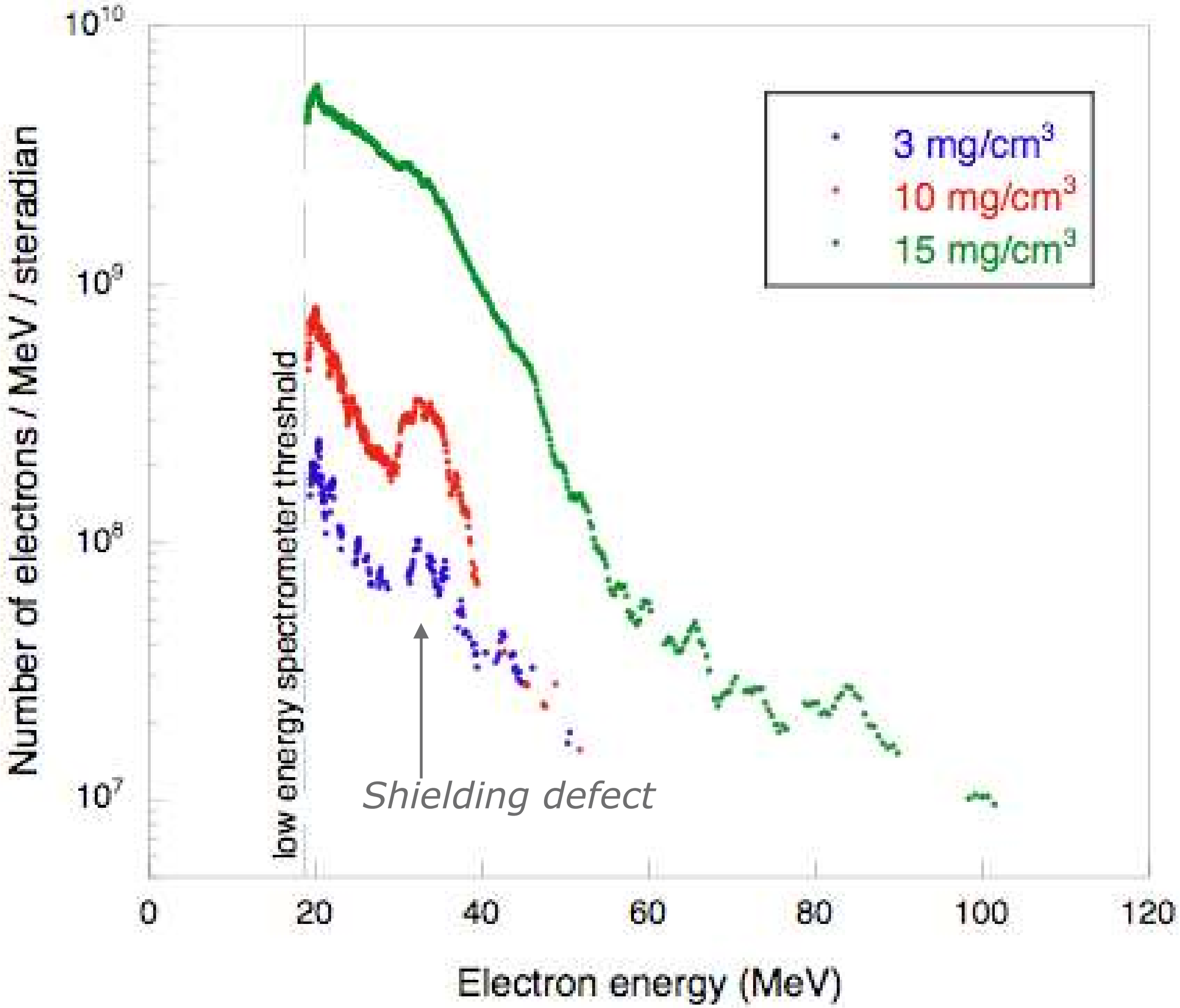
Near critical density experiment
Experimental set up



Near critical density experiment
Electron spectra

Initial results measuring the electron spectra along the laser axis showed high energy electron spectra

No electrons above the spectrometer threshold were measured from the comparison shot onto the 10 μm mylar target



