Investigating magnetised, radiatively driven plasmas with a university scale pulsed-power generator

Jack Halliday (jack.halliday12@imperial.ac.uk, : @_jack_halliday)

Imperial College (MAGPIE, Experimental): S. N. Bland, S. V. Lebedev, L. G. Suttle, D. R. Russell, V. Valenzuela Villaseca, S. Merlini

Imperial College (CIFS, Computational): A. Crilly, J. Chittenden, S. Rose

University of Nevada, Reno: R. C. Mancini

Imperial College London

MAGPIE

CIFS

University of Nevada, Reno

Overview of experimental setup

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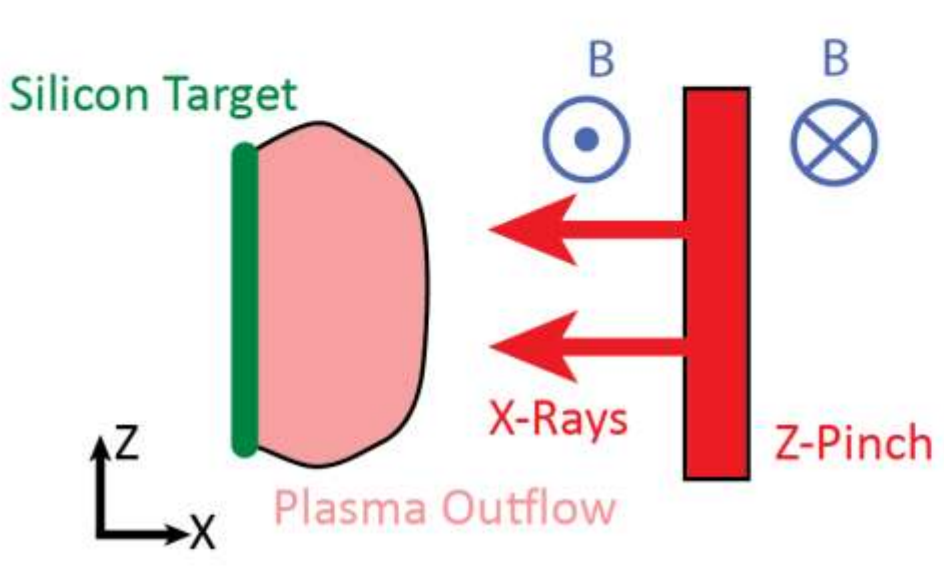
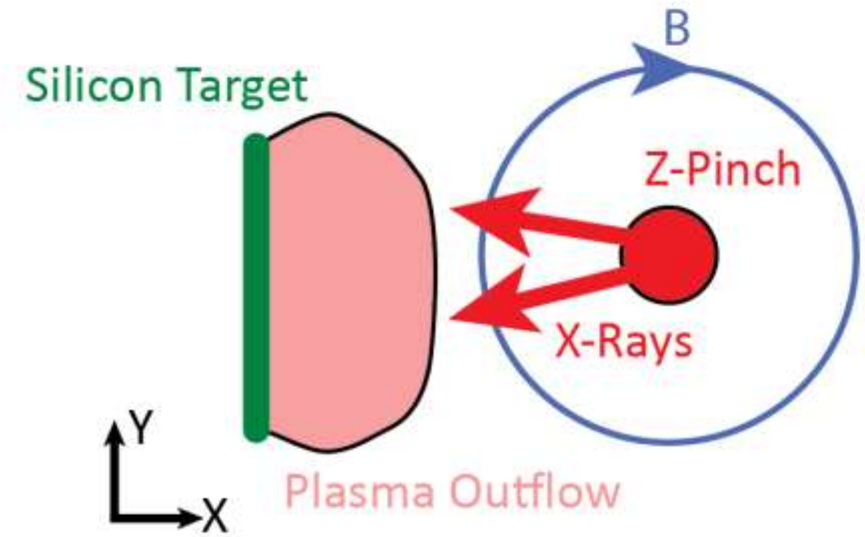


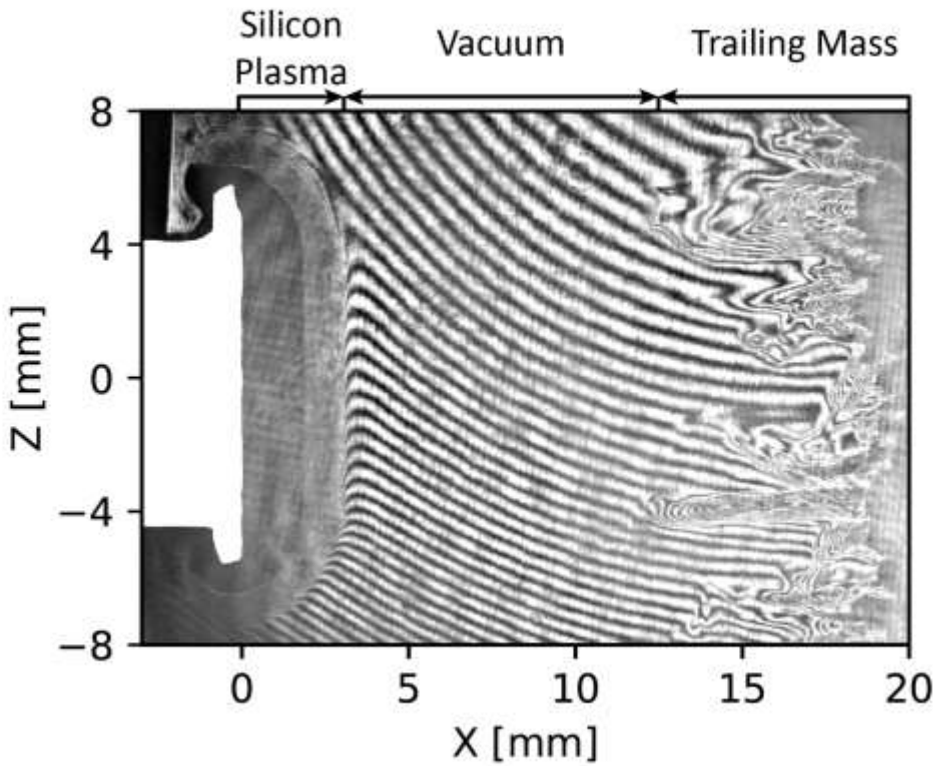
Side-On (X-Z plane) view of the experiment

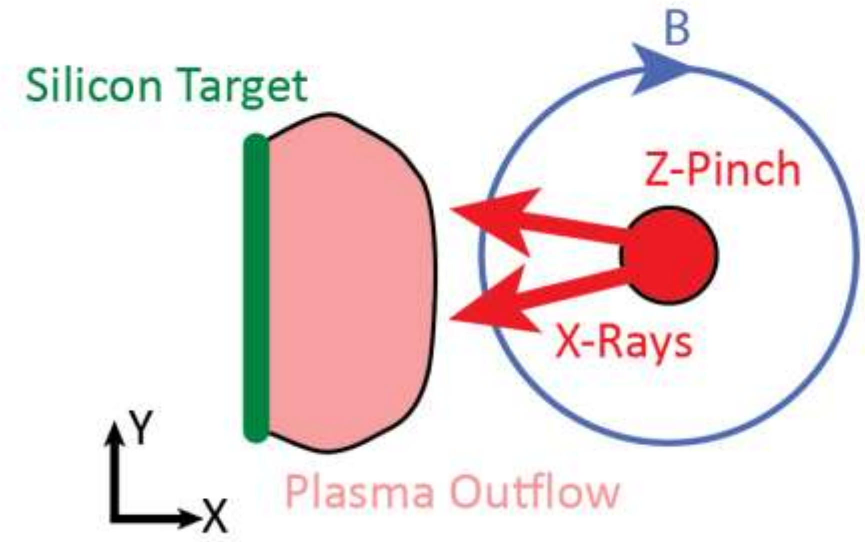


End-On (X-Y plane) view of the experiment

- X-Rays from aluminium wire array Z-Pinch
- Experiments driven by MAGPIE (1.4 MA, 240 ns)
- Ablated silicon plasma expands into ~ 10 T magnetic field
- Target positioned $1.5 - 4$ cm from pinch

Overview of experimental setup





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Structure of talk

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- Discuss X-Ray driver (MAGPIE generator, wire array Z-pinches)
- Diagnosis of self-emission / laser interferometry & comparison with R-MHD simulations
- Velocity, temperature, & ionisation profiles from Thomson scattering
- Magnetic field profiles from Faraday rotation imaging

