Development of laser plasma accelerators and their applications

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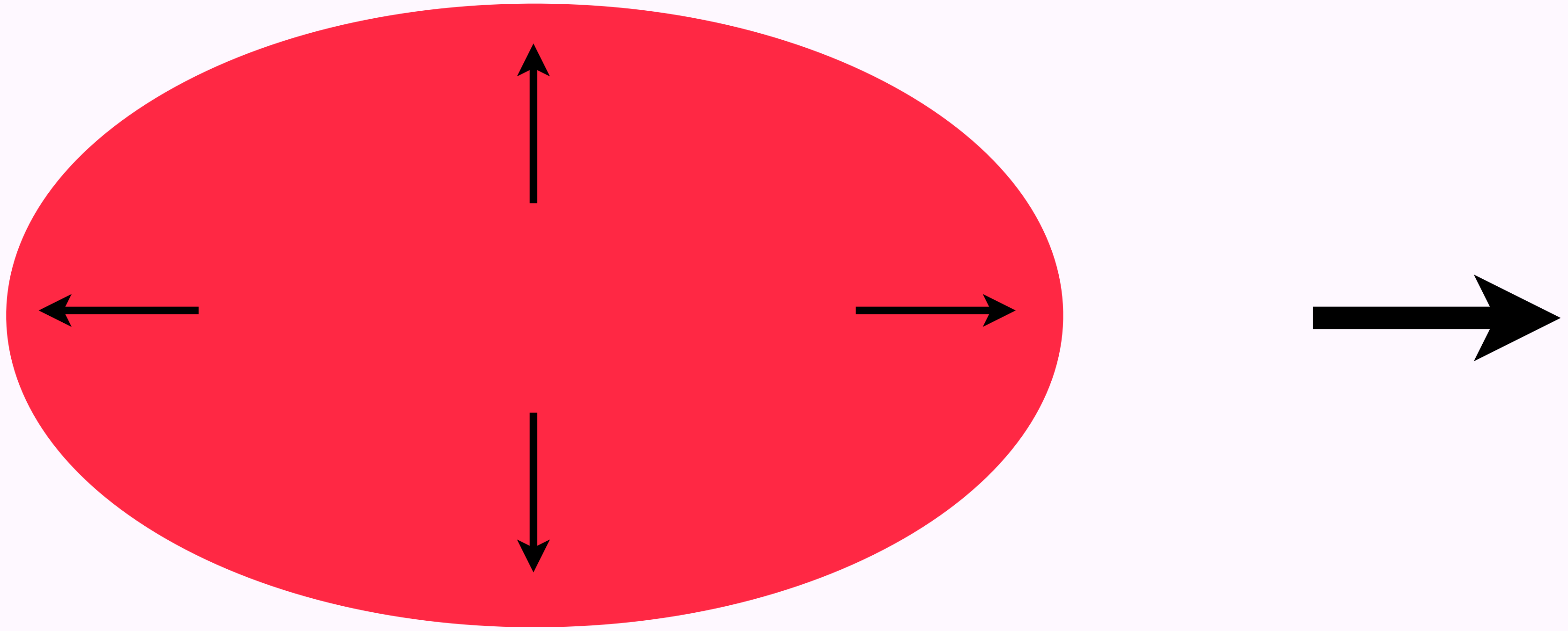
UK-India Workshop on Laser Plasma Accelerators
International Centre for Theoretical Sciences
9th March 2017

Outline

- Laser wakefield acceleration of electrons
- Radiation generation and applications
- Ion acceleration

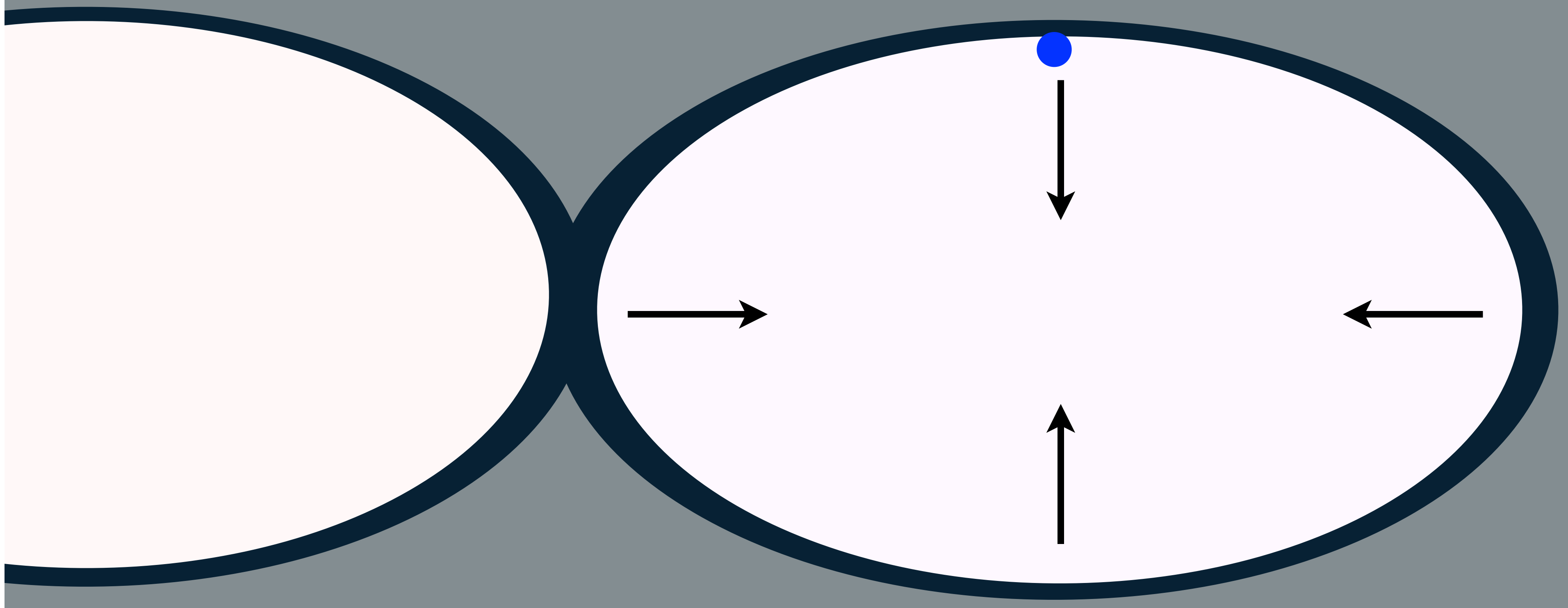
Laser wakefield acceleration of electrons

“bubble” plasma wave



$$E = \epsilon \cdot \frac{m_e c \omega_p}{e} \approx \epsilon \sqrt{n_e \,[\mathrm{cm}^{-3}]}\ [\mathrm{Vcm}^{-1}]$$

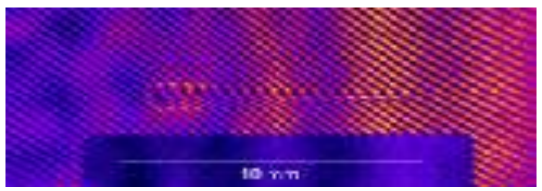
Acceleration



$$W \simeq \epsilon \cdot 2{\gamma_\phi}^2 m_e c^2$$

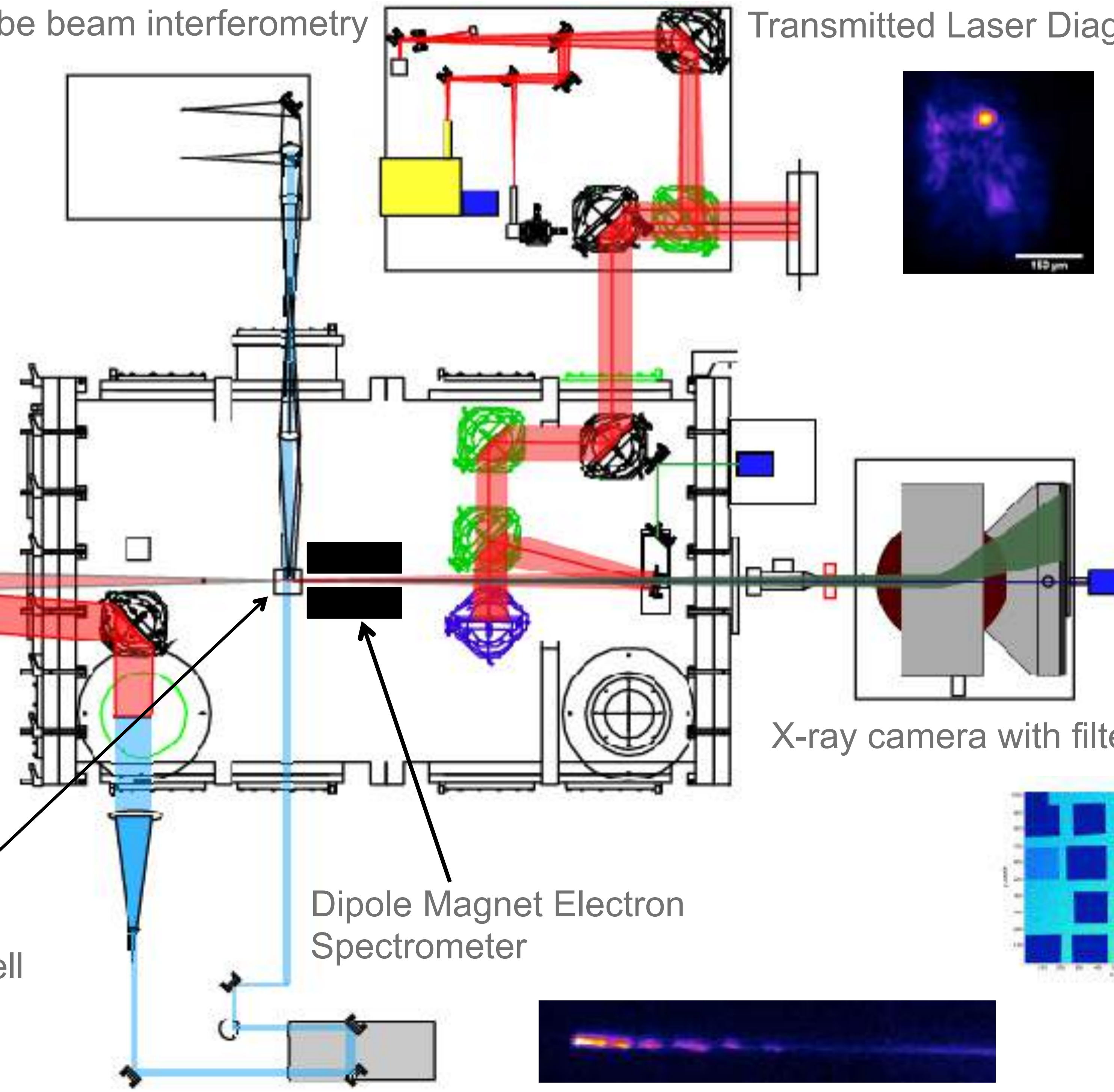
Astra Gemini Set-Up

centimetre scale channel



10 J, 55 fs
f/20 parabolic mirror
25μm FWHM
a=3.8 I = 2×10^{19} $\mathrm{Wcm^{-2}}$

Probe beam interferometry



Gas jet/ Gas Cell

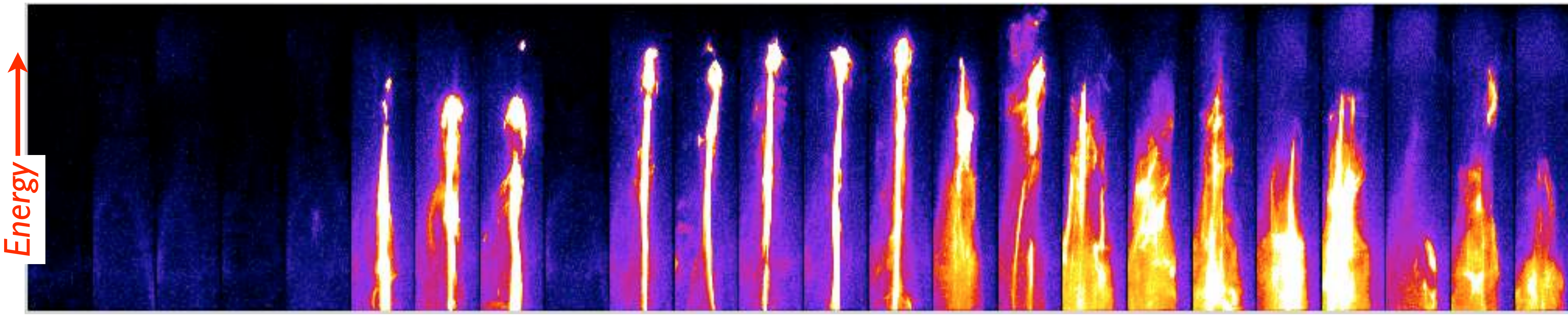
Dipole Magnet Electron Spectrometer

Transmitted Laser Diagnostics

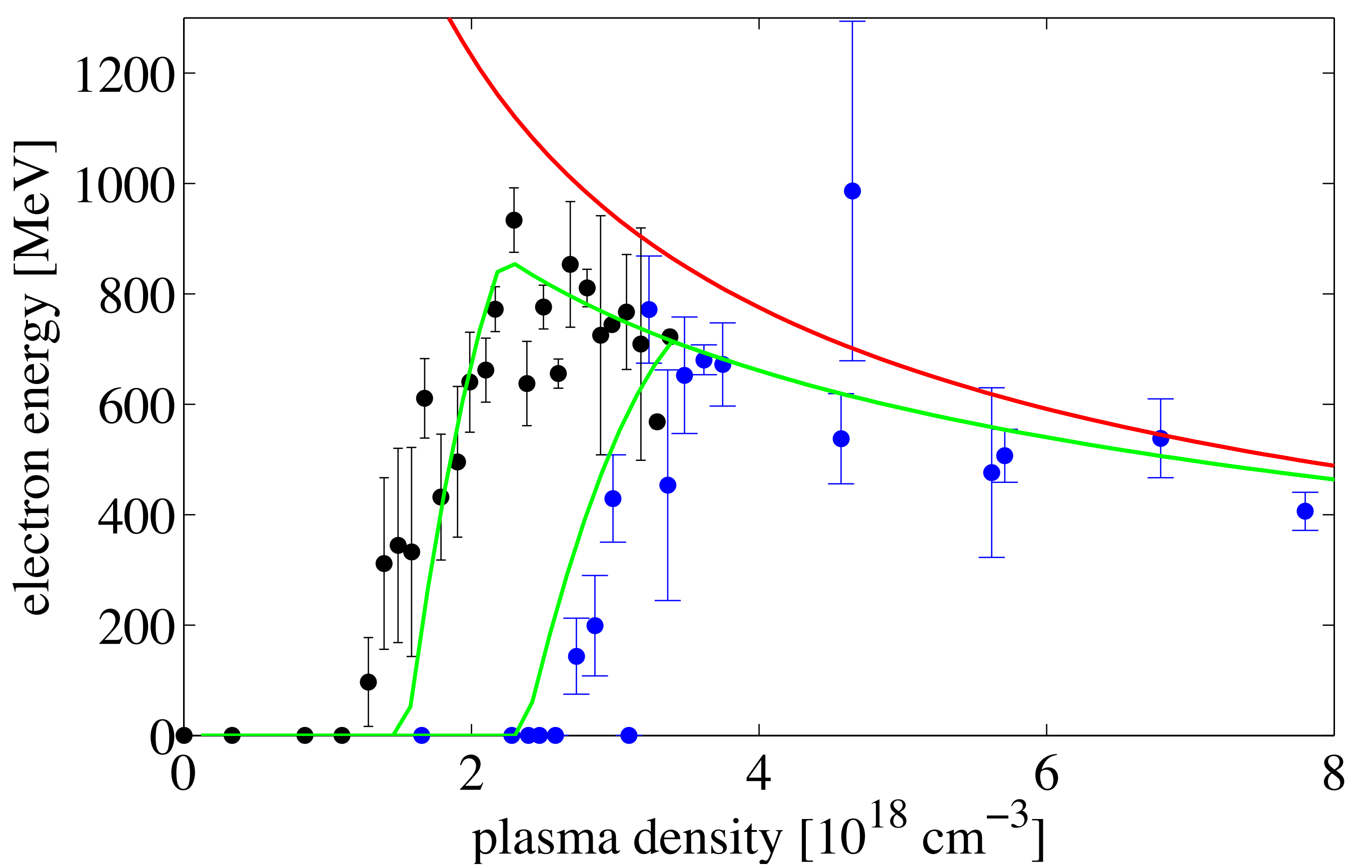
X-ray camera with filter pack

GeV electron energies

GeV self guided acceleration

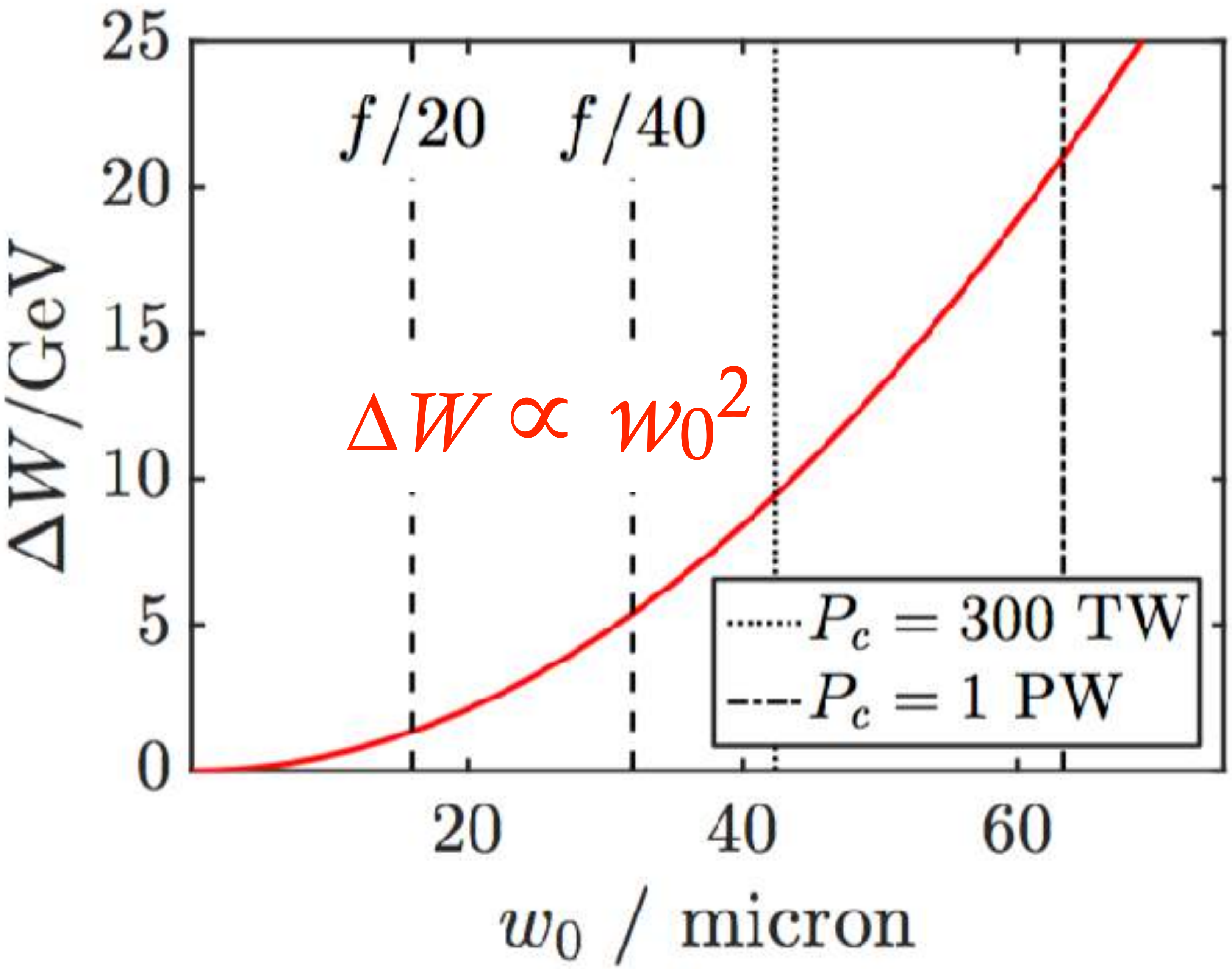


Density



Maximum electron energy
blue: 10 mm nozzle
black: 15 mm nozzle
Red Curve: Wei Lu scaling
(including compression and self-focusing)
Green Curve: PIPE model prediction
(fitted to 10 mm, no additional fitting to 15 mm)

Energy scaling for LWFA guided with matched spot size



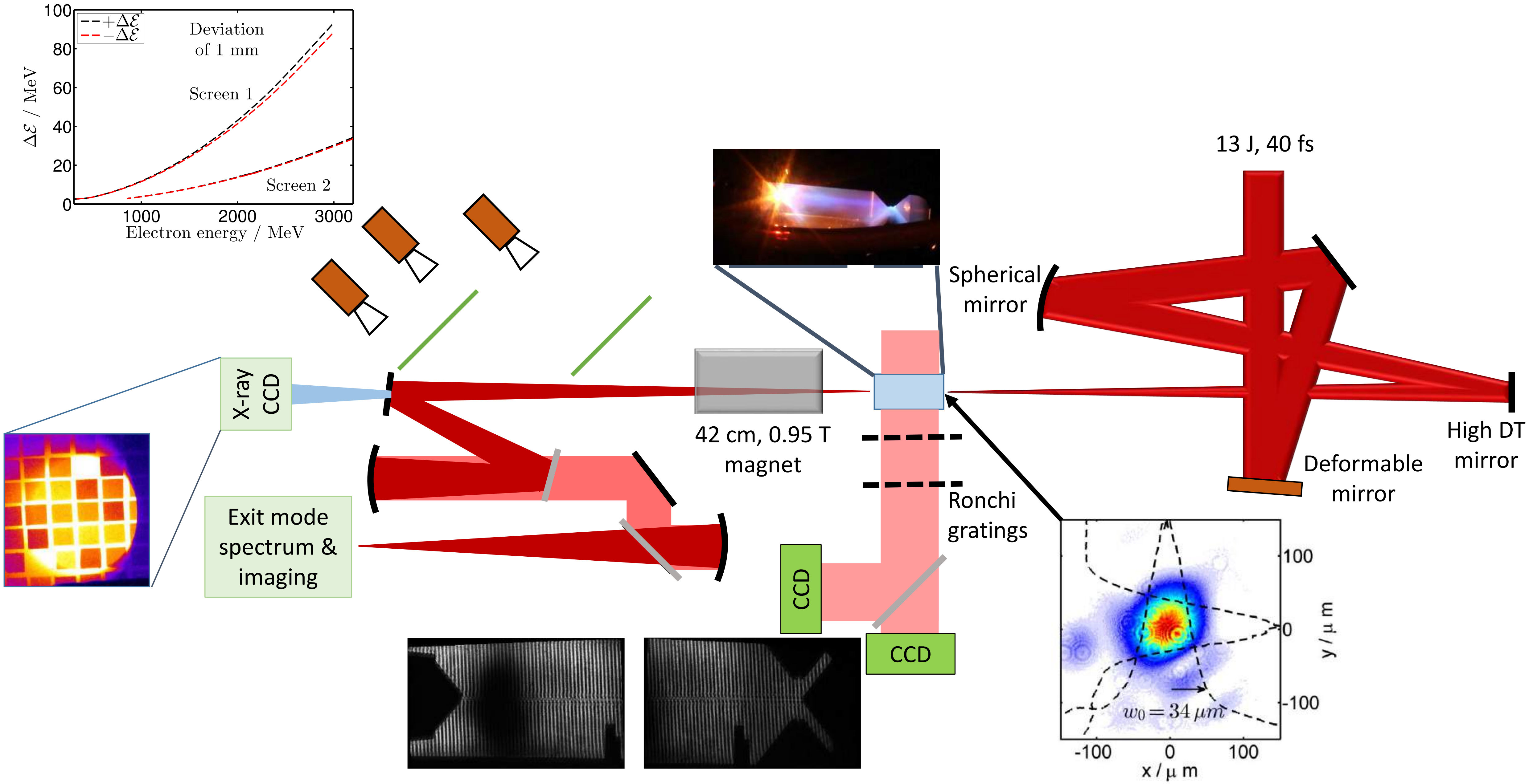
$$k_p w_m = 2\sqrt{a_0}$$

$\rightarrow$ $$w_m{}^4 \propto n_e{}^{-1}$$

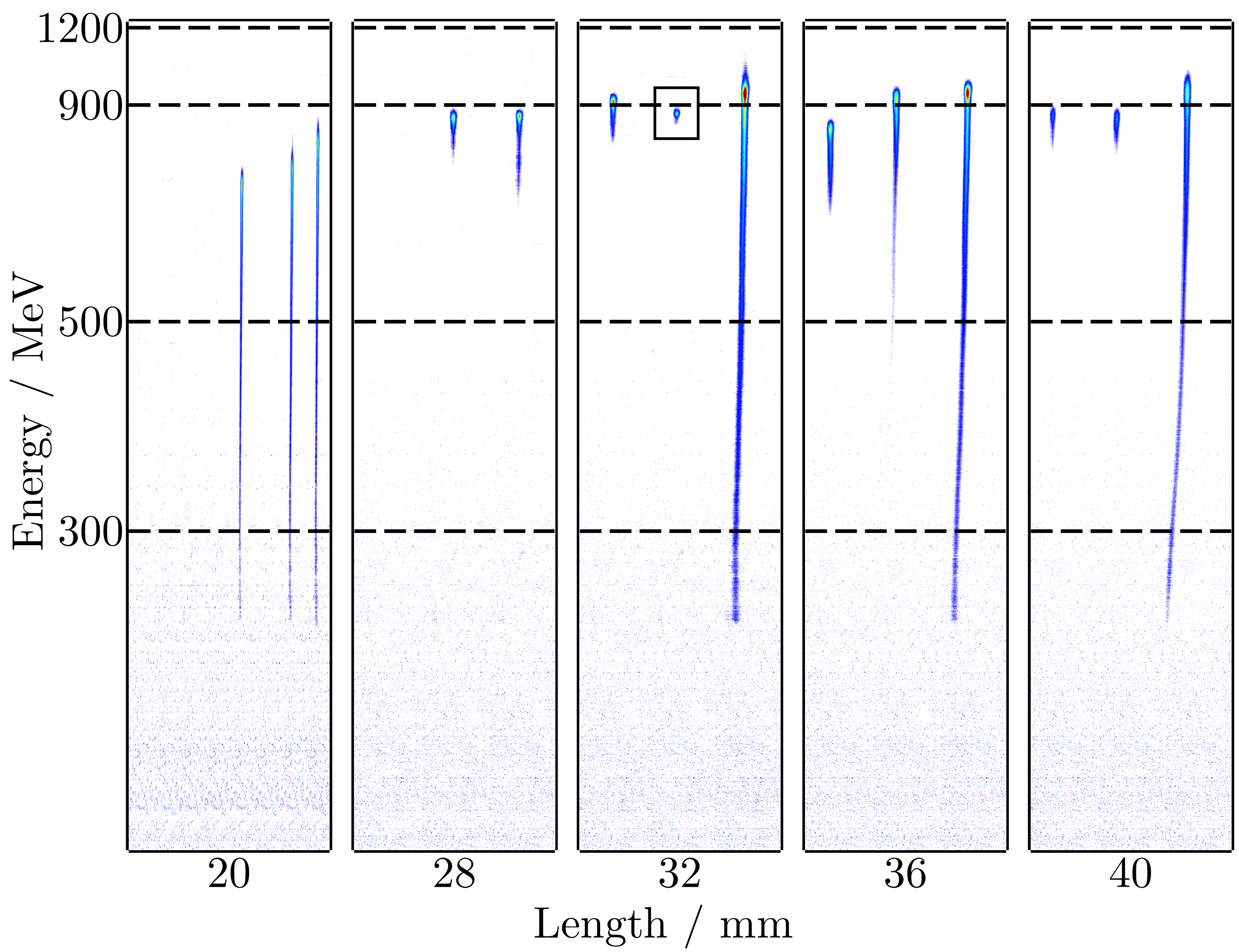
but $$\Delta W \propto a_0/n_e$$

so $$\Delta W \propto w_m{}^2$$

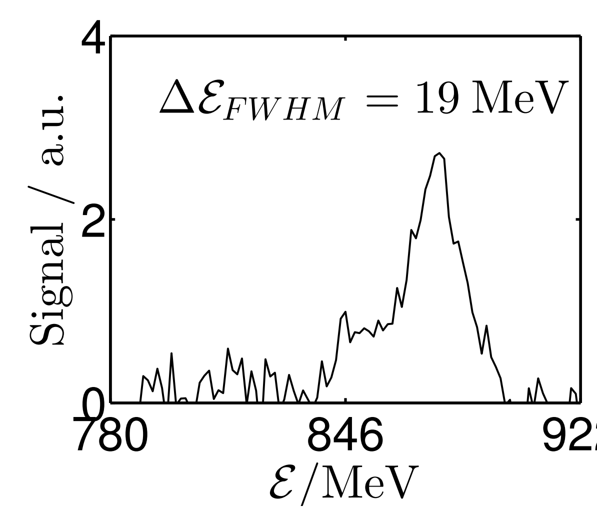
f/40 Gemini Set-Up



Narrow energy spread beams

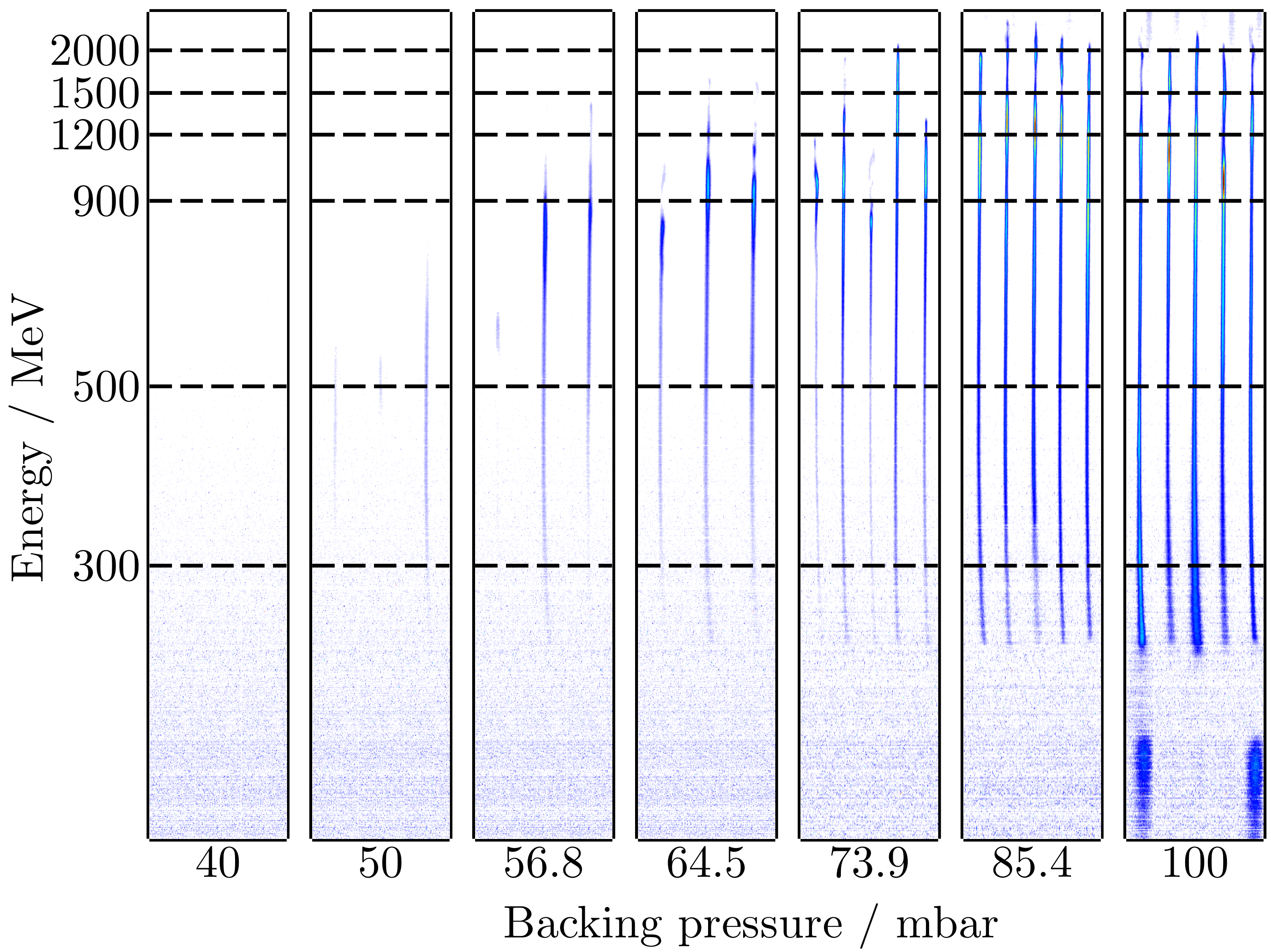


Energy on target
9.5 ± 0.2 J
Backing pressure
55 mbar
$n_e \sim 1.5 \times 10^{18}\ \mathrm{cm}^{-3}$