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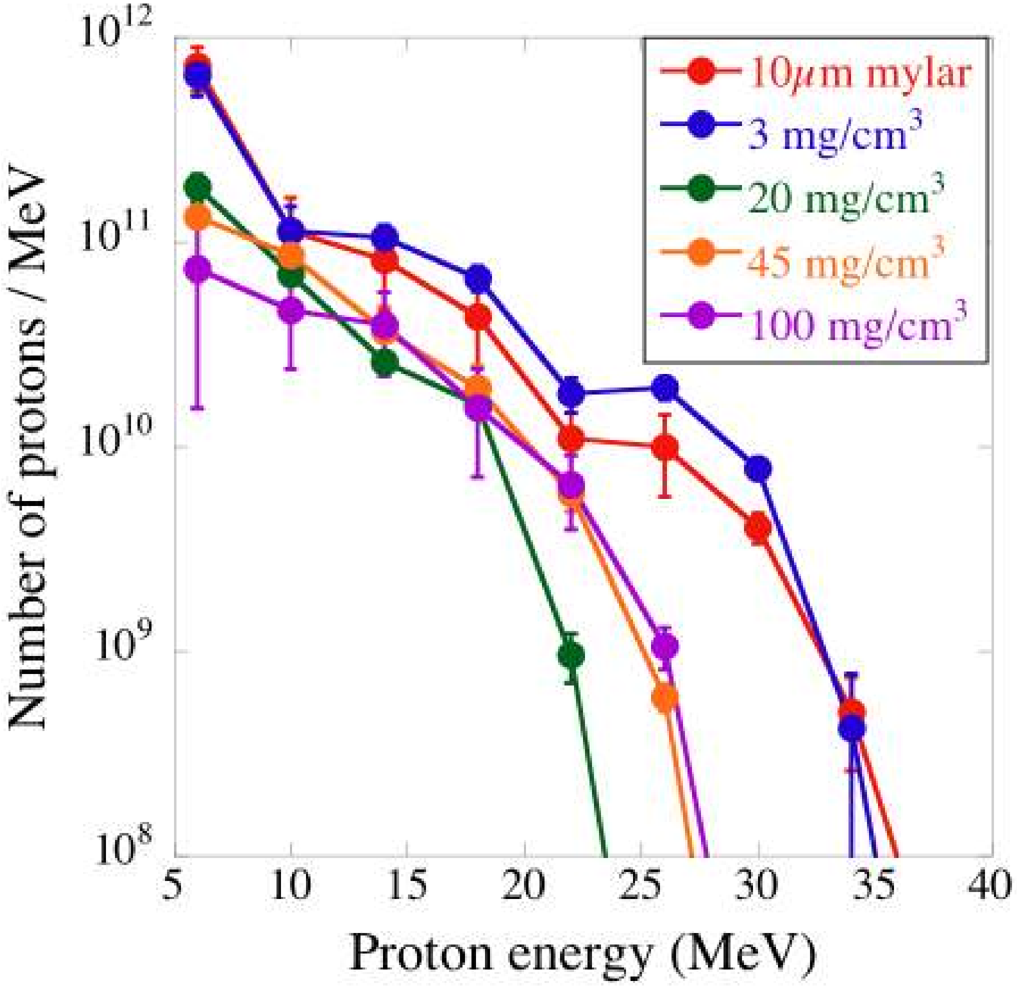
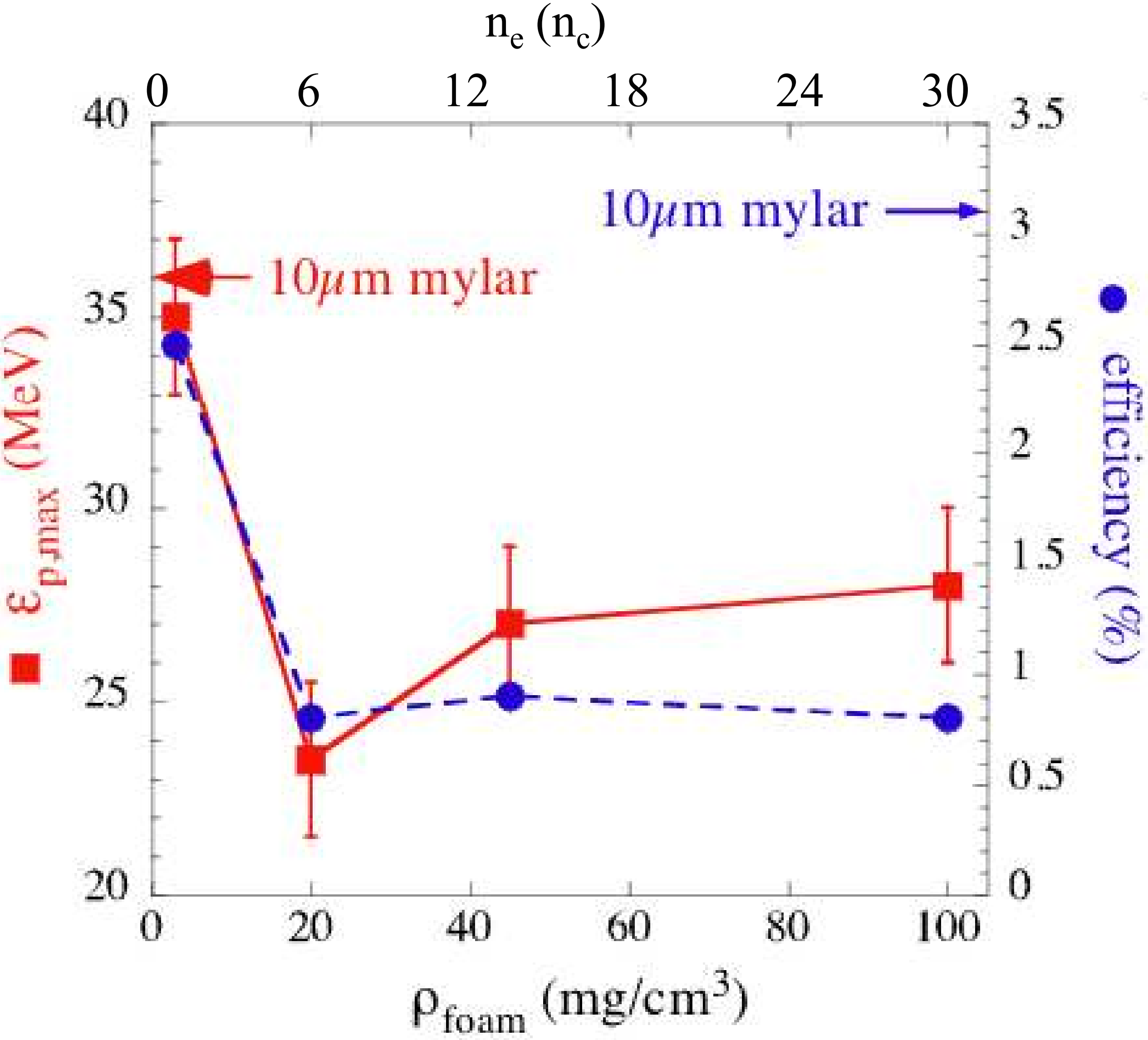
Near critical density experiment
Proton acceleration

Copper activation stacks were used to measure the whole proton beam spectra.