The MAGPIE pulsed power generator

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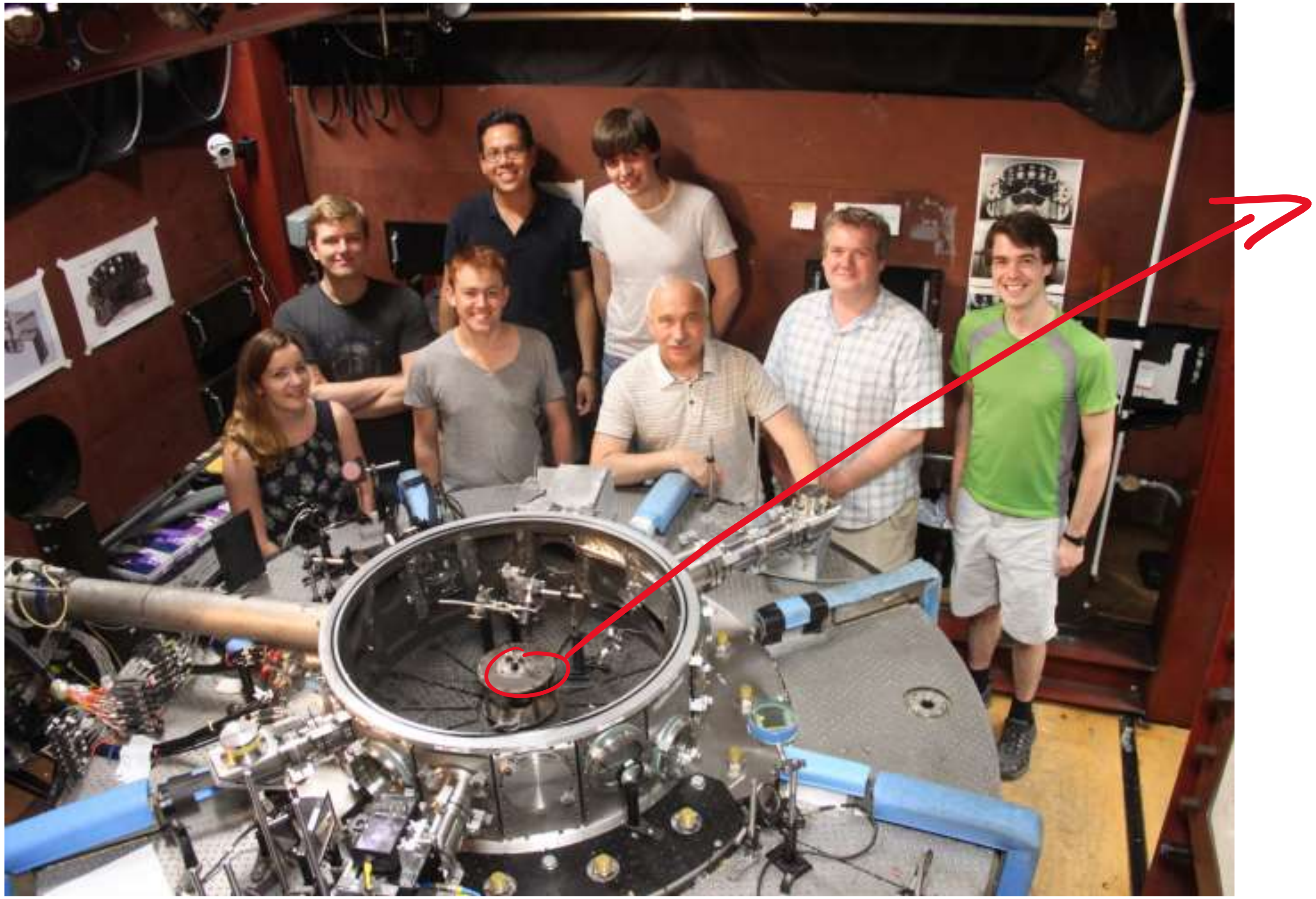
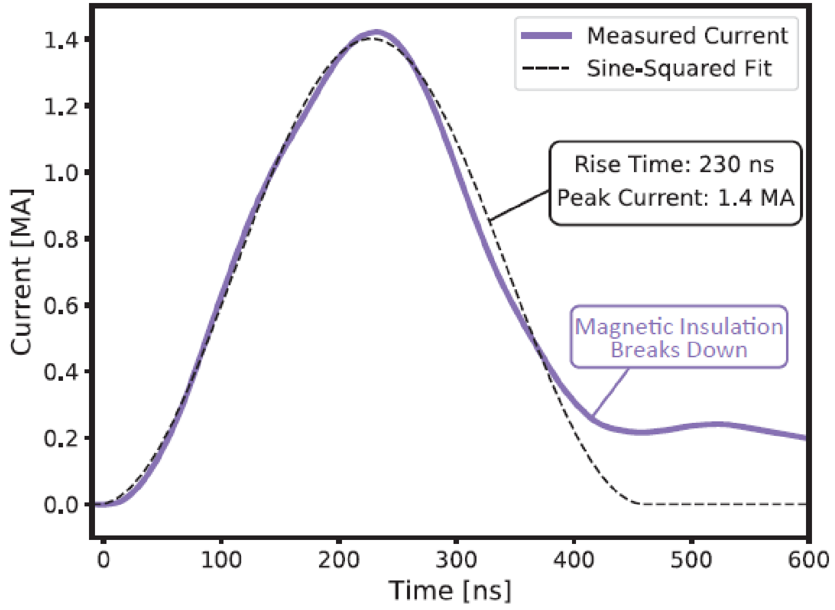
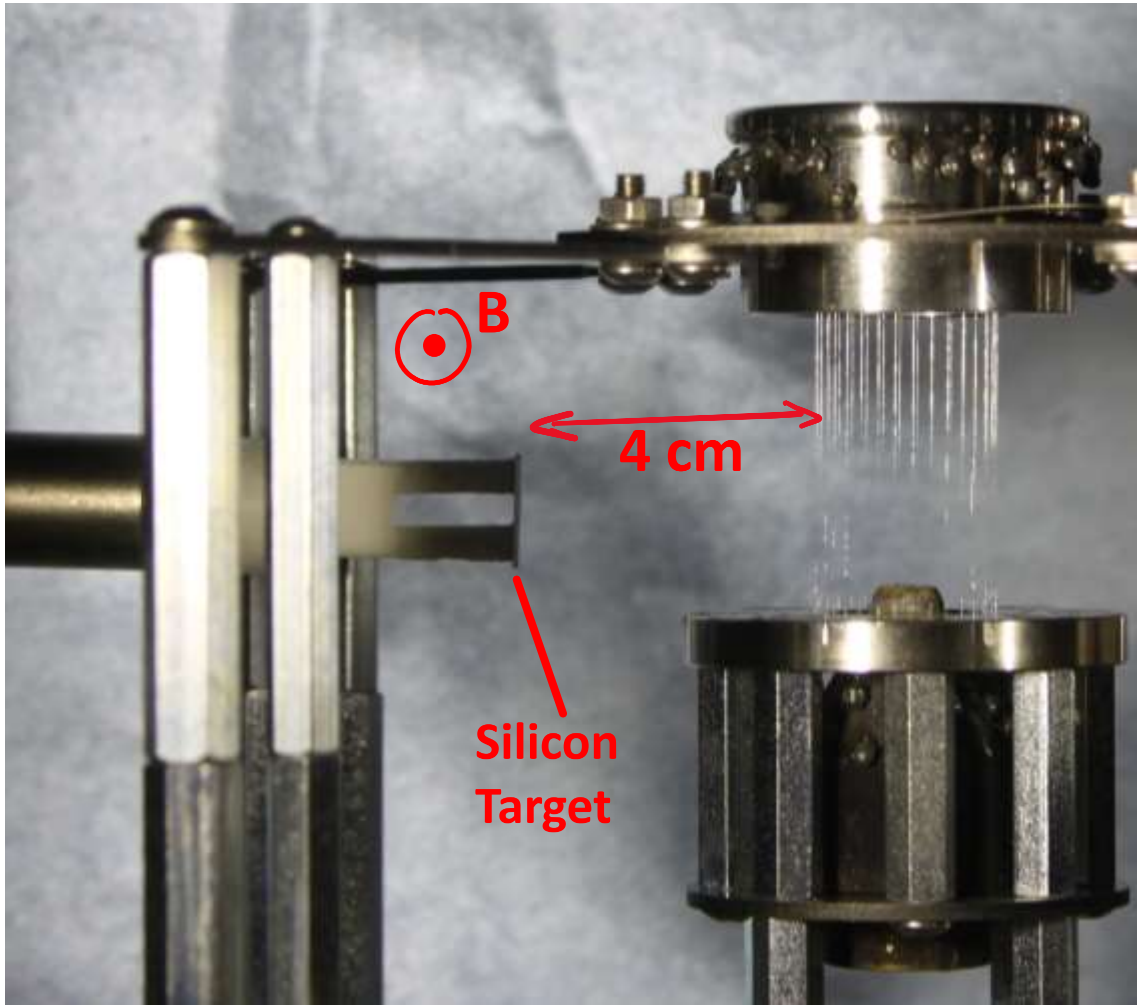


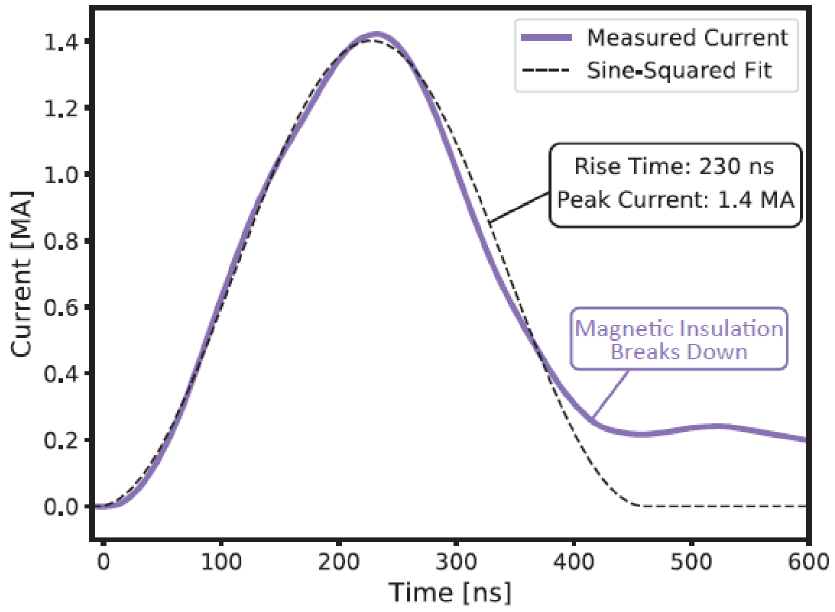


1.4 MA, 240 ns Current Pulse

X-Ray Pulse ~ 1 TW

Wire Array Z-Pinches are an Efficient X-Ray Source

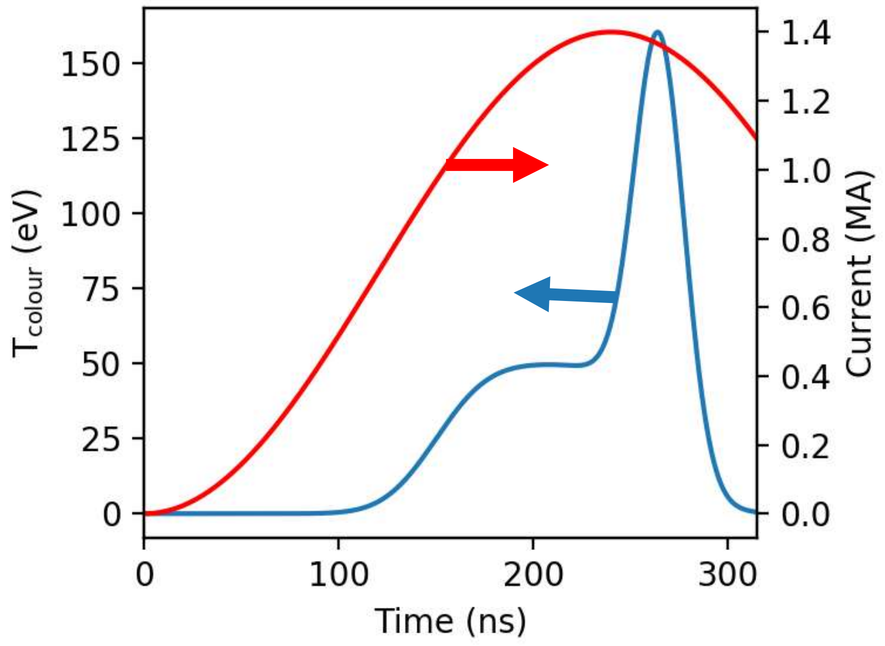




1.4 MA, 240 ns Current Pulse

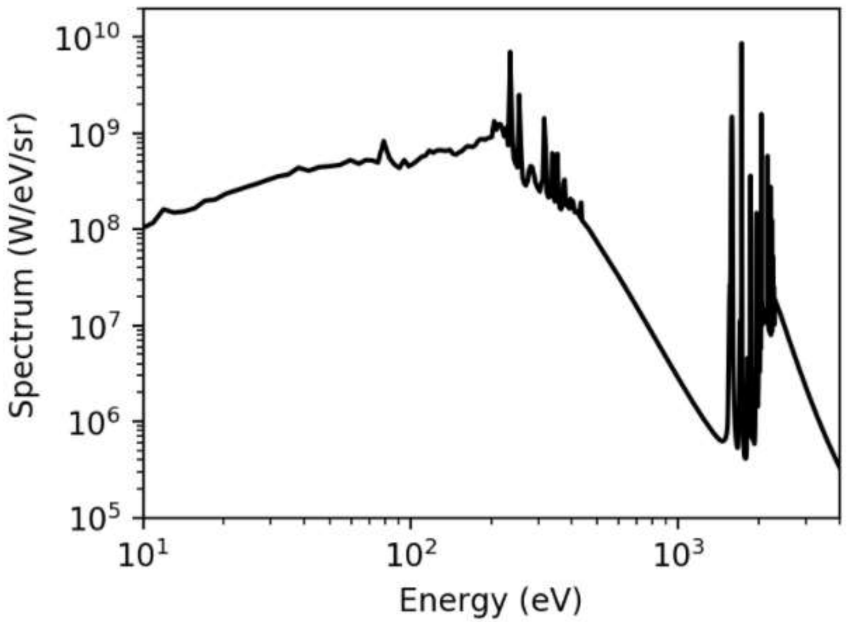
X-Ray Pulse ~ 1 TW

Spectral Character of Radiation at ~1 MA Level



- **Precursor (pre-pulse):**
  - Colder spectral character ($T_c \sim 50$ eV)
  - Radiates ~ 400 J in total
  - Time duration ~100 ns
- **Implosion:**
  - Emitted radiation~15 kJ over ~30 ns
  - Estimate $T_c \sim 150$ eV

Spectral Character of Radiation at $\sim$1 MA Level



- **Precursor (pre-pulse):**
  - Colder spectral character ($T_c \sim$ 50 eV)
  - Radiates $\sim$ 400 J in total
  - Time duration $\sim$100 ns

- **Implosion:**
  - Emitted radiation$\sim$15 kJ over $\sim$30 ns
  - Estimate $T_c \sim$ 150 eV

Structure of talk

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Optical self emission images [qualitive dynamics]