Density Variations

Extended electron energies for same laser energy



Energy on target

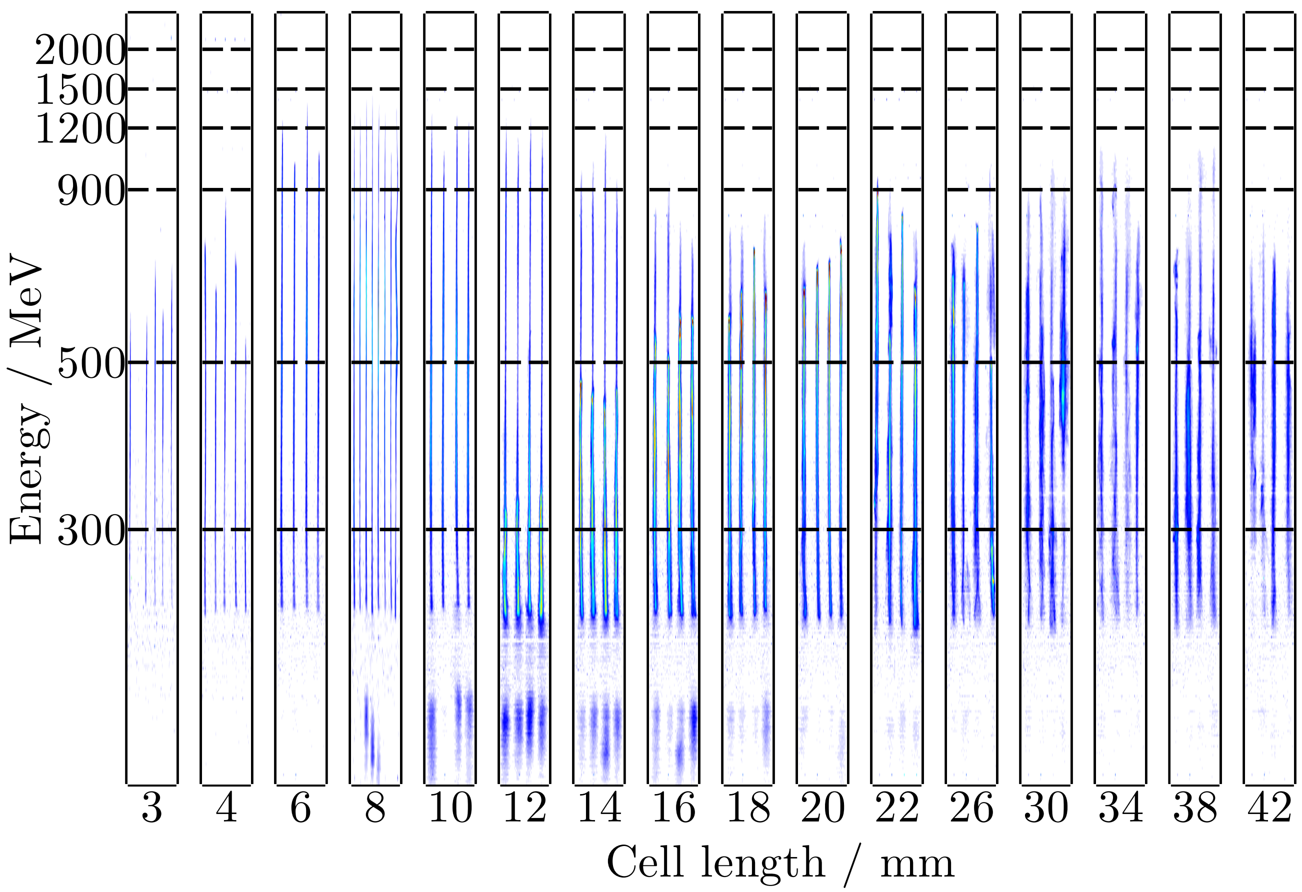
10.0 ± 0.3 J

$L_{cell} = 20$ mm

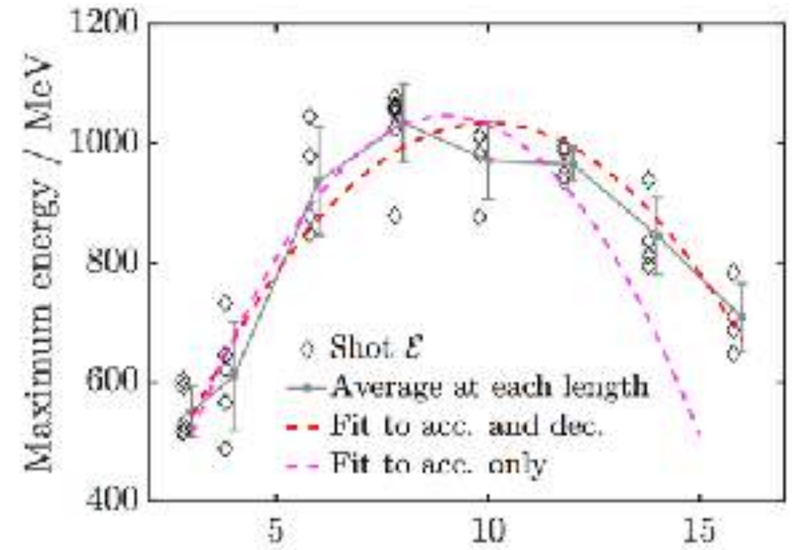
100 bar = $n_e \sim 3.0\times10^{18}$ cm^{-3}

Length Variations

Length scans probe injection and acceleration



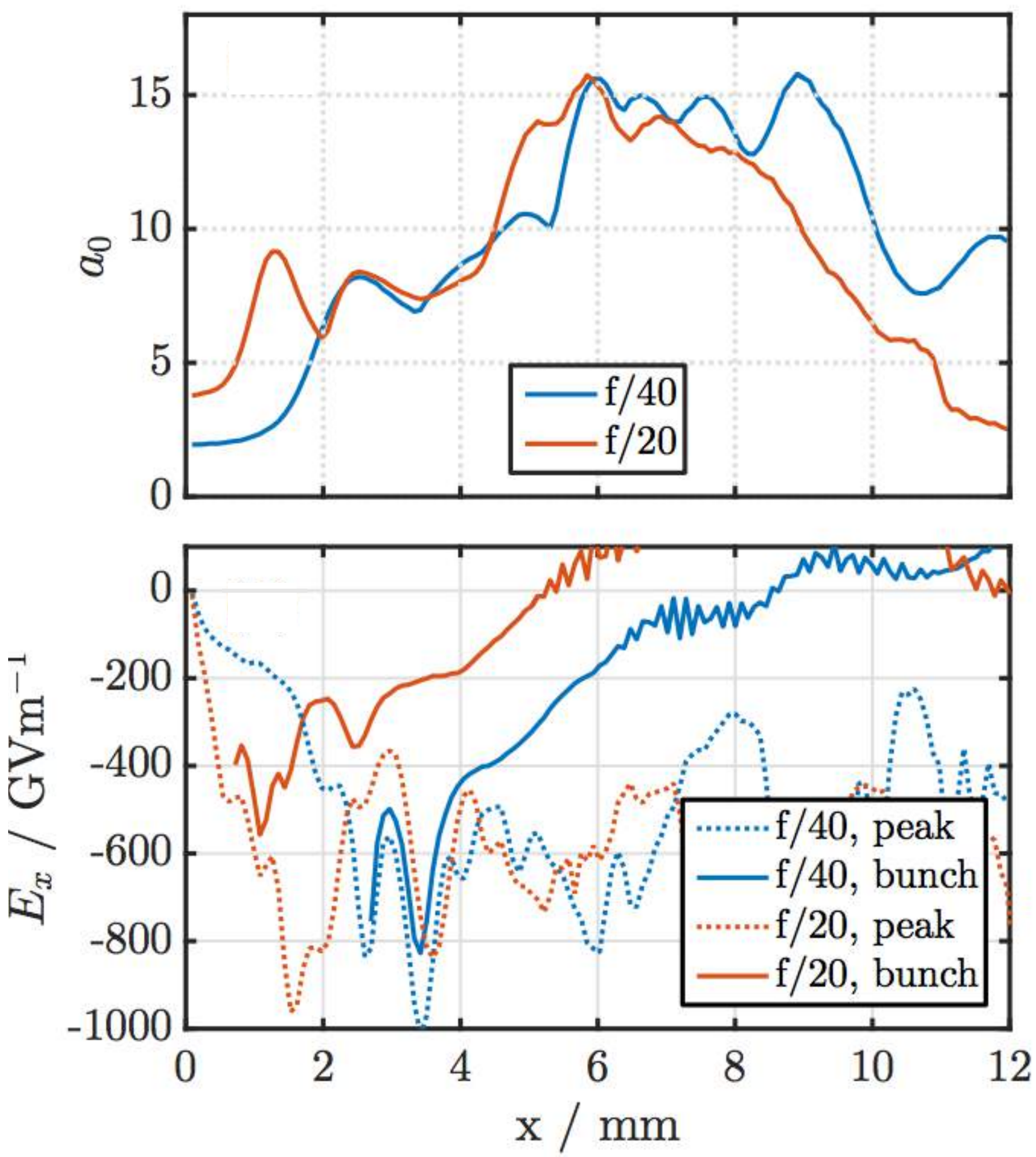
Energy on target
5.6 ± 0.7 J
Backing pressure
84.6 mbar
$n_e \sim 2.5\times10^{18}$ cm^{-3}

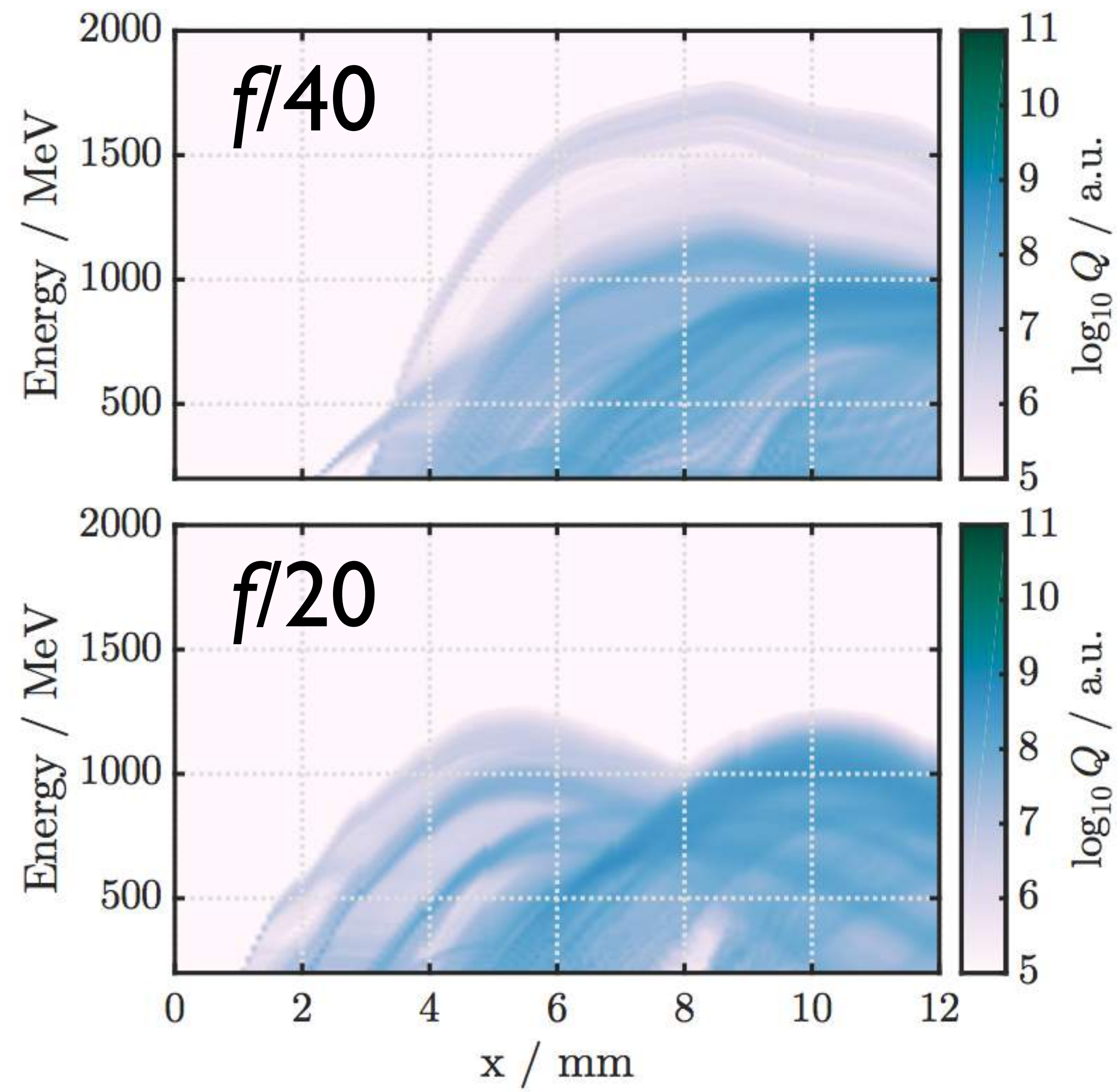


$$W(\ell) = \tilde{E}_p \cdot \ell \left(1 - \frac{\ell}{2L_{dp}}\right)$$

a_0	n_e $10^{18}\,\mathrm{cm}^{-3}$	E_{peak} GV/m		L_{dph} mm		x_{inj} mm	
		Acc only	All	Acc only	All	Acc only	All
1.5	1.6	113 ± 4	124 ± 15	34.4 ± 1.6	30.0 ± 5.6	1.6 ± 3.1	2.3 ± 11.0
1.1	2.3	362 ± 27	349 ± 39	10.3 ± 1.0	10.4 ± 1.7	0.2 ± 2.0	0.0 ± 3.2
1.0	2.6	339 ± 49	336 ± 62	9.7 ± 1.9	9.6 ± 2.4	-0.2 ± 3.6	-0.4 ± 4.7
1.5	2.6	290 ± 15	284 ± 24	12.0 ± 0.8	12.6 ± 1.6	1.0 ± 1.5	0.9 ± 3.2
1.0	3.2	570 ± 190	540 ± 200	5.6 ± 2.4	5.8 ± 2.7	0.9 ± 4.3	0.6 ± 5.1

Comparing *f*/20 to *f*/40

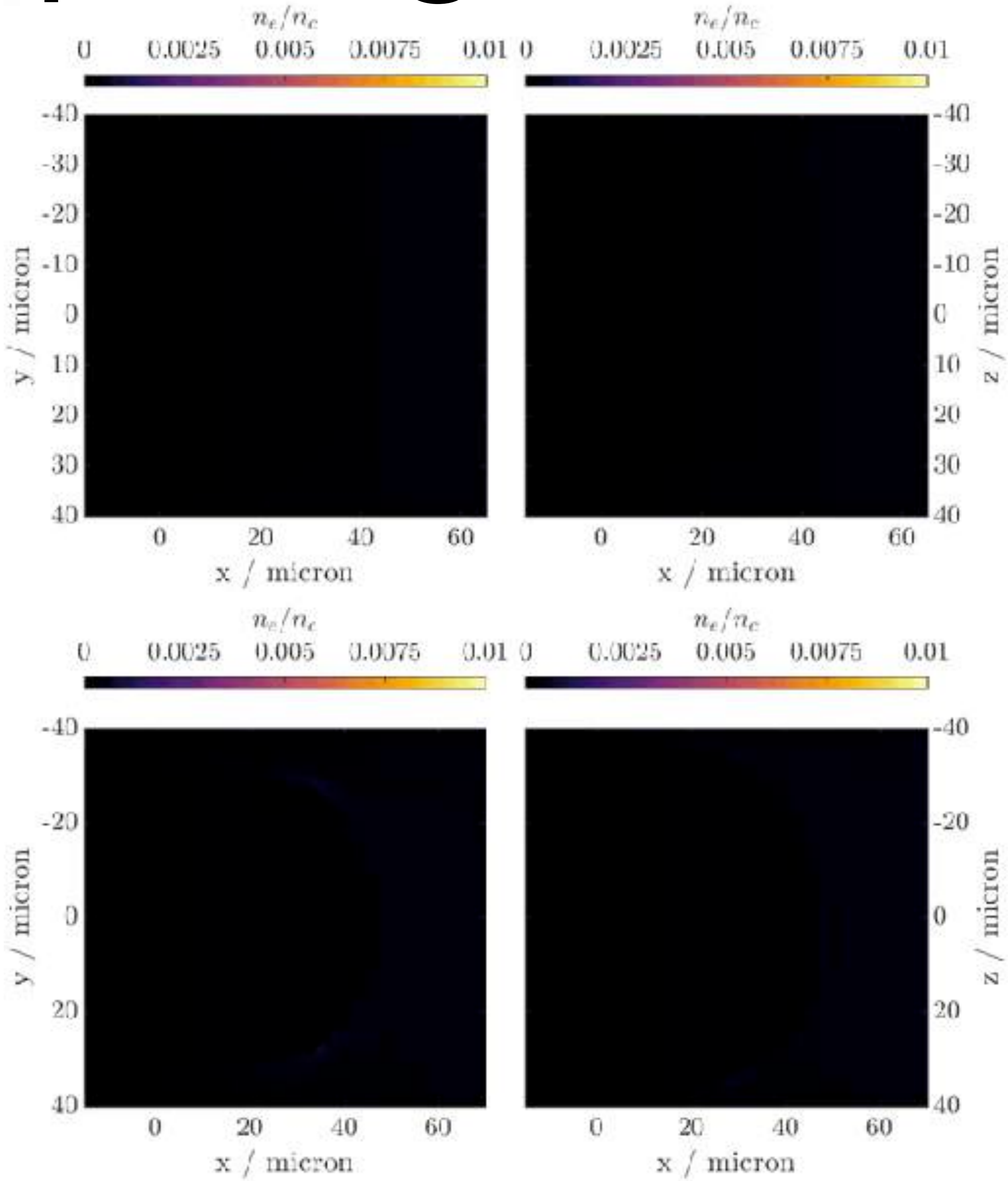




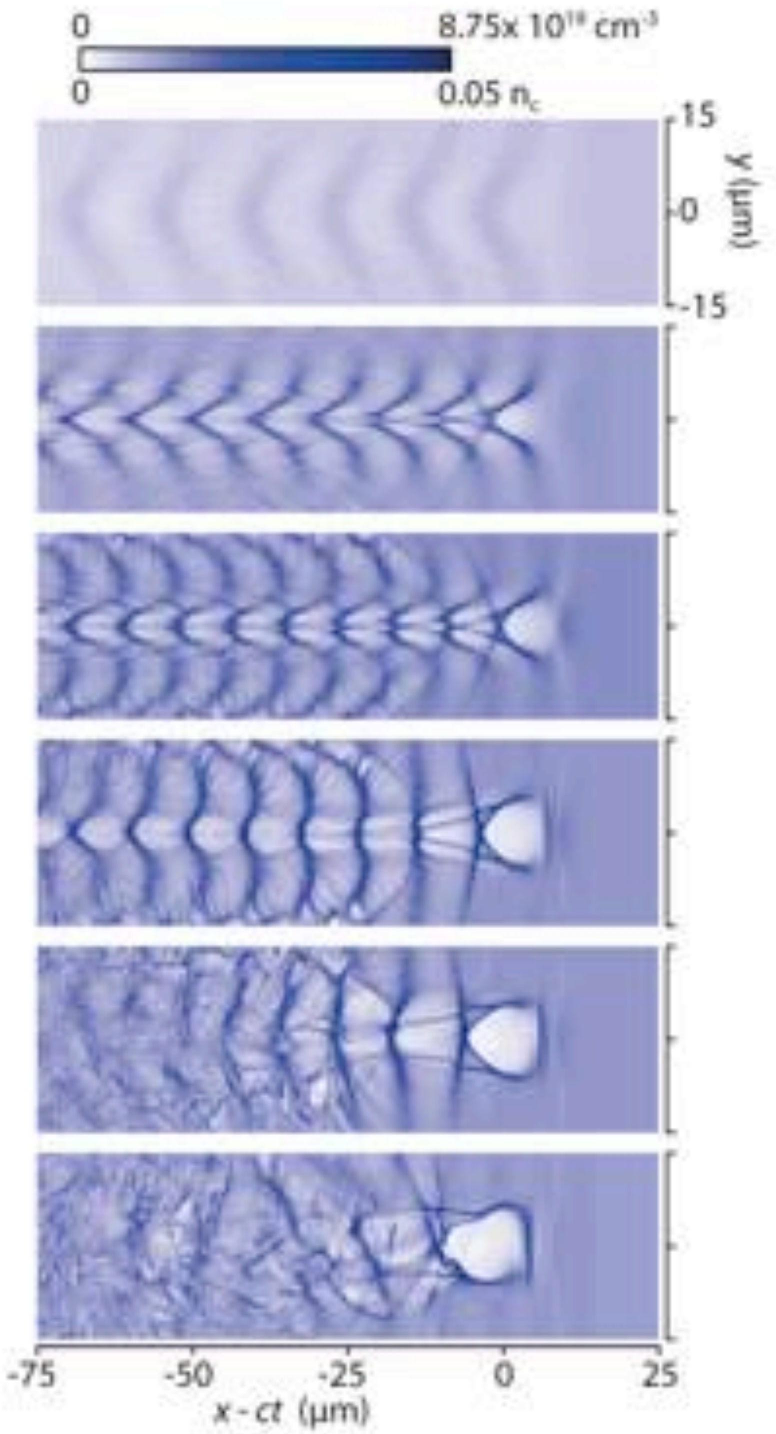
Comparing f/20 to f/40

f/40

f/20

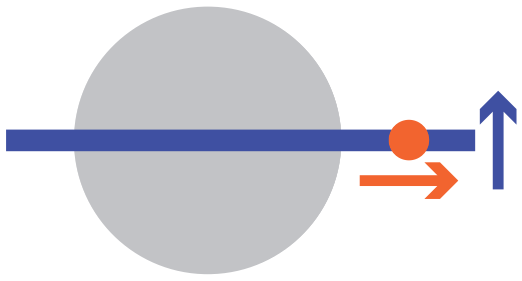


Wakefield imaging at IOQ, Jena

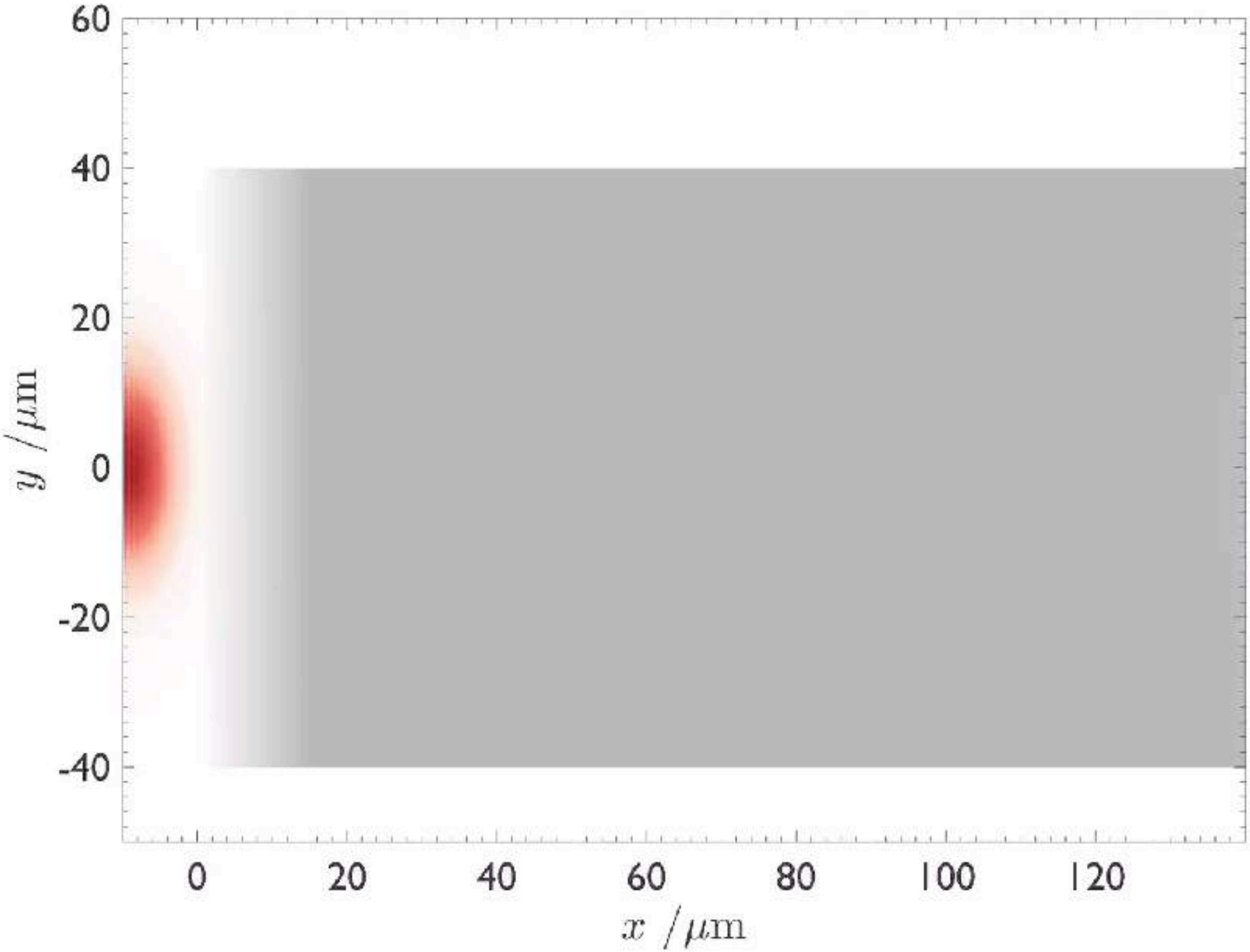


A. Sävert, et al. Near-GeV Acceleration of Electrons by a Nonlinear Plasma Wave Driven by a Self-Guided Laser Pulse. Phys. Rev. Lett. 115, 055002 (2015).

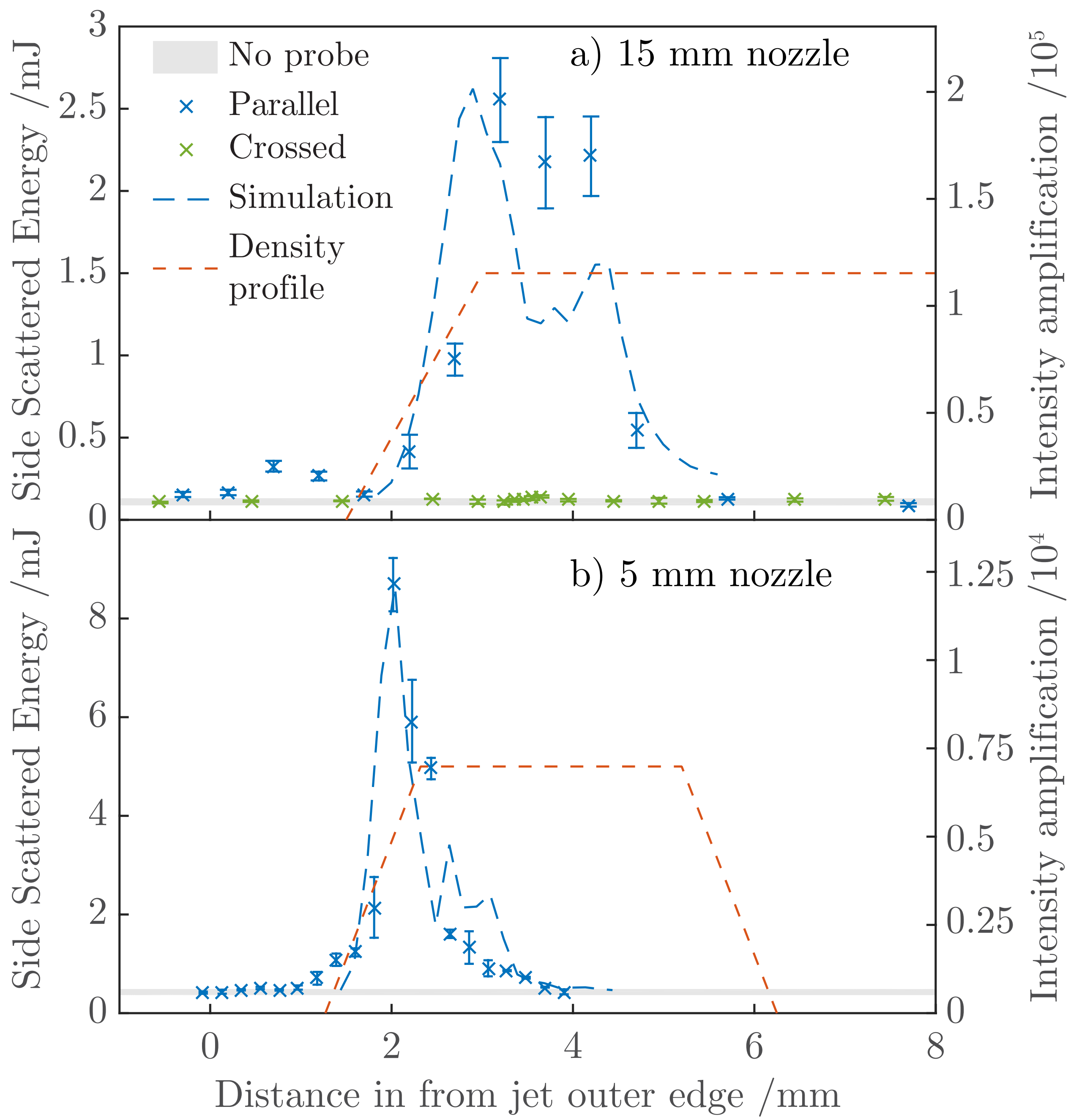
Imaging on Astra Gemini



Simulation of amplification



Superradiant amplification



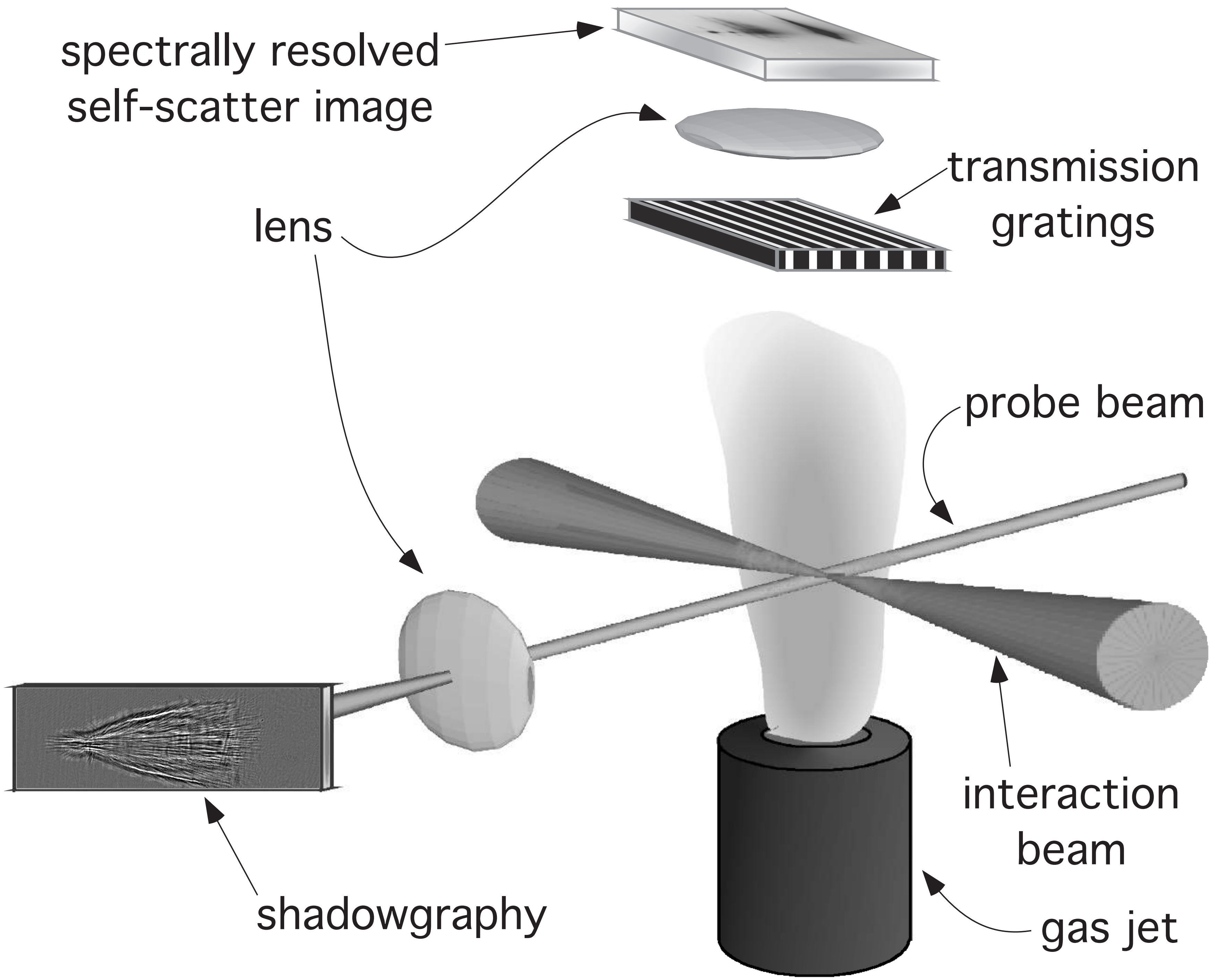
Intensity amplification of >10^5 seen in a crossing distance of < 30 μm

$$a^2 \approx \frac{64}{9}\left(\frac{n_e}{n_c}\right)^2\left(\frac{x}{\lambda_0}\right)^2 a_0^2.$$