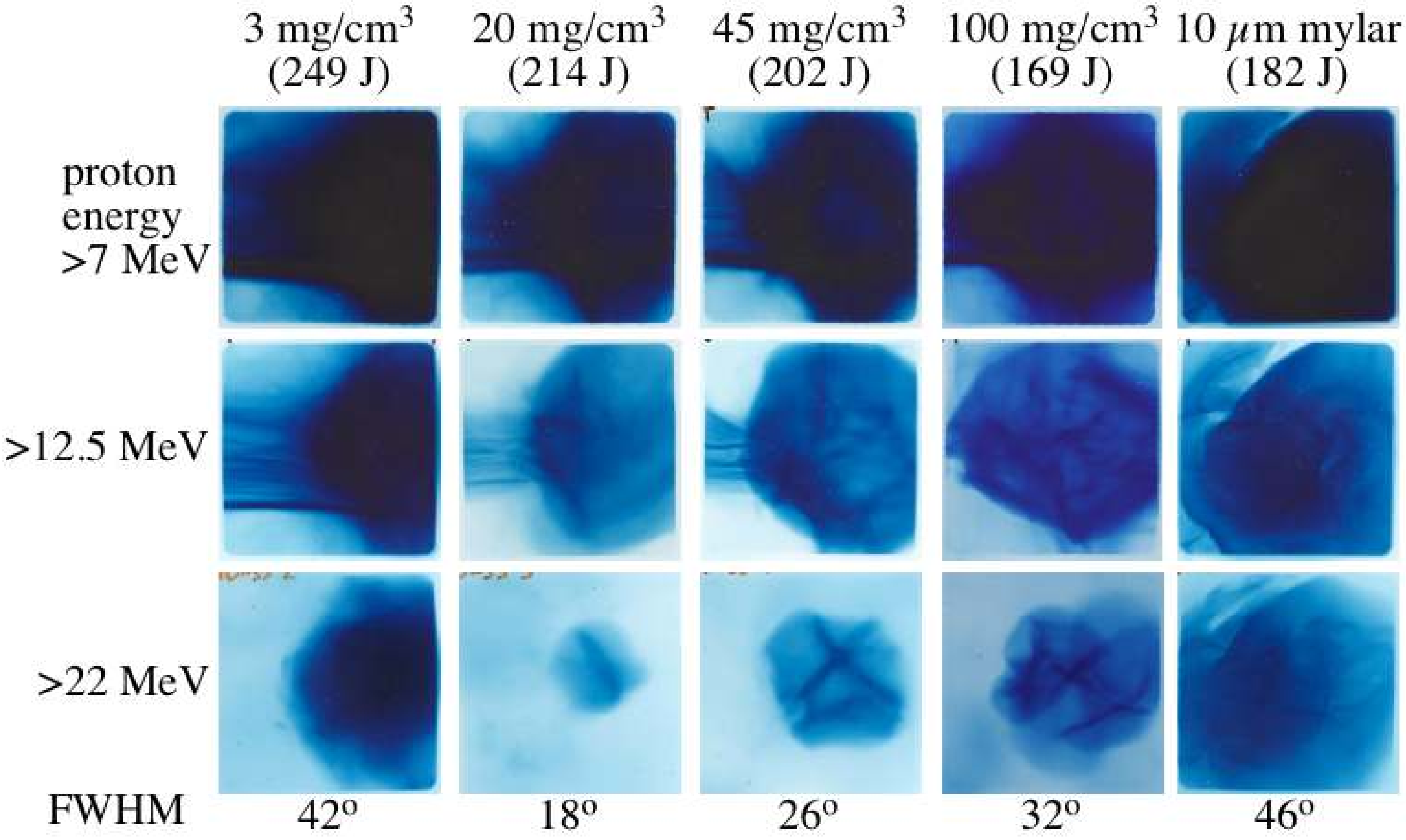
Proton spectra have higher maximum energy and greater number for both the 10 µm mylar and 3 mg/cm^3 (0.9n$_c$) foam.



Near critical density experiment
Proton acceleration



Near critical density experiment
Proton beam divergence



Near critical density simulations
Simulation set up

OSIRIS - 3D3V particle-in-cell code (Run as 2D3V)
- Run on a computer cluster using up to 32 nodes