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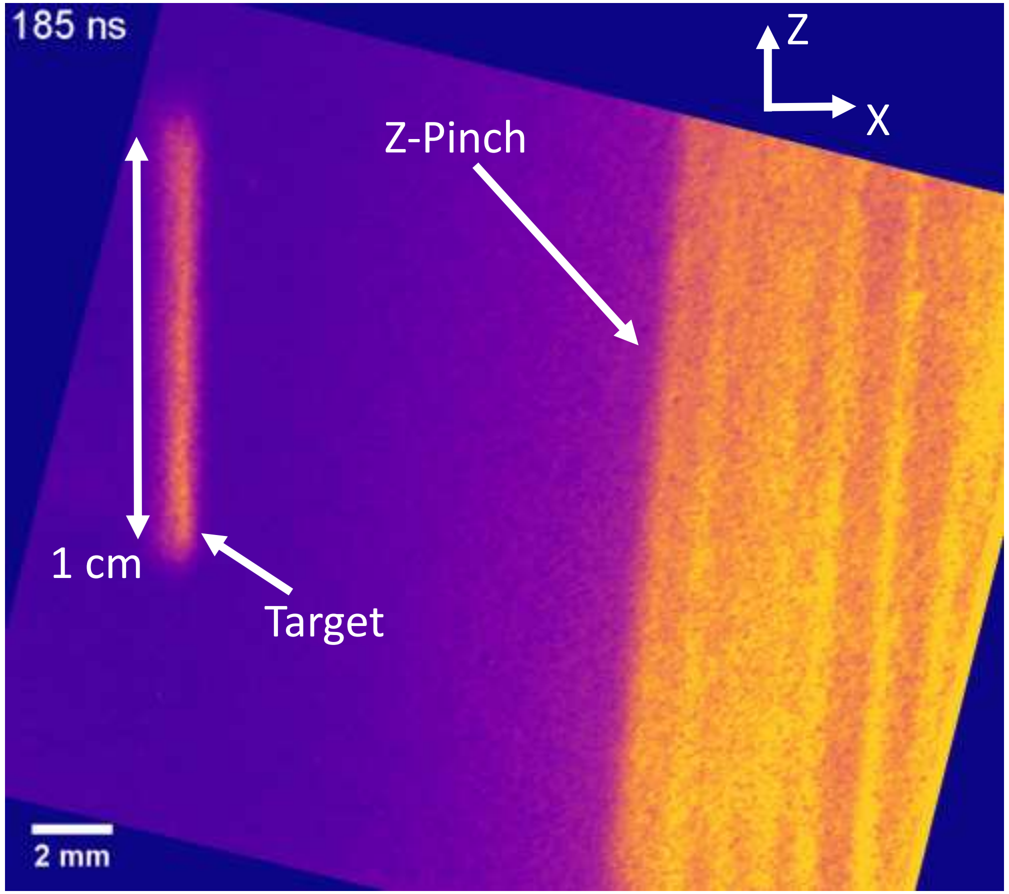
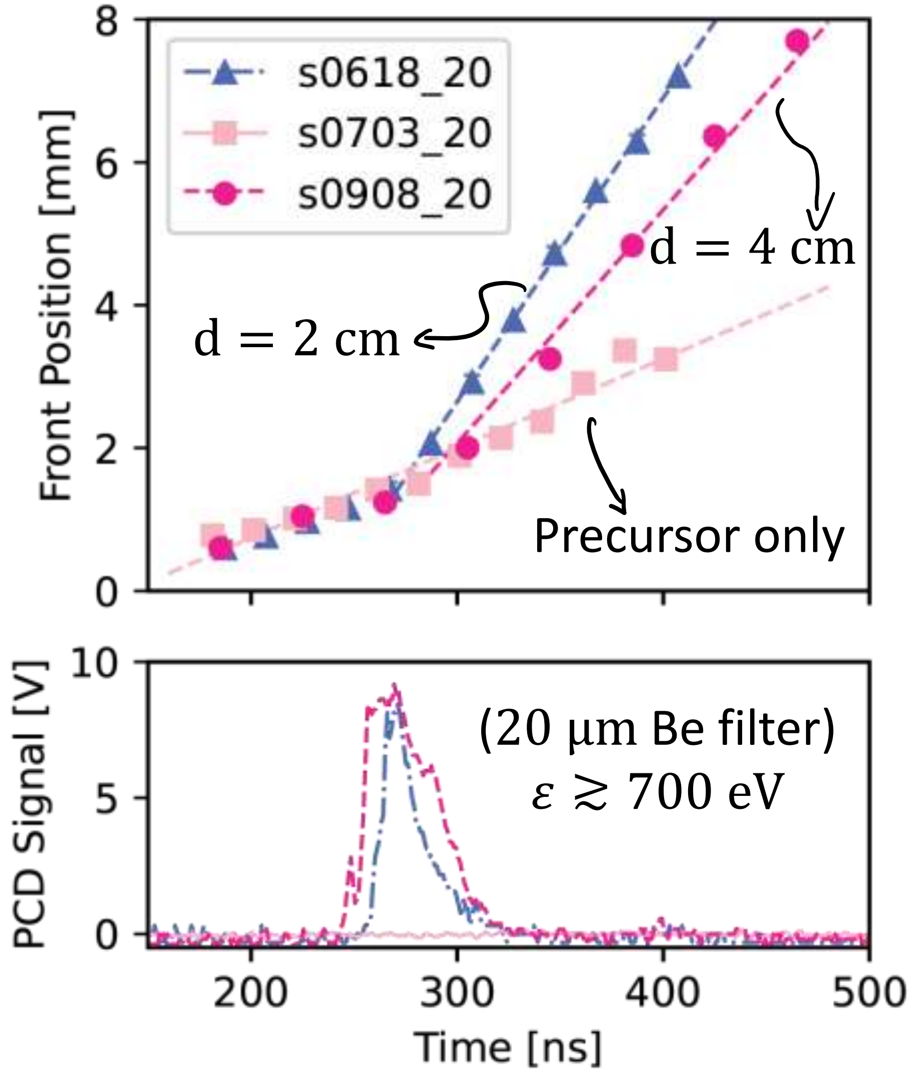


Self emission images [$600 \lesssim \lambda \lesssim 900$ nm]



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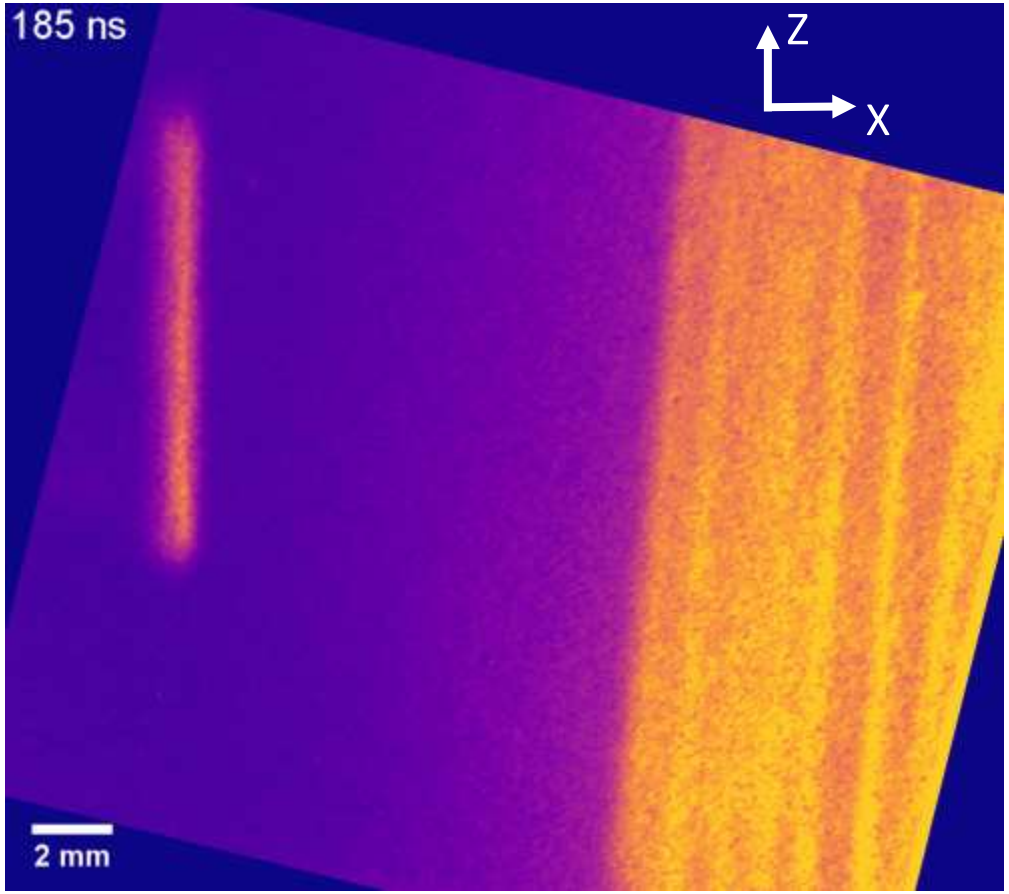

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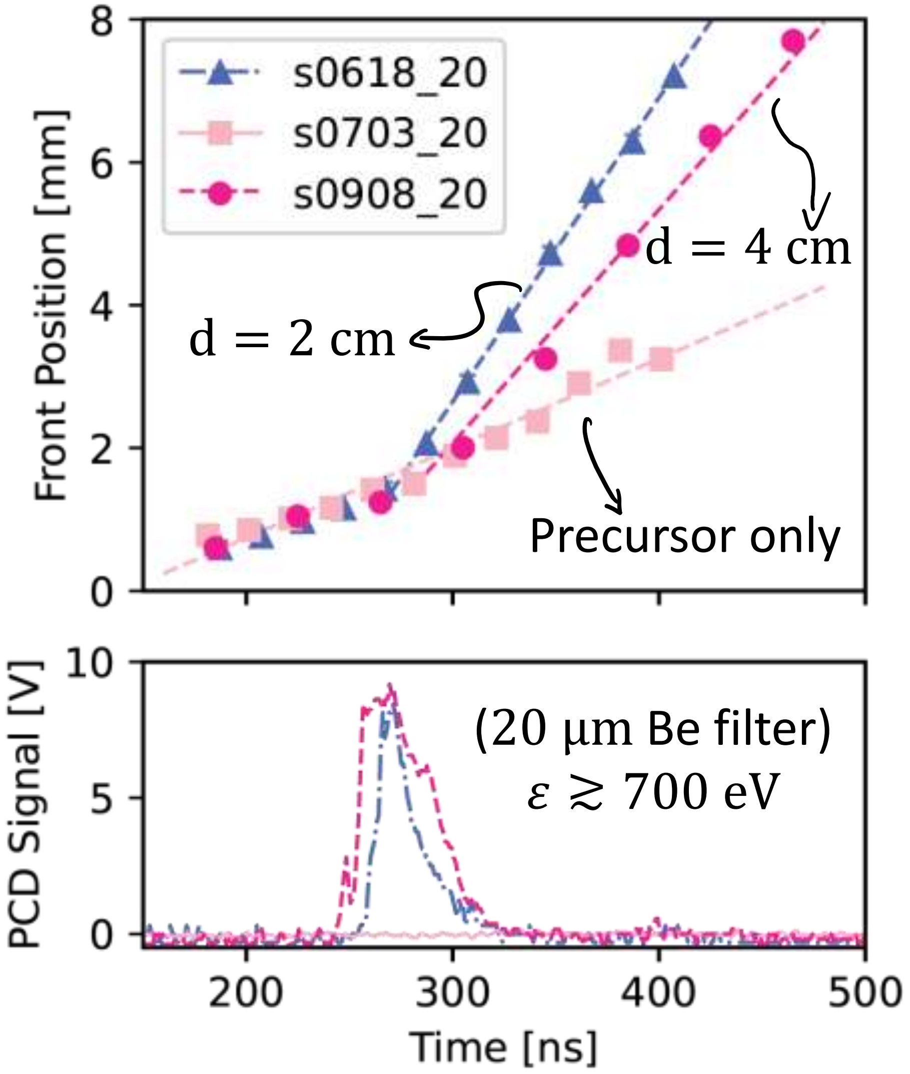