Scaling of growth $\propto n_e^2$

➔ super radiance

Imaging on Vulcan TAW



Laser energy ~ 30 J
Pulse length 1 ps
f/3 focussing
Intensity > 10^{19} Wcm^{-2}

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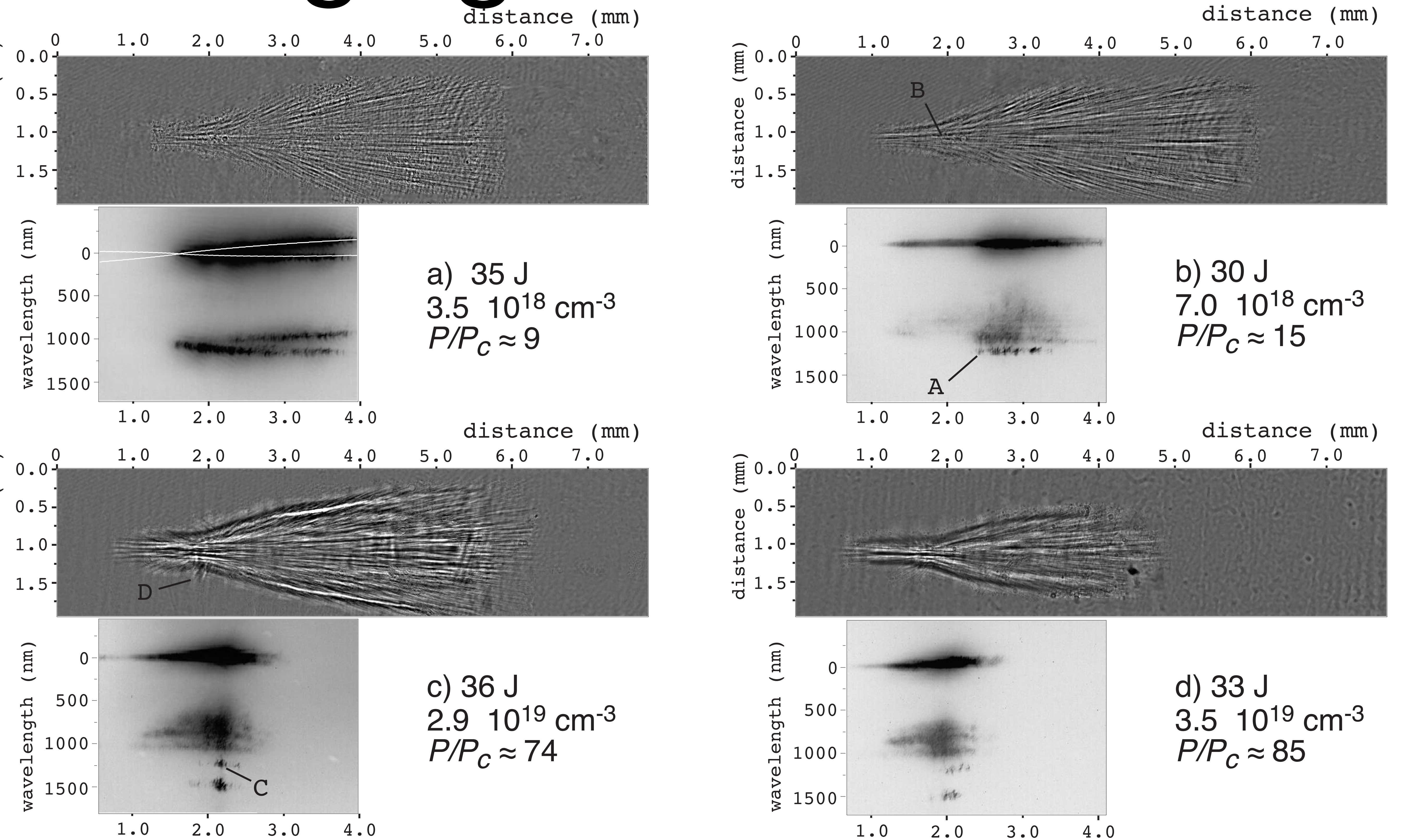
Imperial College London

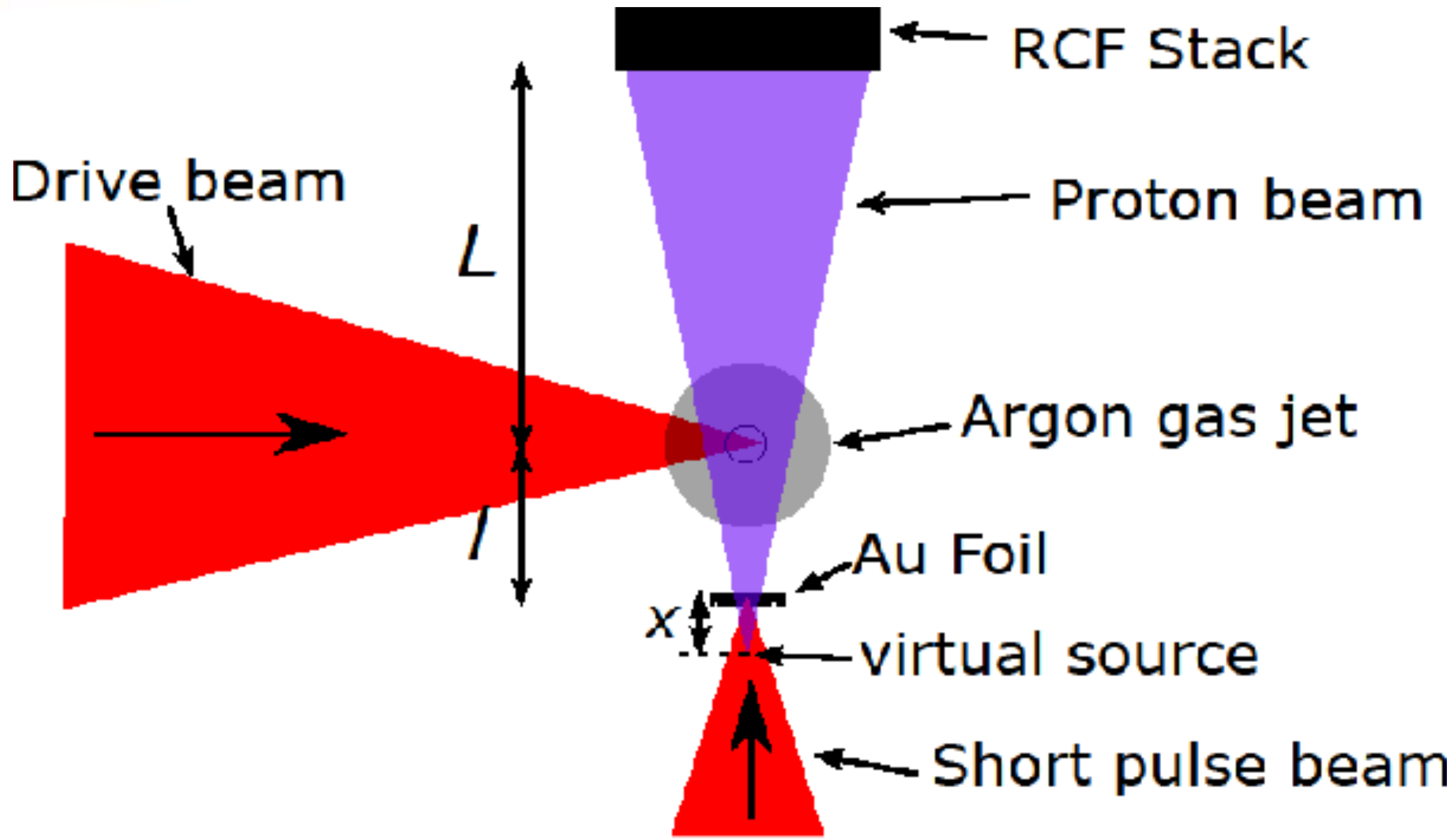
UNIVERSITY OF OXFORD

Royal Holloway University of London

Imaging on Vulcan TAW



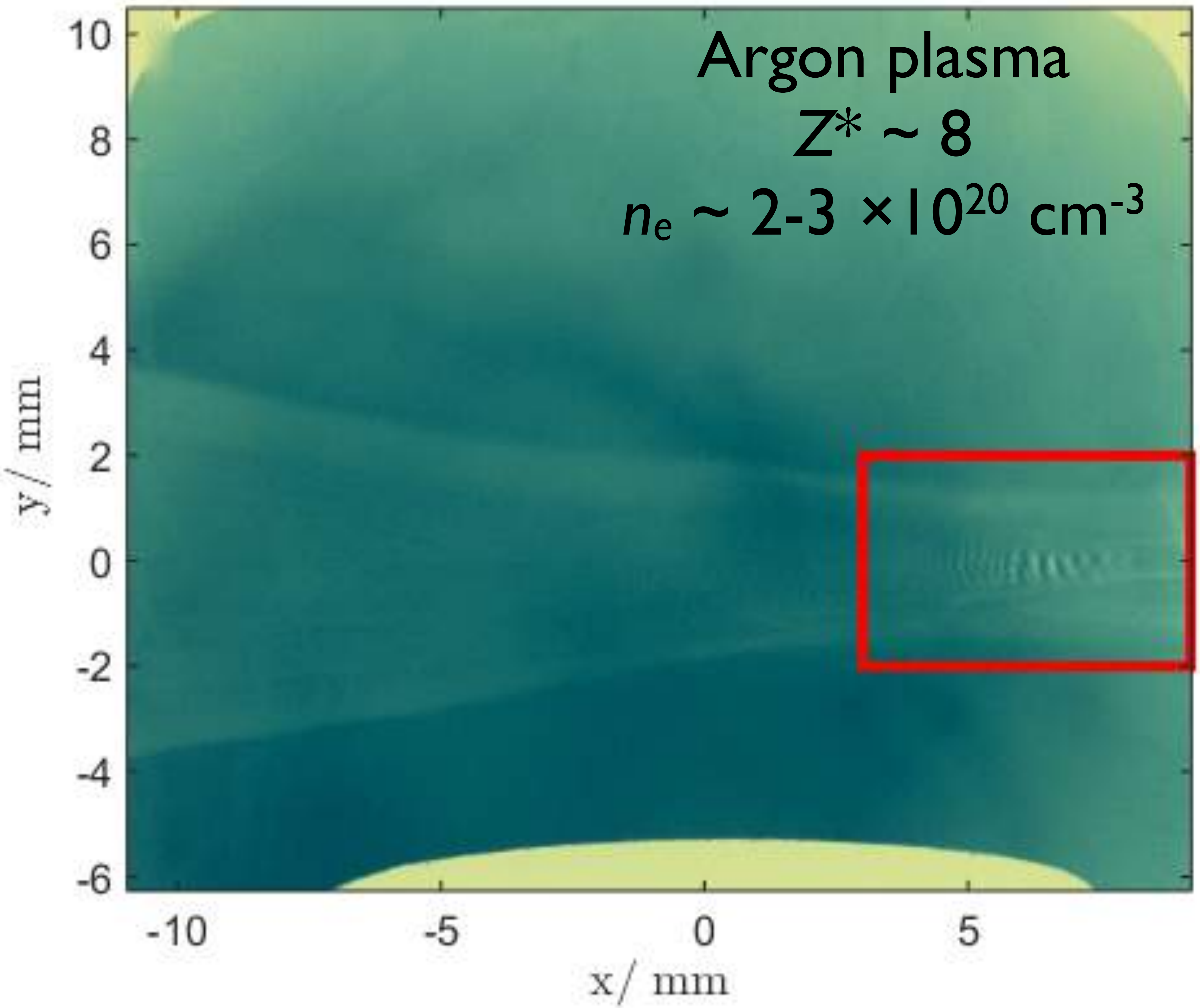
Experimental set-up



	Drive beam	Short pulse beam
Energy/ J	100 ± 10	55 ± 5
Pulse Duration/ ps	15	1
Focal spot size/ μm	20	20
Peak Intensity/ Wcm^{-2}	$9.5 \pm 0.9 \times 10^{17}$	$7.5 \pm 0.7 \times 10^{18}$
a_0	0.88	2.53

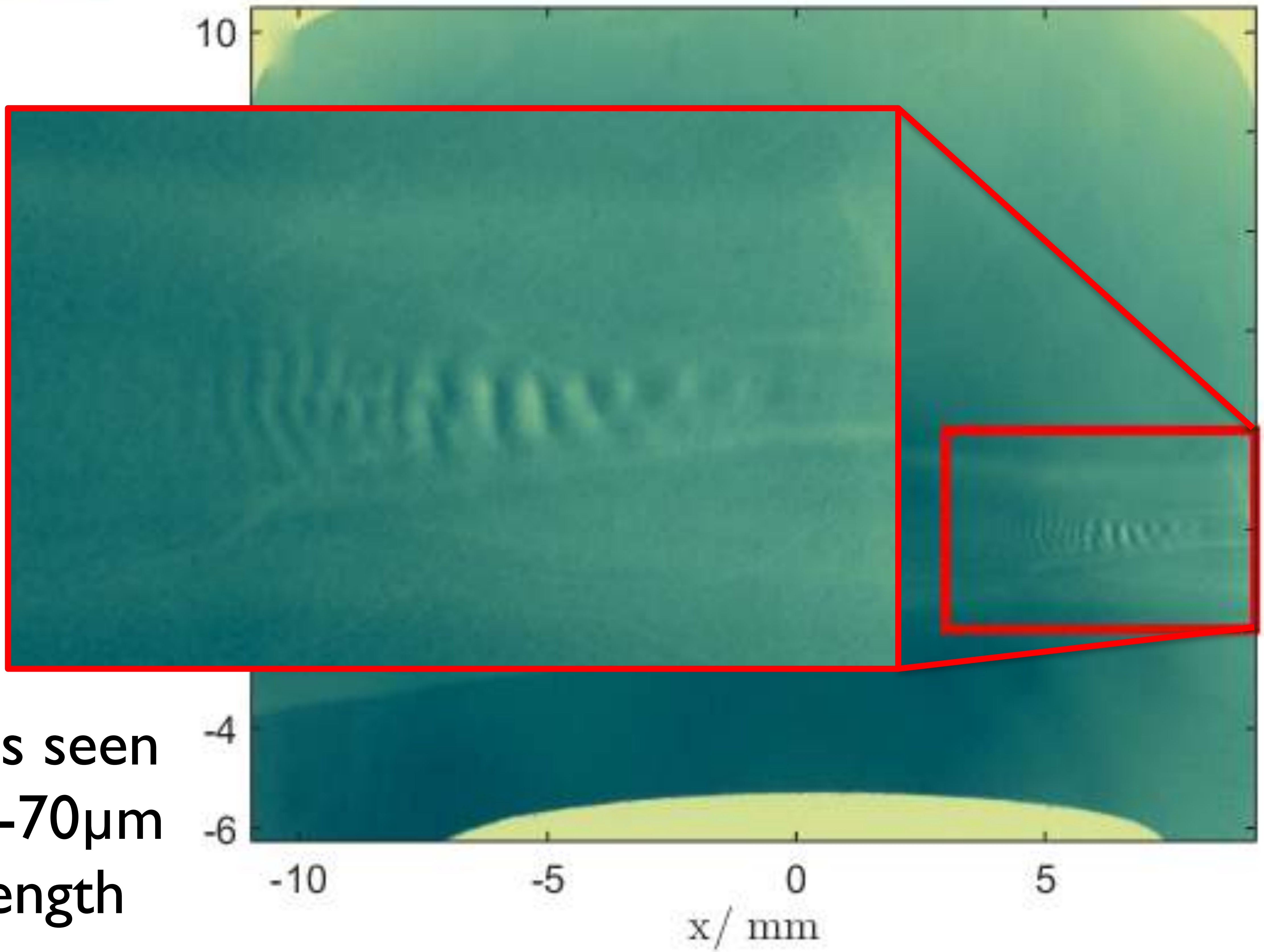
Experimental Data

Laser propagation direction



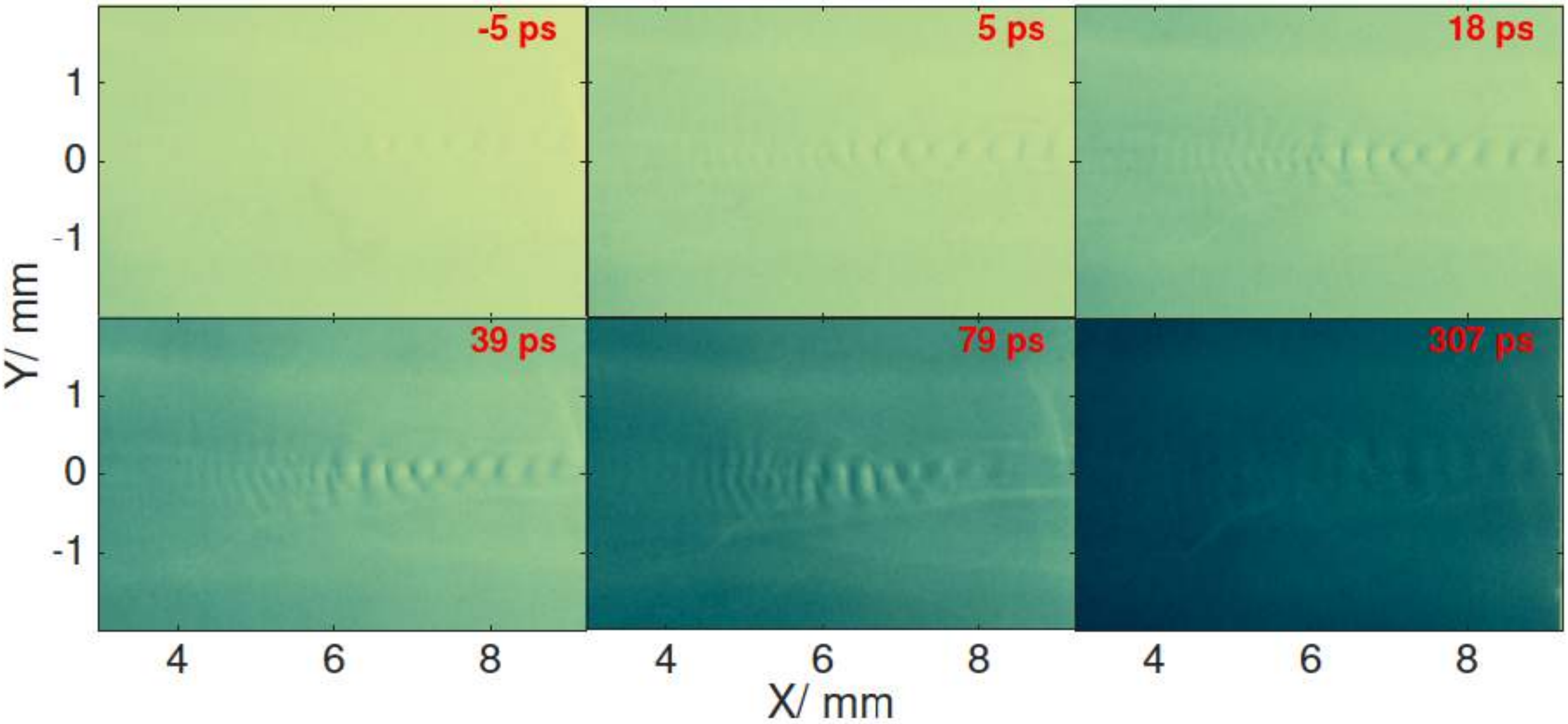
Experimental Data

Laser propagation direction



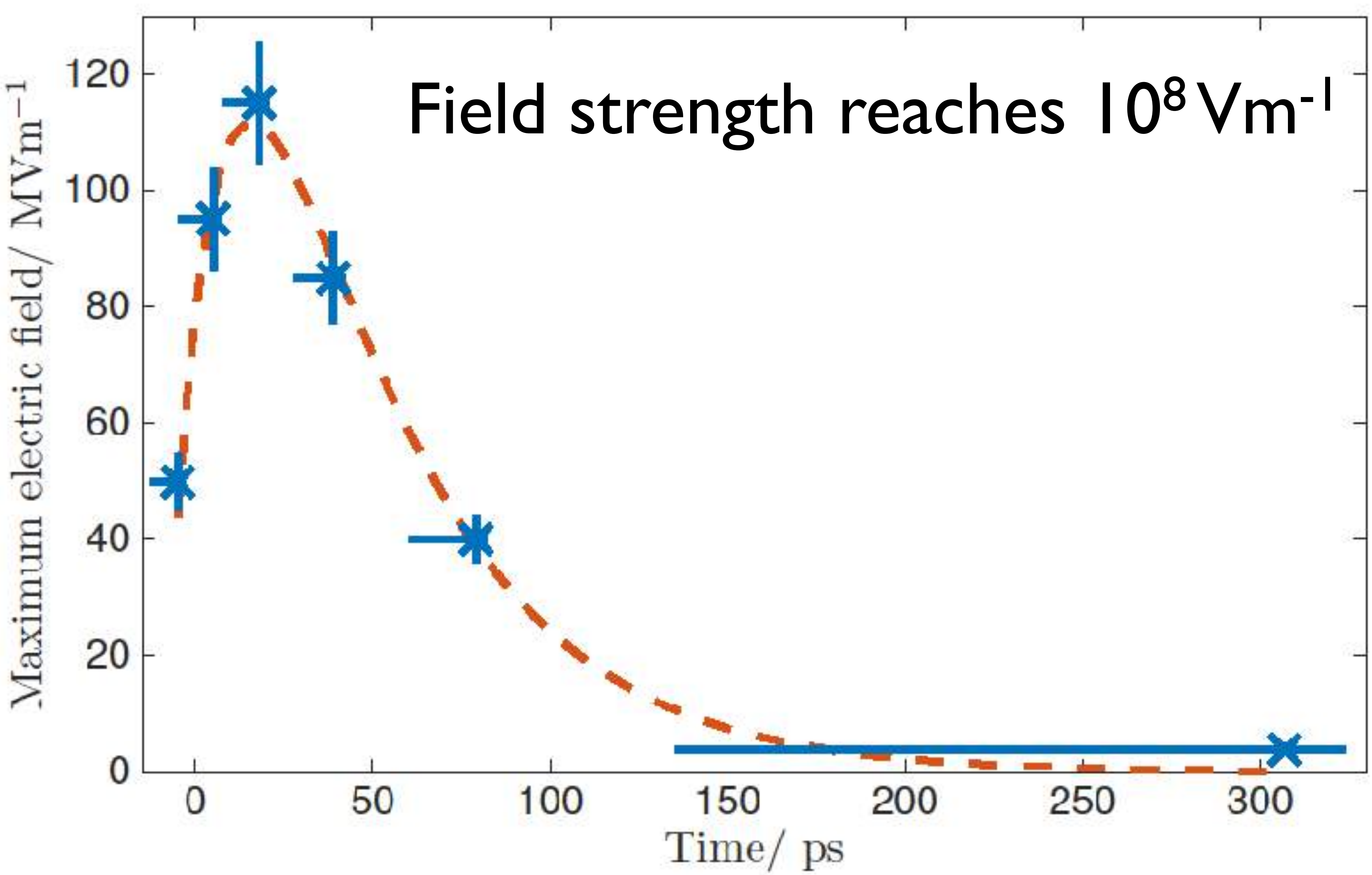
Features seen with 30-70μm wavelength

Oscillatory structure



Deflecting electric field

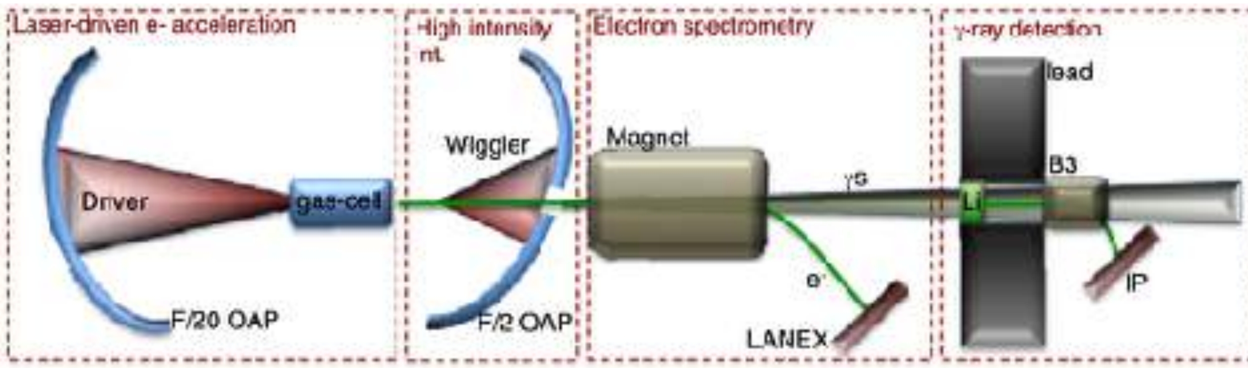
- Fit an electric field for each timestep



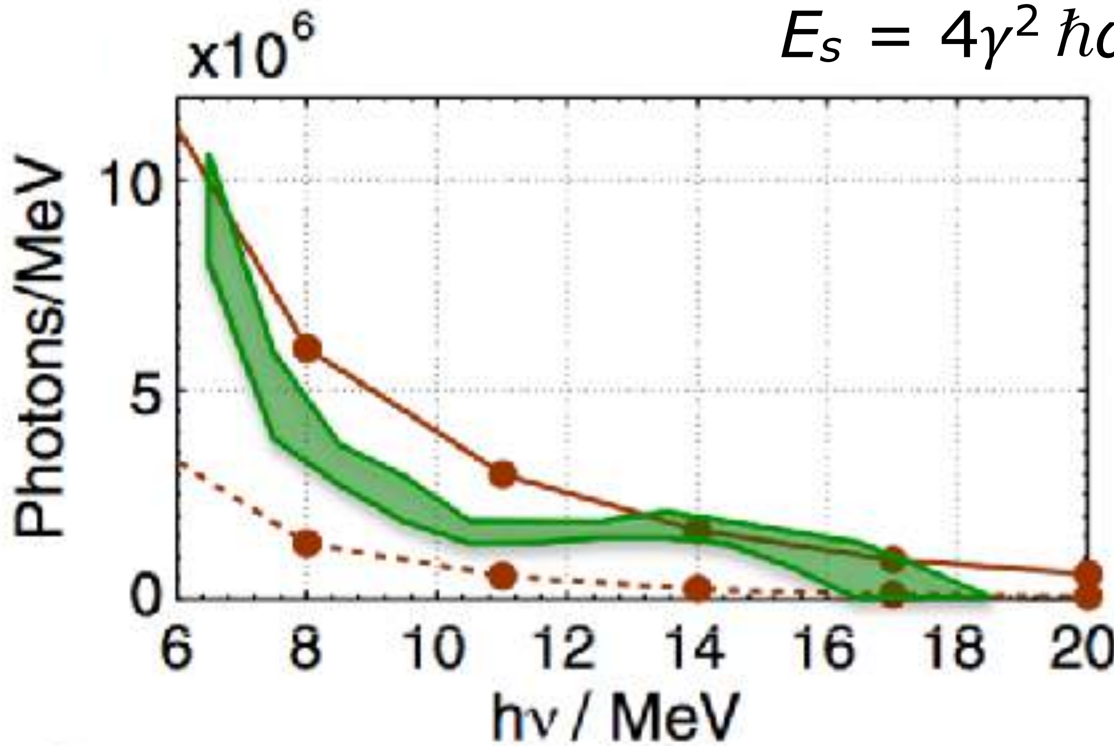
Radiation Generation and Applications

John Adams Institute for Accelerator Science · Queen's University Belfast · Imperial College London · University of Oxford · Royal Holloway University of London

Compton Scattering



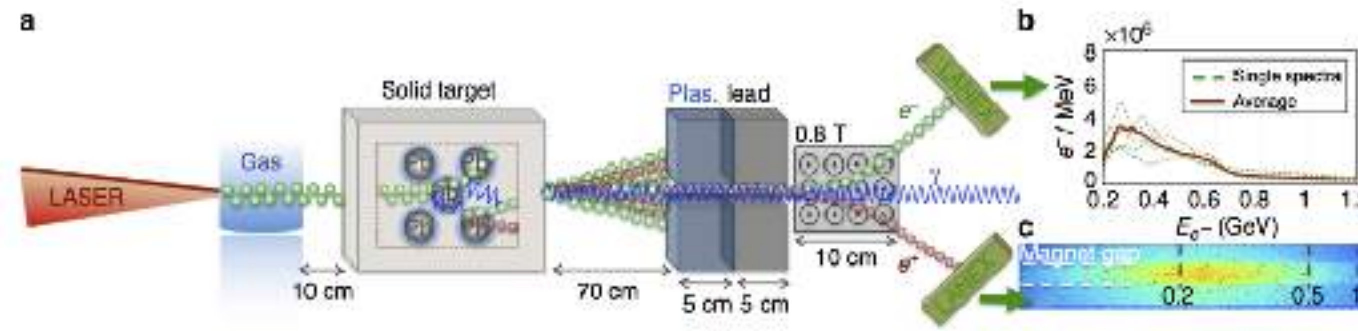
$E_s = 4\gamma^2 \hbar\omega$

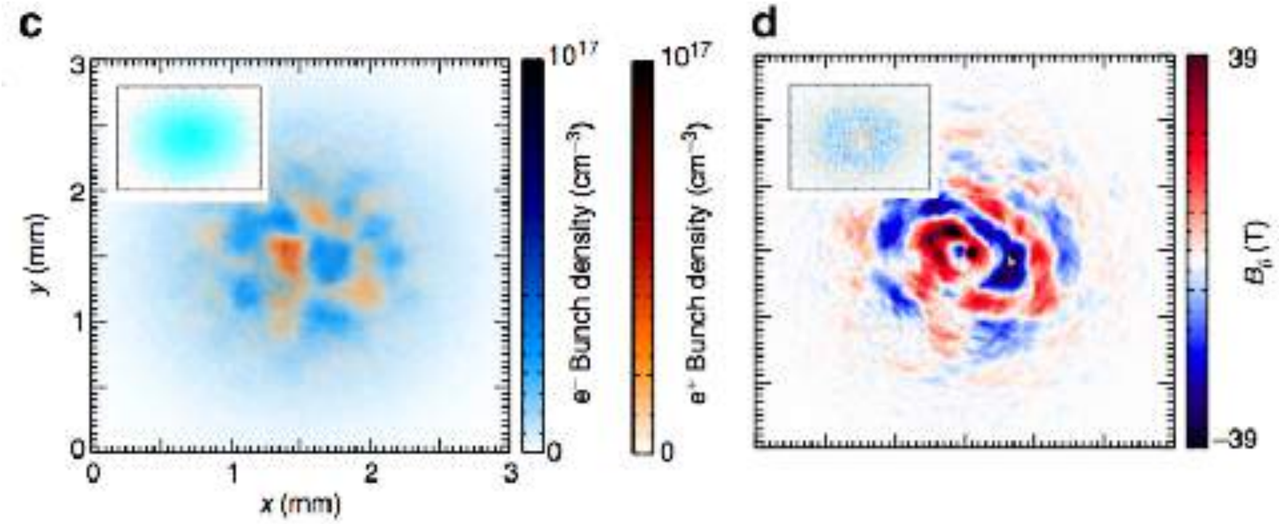


B >10^{20} photons / sec mrad^2 mm^2 0.1%BW

Sarri, G. et al. Ultrahigh Brilliance Multi-MeV γ-Ray Beams from Nonlinear Relativistic Thomson Scattering. Phys. Rev. Lett. 113, 224801 (2014).

Near-neutral Positron

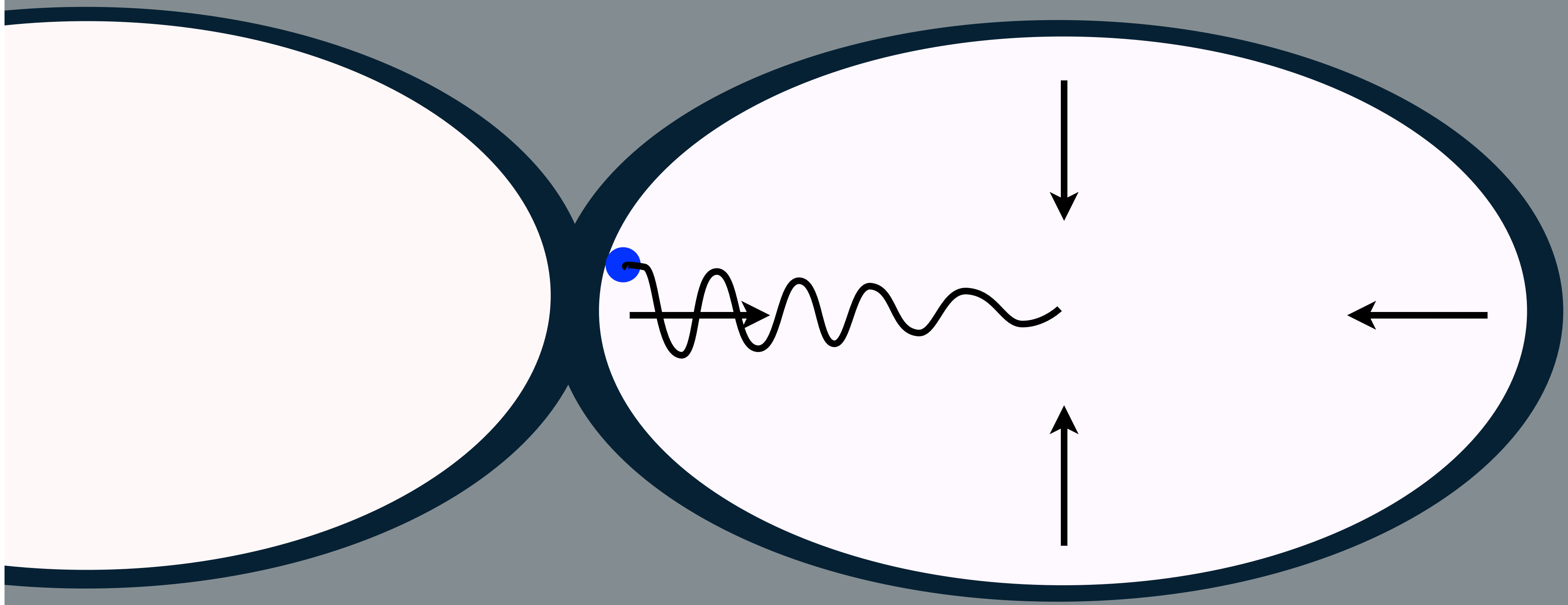




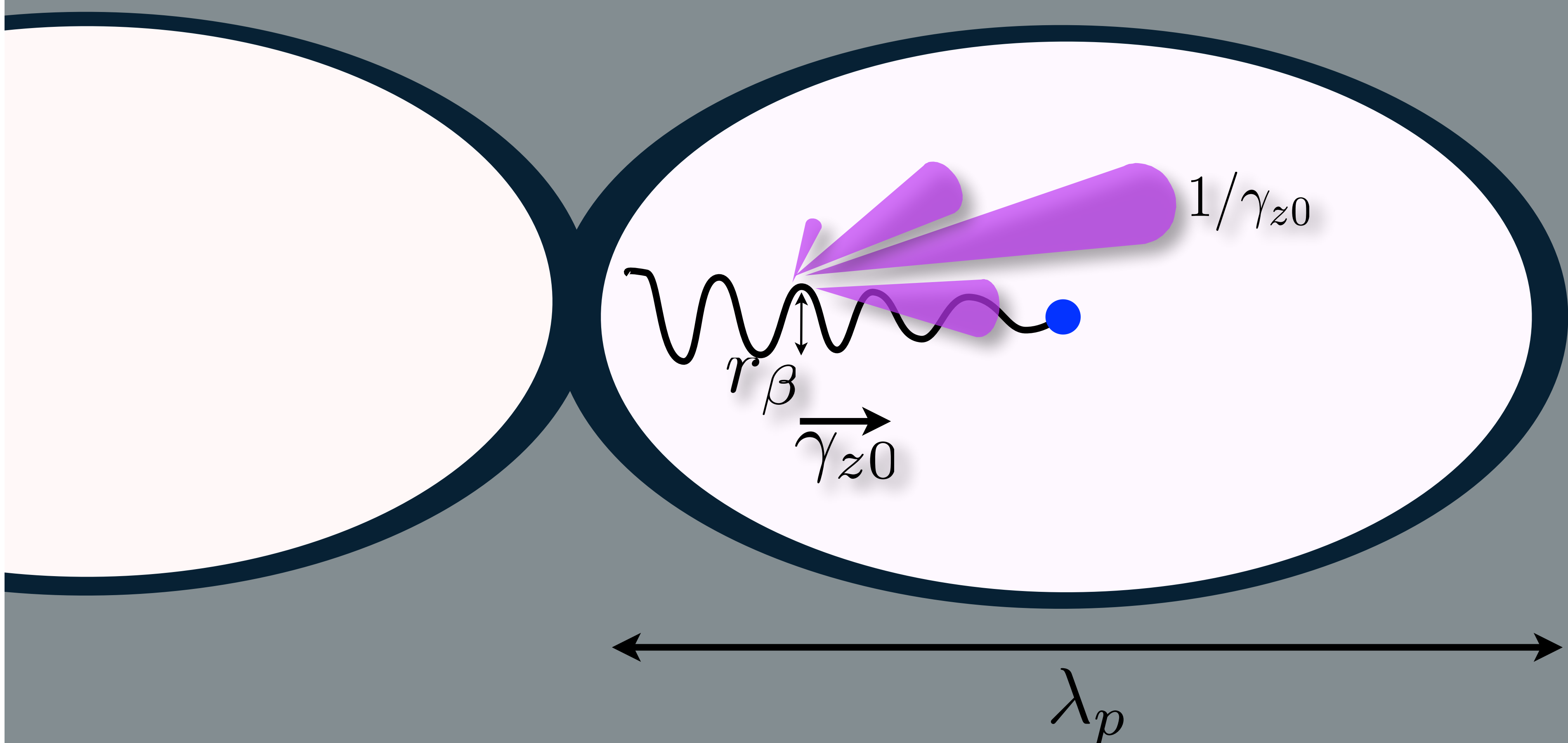
Prone to Weibel instabilities

Sarri, G. et al. Generation of neutral and high-density electron-positron pair plasmas in the laboratory. Nat. Commun. 6, 6747 (2015).