1. Stationary box - allows the observation of plasma evolution after the laser has passed

2. Moving box - simulation box travels at the speed of light so that large propagation lengths can be investigated

$a_0 = 15$, $\tau_L = 500$ fs

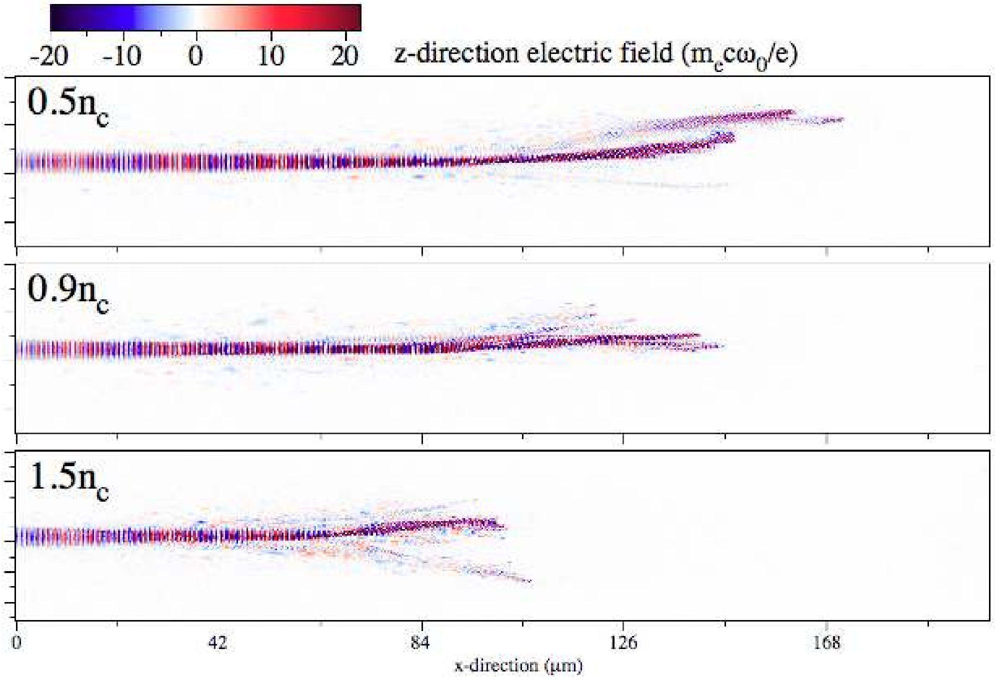
$n_e = 0.9 - 30\ n_c$

Proton plasma

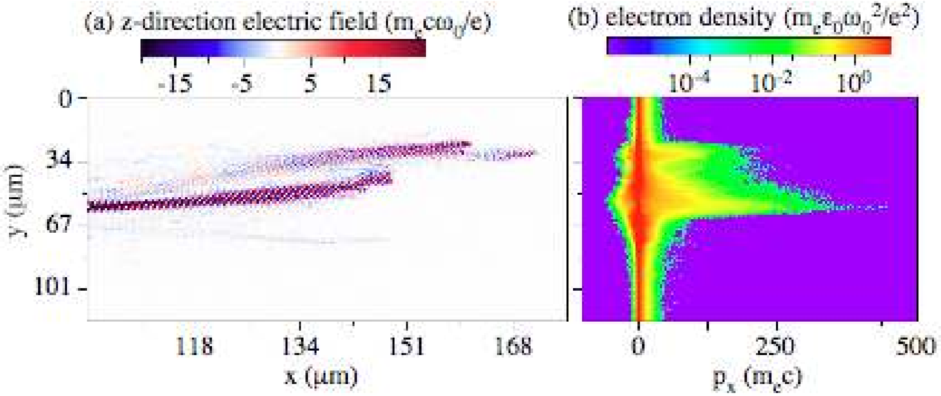
Simulations performed using OSIRIS. We gratefully acknowledge the OSIRIS consortium UCLA/USC/IST for the use of the code

Near critical density simulations
Laser propagation

Moving box simulations



The retardation of the laser pulse can be seen as the density increases - still the laser is propagating beyond n_c, the non-relativistic plasma density



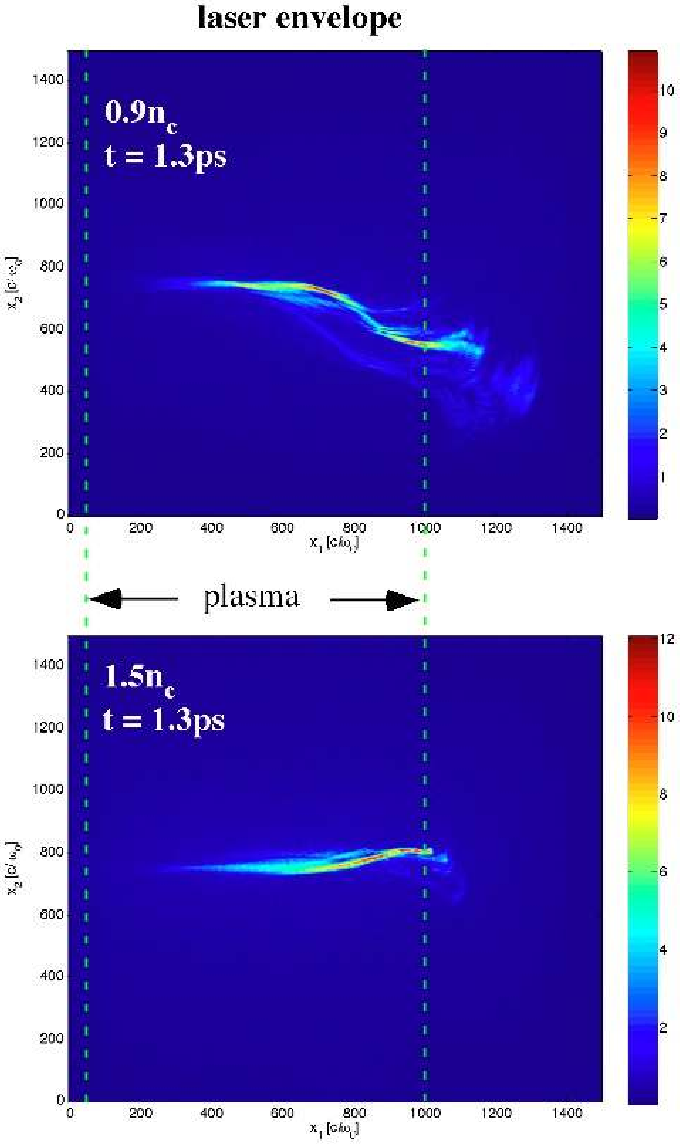
Laser beam filamentation can be seen to affect the electron beam acceleration