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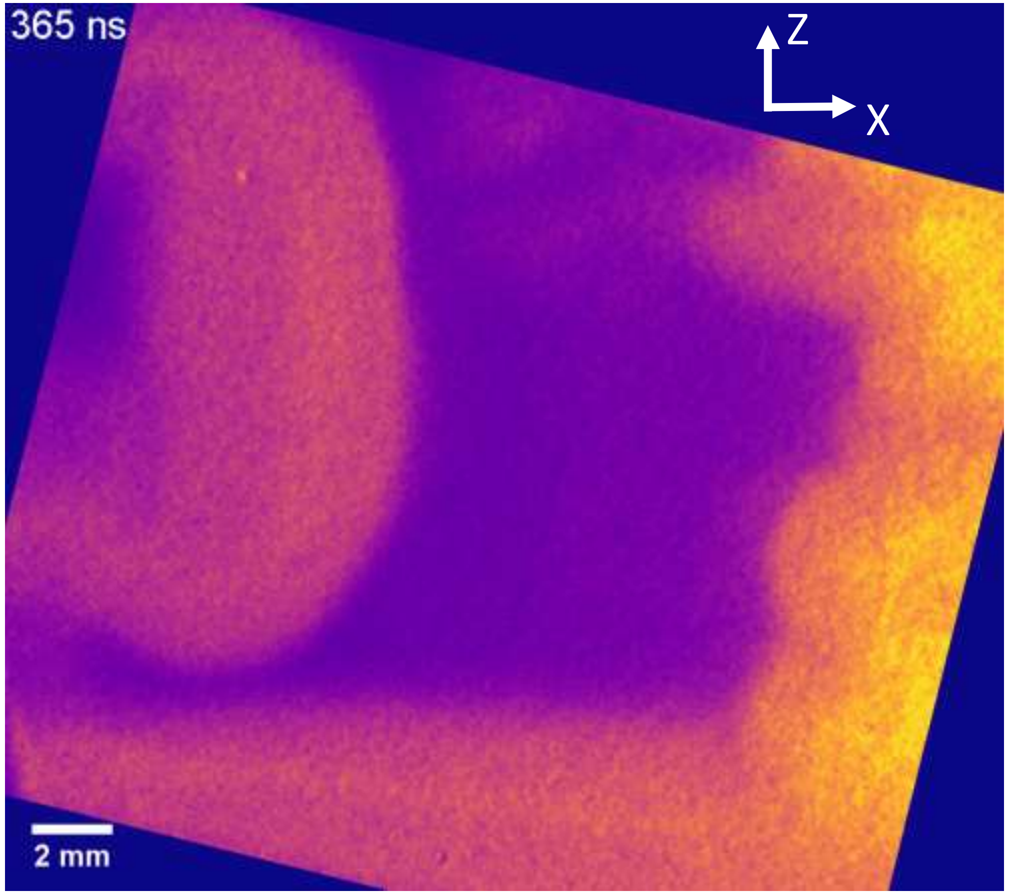

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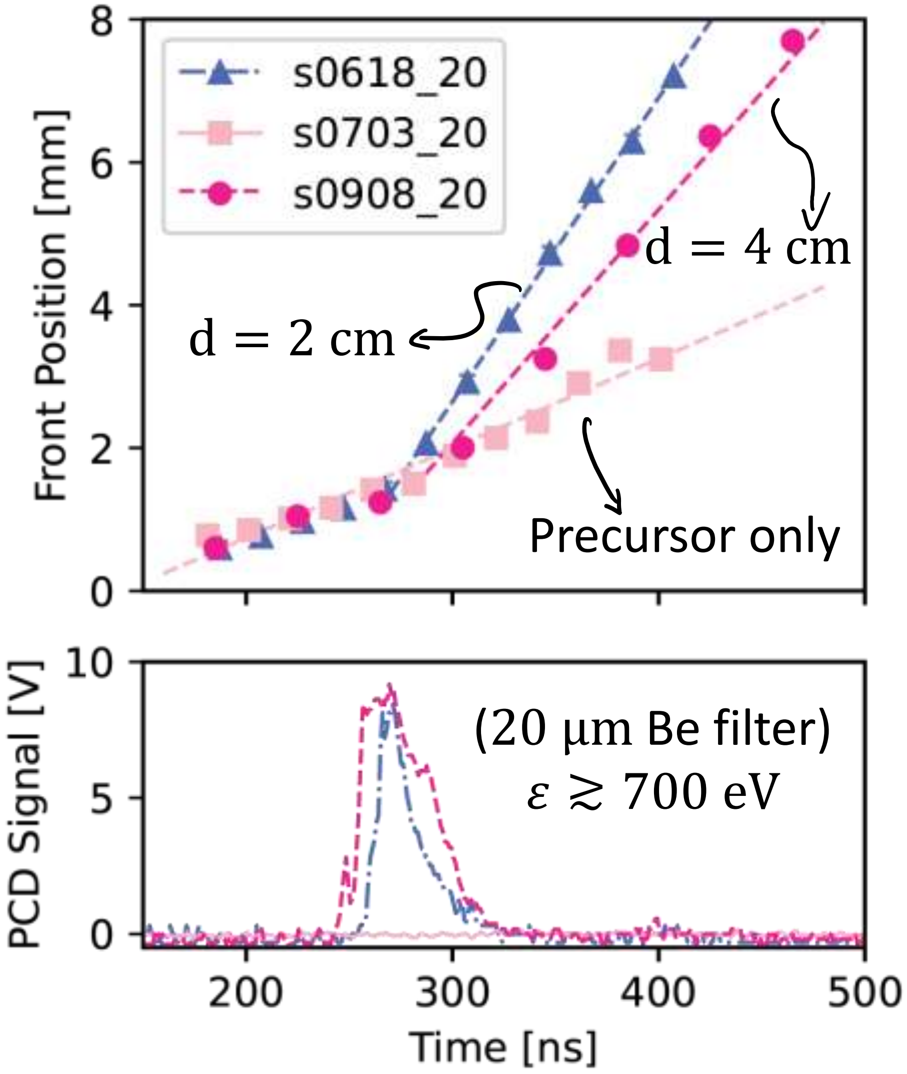

Interferometry [line integrated electron density]

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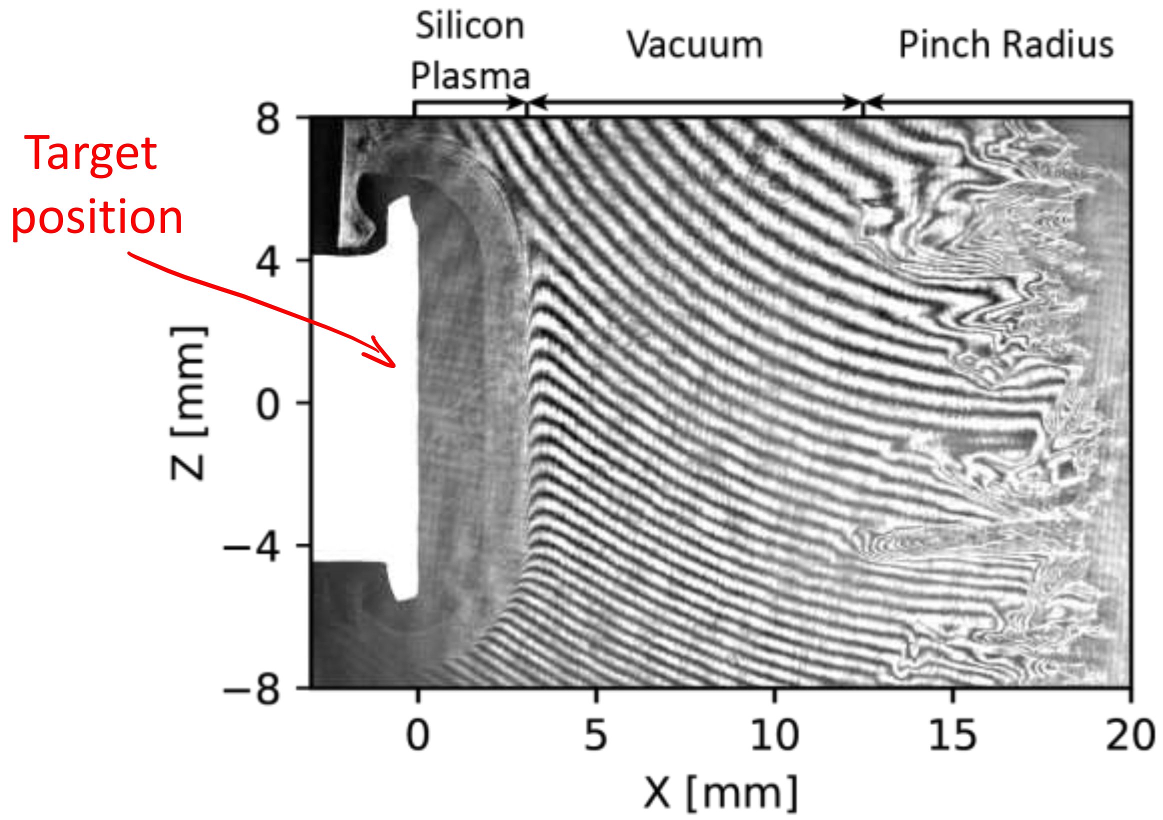
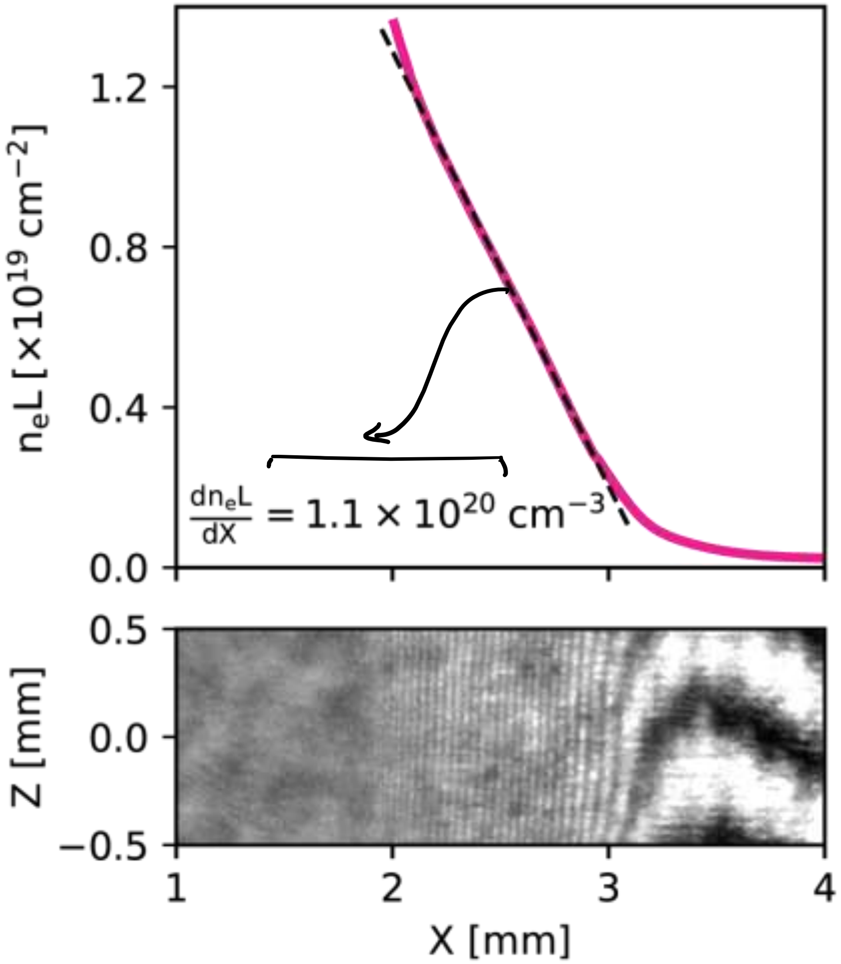
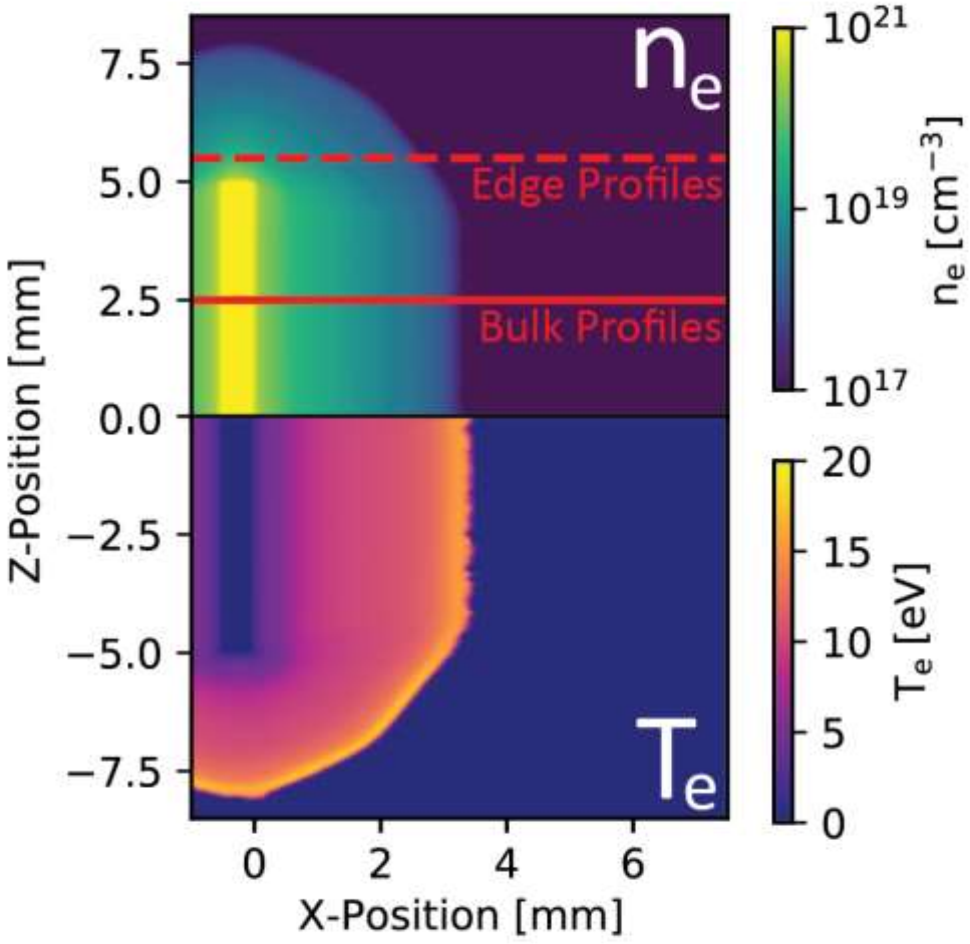
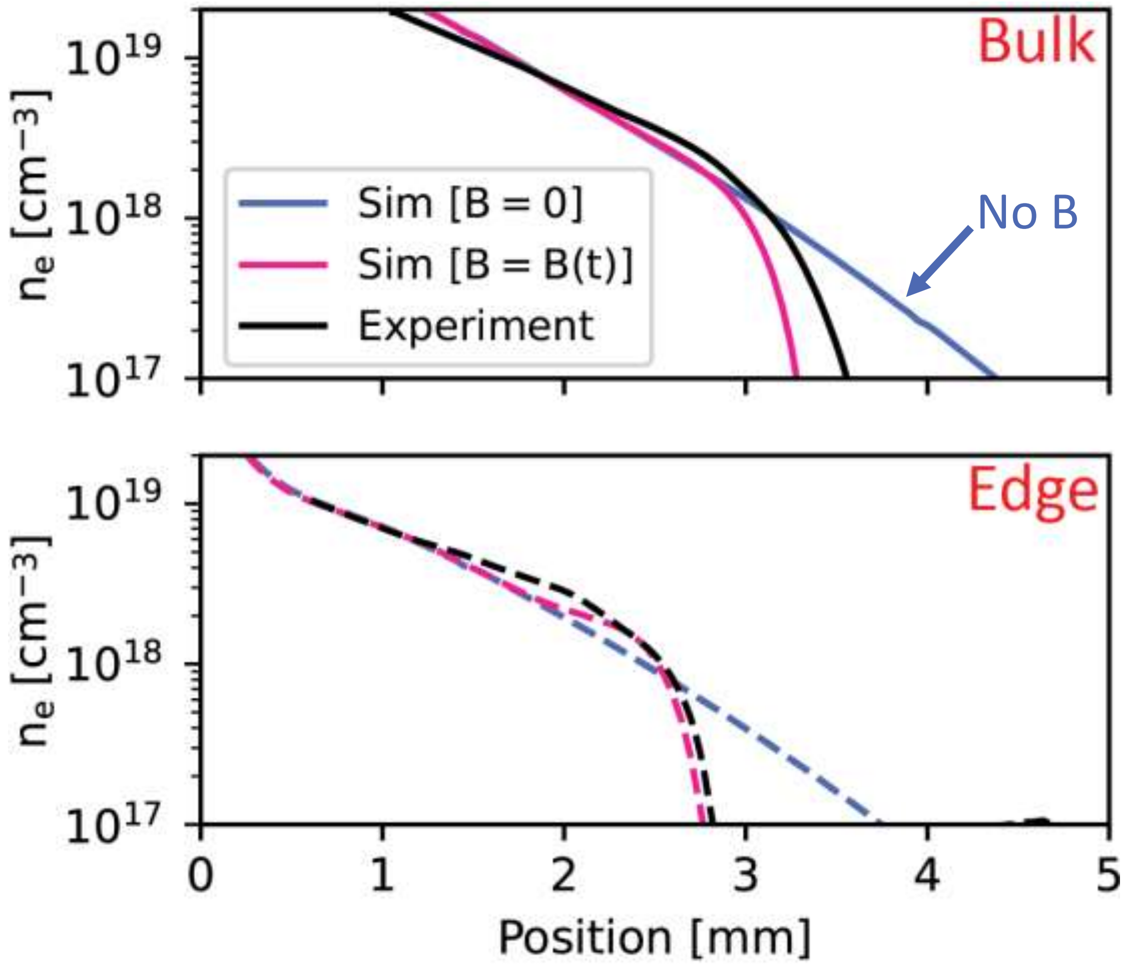