Acceleration



Radiation



$$P_s = \frac{e^2 c}{3}\gamma_{z0}^2 k_\beta^2 a_\beta^2$$

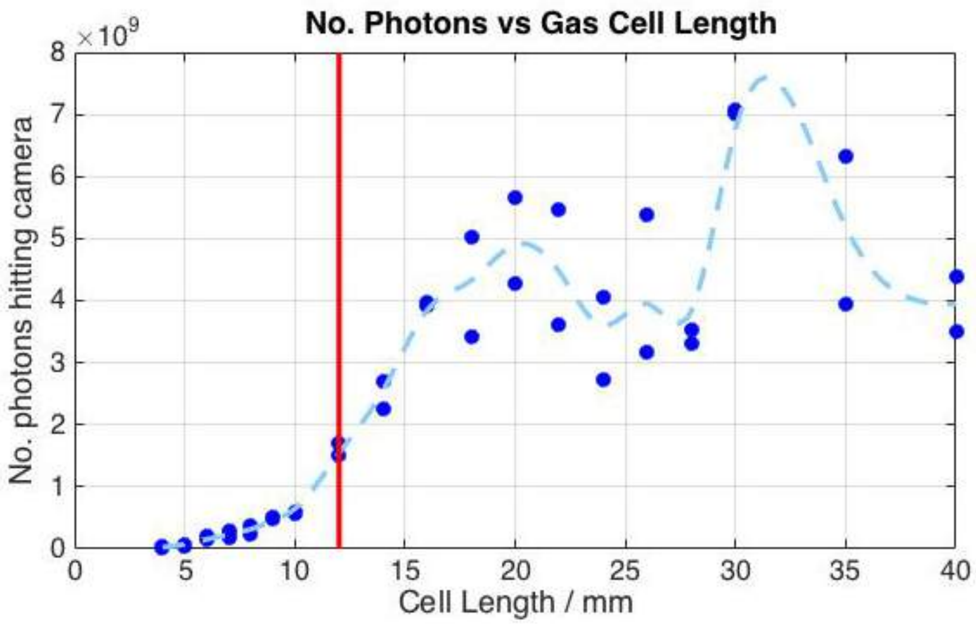
$$a_\beta = \gamma_{z0} r_\beta k_\beta$$

$$\omega_c = 3\gamma^3 \omega_\beta^2 r_\beta / c$$

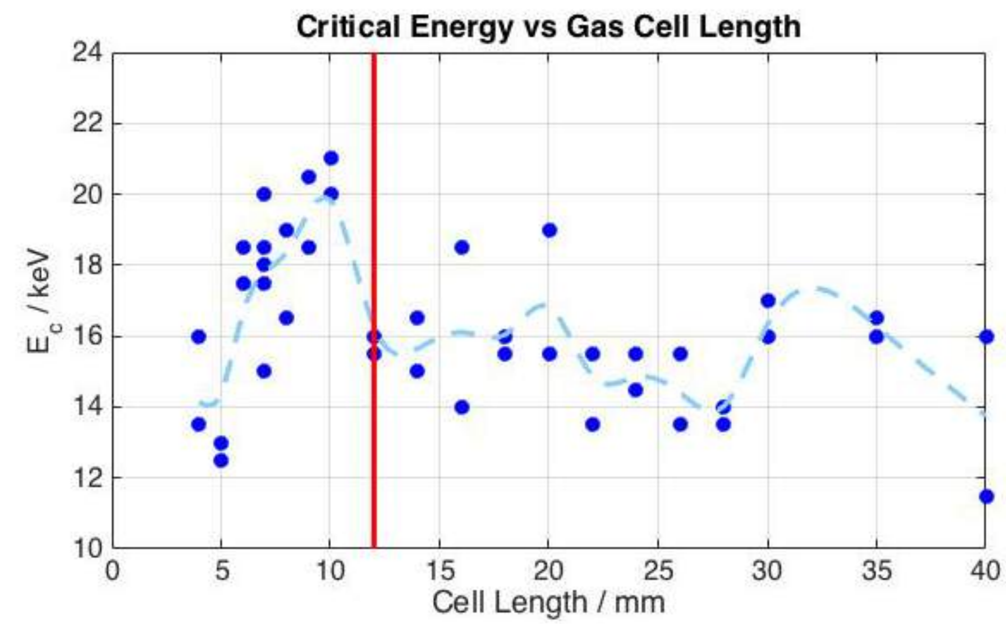
E Esarey PRE **65**, 056505 (2002)

Betatron Radiation Characteristics

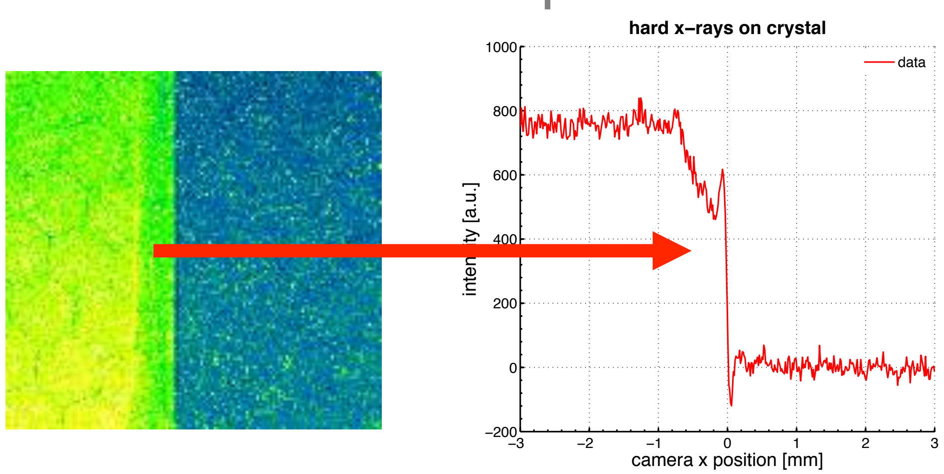
density n_e = 2.25x10^{18} cm^{-3}



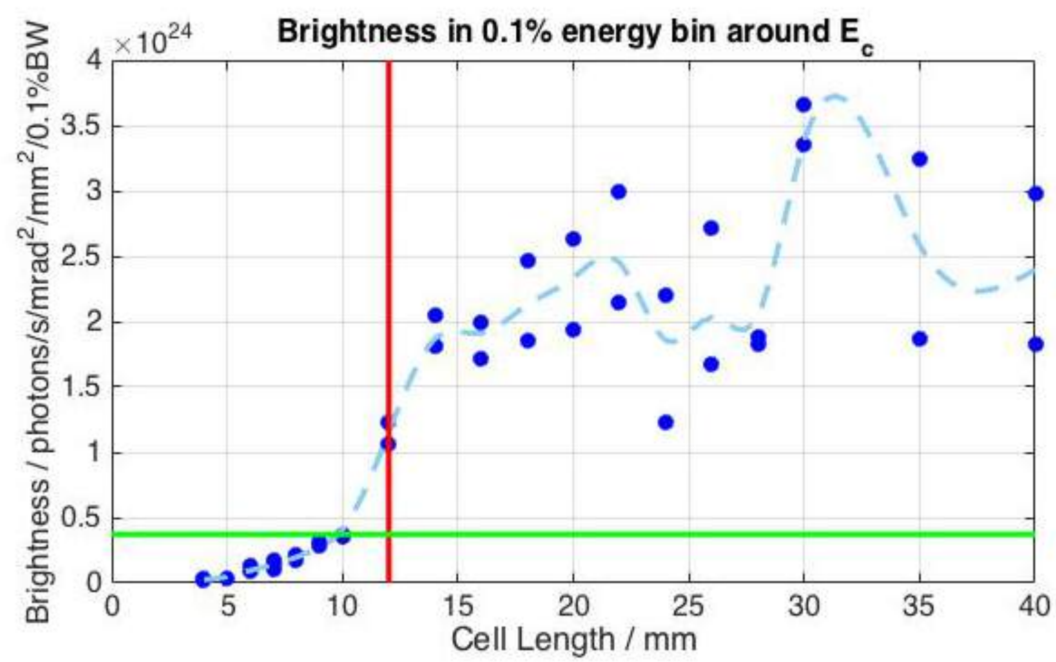
spectrum obtained by differential transmission



Source size **2.65** μm fwhm



small source size ideal for phase contrast imaging



Properties of β-tron sources

'Hard' photon energy - $E_{crit} > 25$ keV

- investigating dense material, biological materials

Small source **size** (~ μm)

- intrinsically high resolution
- exhibits spatial resolution

Small **divergence** (~ 10 mRad)

- makes beam line

Short pulse (~10s fs)

- suitable for ultrafast dynamics

Bright (>10^9 photons per shot)

- suitable for single shot imaging

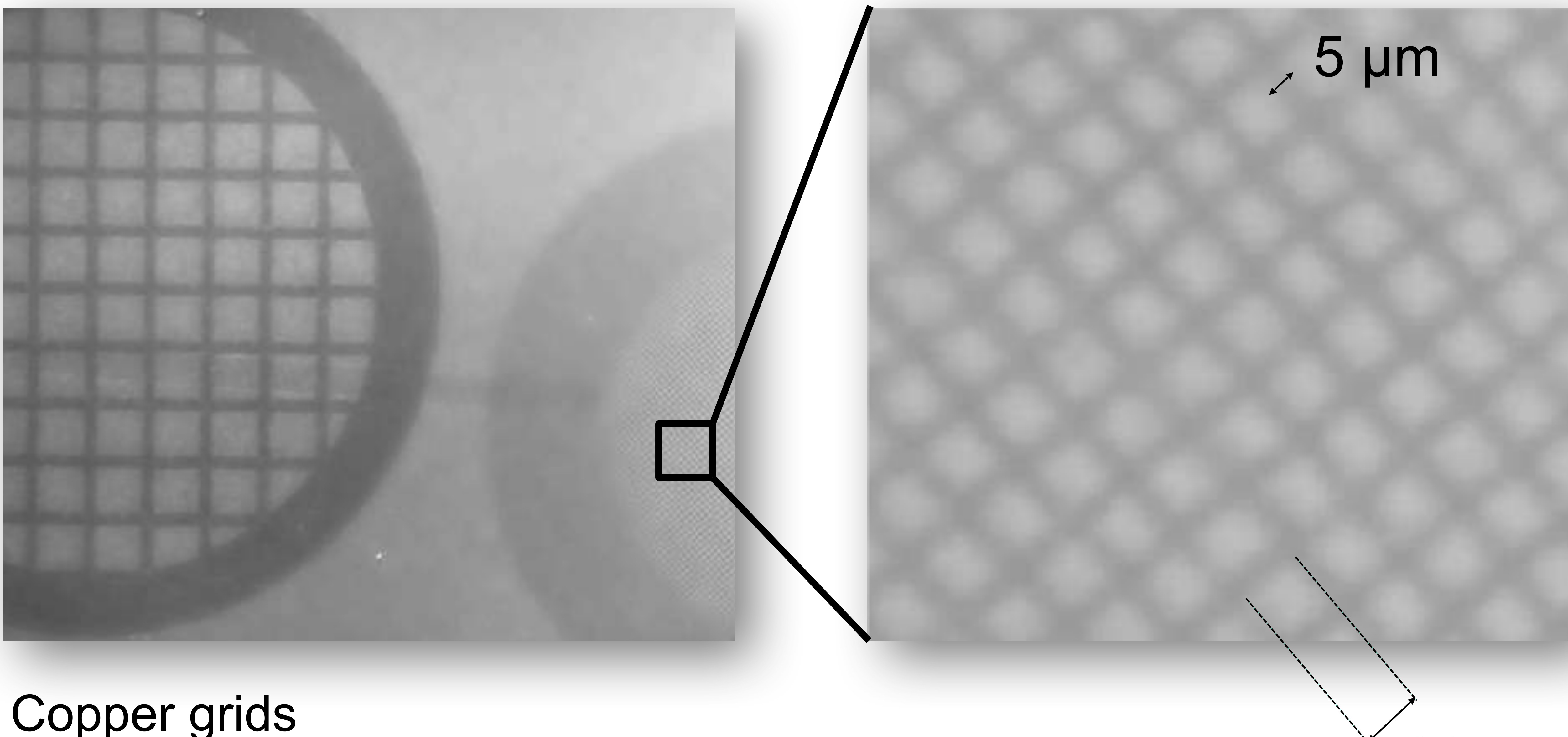
All of these things makes for a unique imaging capability

X-ray beams

Source size < 3 µm

Resolution target + processing

Zoom

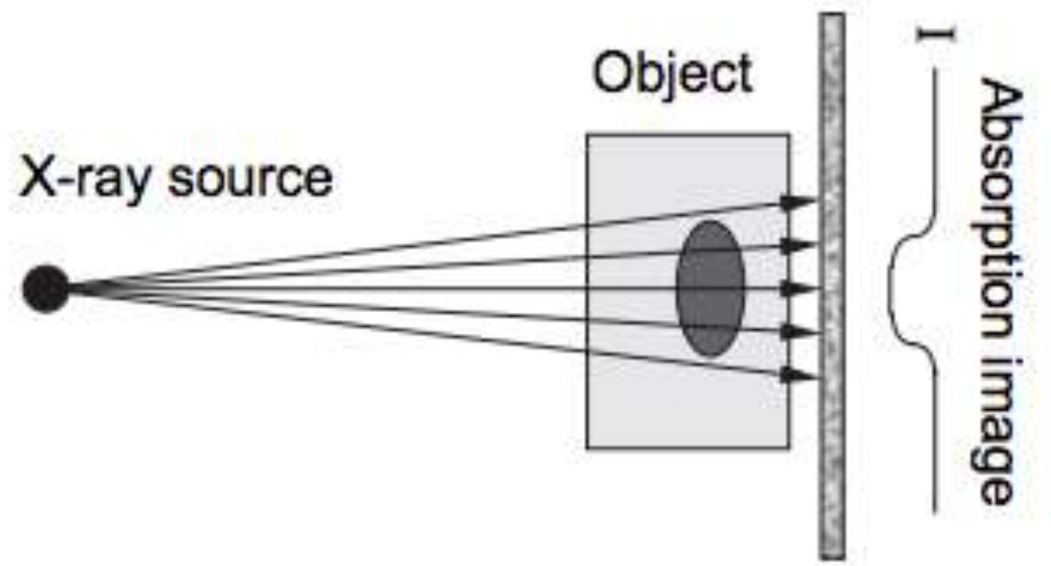


Copper grids

Phase vs. absorption contrast

Absorption contrast

Contrast through photon absorption



Phase shift — Absorption

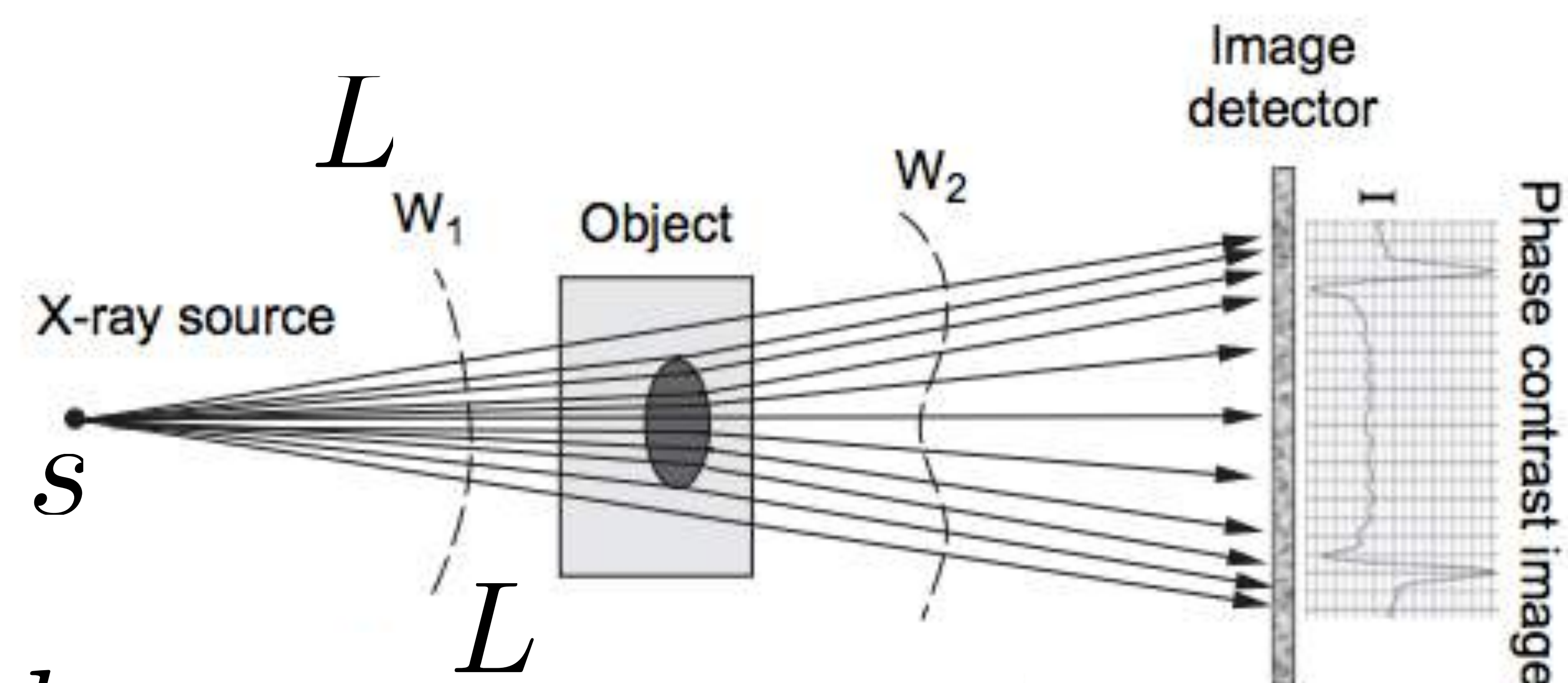
$$n = 1 - \delta - i\beta$$

$$\frac{\delta}{\beta} \propto E^2$$

Phase contrast

Object deflects photons, highlighting edges

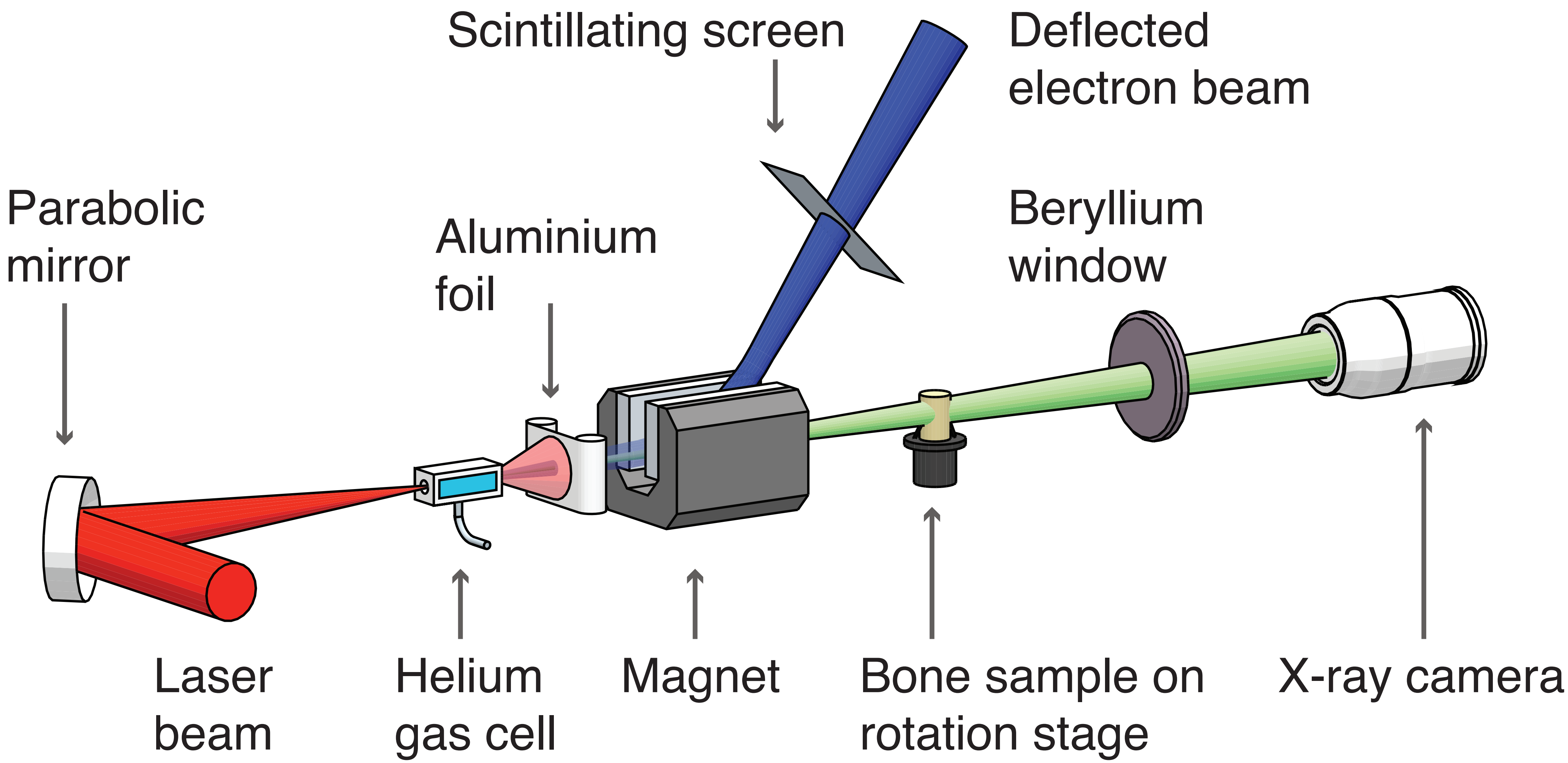
Propagation-based, works for polychromatic sources