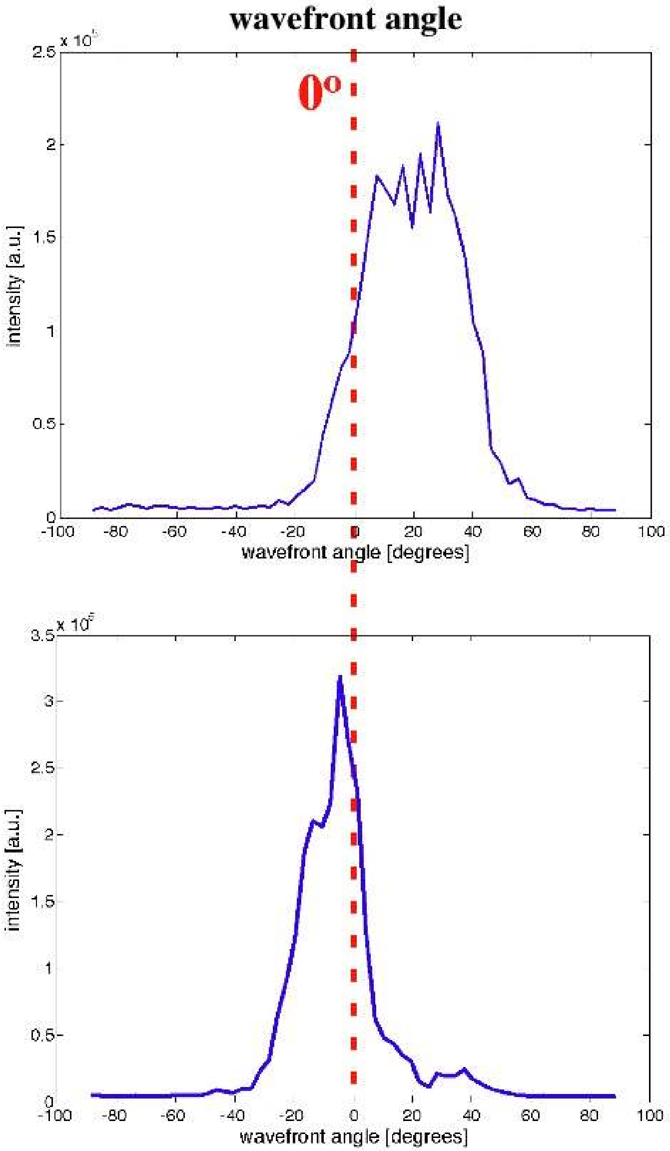
Near critical density simulations
Laser propagation direction