- Interferogram captured at $t = 320$ ns
- Smooth $\sim$1D expansion profile confirmed by orthogonal laser probing

Radiative MHD simulations [Chimera]





Density profile is affected by B-Field.

Radiative MHD simulations [Chimera]

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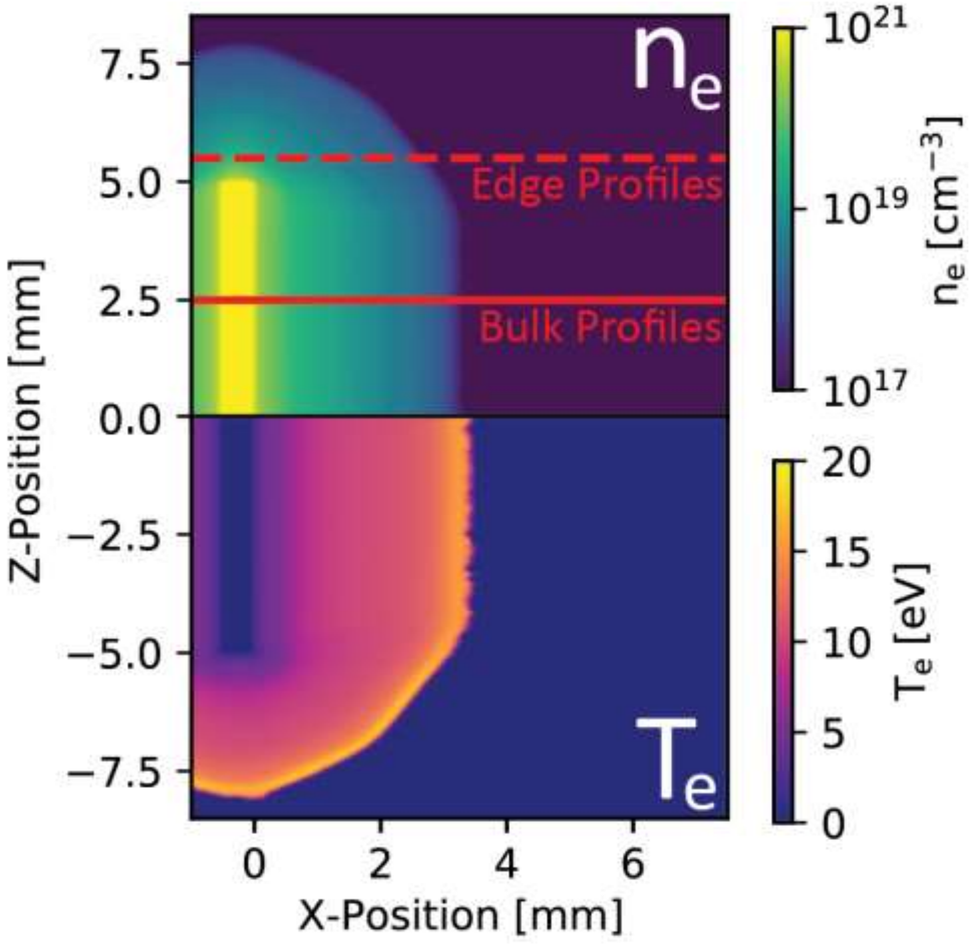

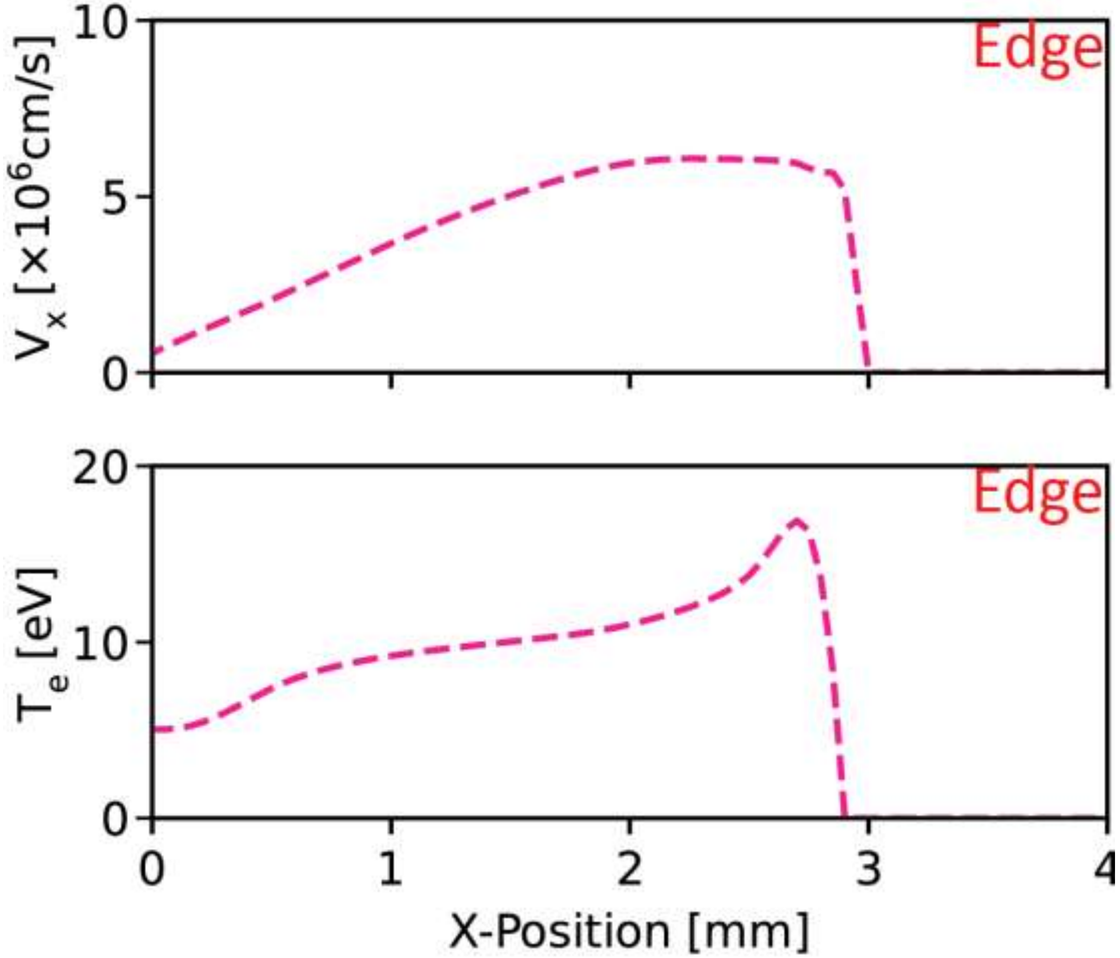

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Thomson scattering [localised diagnosis of T, V, Z]