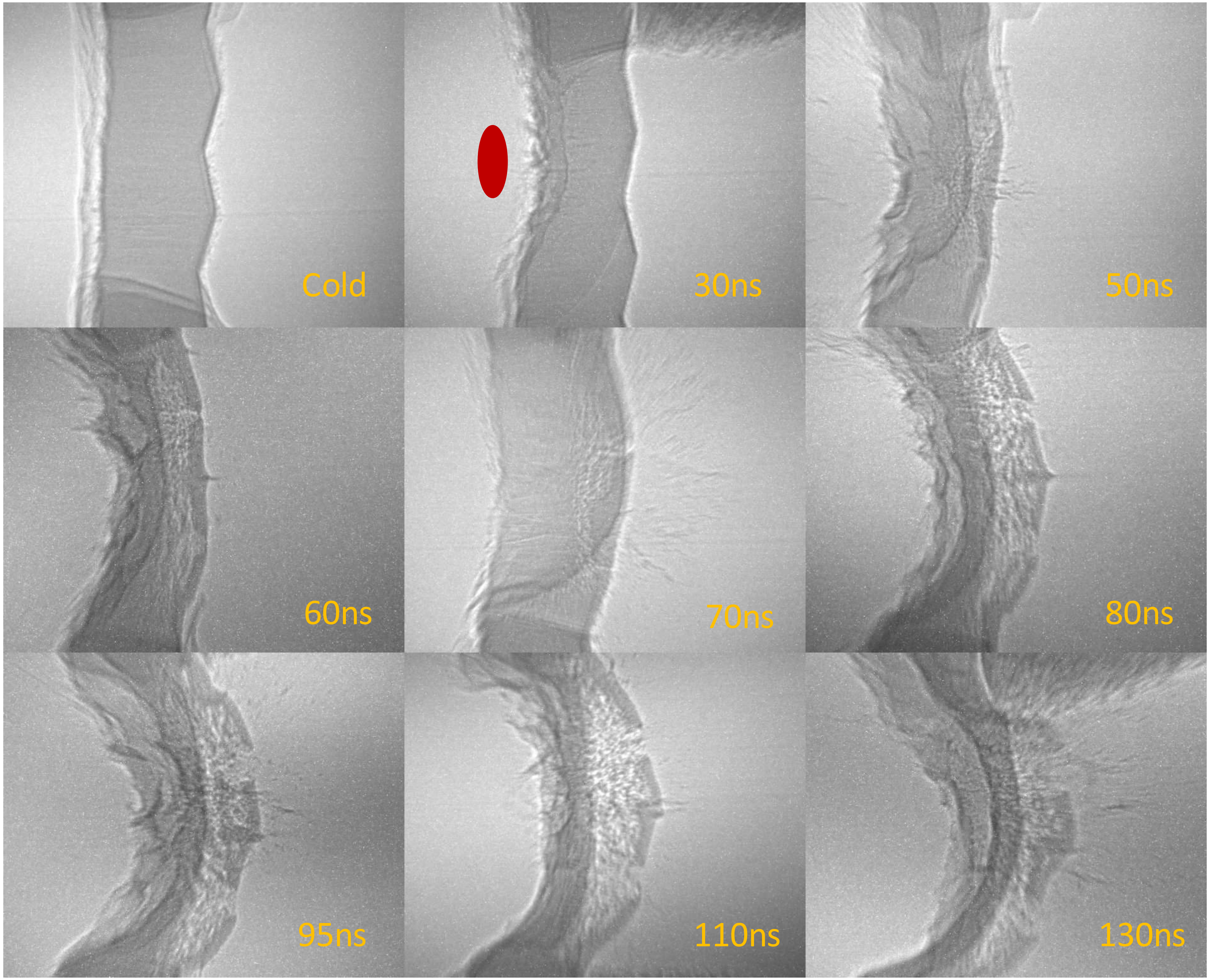
$$l_{coh} = \frac{L}{sE}$$

Zhou S-A and Brahme A, Physica Medica (2008) **24**

Experimental Set-up



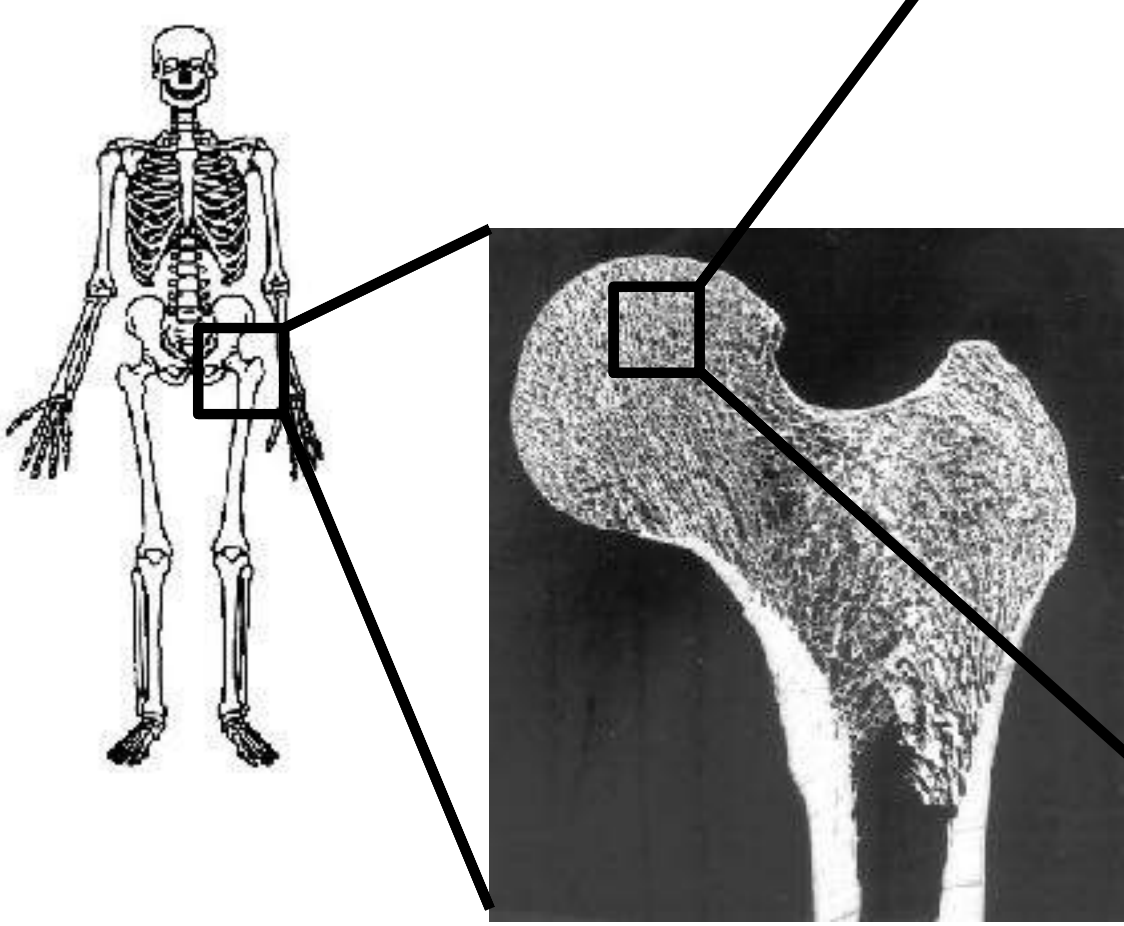
Time Series: corrugated target

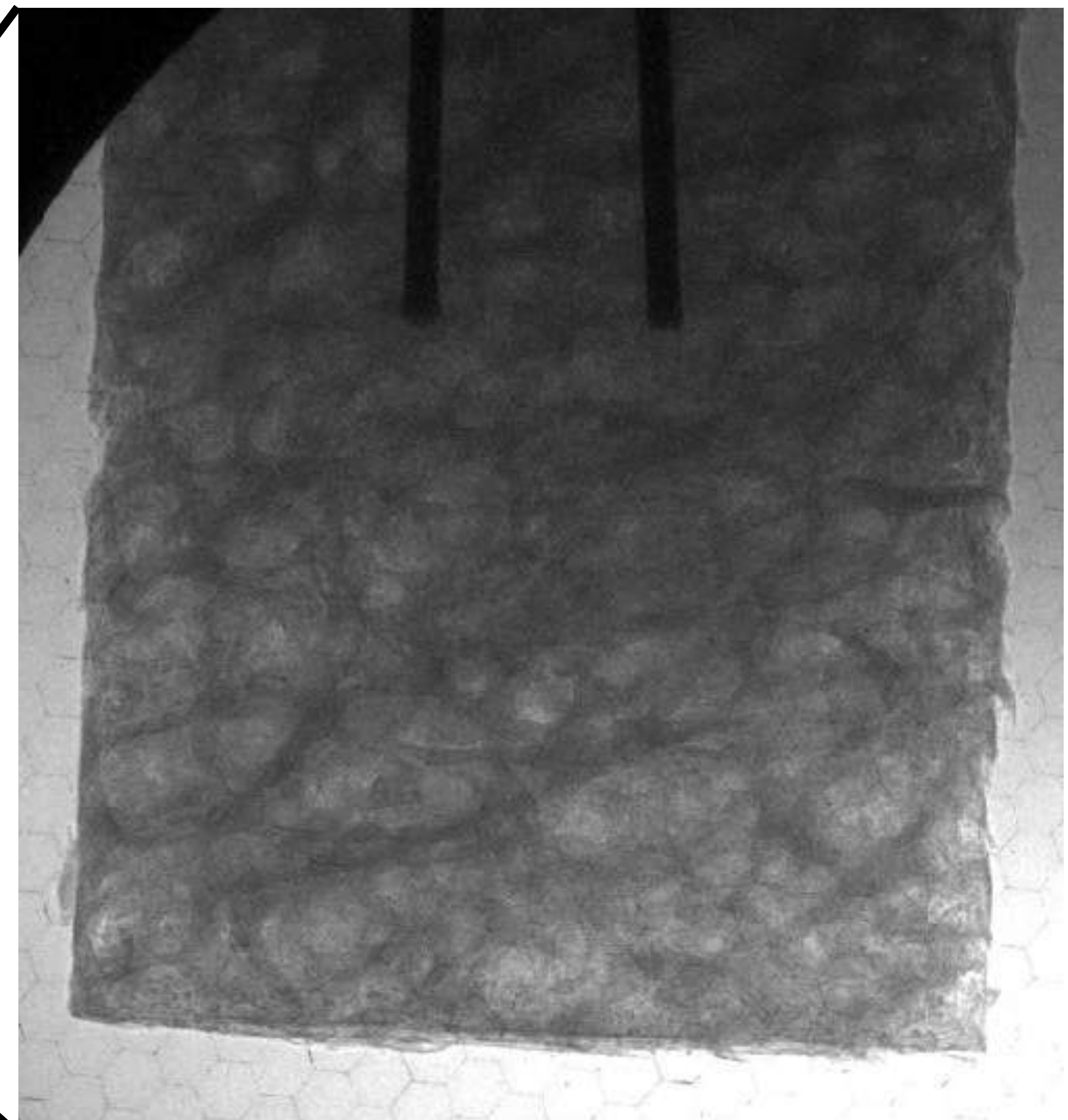


Bone tomography

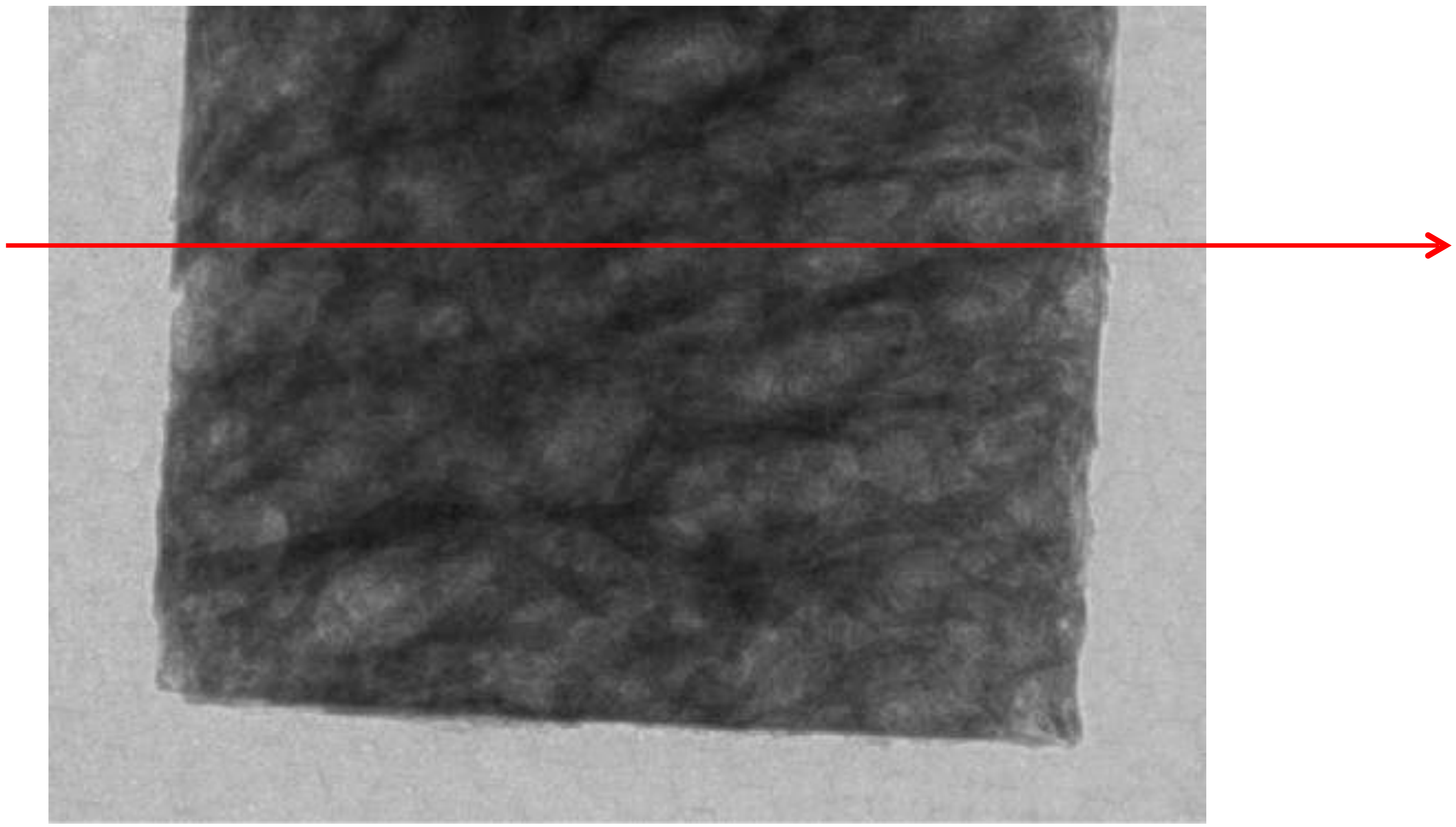
Cylindrical trabecular bone section from human femur

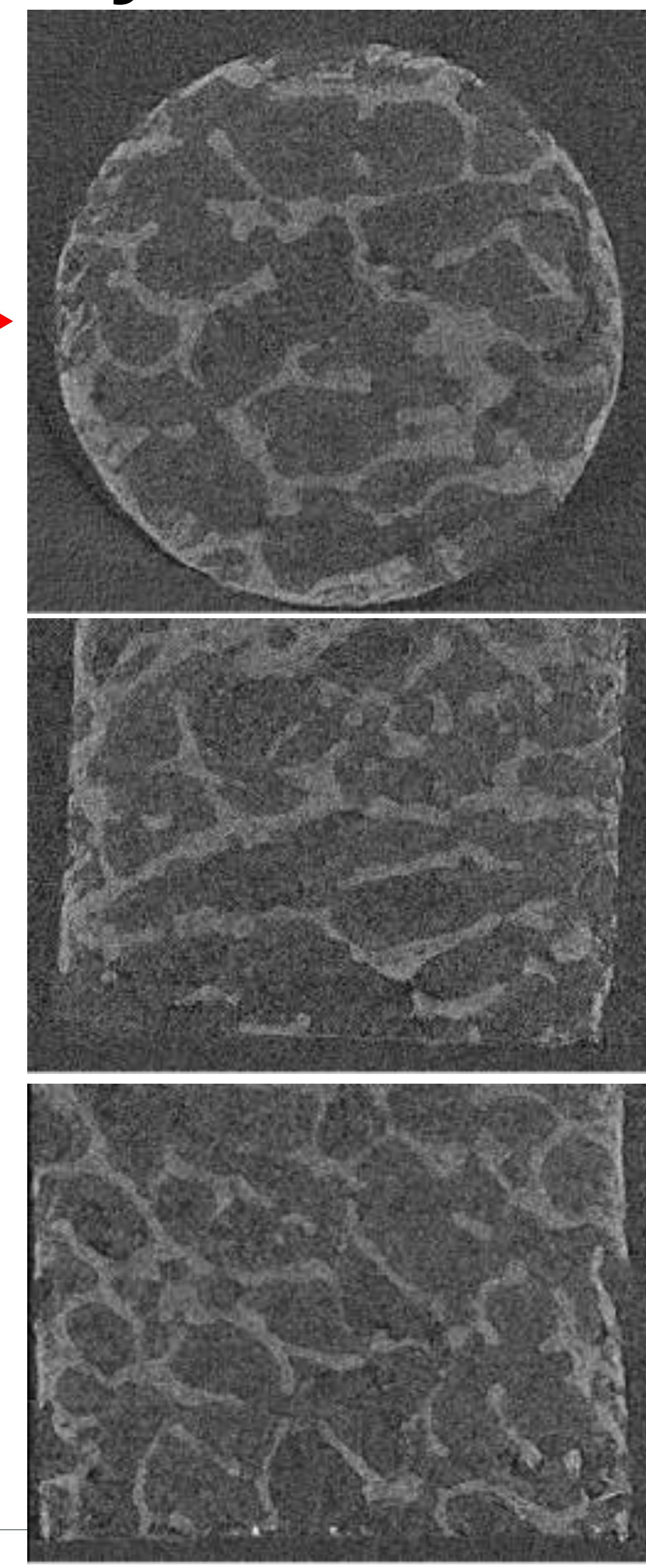
- ✓ Single shot
- ✓ Good contrast
- ✓ High resolution
- ✗ Poor beam profile





Record 180 consecutive projections





Reconstruct single-pixel slices at a time (after correcting for beam fluctuations)

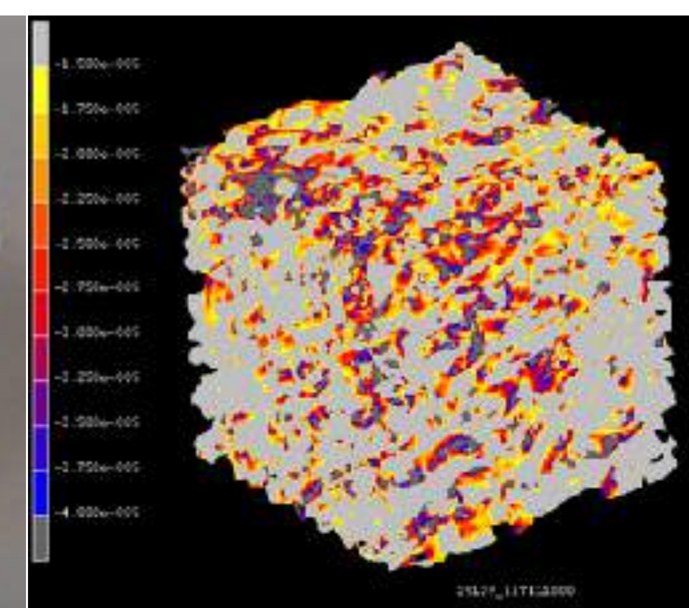
Repeat to recover full 3D reconstruction

3D reconstruction

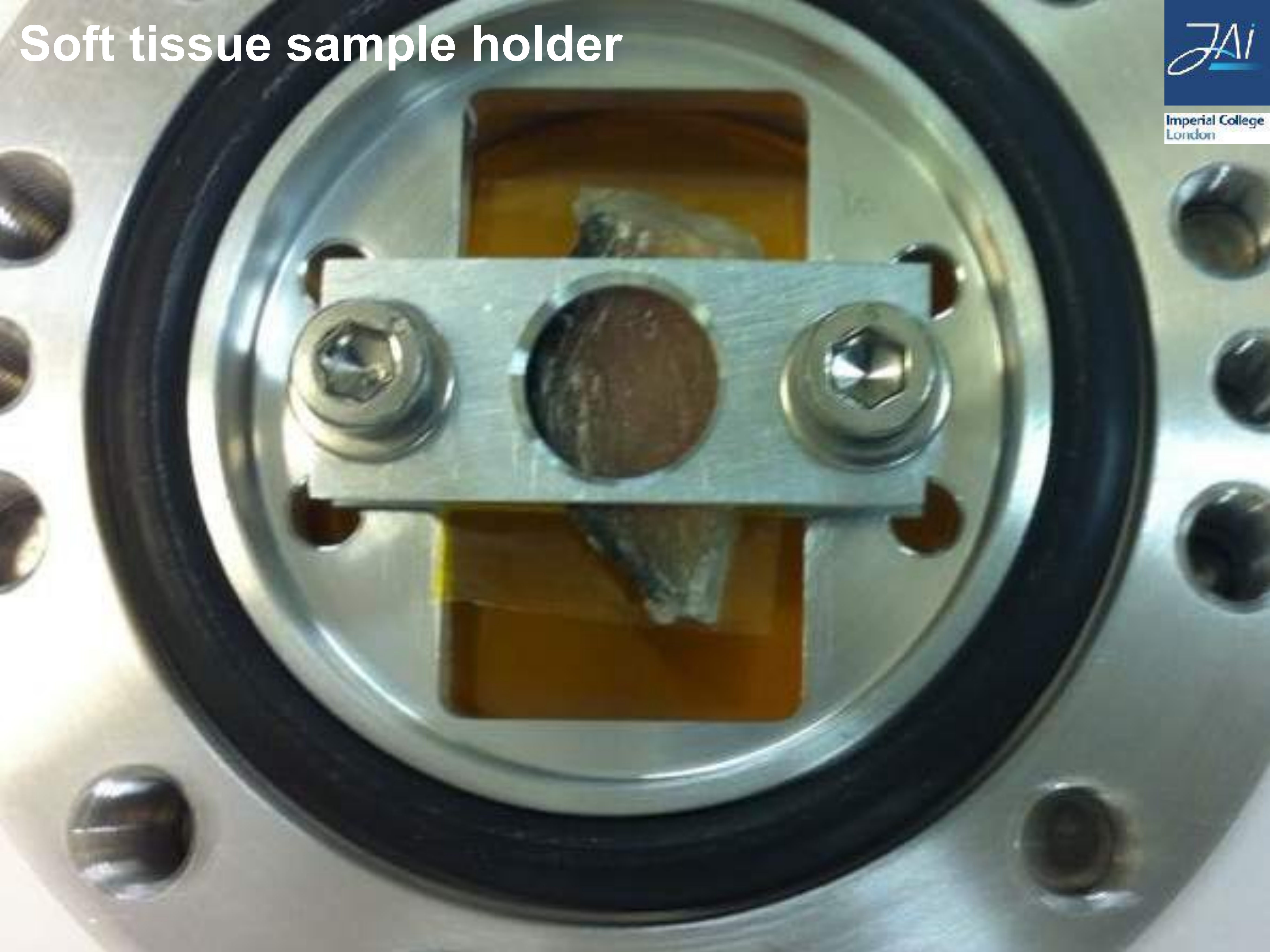
Voxel size
4.8 x 4.8 x 4.8 µm

Best resolution ~50 µm, limited by number of projections, photon noise and detector PSF

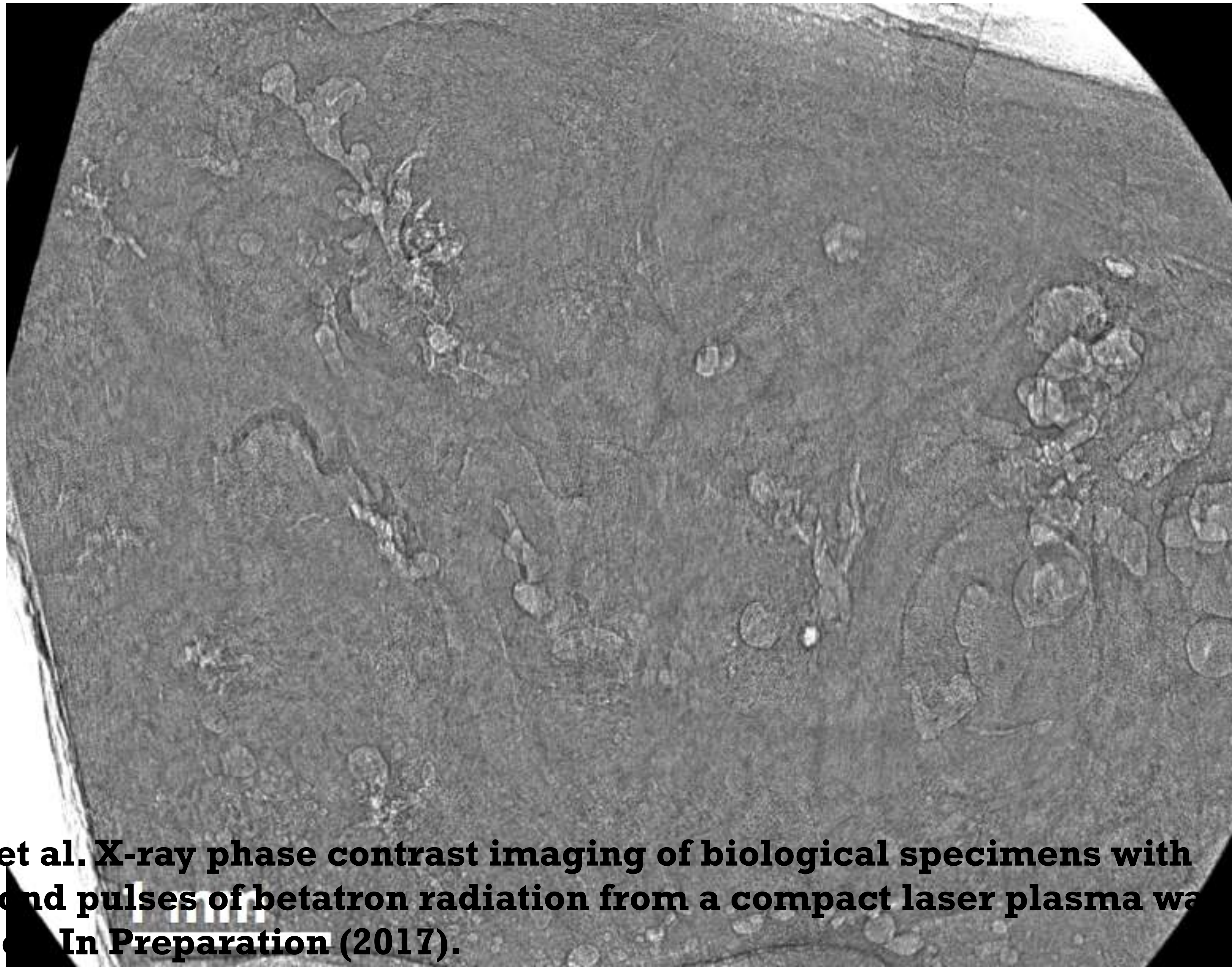
Total scan time 4 hours



Soft tissue sample holder



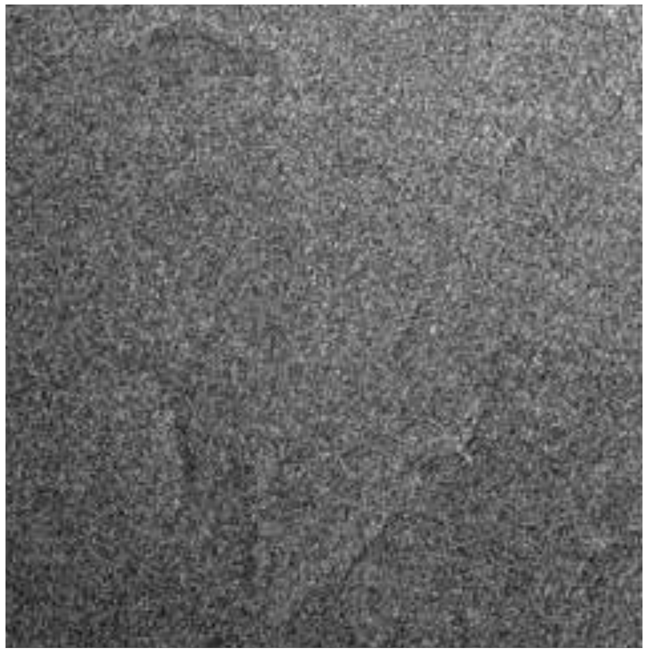
Prostate Imaging with Gemini



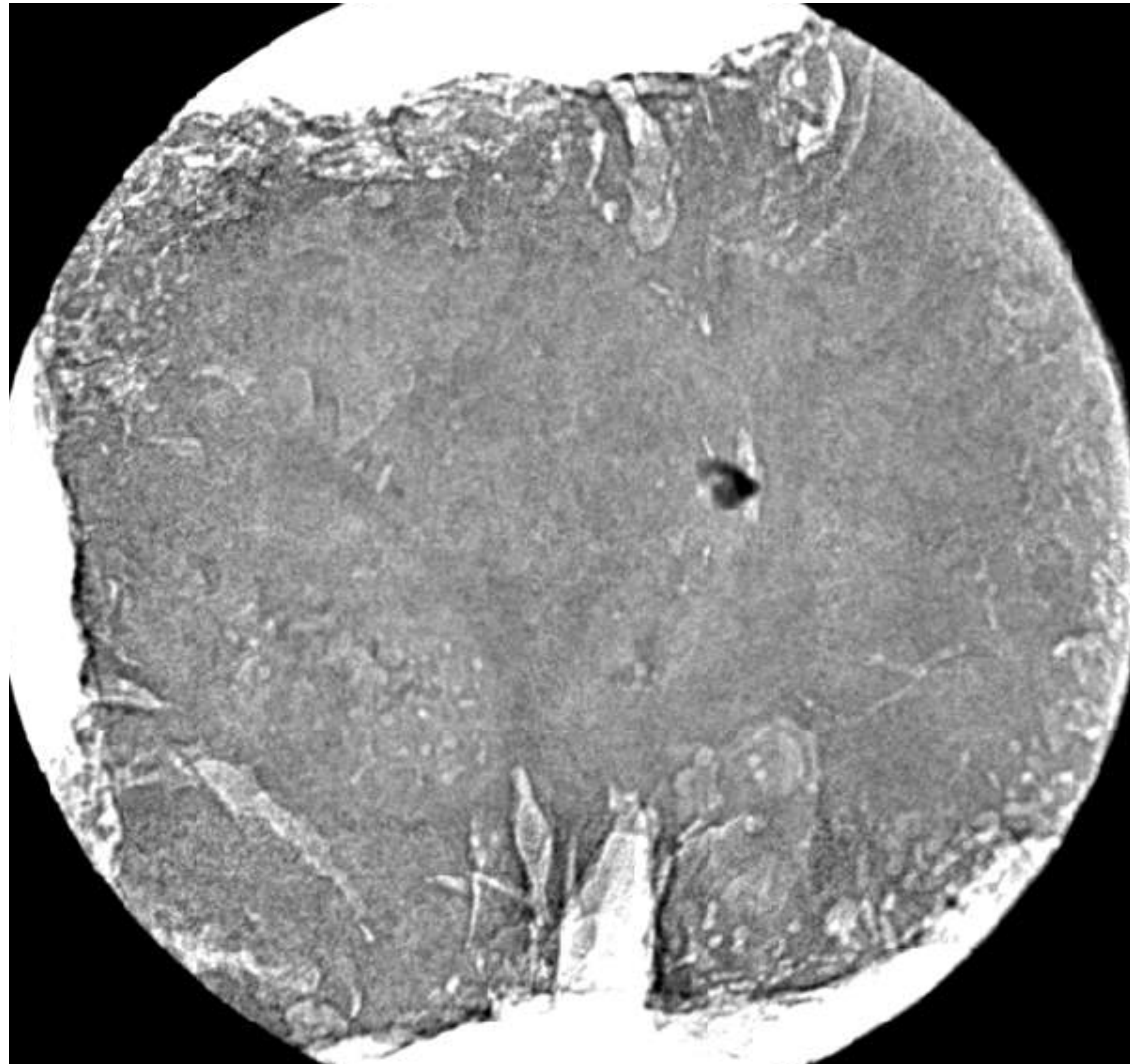
Lopes N. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. In Preparation (2017).

Breast raster scan

Raw data



Raster scan + noise reduction



Raw data relatively noisy

Advanced stitching and denoising techniques developed at IC

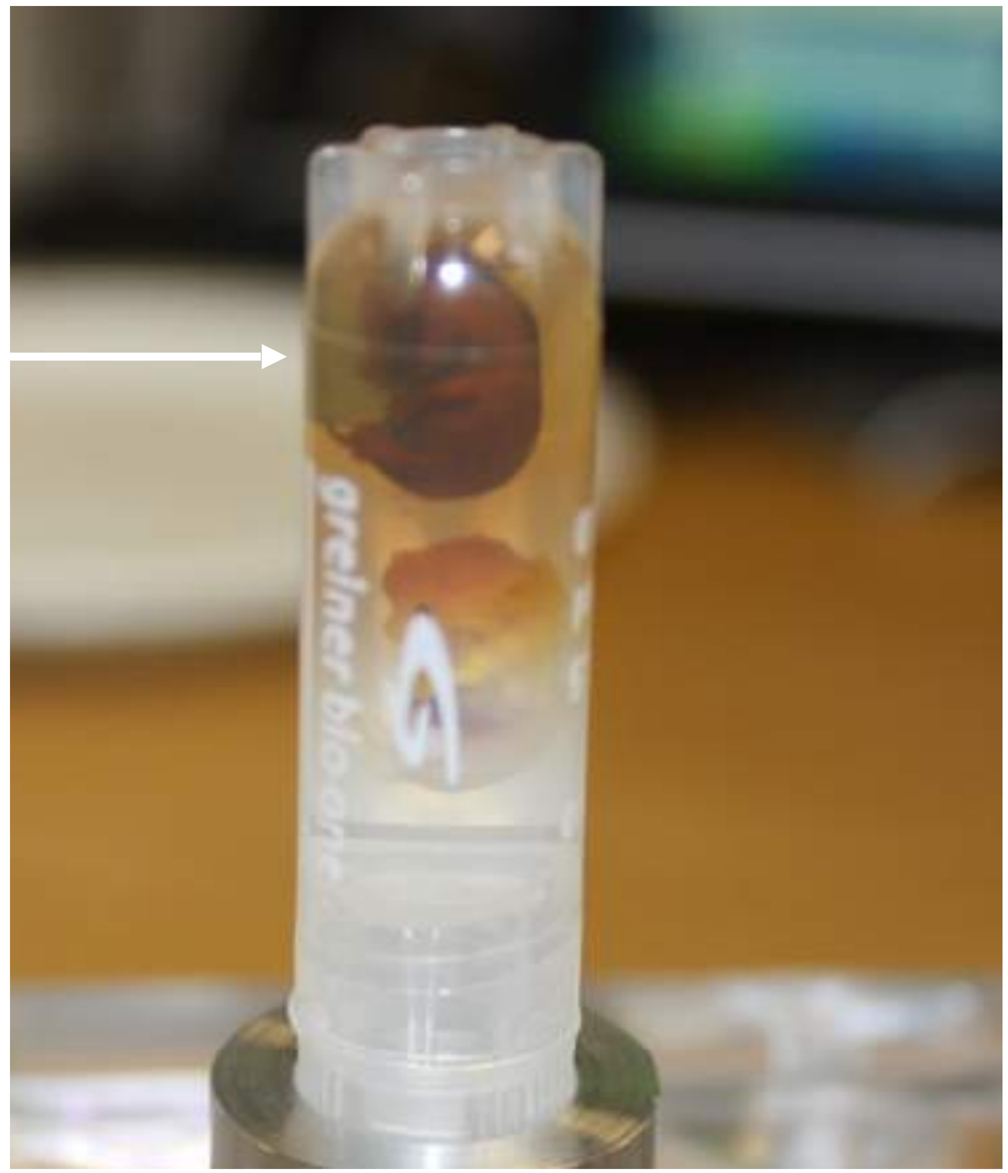
(Nelson Lopes)

Mouse embryonic samples

14.5 day-old embryo

Stained with iodine

Suspended in agarose – important to stop dehydration



Mouse embryo imaging important in the context of International Mouse Phenotyping Consortium (>$1B project)

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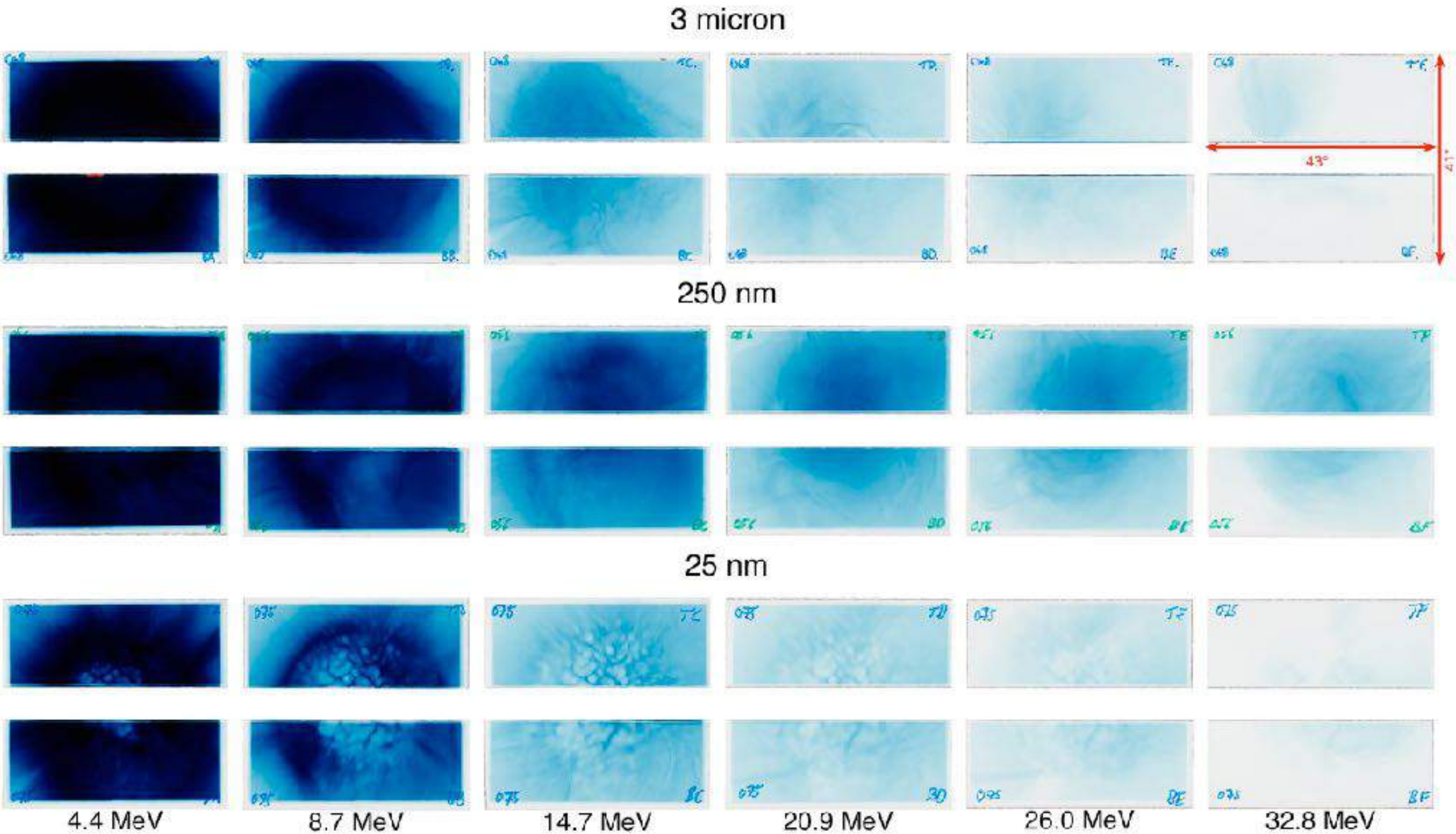
Mouse 14.5day tomography