Stationary box

0.9nc

1.5nc



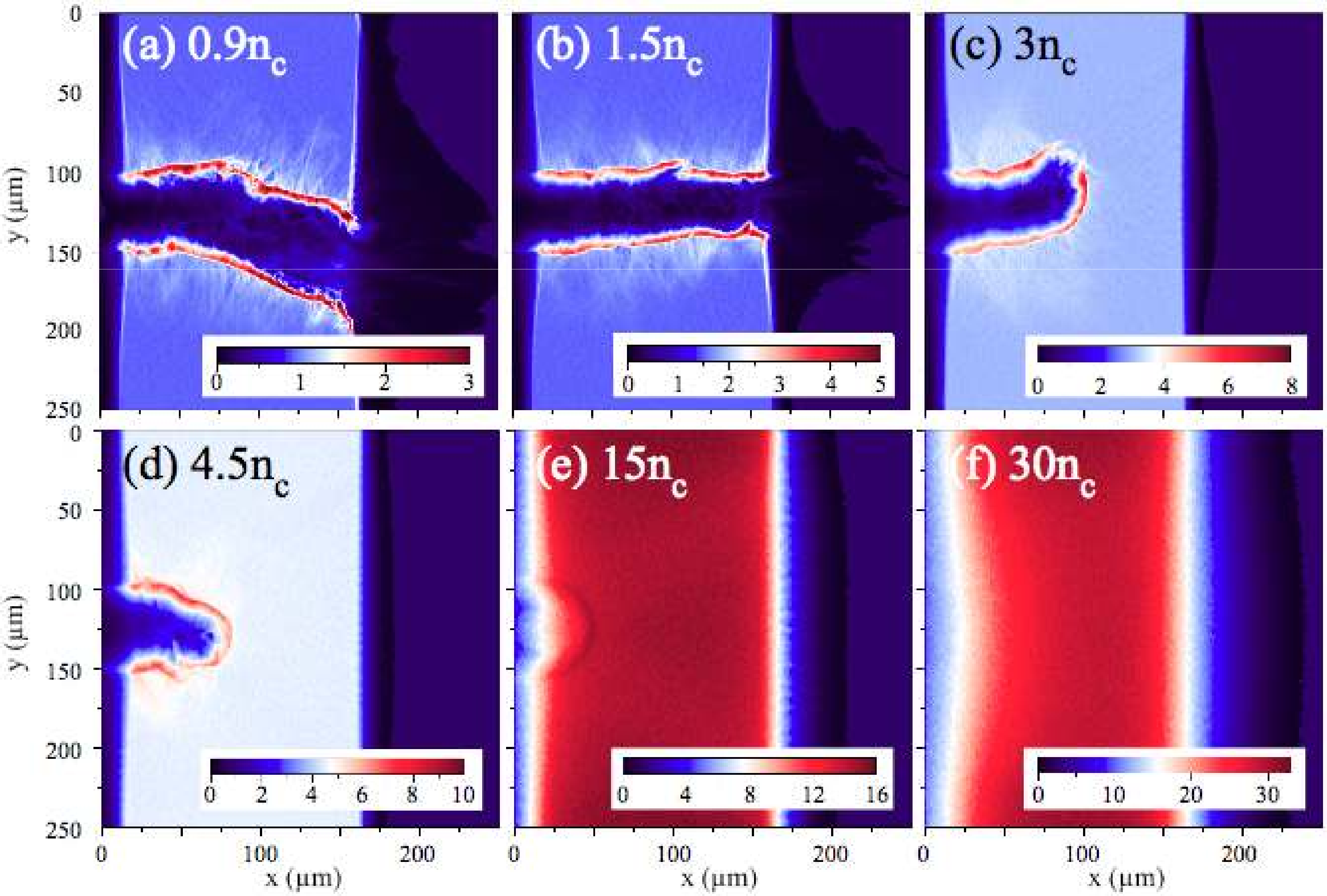


Near critical density simulations
Laser propagation

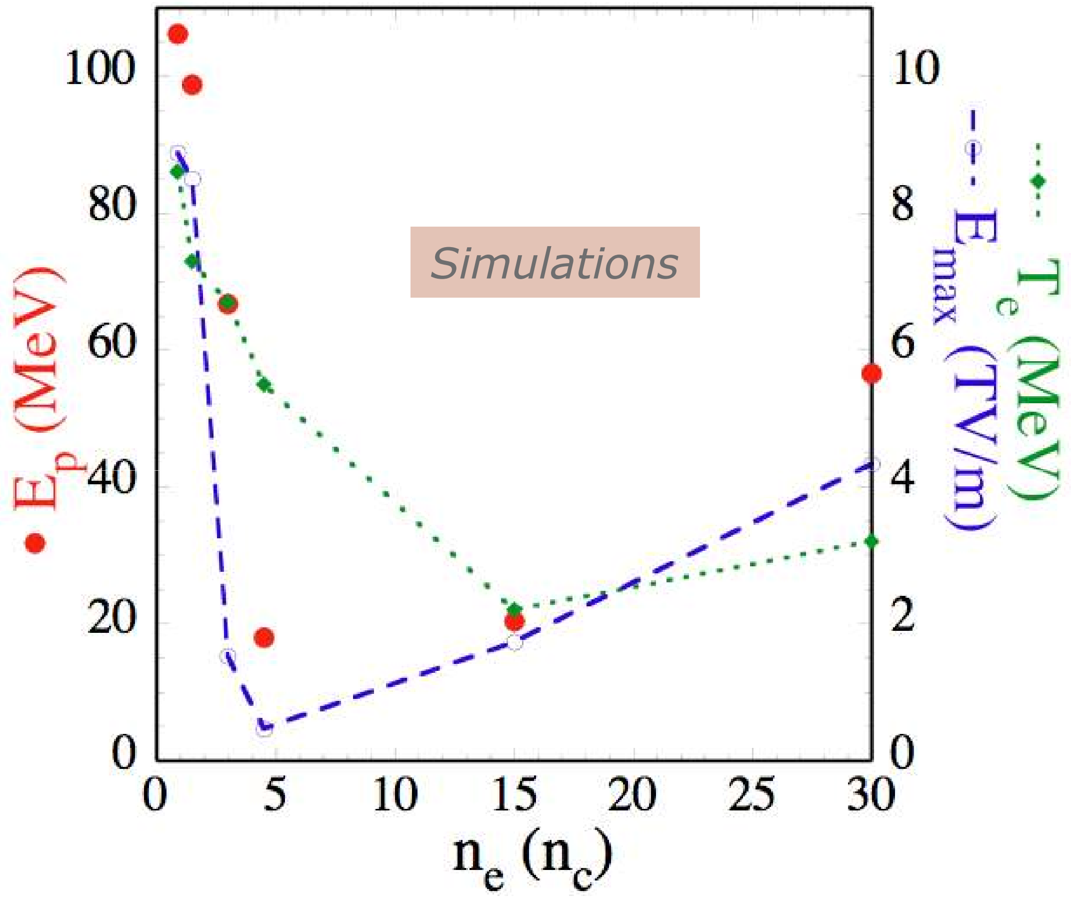
Stationary box

As the density increases the laser propagation is reduced.