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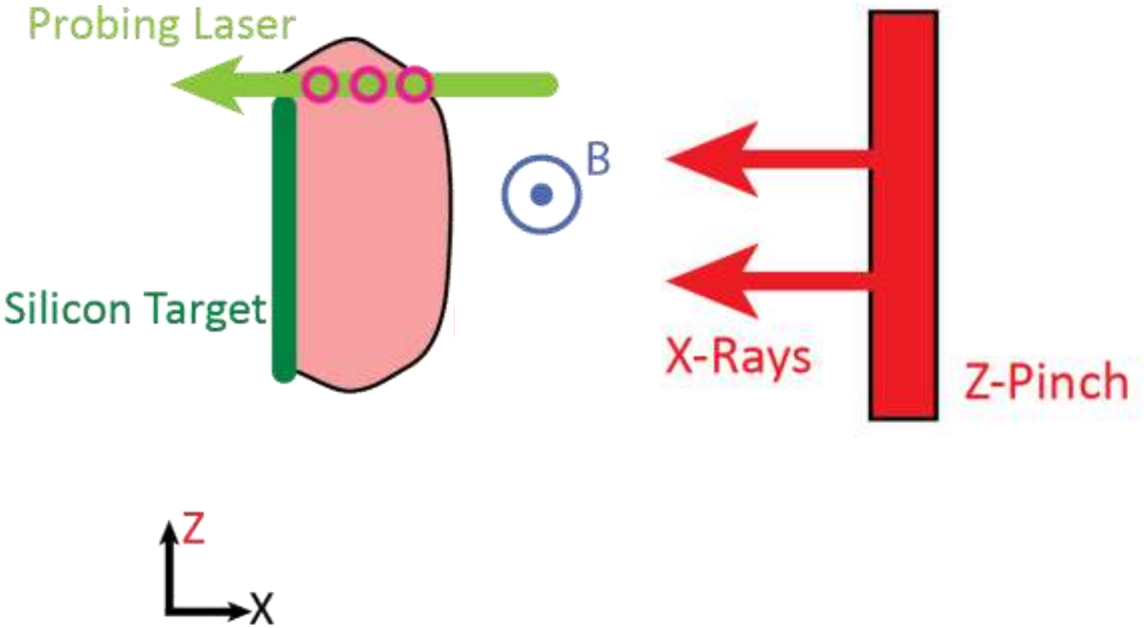
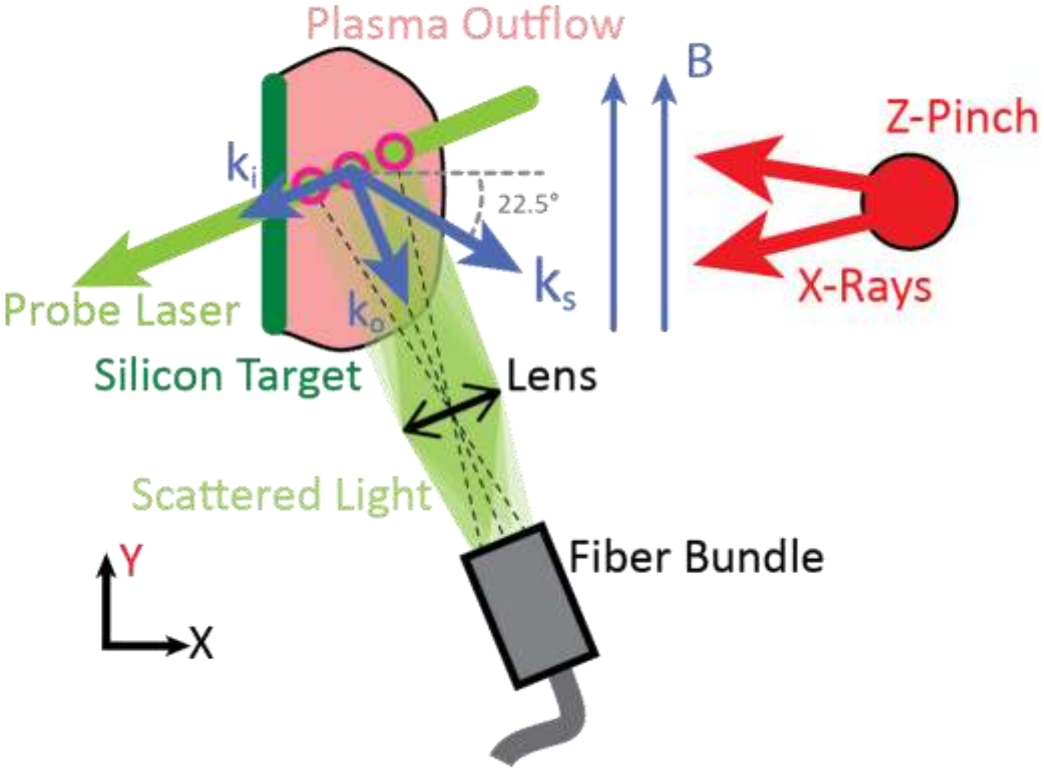
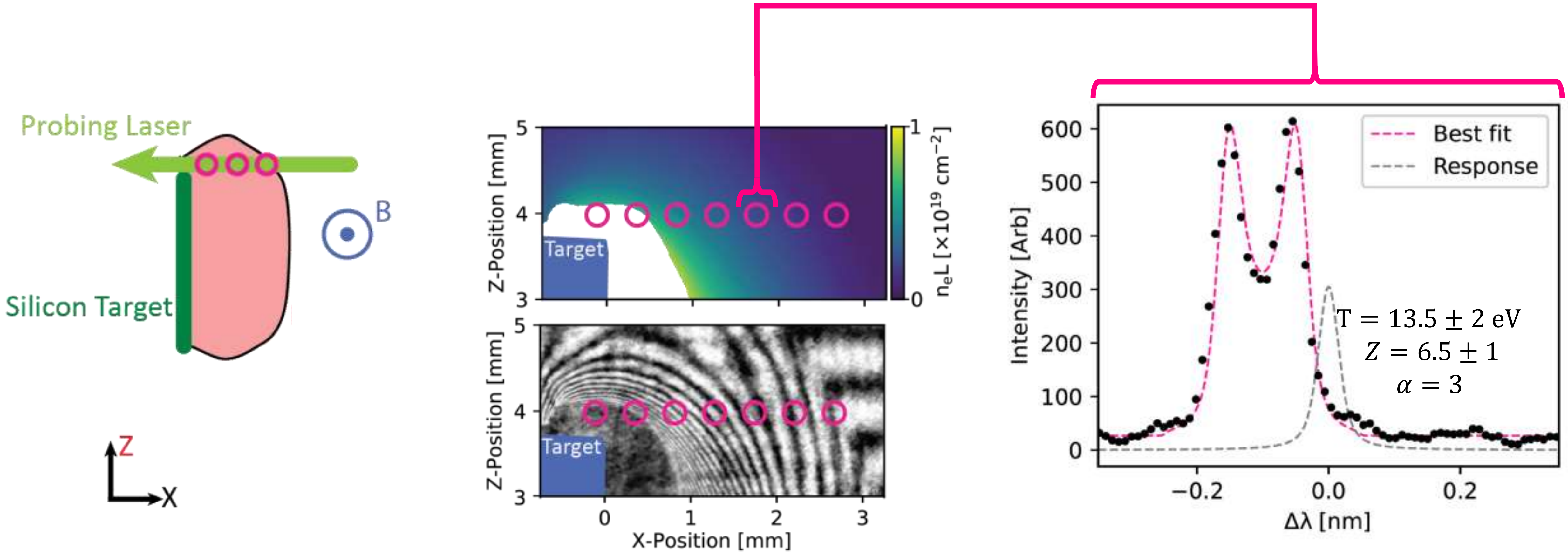


Side-On (X-Z plane) view of the experiment



End-On (X-Y plane) view of the experiment

Thomson scattering [localised diagnosis of T, V, Z]



Analysis of Ion-Acoustic Thomson Scattering Data

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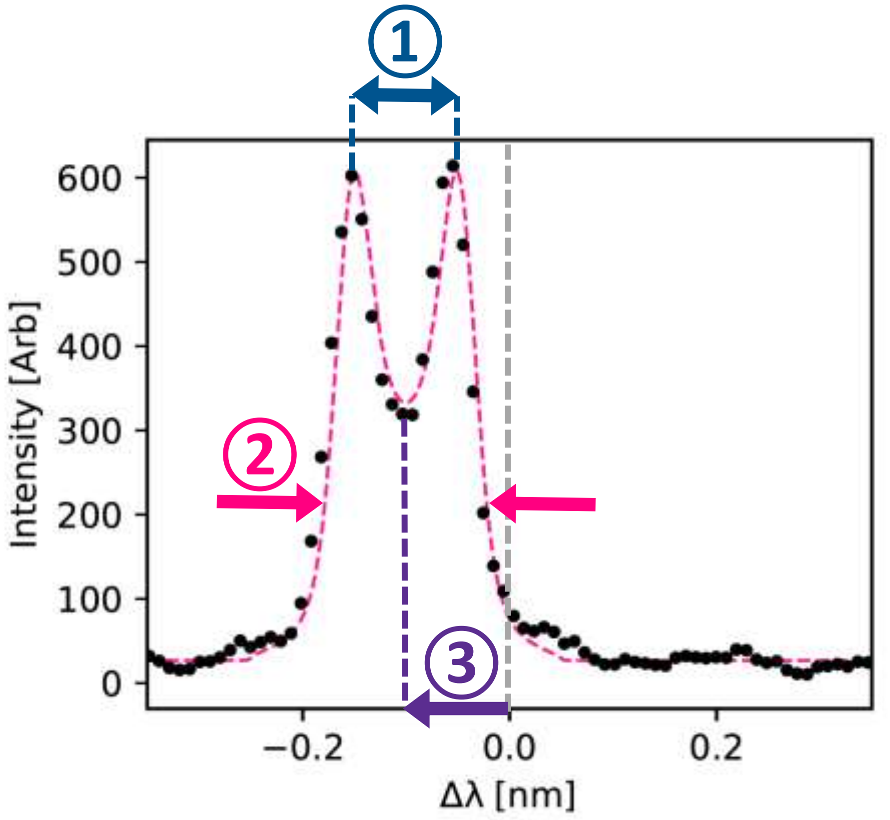
①: Ion Acoustic peak **separation** depends on $\overline{Z} \times T_e$

②: Feature **width** depends on n_e, T_i, and spectral response

③: Doppler **shift** from probe wavelength depends on $\vec{V}.\widehat{k_s}$



Enforced $\mathrm{T_e} = \mathrm{T_i}$, and allowed $\overline{Z}$ to vary ($\tau_{ei} \lesssim 1$ ns).

Convolved calculated spectra with measured spectral response.

Constrained value of $\mathrm{n_e}$ from (near simultaneous) interferometry.

Analysis of Ion-Acoustic Thomson Scattering Data

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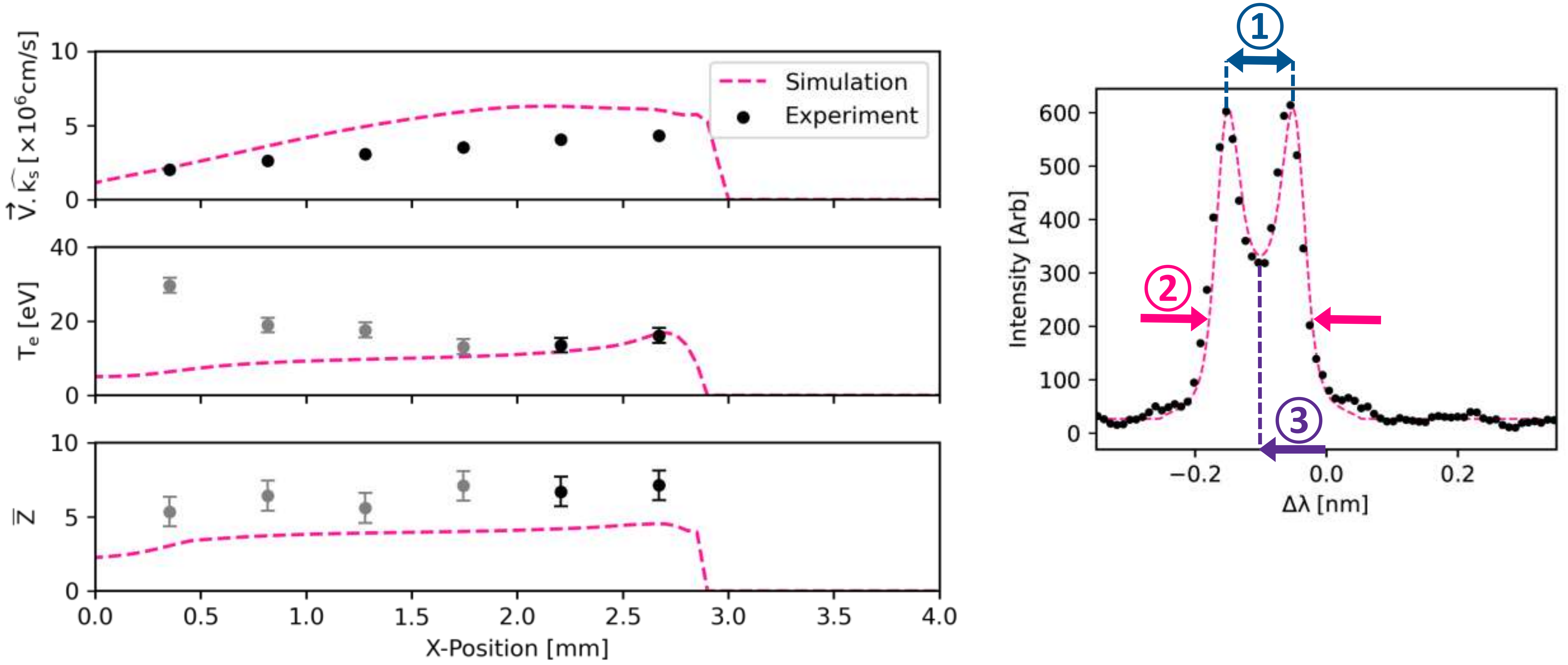