Ion acceleration

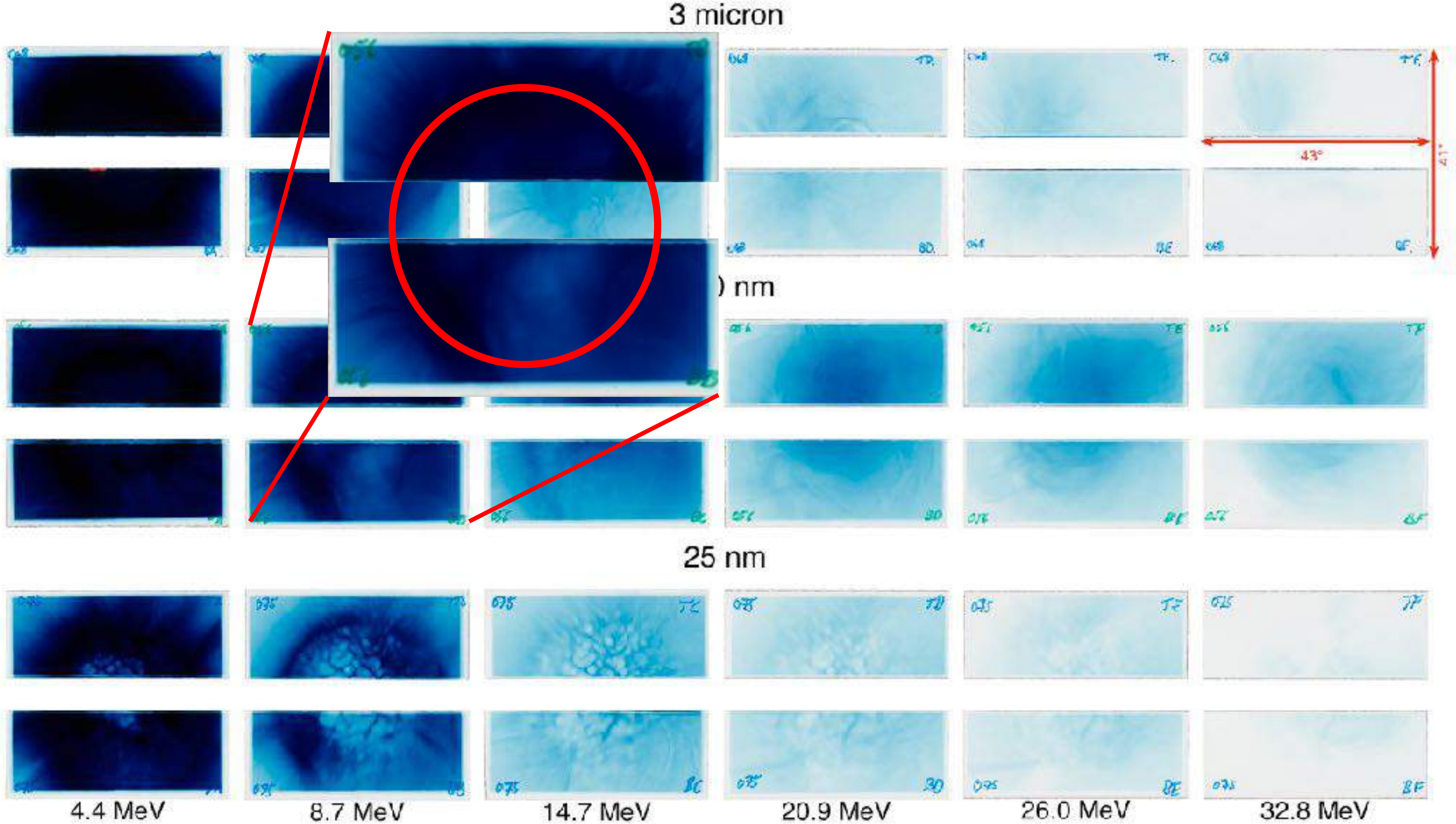
Radiochromic Film

- **Beam profiles from varying thickness formvar target**



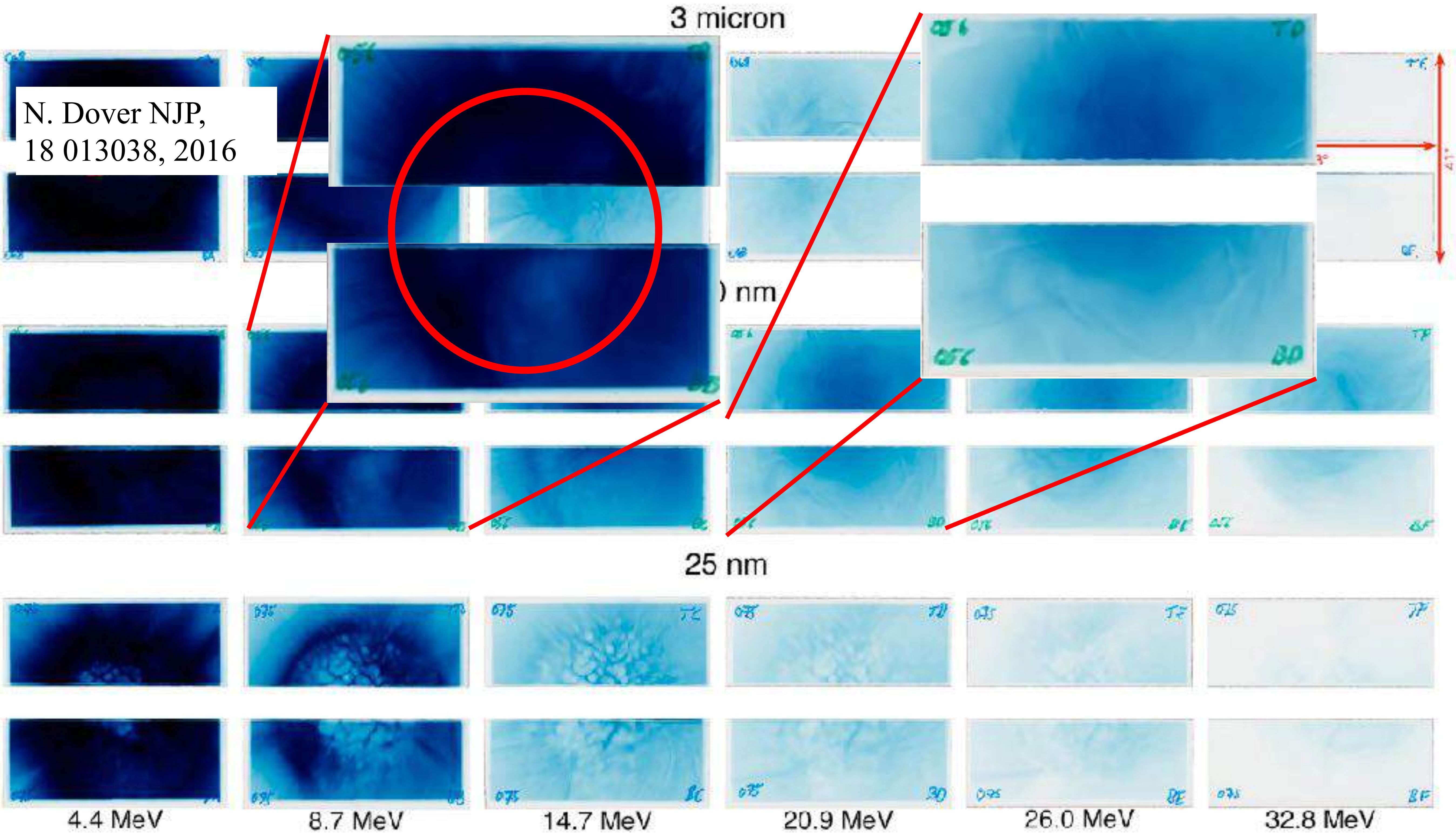
Radiochromic Film

- **Beam profiles from varying thickness formvar target**



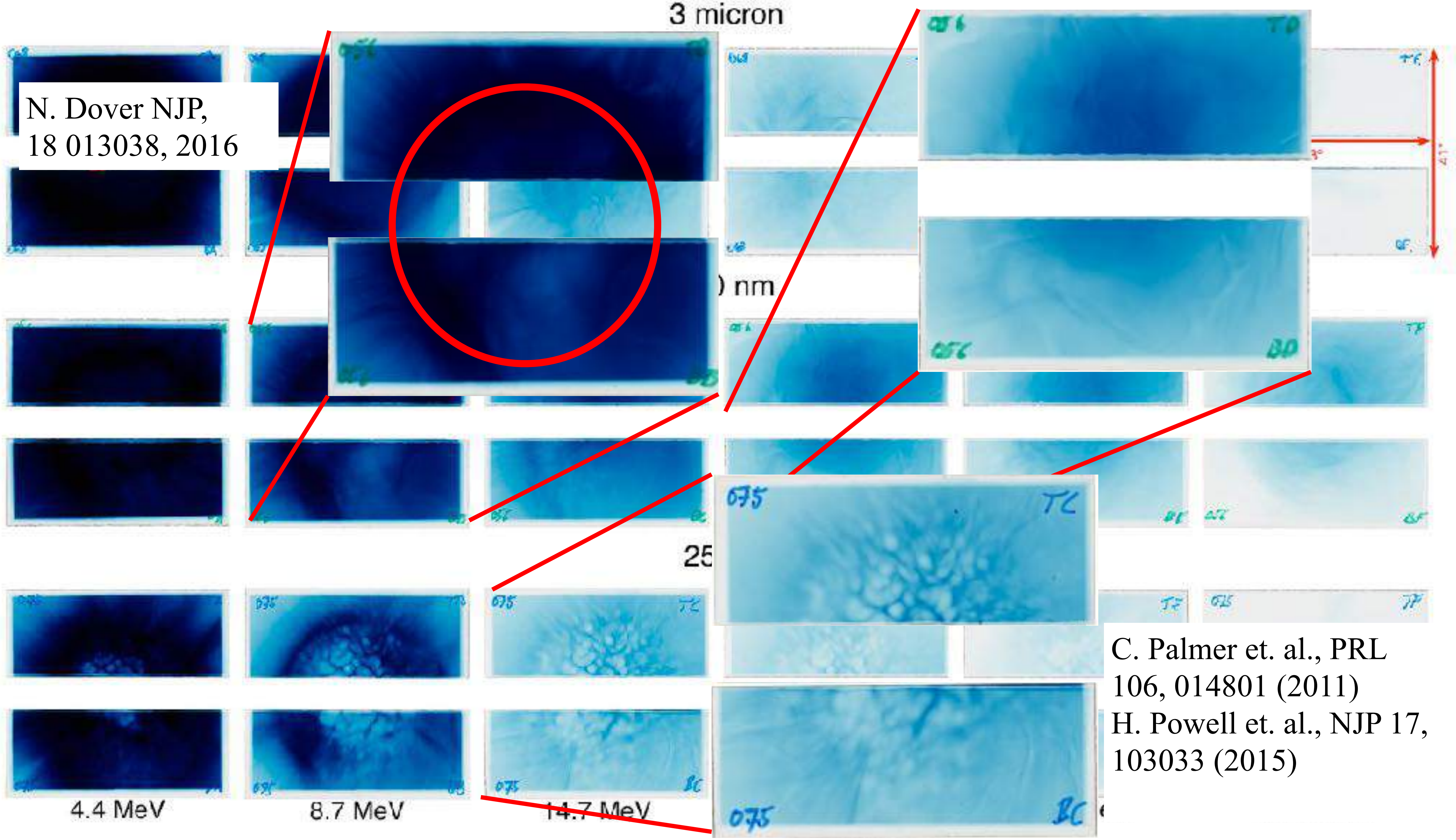
Radiochromic Film

- **Beam profiles from varying thickness formvar target**



Radiochromic Film

- **Beam profiles from varying thickness formvar target**

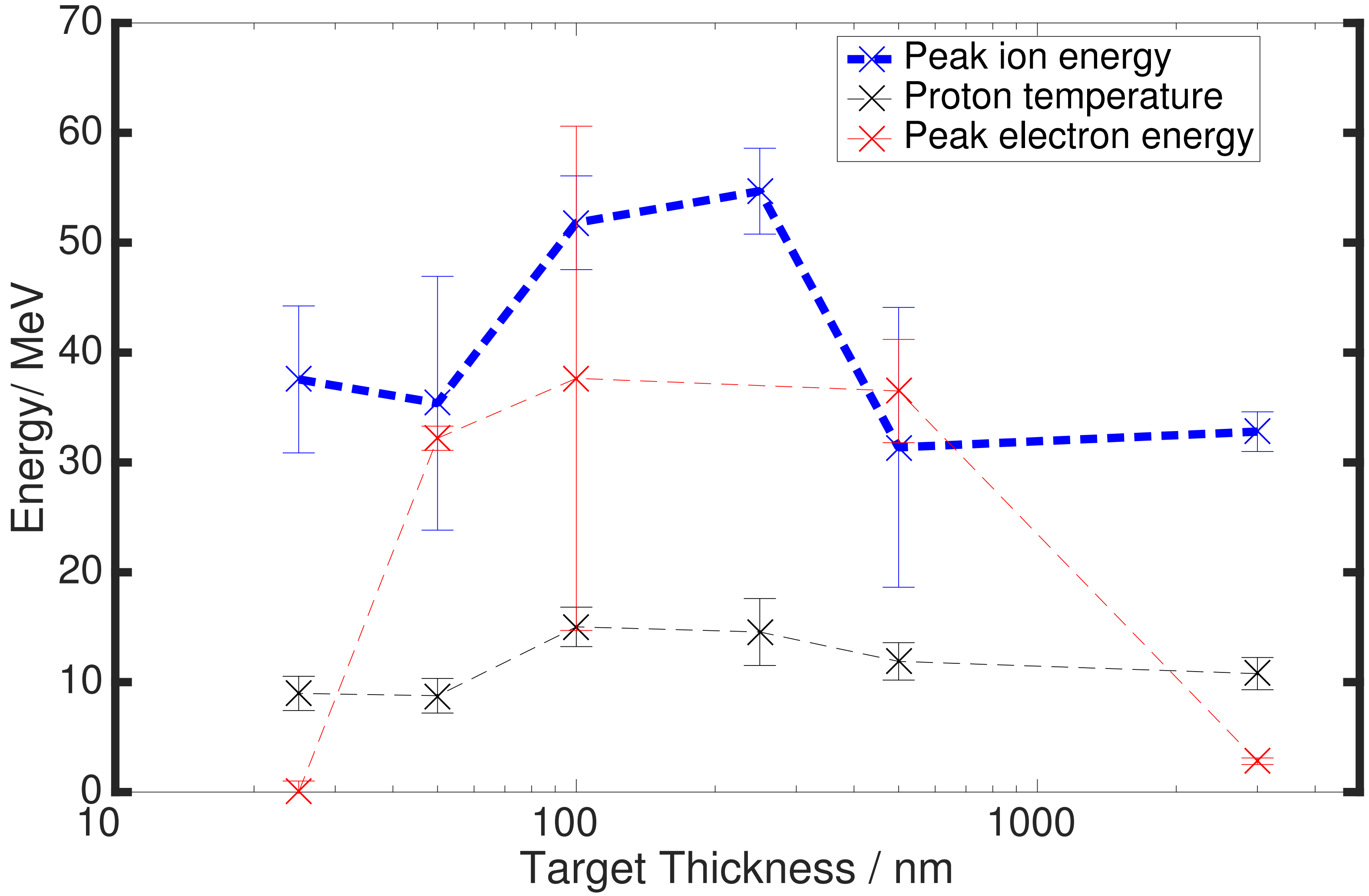


Experimental Results

- Enhancement of maximum proton energy and proton temperature for 100-250 nm thick targets

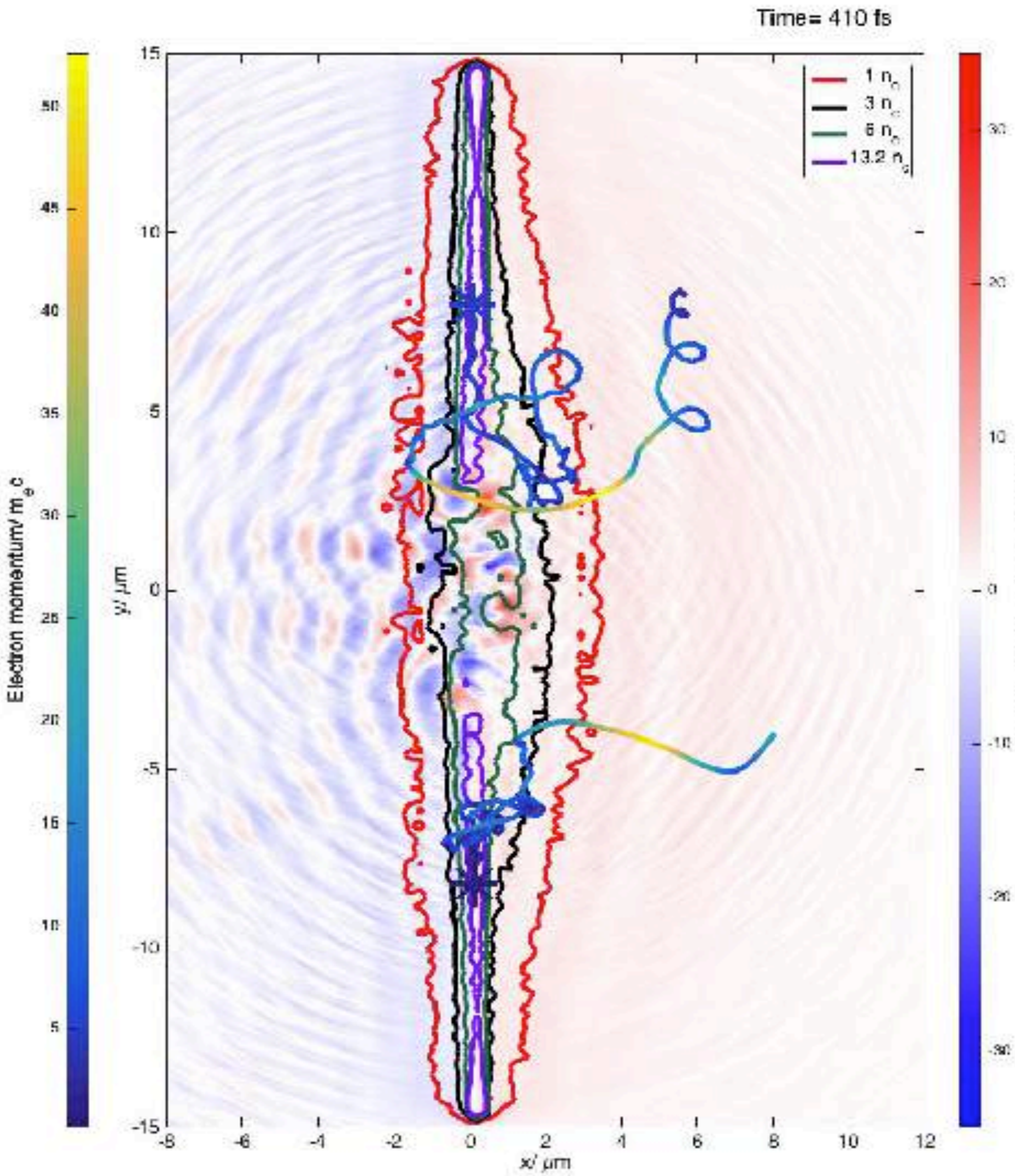
- **High energy of up to 53MeV at detector limit of $3x10^8$ protons $MeV^{-1}srad^{-1}$**

- **High flux of $1.1x10^{11}$ protons $MeV^{-1}srad^{-1}$ above 40MeV**



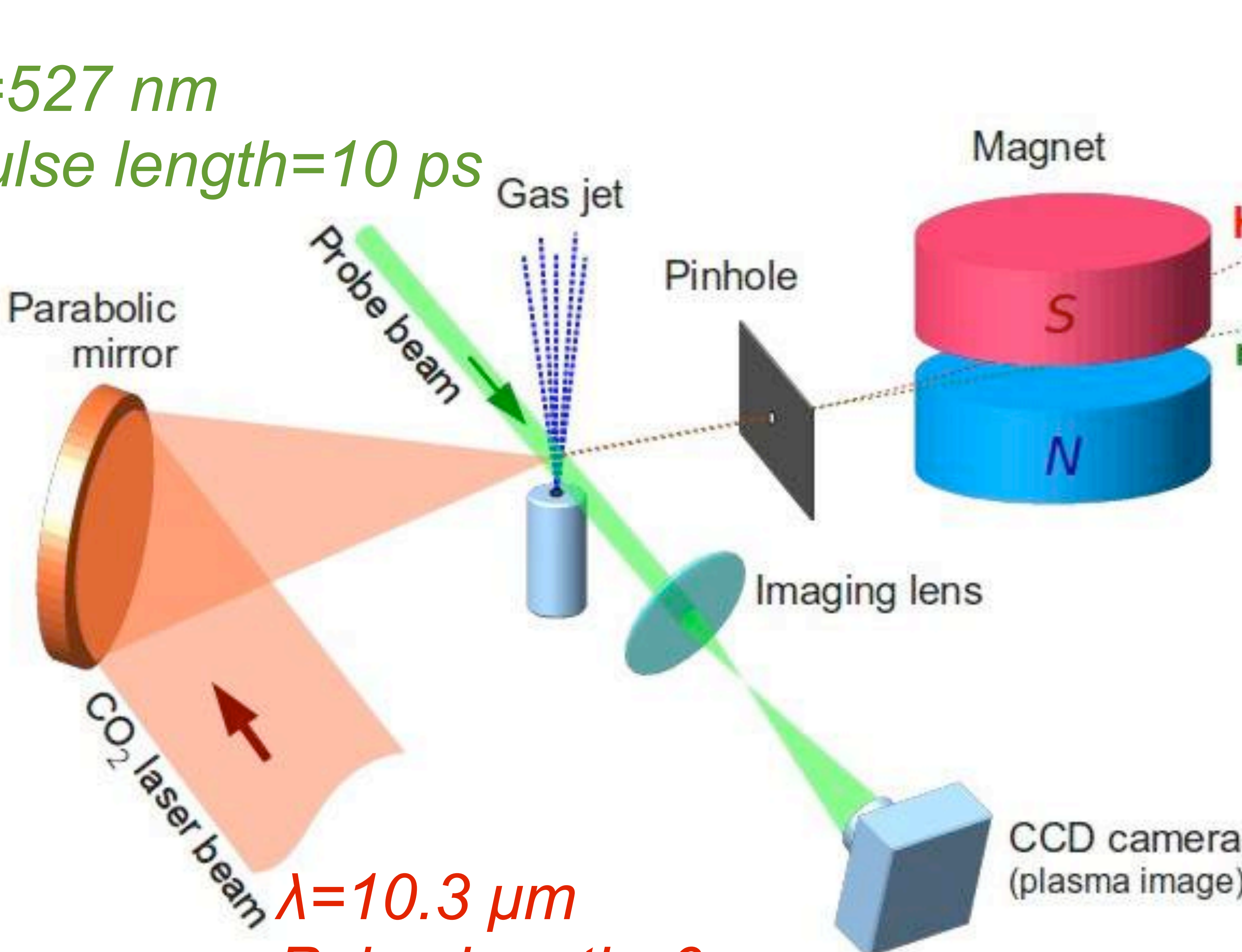
EPOCH particle tracking

- Electrons at edge of the aperture drift into strong laser field



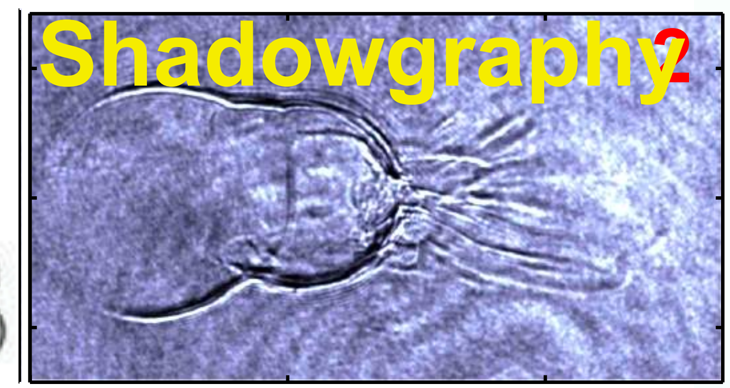
Experimental set-up

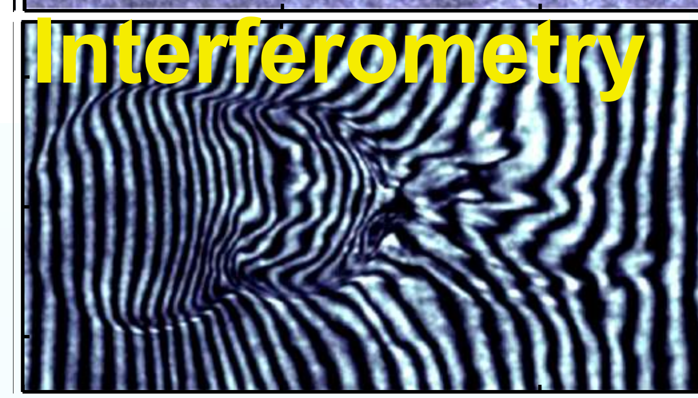
λ=527 nm
Pulse length=10 ps



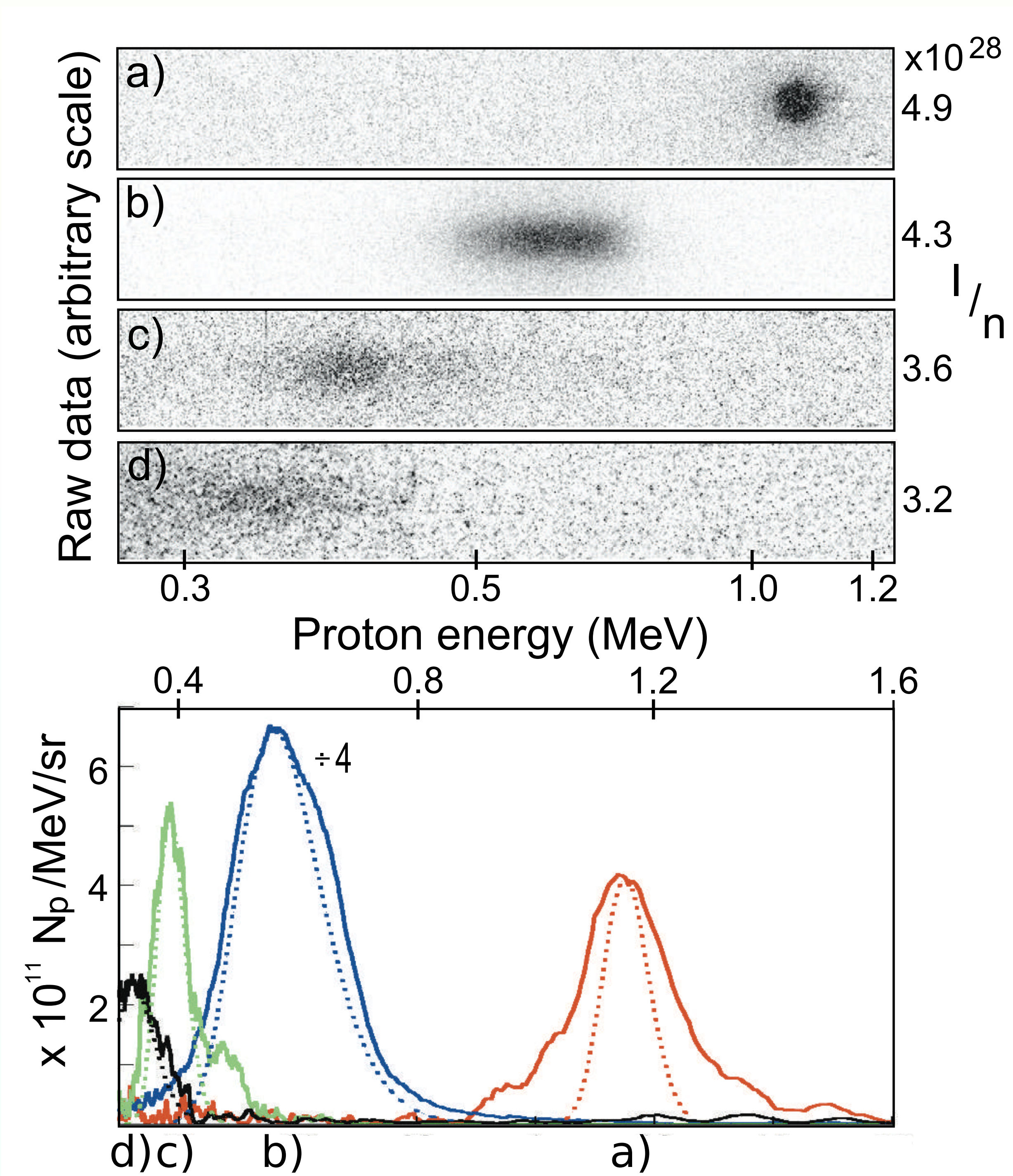
λ=10.3 μm
Pulse length=6 ps
Spot size = 70 μm
Intensity ~ 10^{16} W/cm^2