Late time proton density

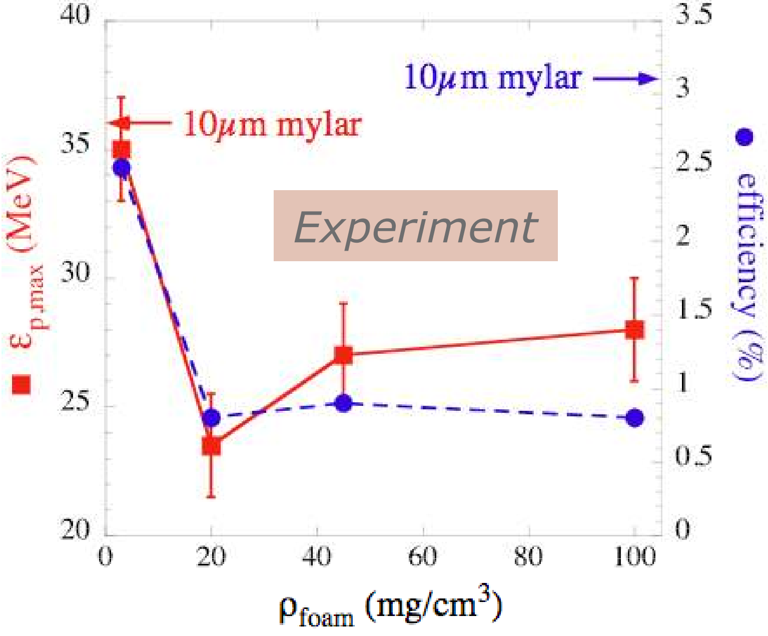


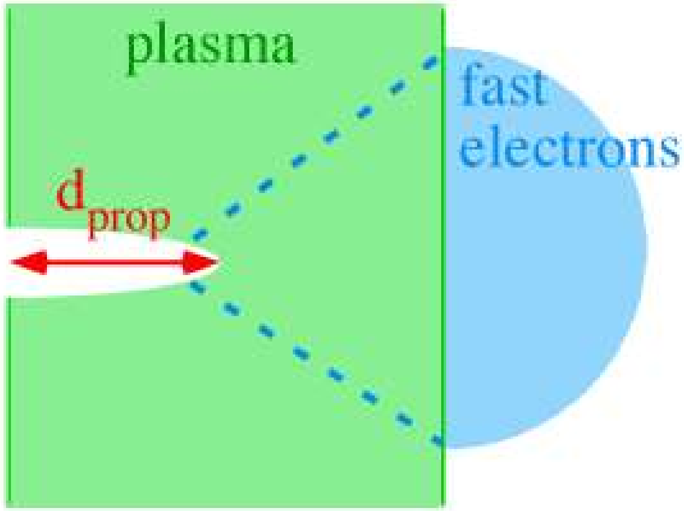
Near critical density simulations



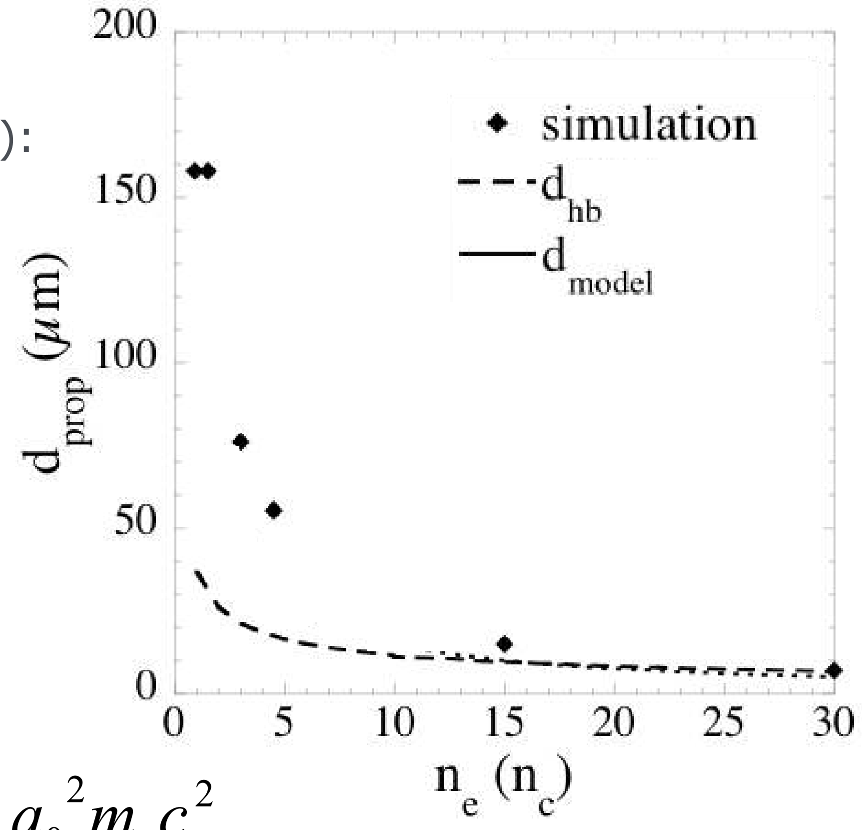
Similar general trends in maximum proton energy

The larger the distance from the end of the channel to the rear surface, the larger the area the electrons emerge from, reducing the electric field strength





Near critical density simulations
Propagation depth



Ponderomotive hole boring (Wilks, PRL, 1992):

$$v_{hb} = 0.7ca_0\sqrt{\frac{m_e n_c}{m_i n_e}}$$

For $a_0 = 15$, $\tau_L = 500$ fs

$\boxed{\rightarrow d_{hb} = v_{hb}\,\tau_L}$

focal spot

Model:

Laser energy
$$\varepsilon_L = \tau_L A \frac{c\varepsilon_0}{2}\left(\frac{a_0 m_e c\omega_L}{e}\right)^2$$

Complete absorption into e⁻
$$(\gamma - 1)m_e c^2 = \tfrac{1}{2}a_0{}^2 m_e c^2$$

Plasma energy
$$\varepsilon_{plasma} = \tfrac{1}{2}a_0^2 m_e c^2 n_e A d_{prop}$$

Equating ε_L to ε_p:
$$d_{prop} = \frac{c\varepsilon_0}{e^2}\frac{\tau_L\omega_L^2}{n_e}$$