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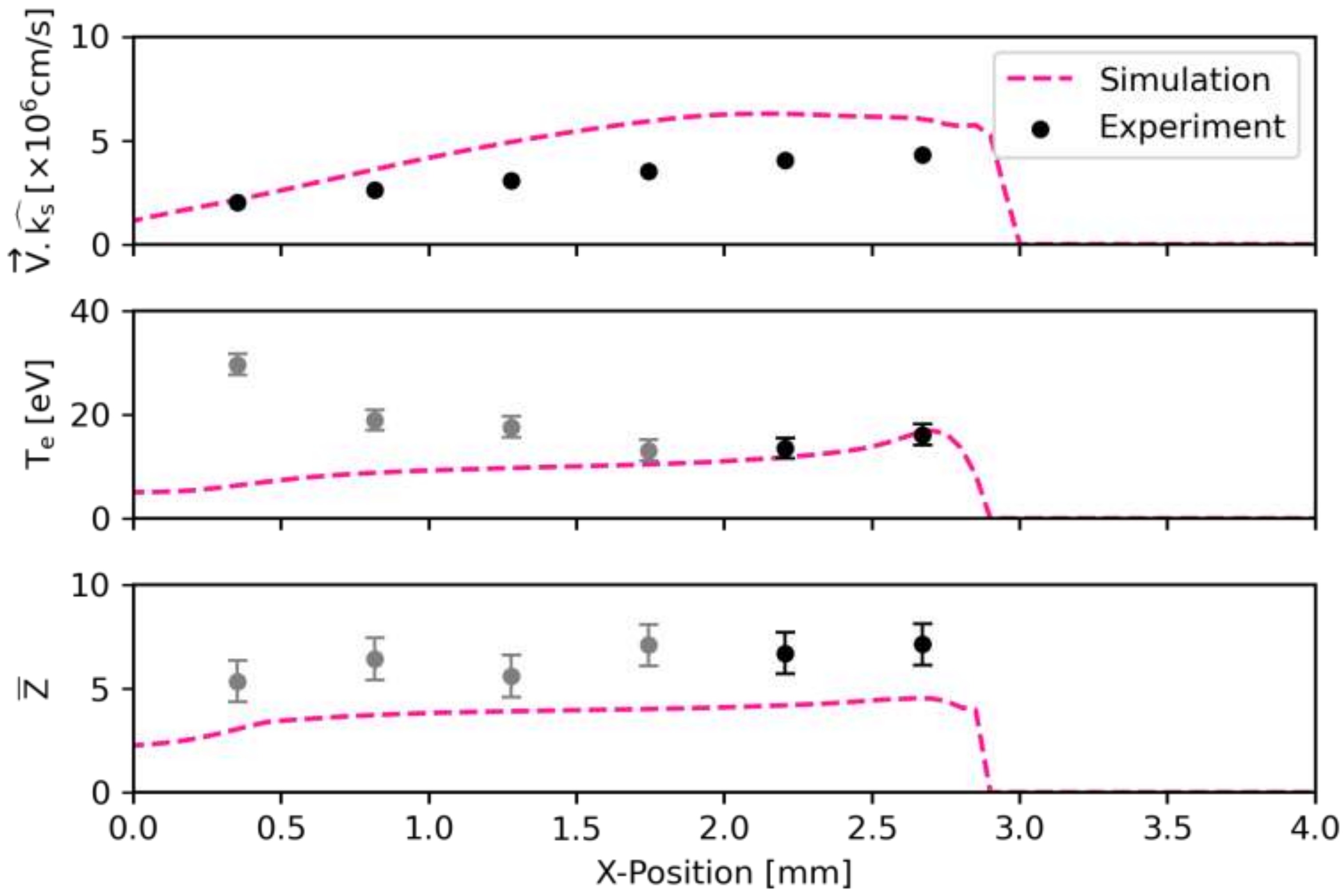
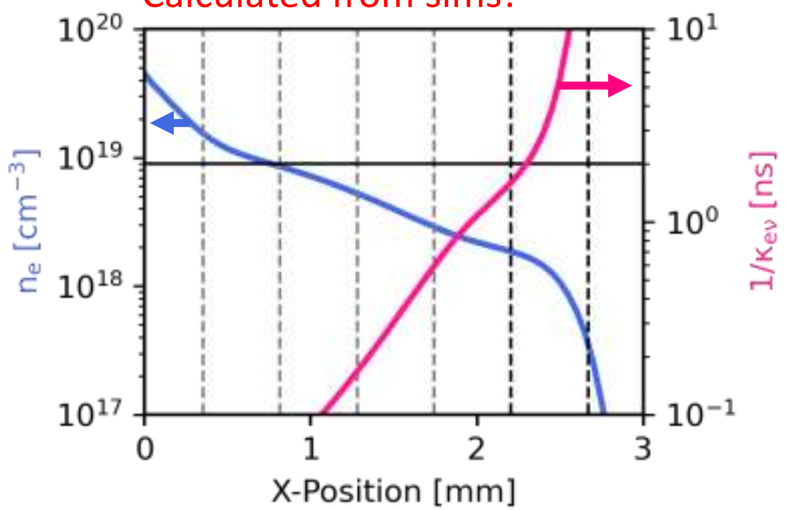


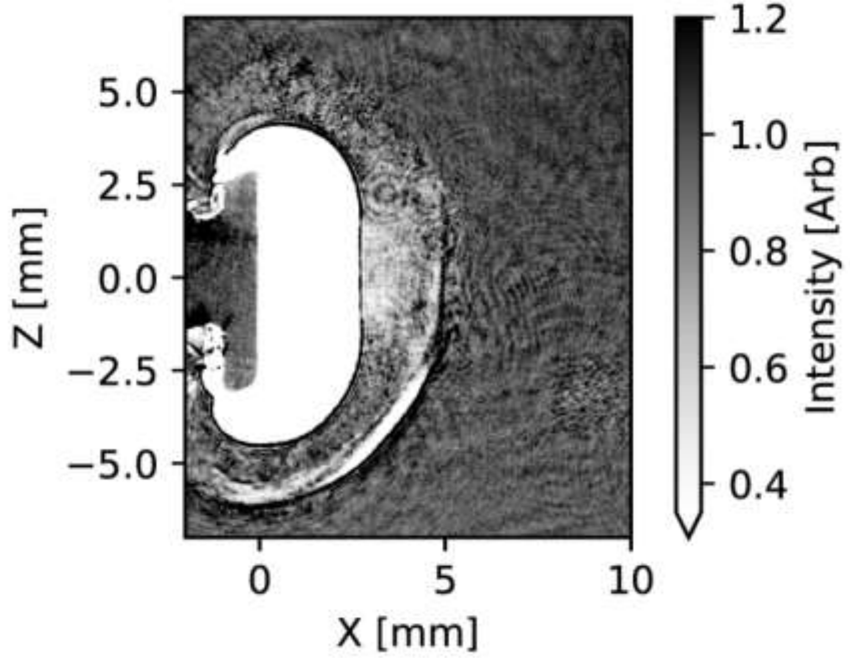
Calculated from sims!



$$\kappa_{\nu e} \propto \frac{Z n_e^2 \ln(\Lambda) T_e^{-\frac{3}{2}}}{\sqrt{\omega^2\left(1-\omega_p^2/\omega^2\right)}}$$

N. R. L. plasma physics formulary

Measurement of Inverse Bremsstrahlung Coefficient



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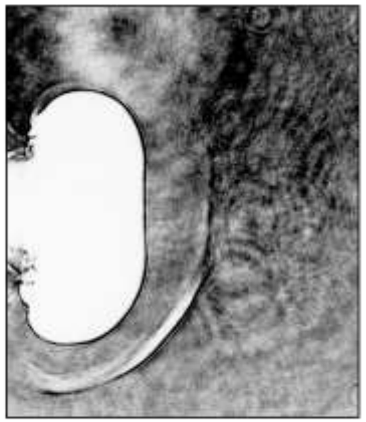
N. R. L. plasma physics formulary

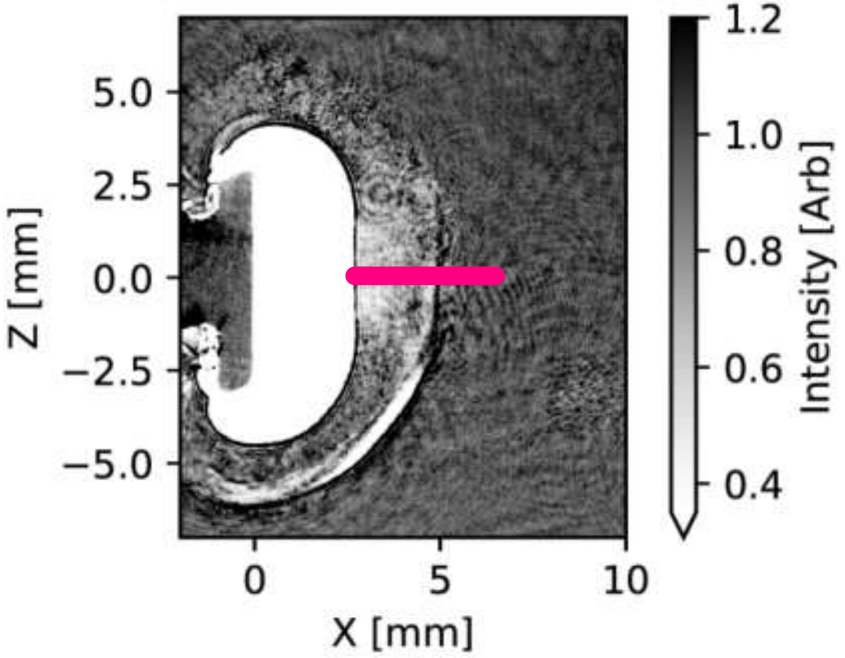
$$I = I_0 e^{-\kappa_{\nu e} x} \Rightarrow \kappa_{\nu e} = \frac{-\ln(I/I_0)}{x}$$

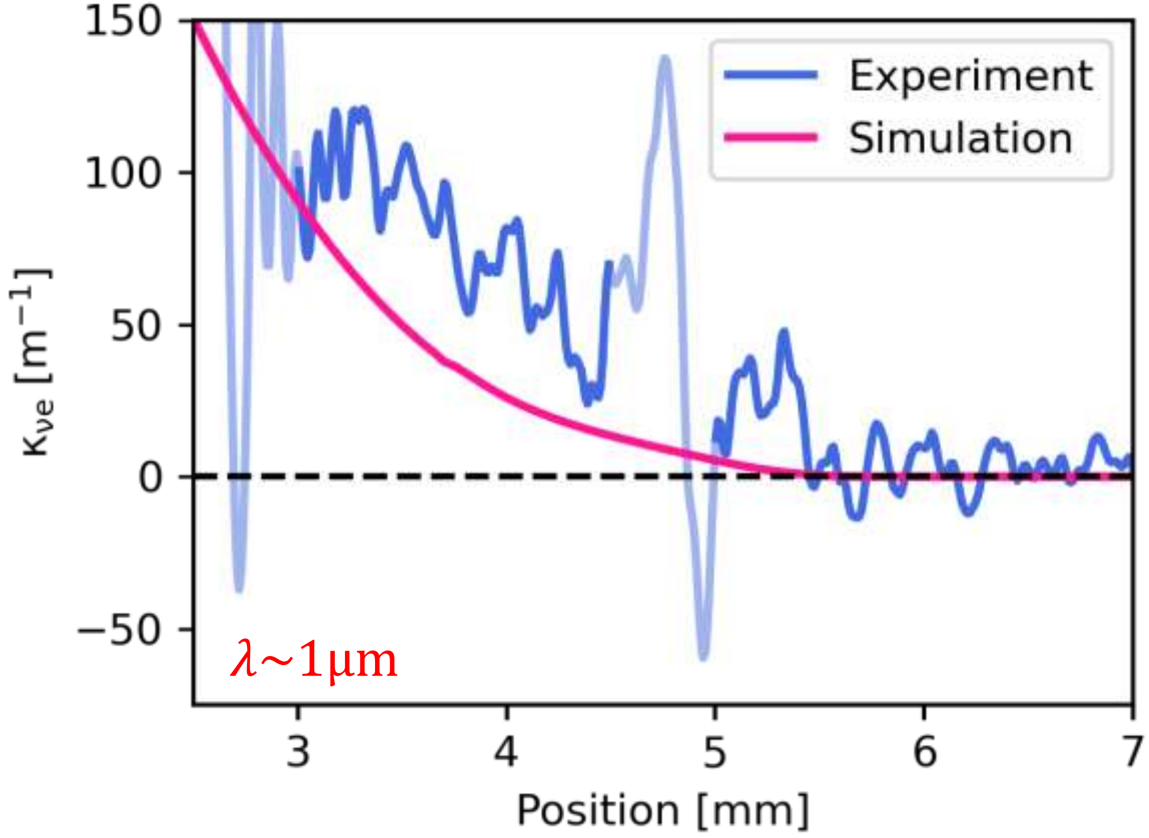
Background Image (I_0)