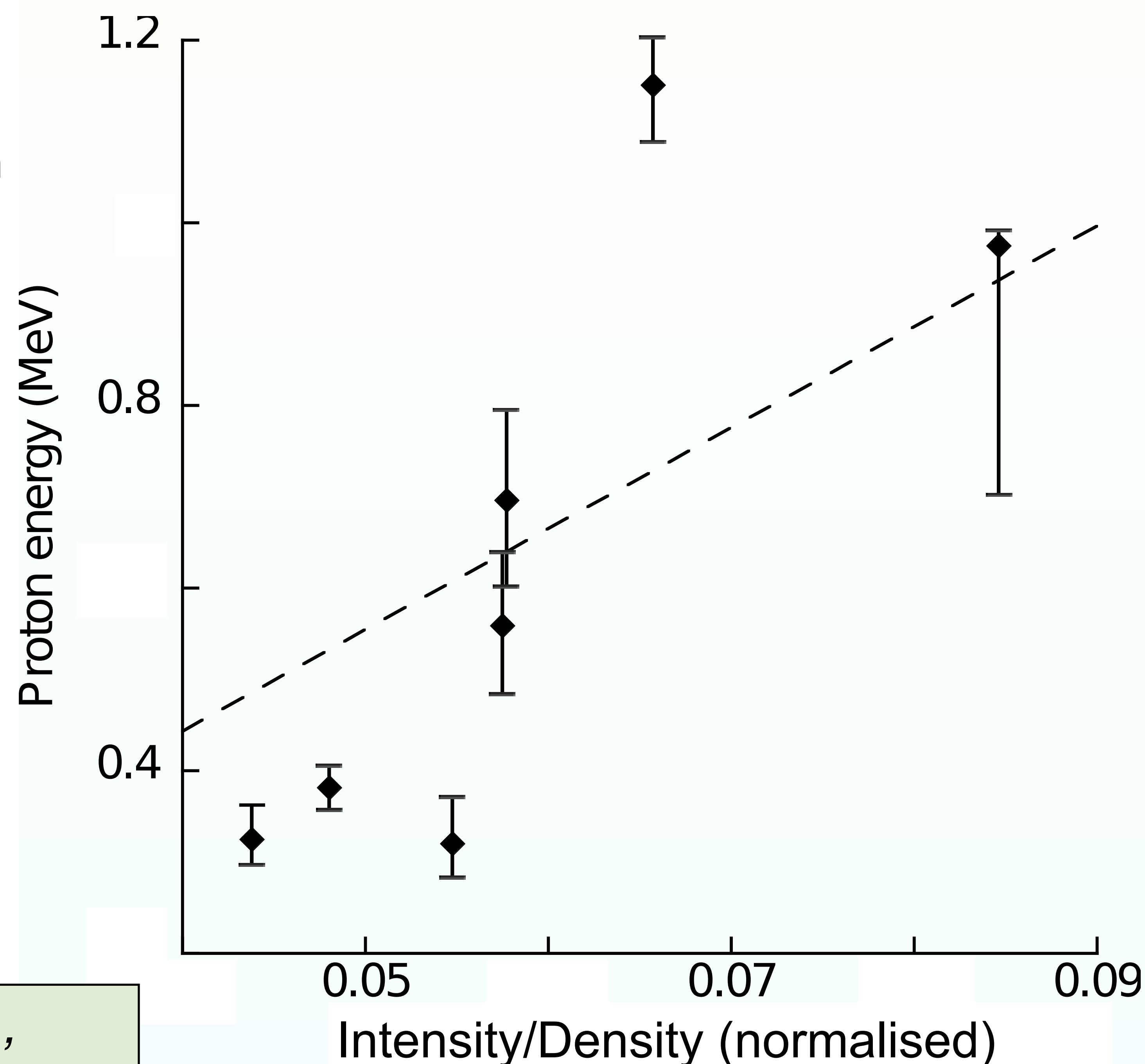
Probe at 2 times on single shot





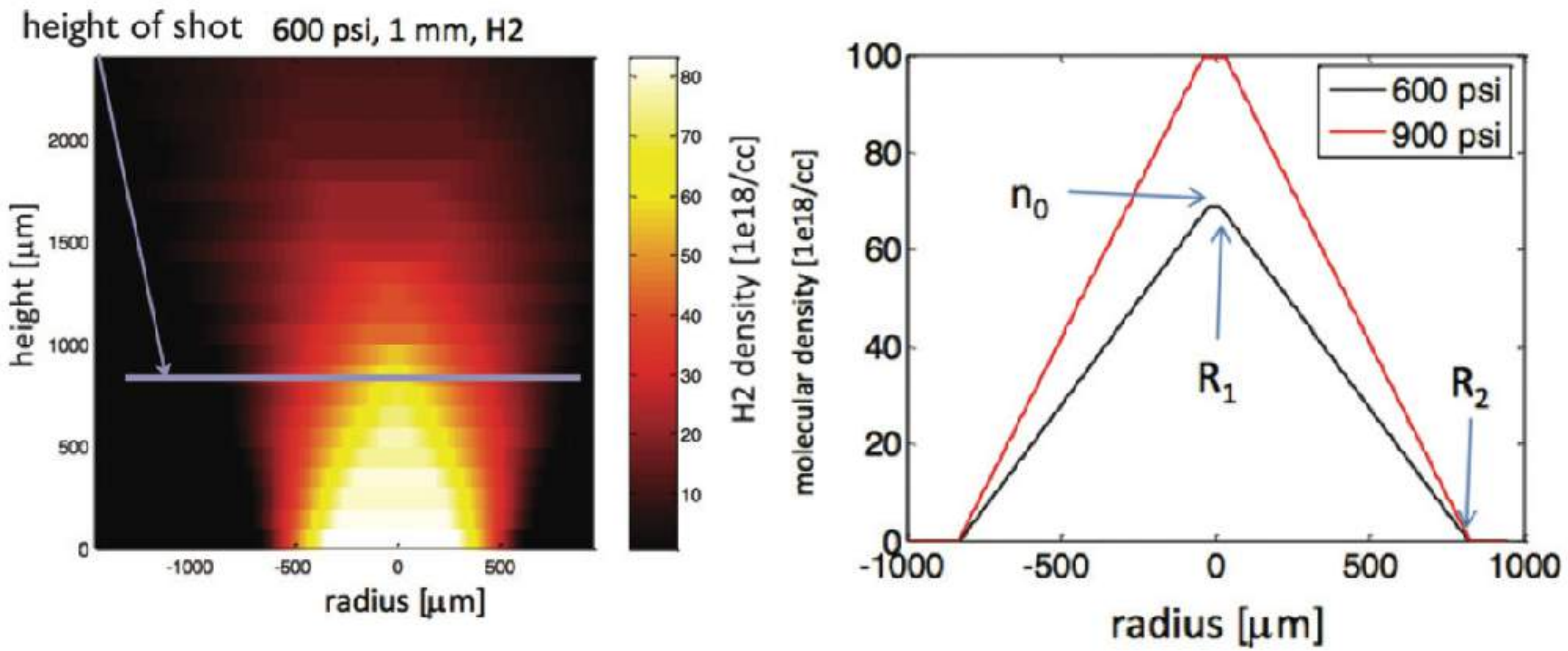
Monoenergetic proton beams





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

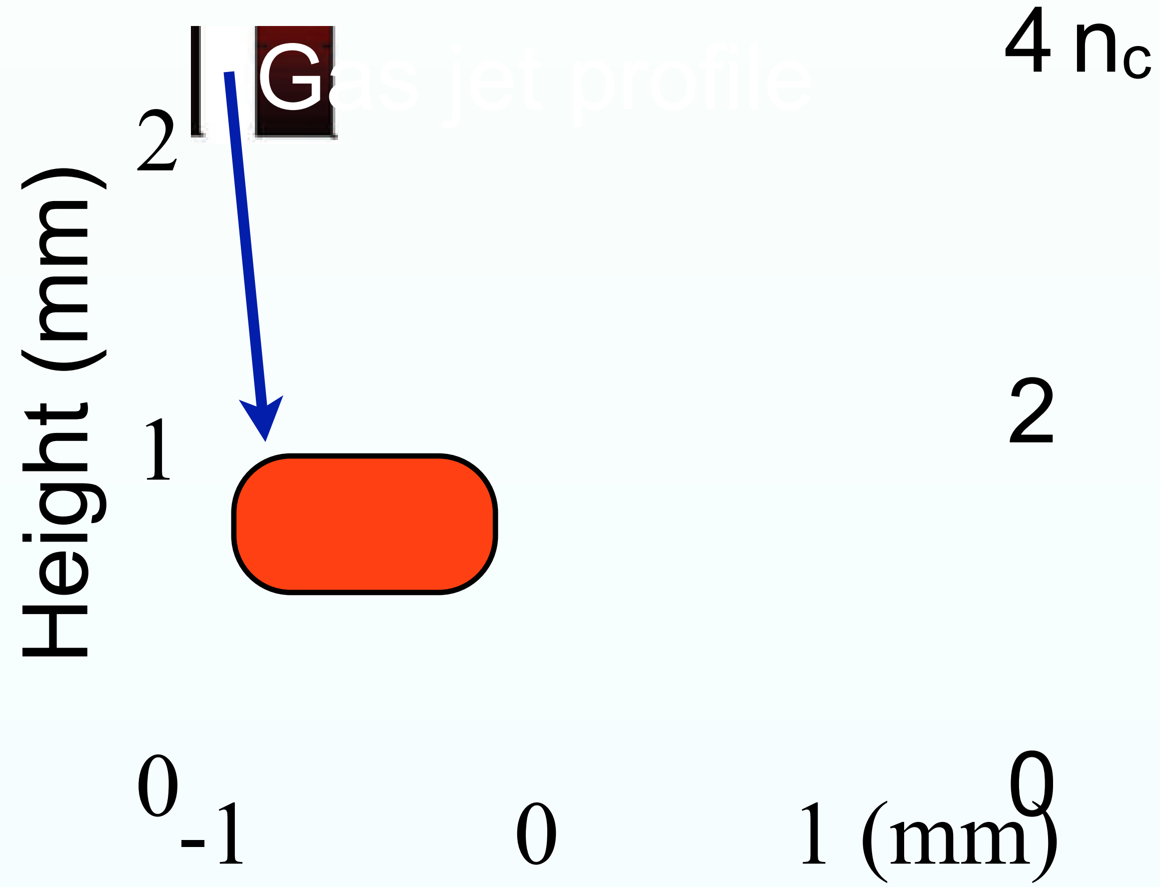
Typical Gas profile

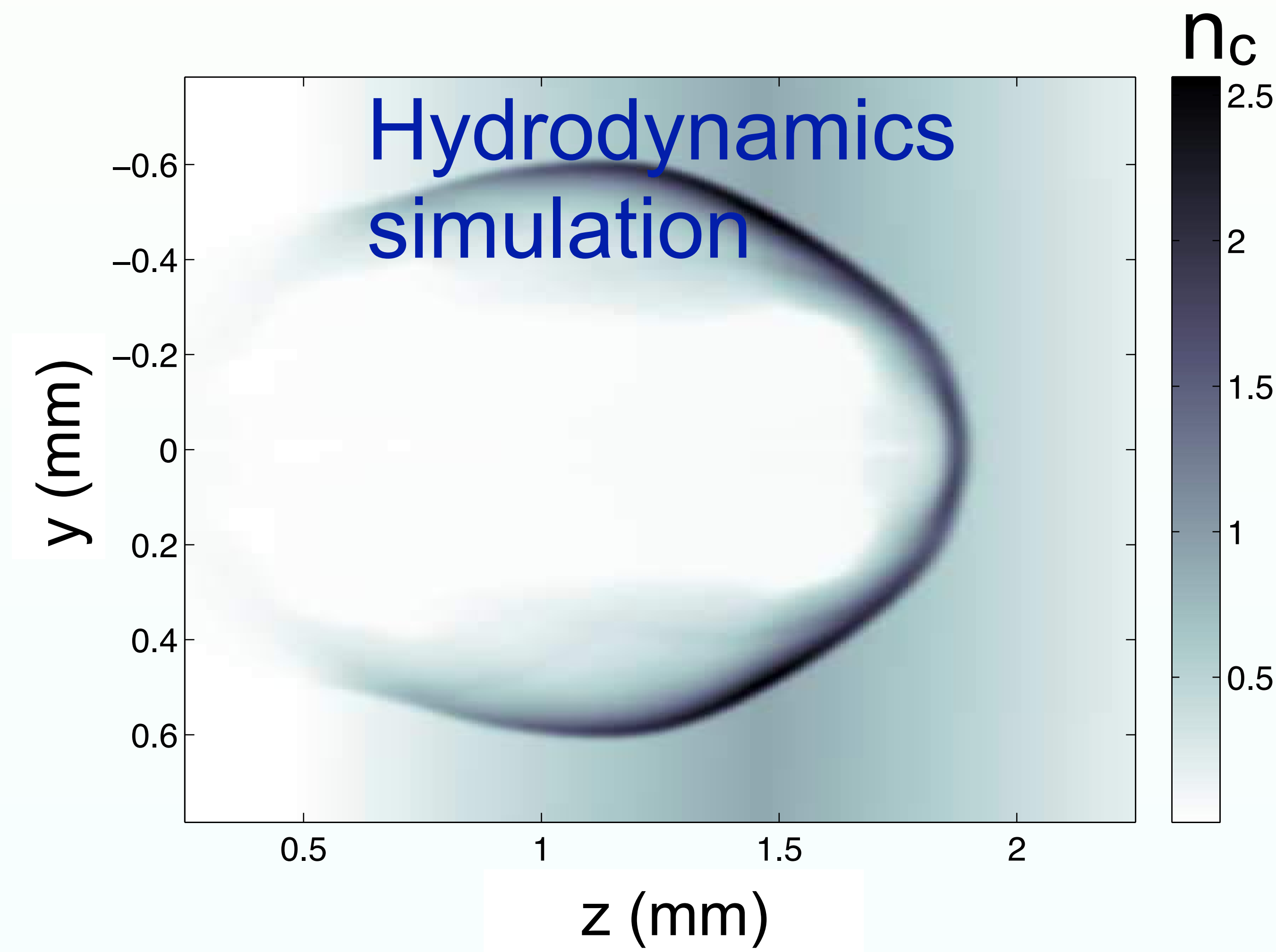


Blast wave shaping

- *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

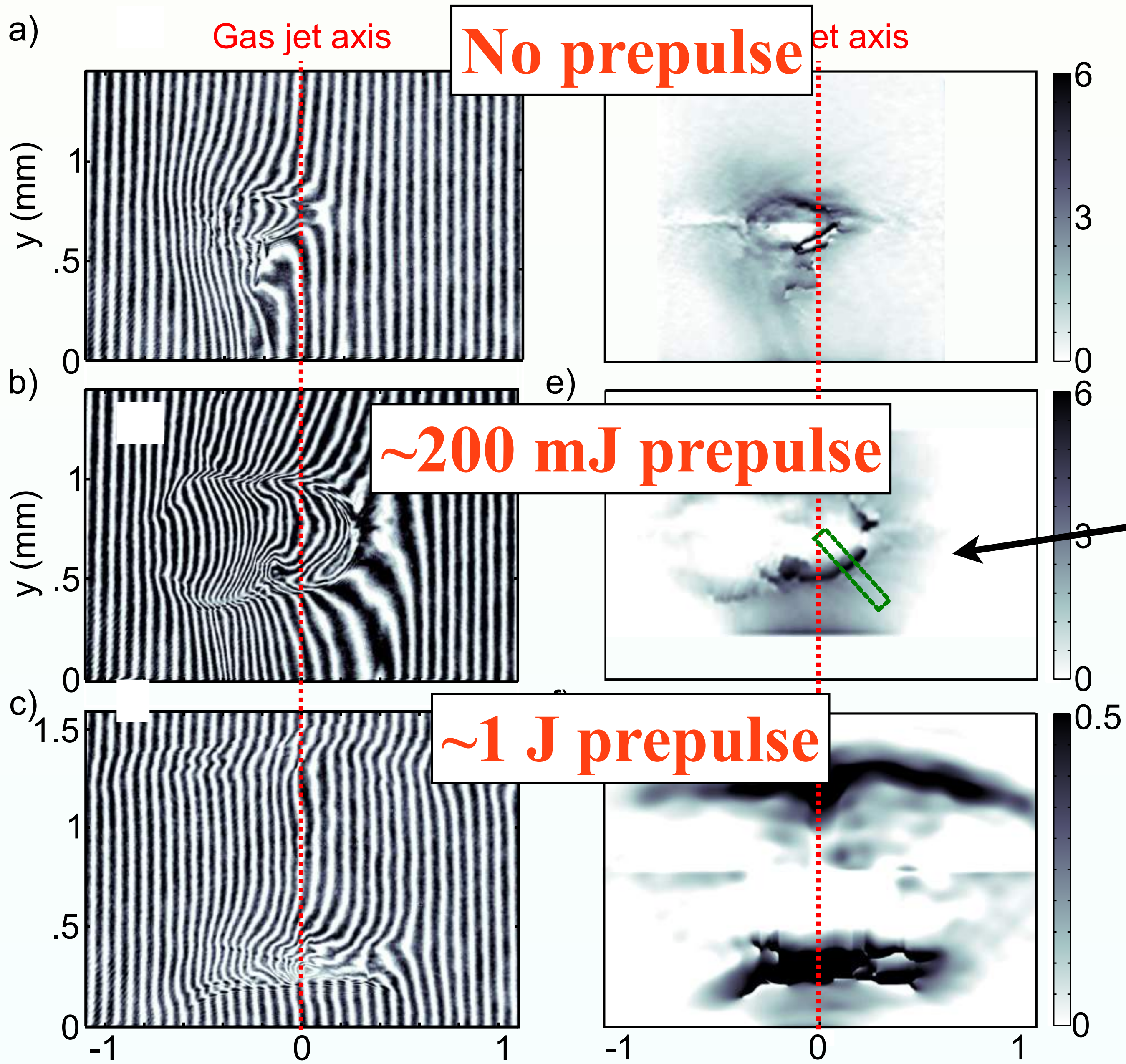
Prepulse deposits energy, gas expands and forms blast wave



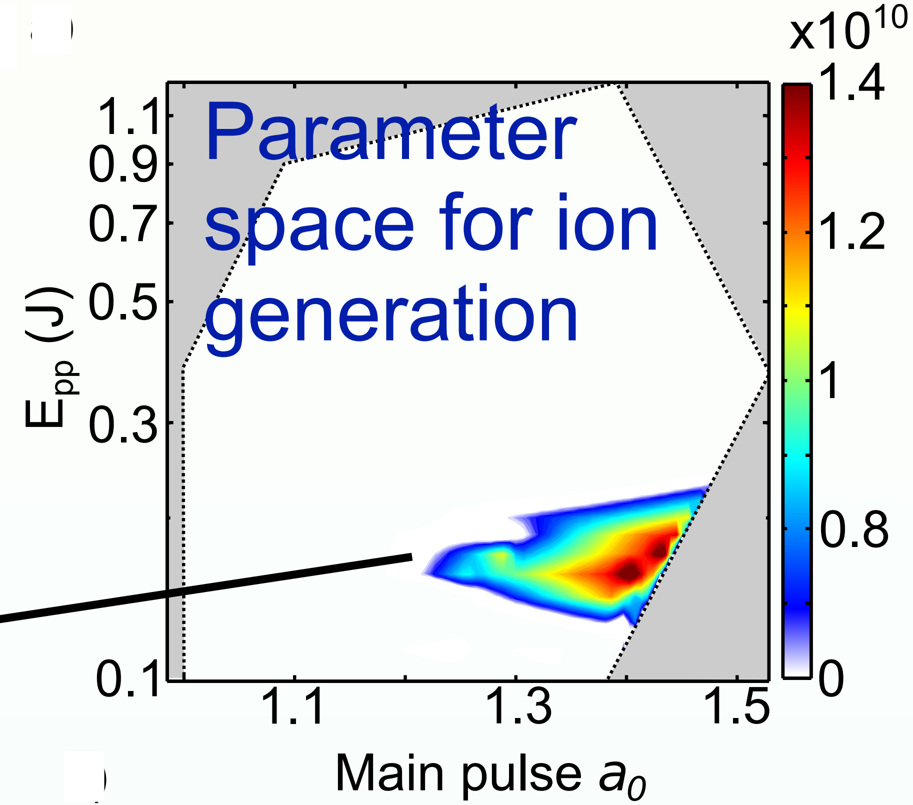


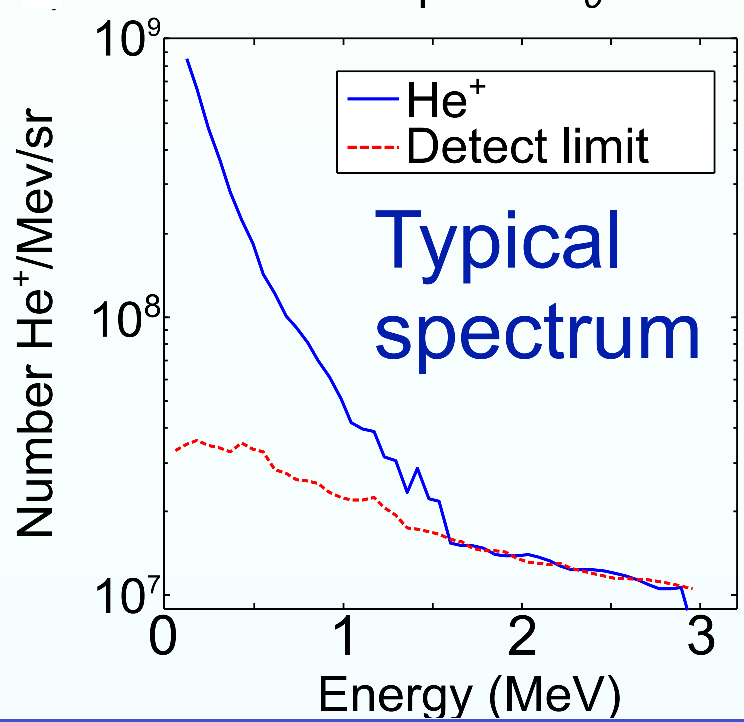
Main pulse interacts with steepened profile

Varying prepulse changes ion beam



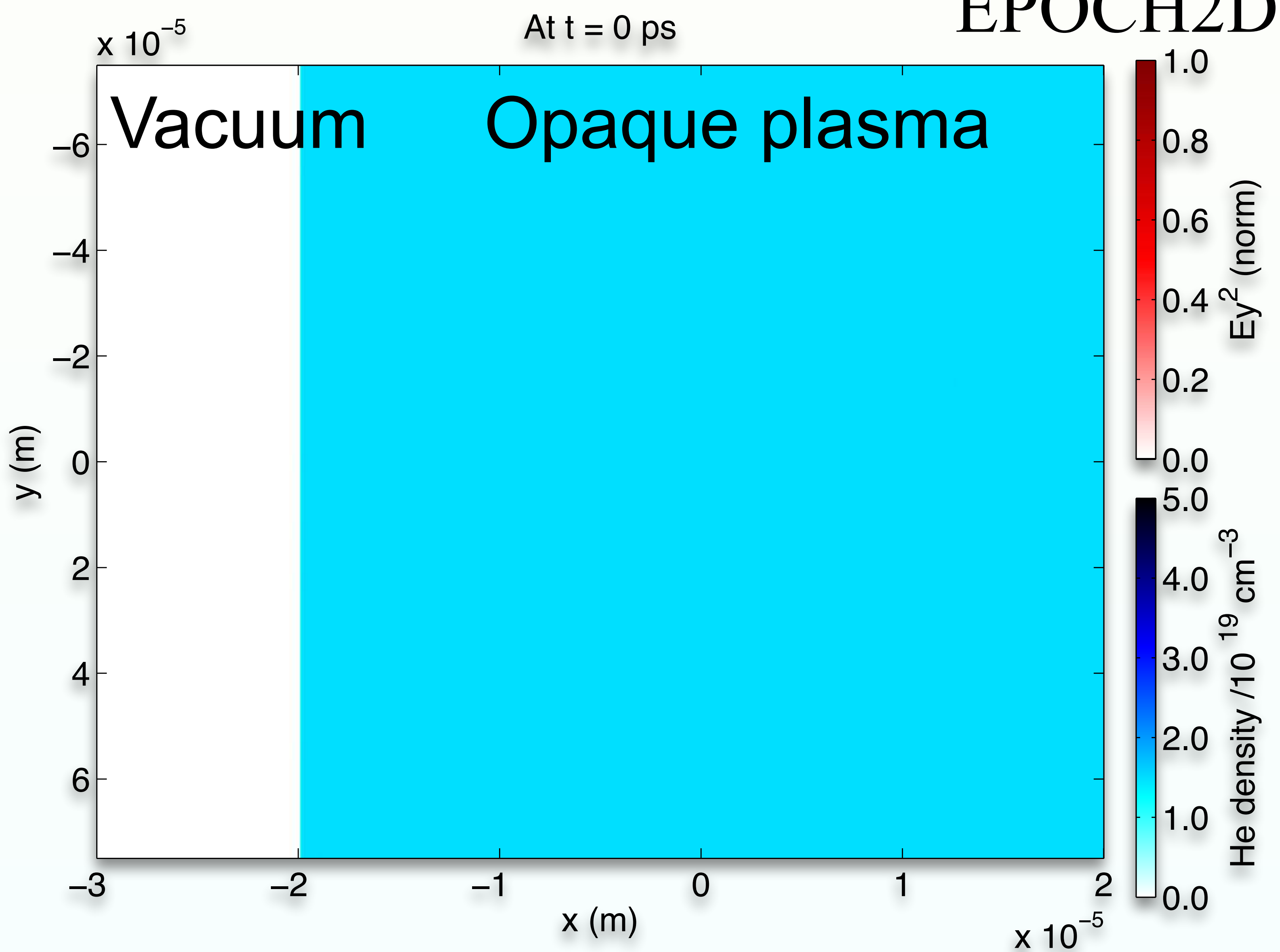
See: Tresca, Dover, Cook et al., Submitted 2014





Ions accelerated from shock

EPOCH2D PIC code



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ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

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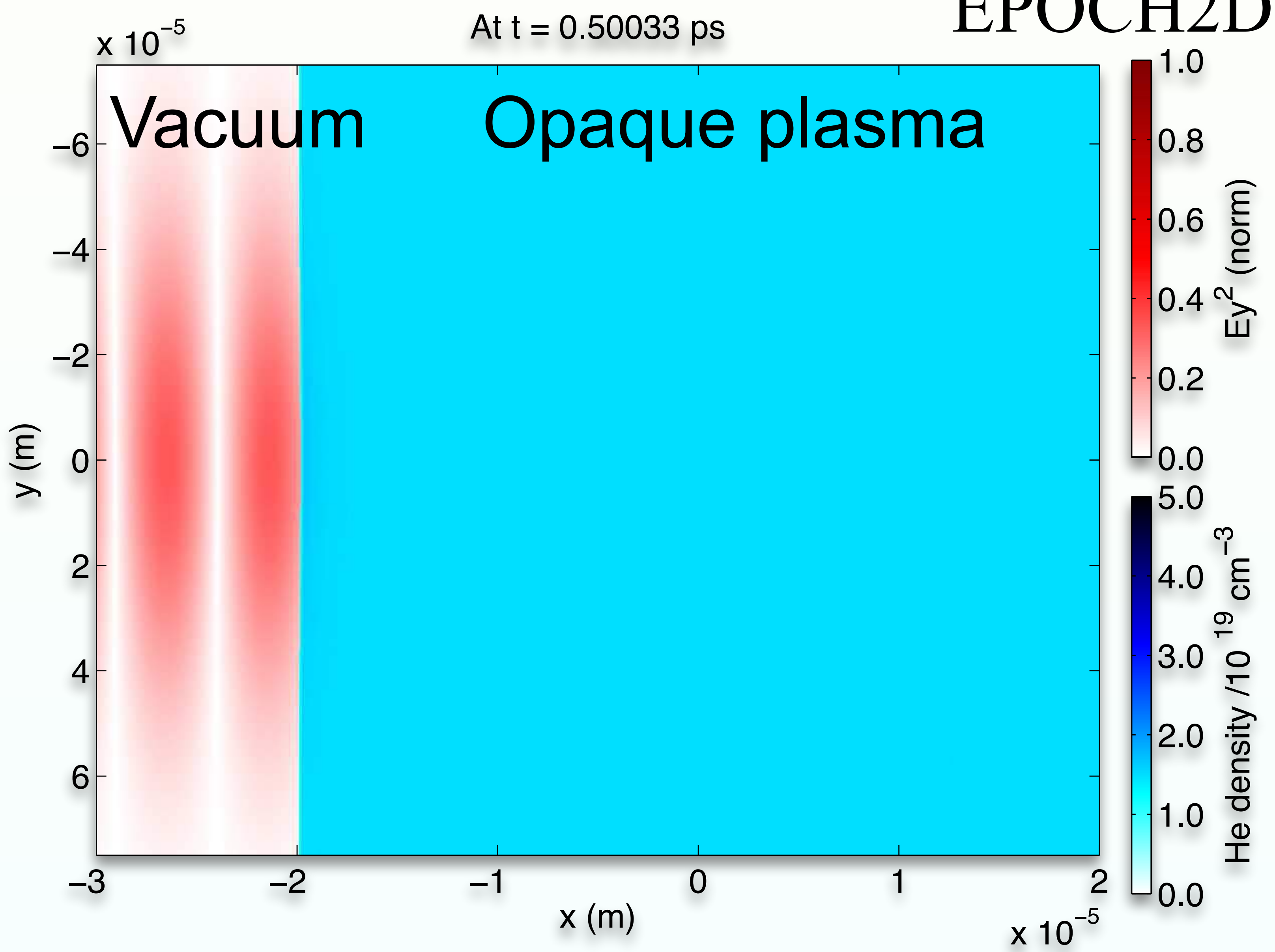
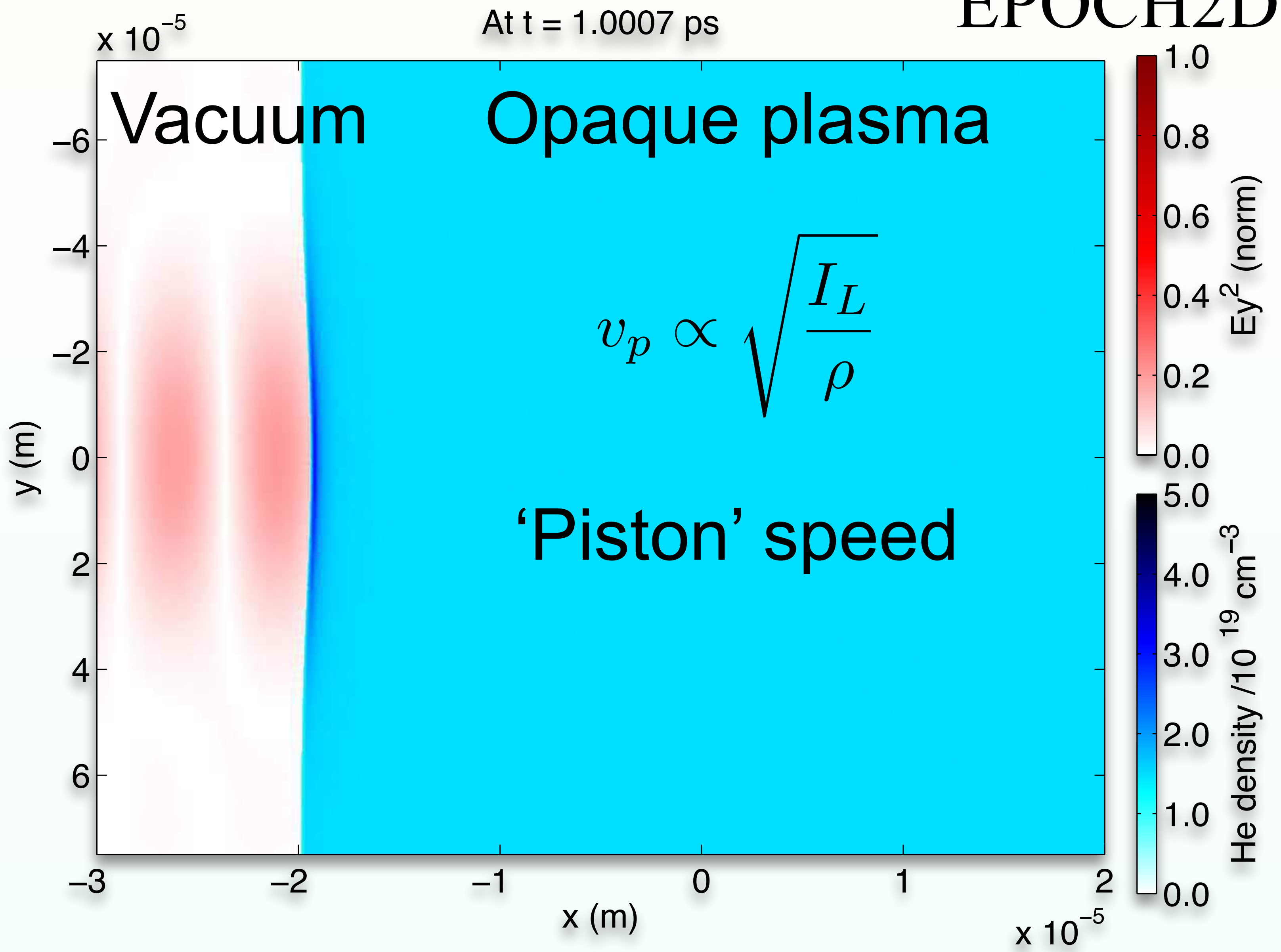
Ions accelerated from a moving shock

EPOCH2D PIC code



Ions accelerated from a moving shock

EPOCH2D PIC code



Ions accelerated from a moving shock

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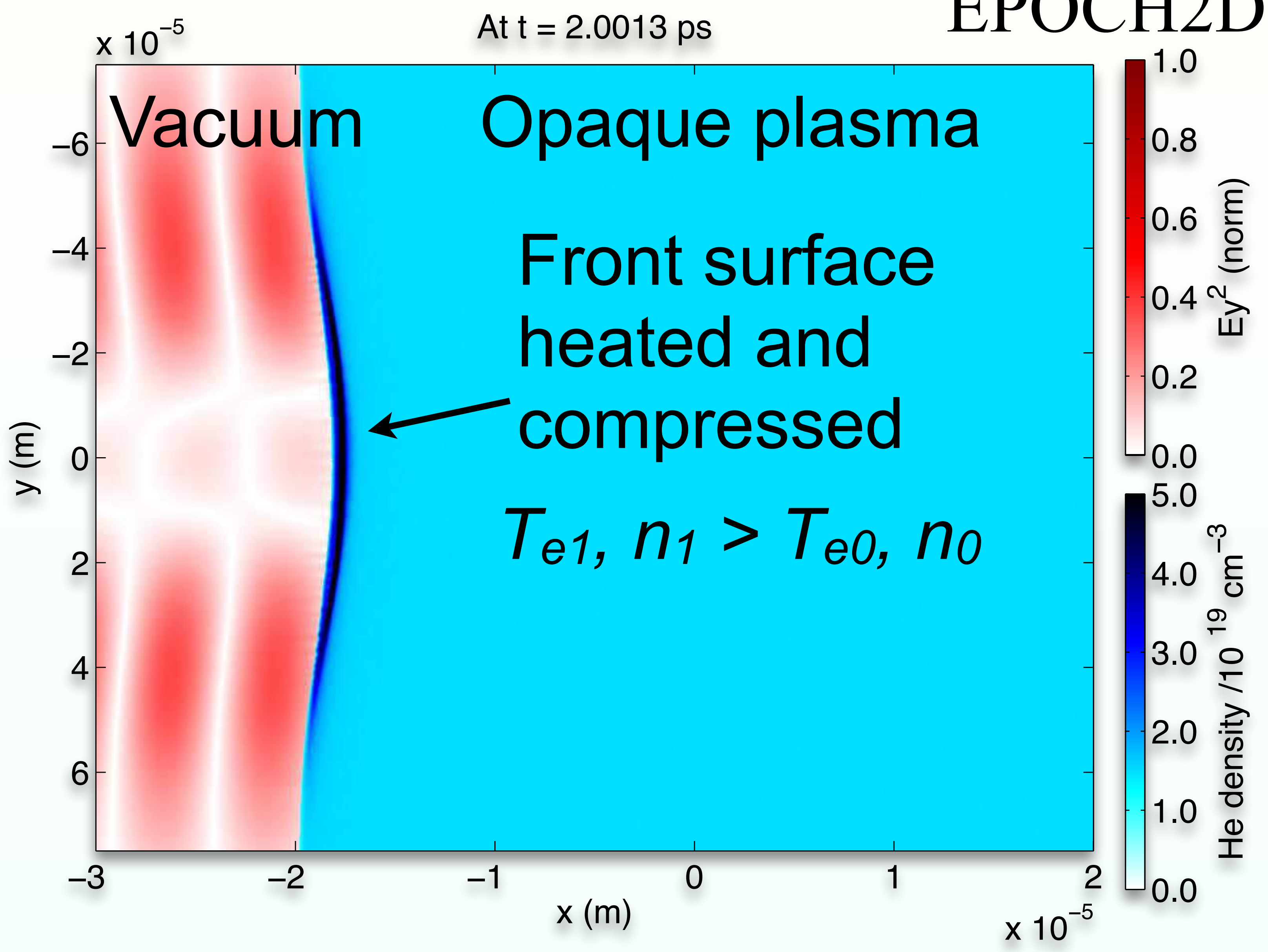

Ions accelerated from a moving shock

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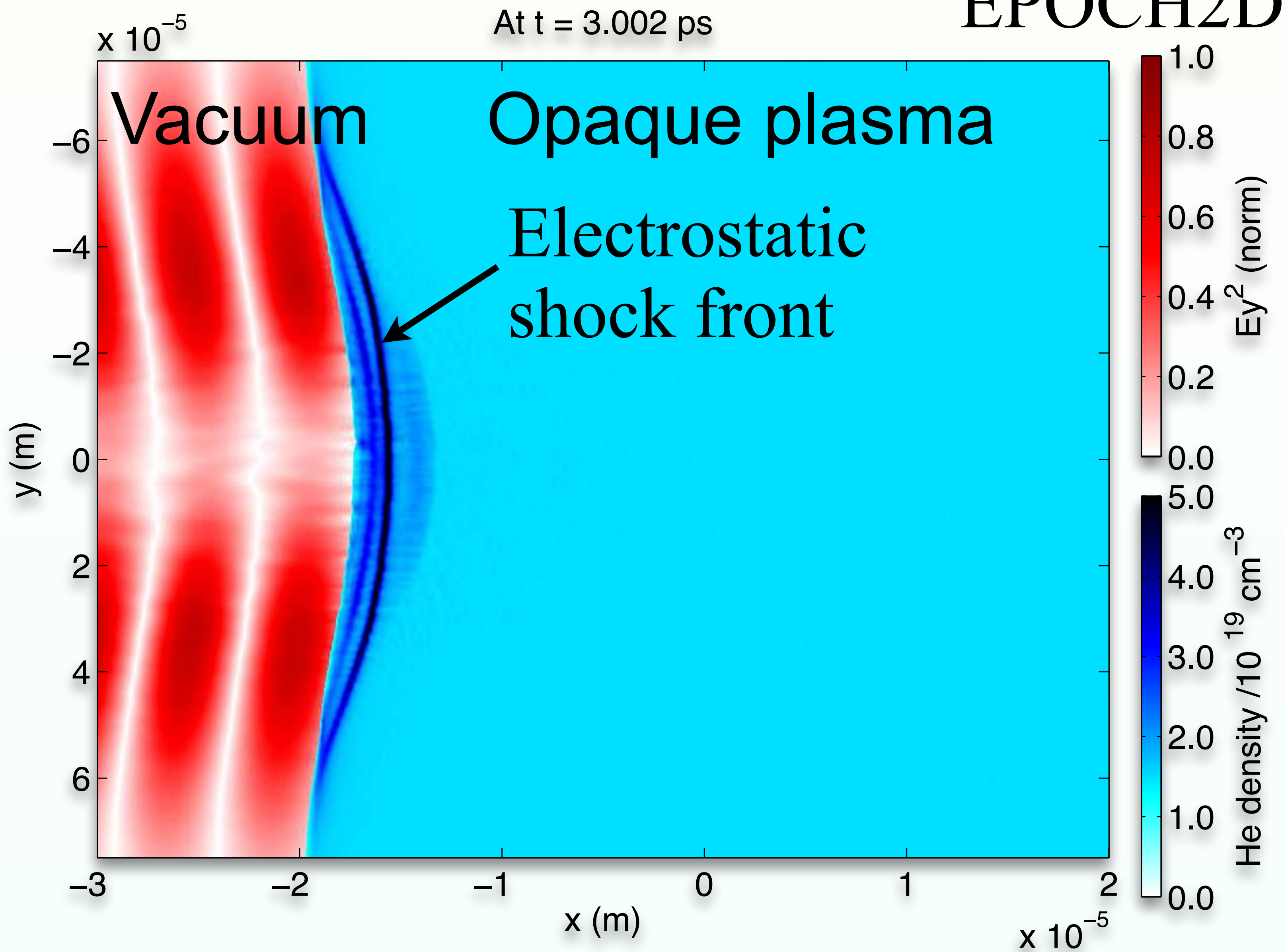