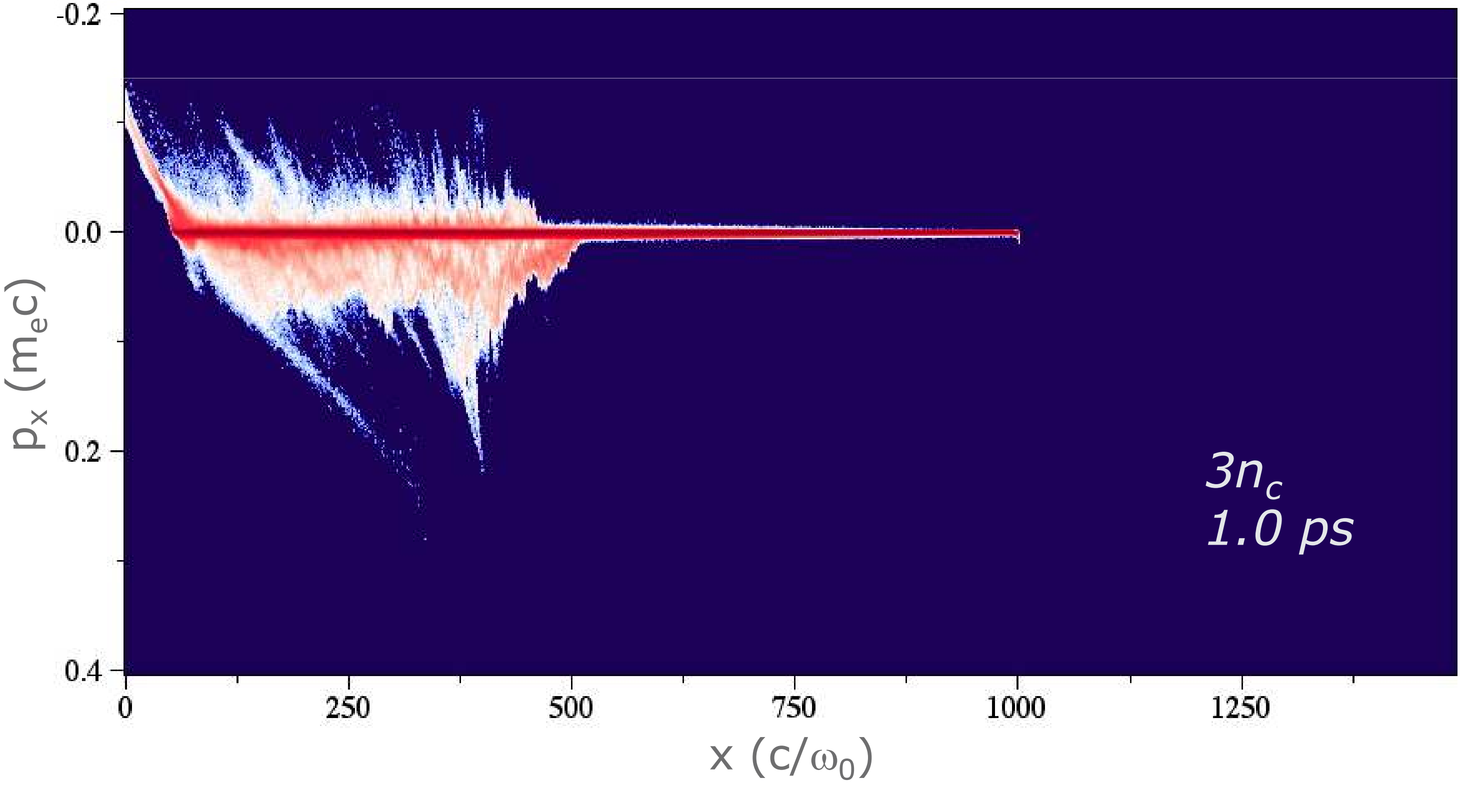
$\boxed{d_{model}\ (\mu\text{m}) = 151/n_e}$ (with n_e in units of n_c)

Near critical density simulations
Shock acceleration of protons

Silva, PRL (2004)

Evidence for shock acceleration of the protons is seen in some of the simulations, particularly in the $n_e = 3n_c - 15n_c$.

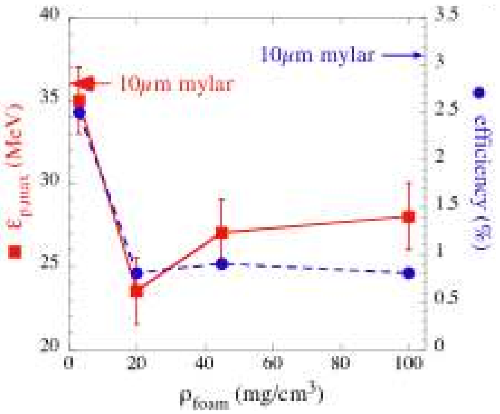
The shock ion acceleration does not reach such high energies that are observed from the rear side TNSA.

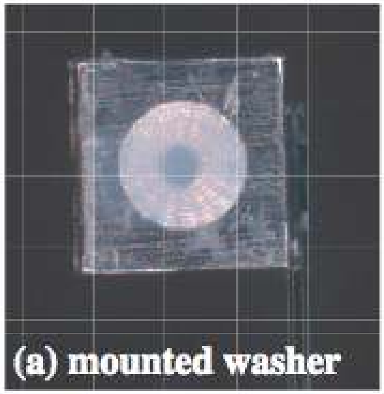


Summary
Relativistic transparency regime investigation

Experiments:

- Foam targets produced near critical density plasma
- proton acceleration diagnosed interaction





Simulations:

- Observed large changes in propagation direction
- Investigate laser propagation depth
- Trends observed agree with experiment