Ions accelerated from a moving shock

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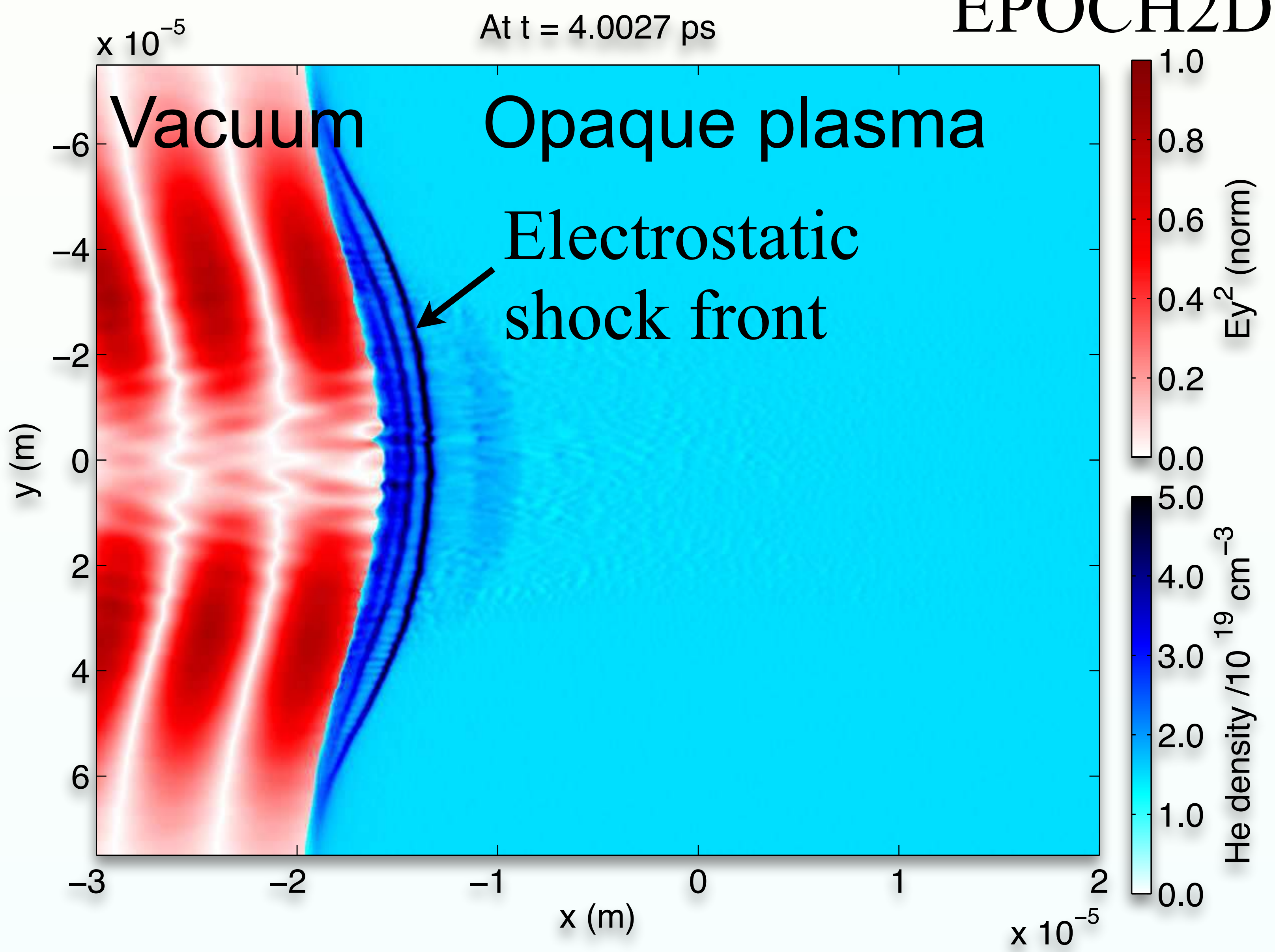

Ions accelerated from a moving shock

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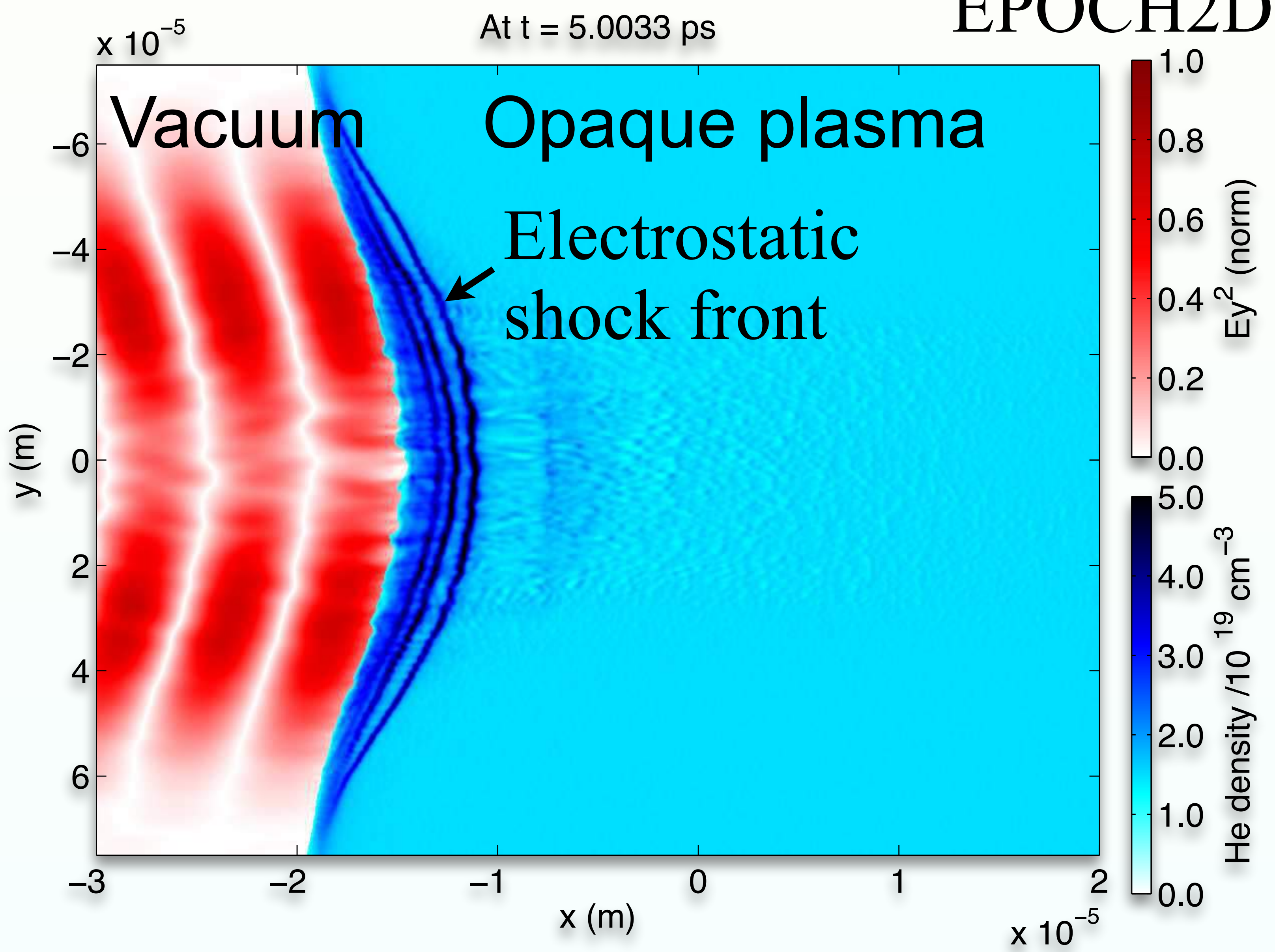
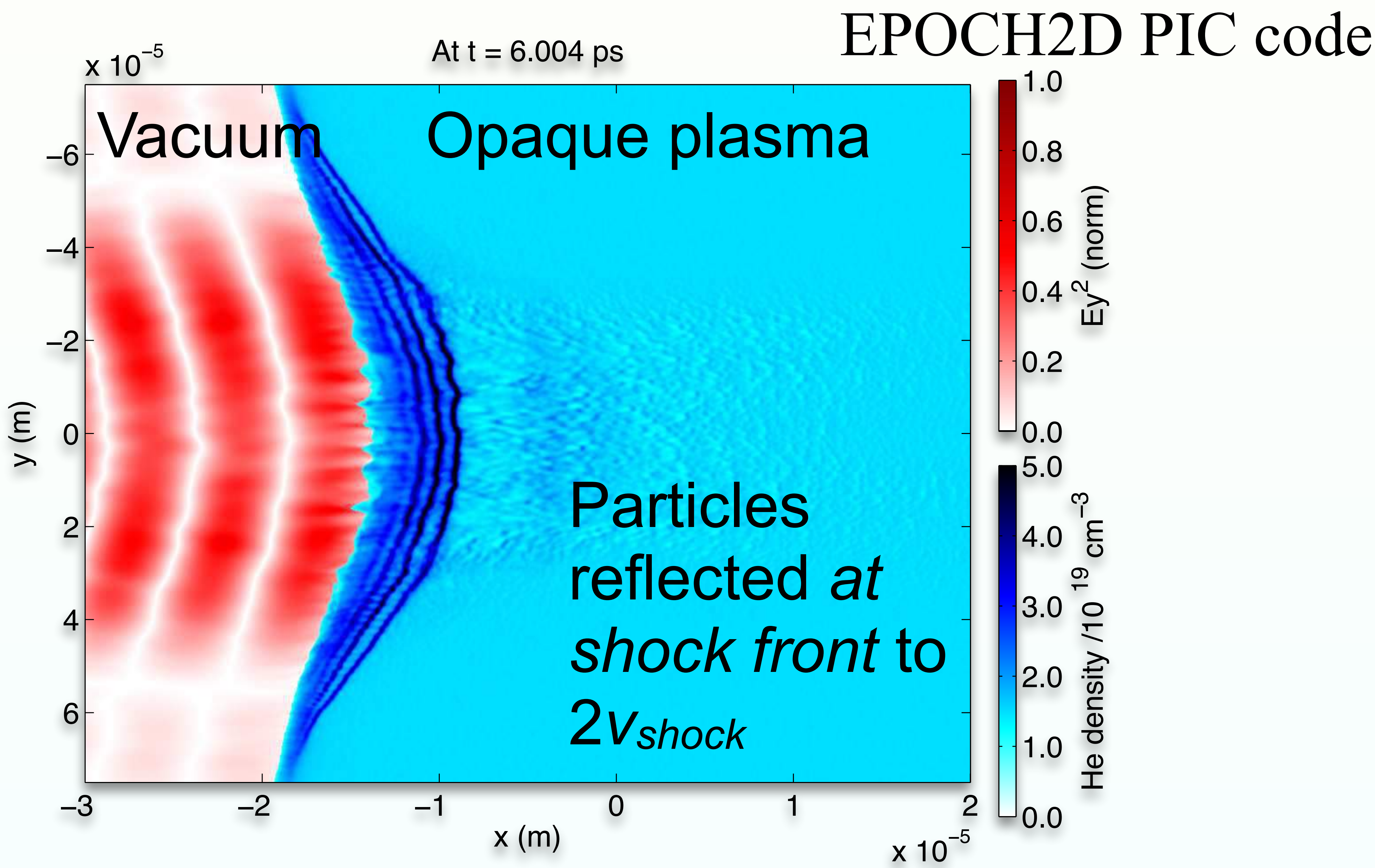


Ions accelerated from a moving shock



Ions accelerated from a moving shock

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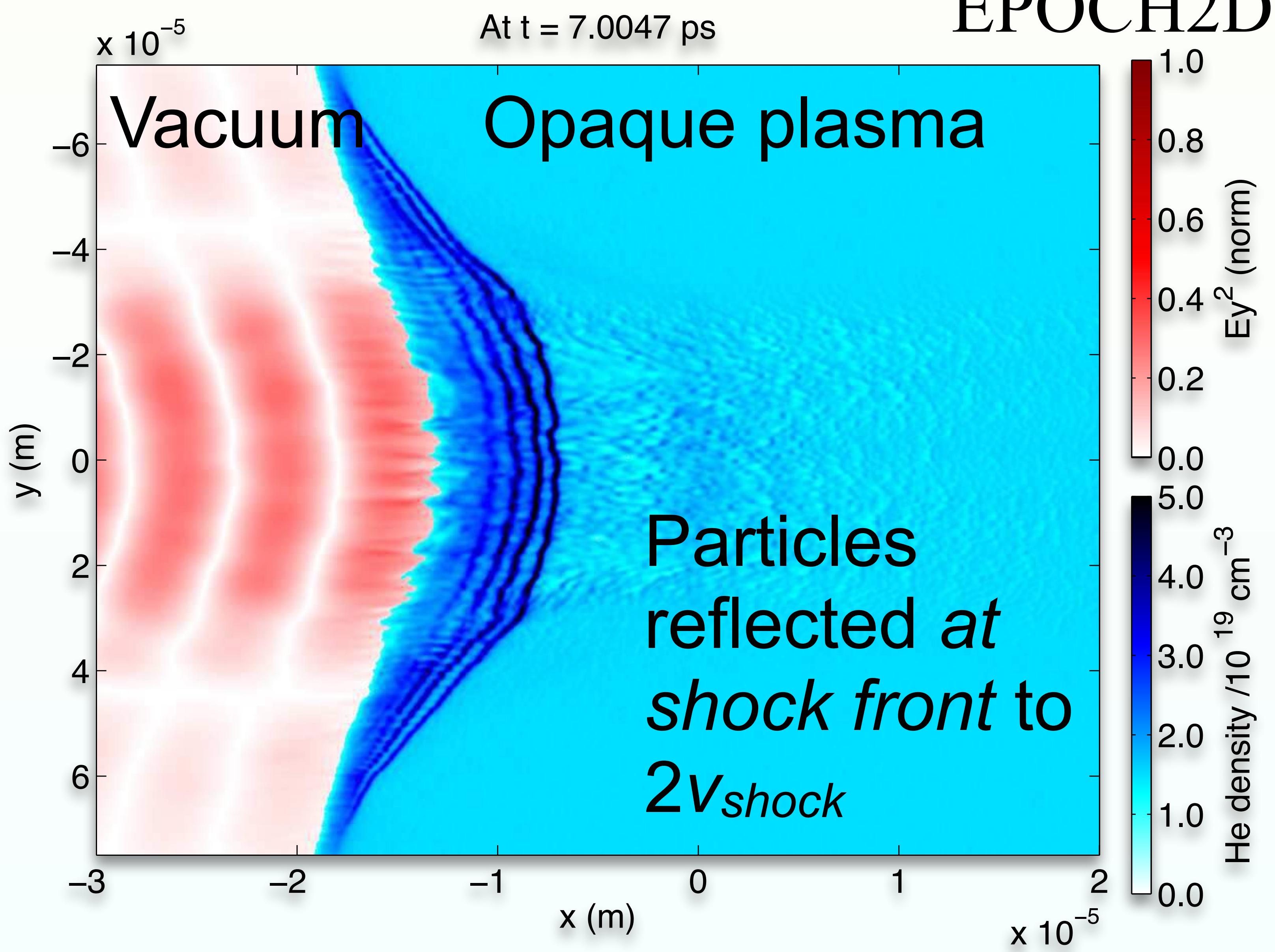

Ions accelerated from a moving shock

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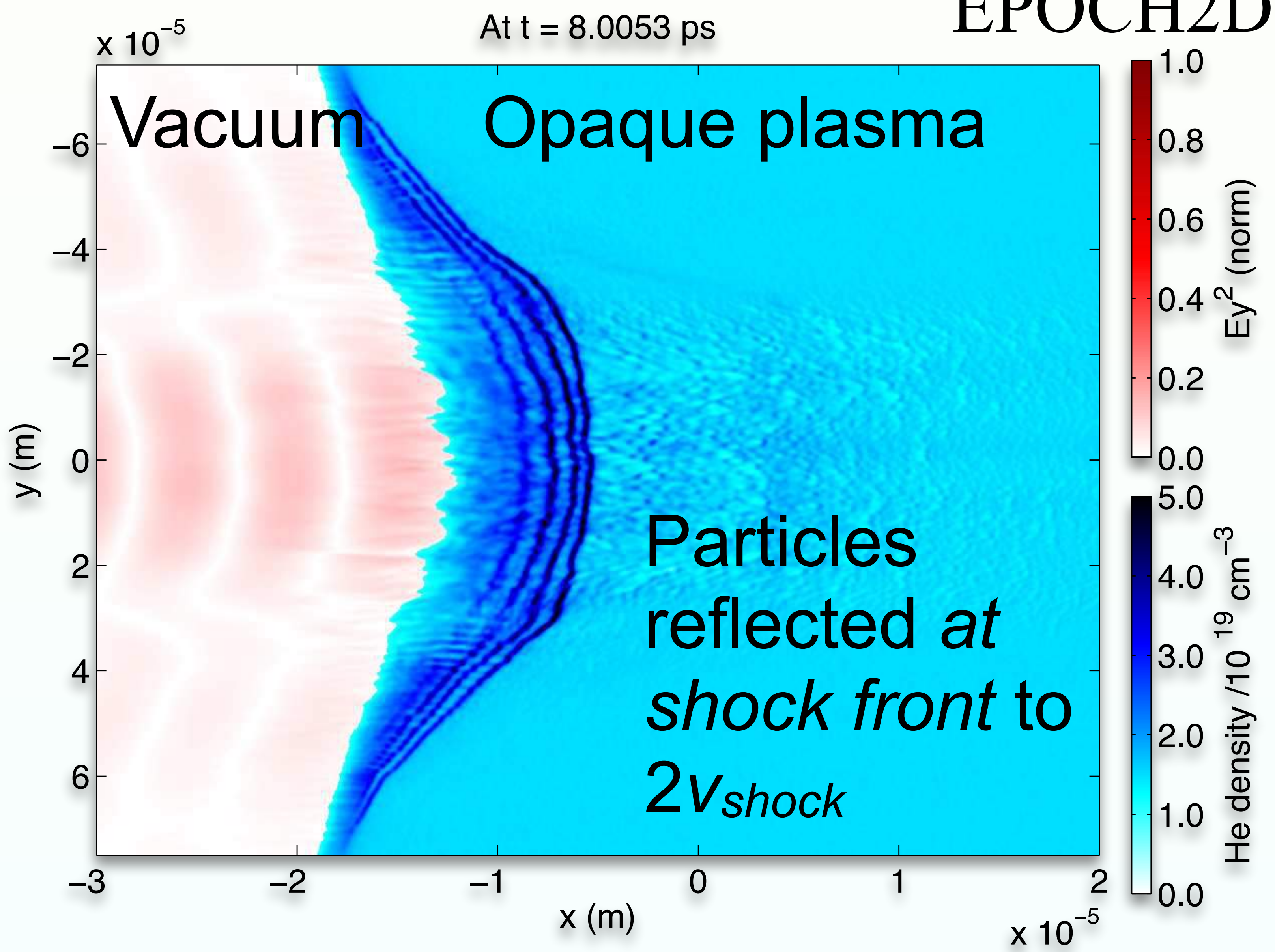
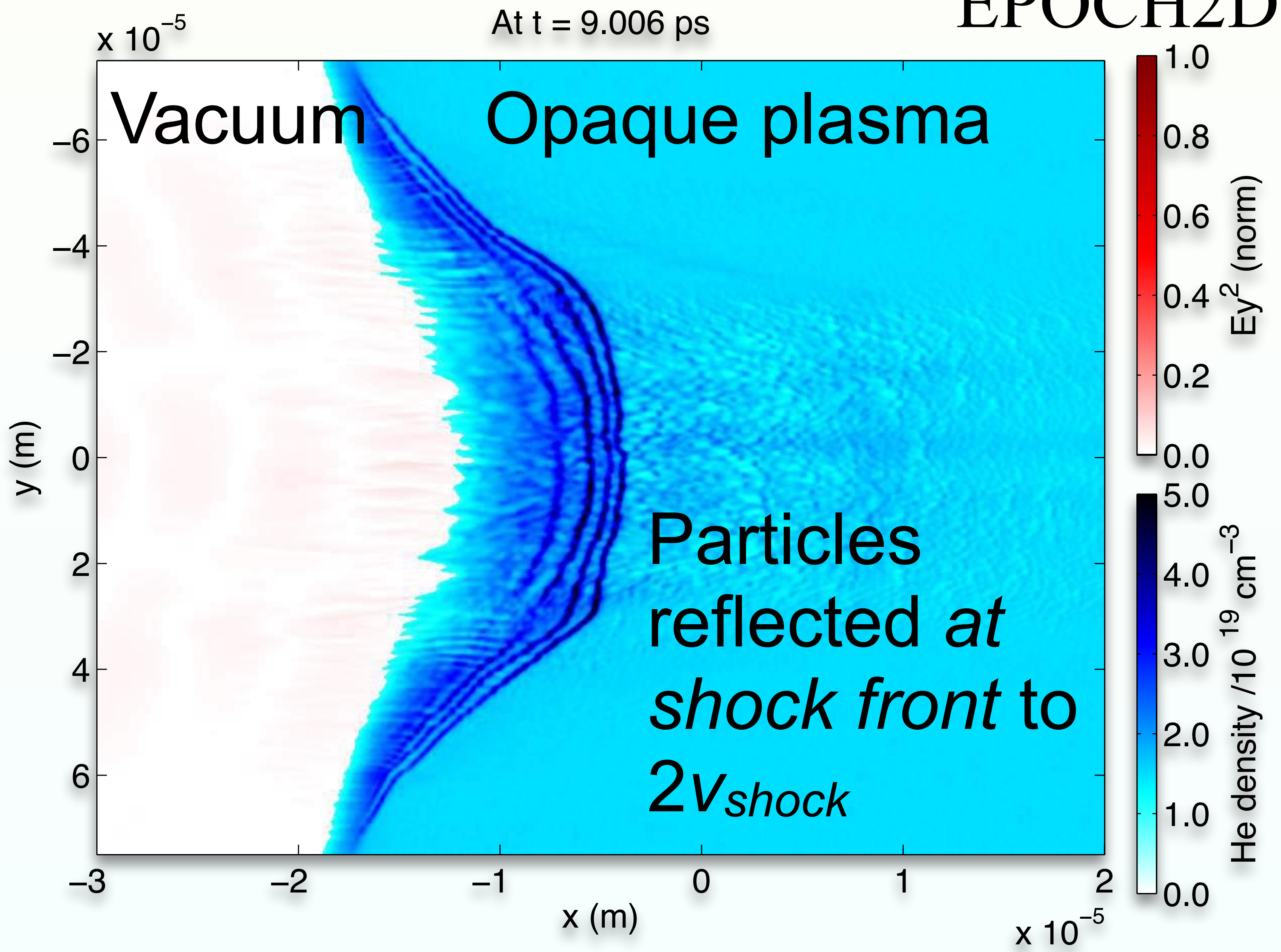


Ions accelerated from a moving shock

EPOCH2D PIC code



Ions accelerated from a moving shock

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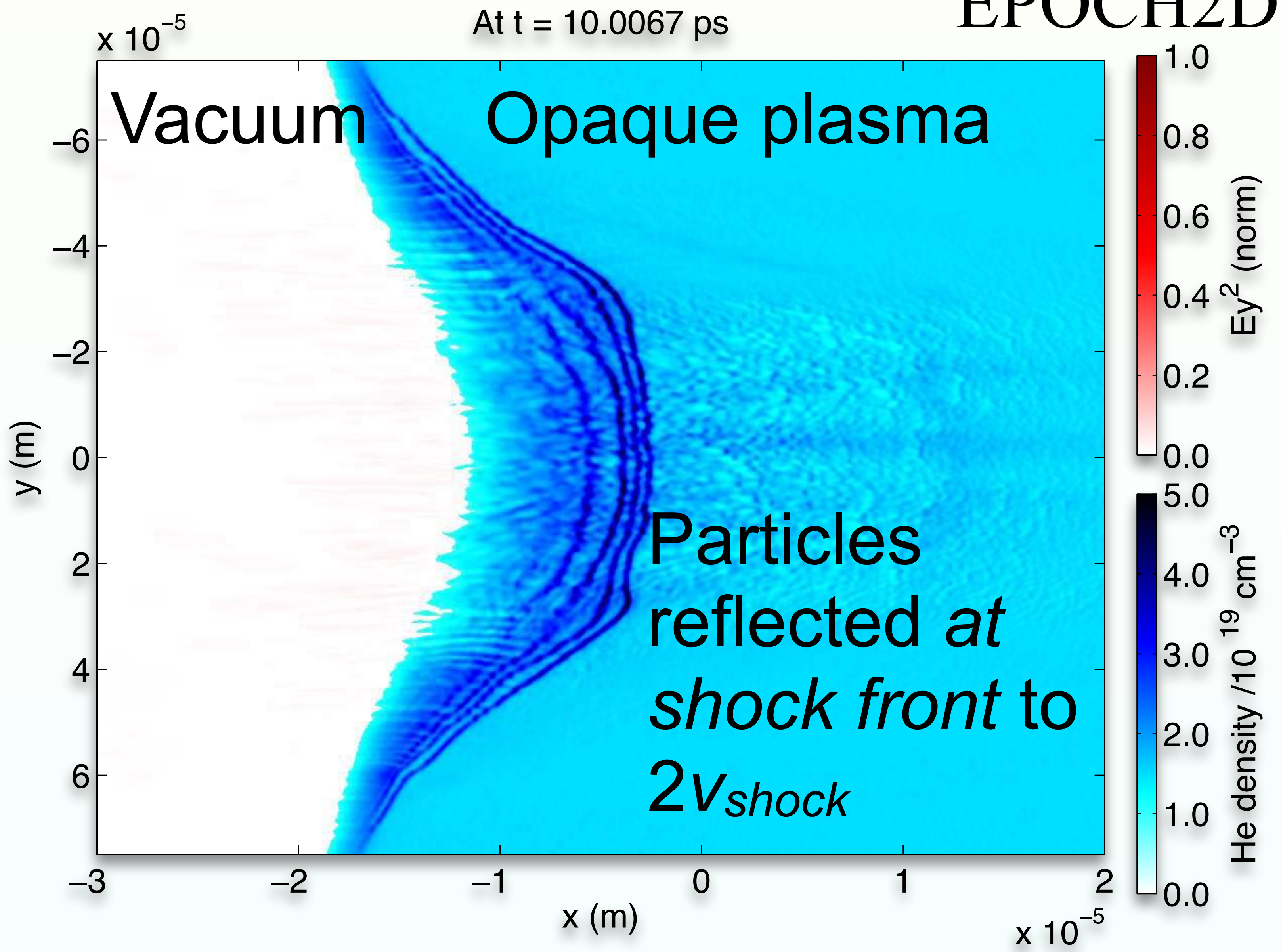

Ions accelerated from a moving shock

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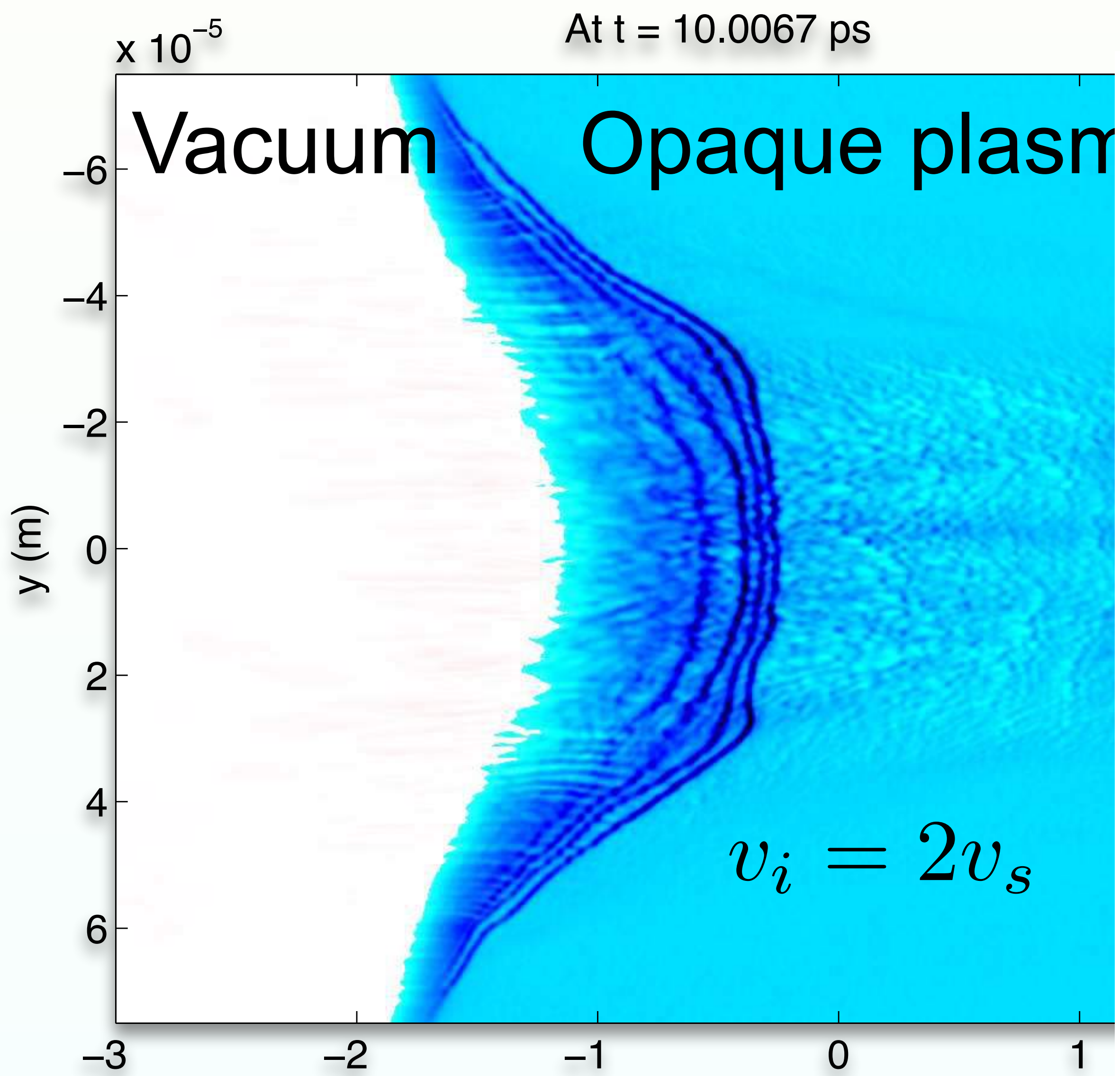

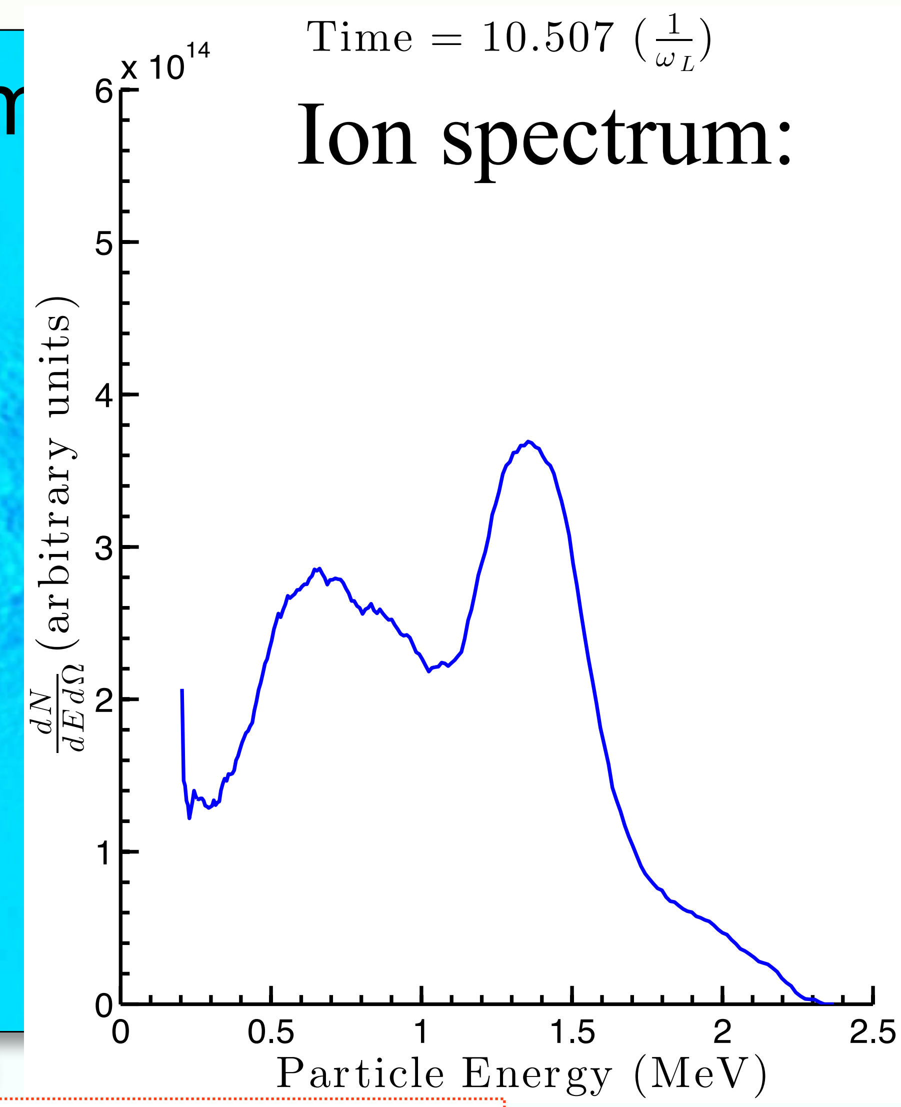

- Needs low density, opaque target
- Reflected ions ➠ Narrow spectrum

Collaborators

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Conclusions

- Wakefields: Energy gain to > 2 GeV in 'Bubble' regime, high charges >100 pC at efficiencies > 5% measured

➔ Future: Understanding of highly non-linear 3D wakes; acceleration in linear wakes

- Radiation: Hard x-rays (>25 keV) with peak brightness >10^{24} photons / sec mrad^2 mm^2 0.1%BW

➔ Future: Better characterisation (e.g. hard x-ray spectra); novel imaging applications

- Ions: Monoenergetic beams (~few MeV) produced by shock acceleration

➔ Future: Scaling to higher intensity; better control of target properties