Shot Image (I)

Measurement of Inverse Bremsstrahlung Coefficient





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N. R. L. plasma physics formulary

Future Work – Laser Absorption & Heat Transport

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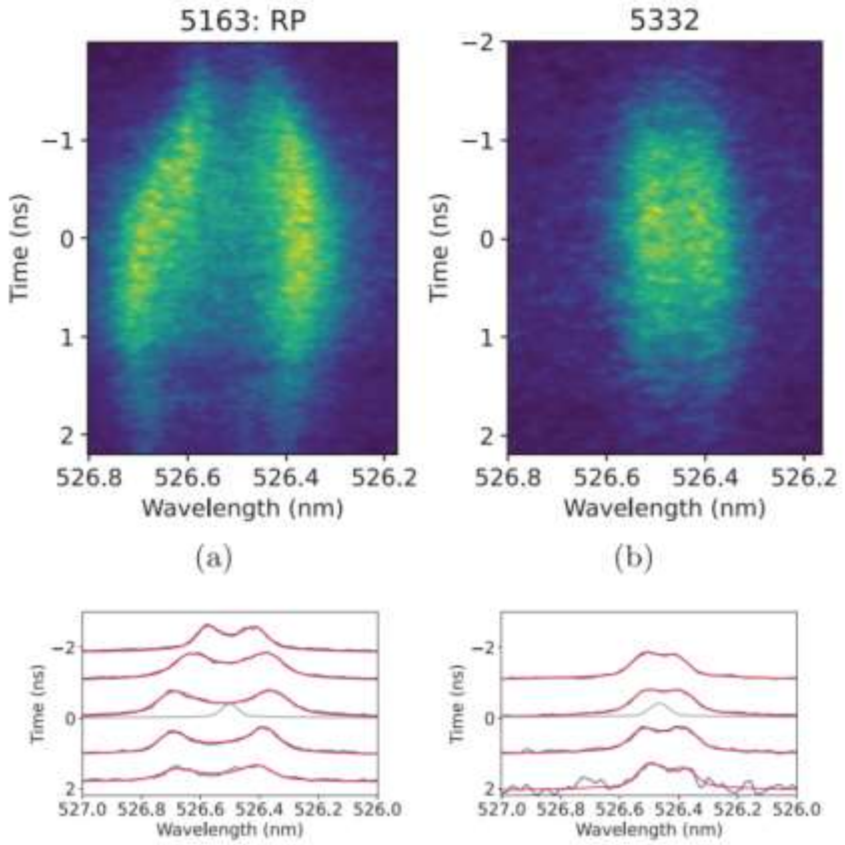
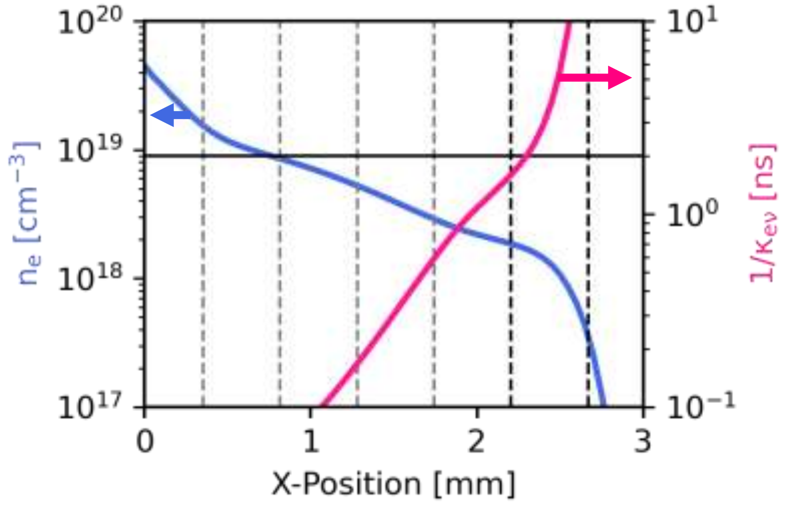


J. T. Banasek *et al* "Current polarity effects on laboratory plasma jets" Physics of Plasmas 2021.

Calculated from sims!



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N. R. L. plasma physics formulary

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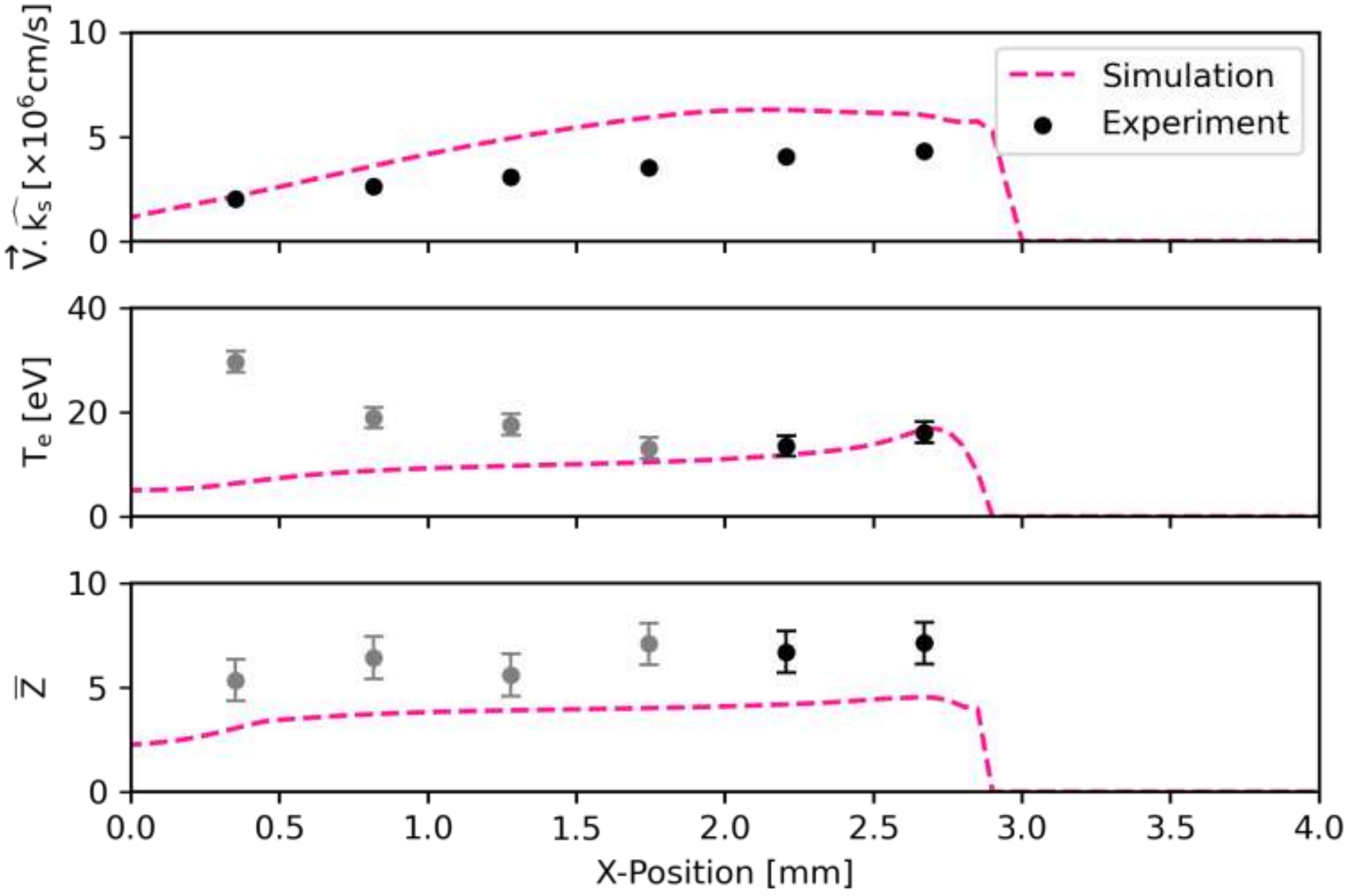
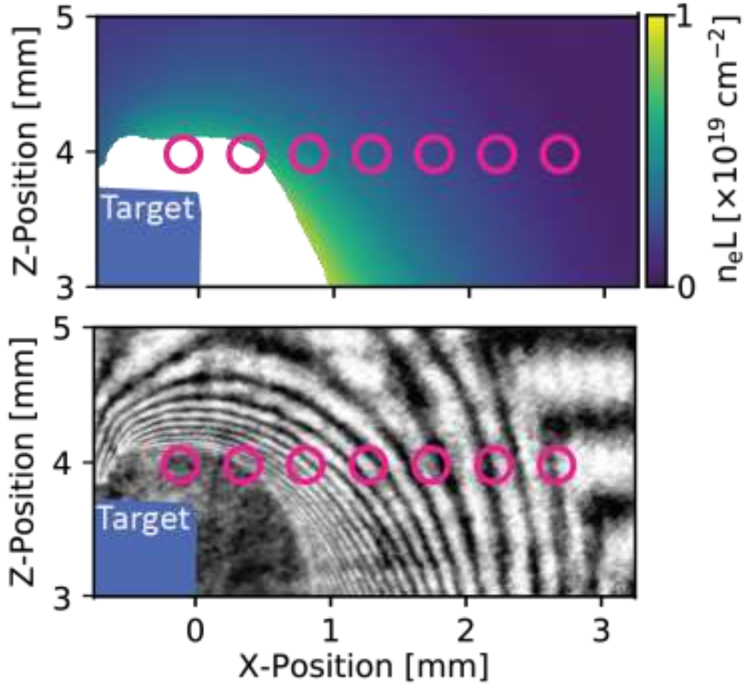
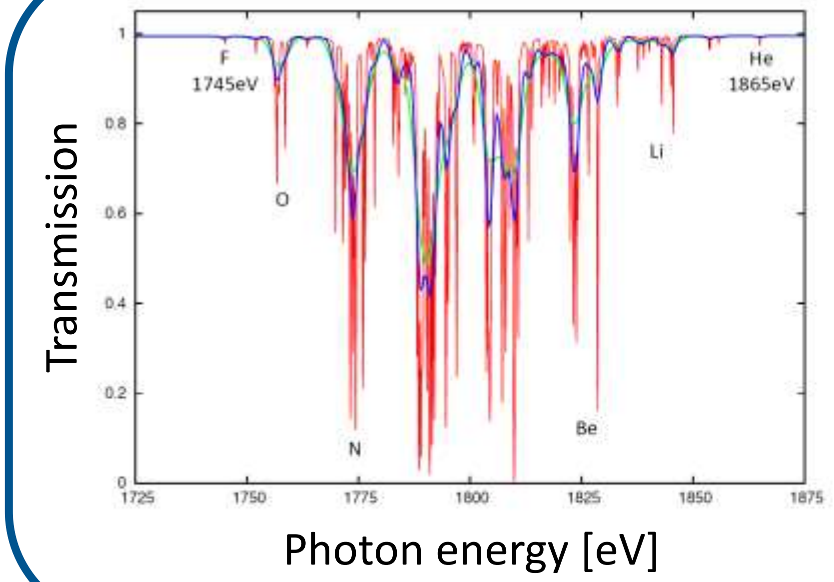


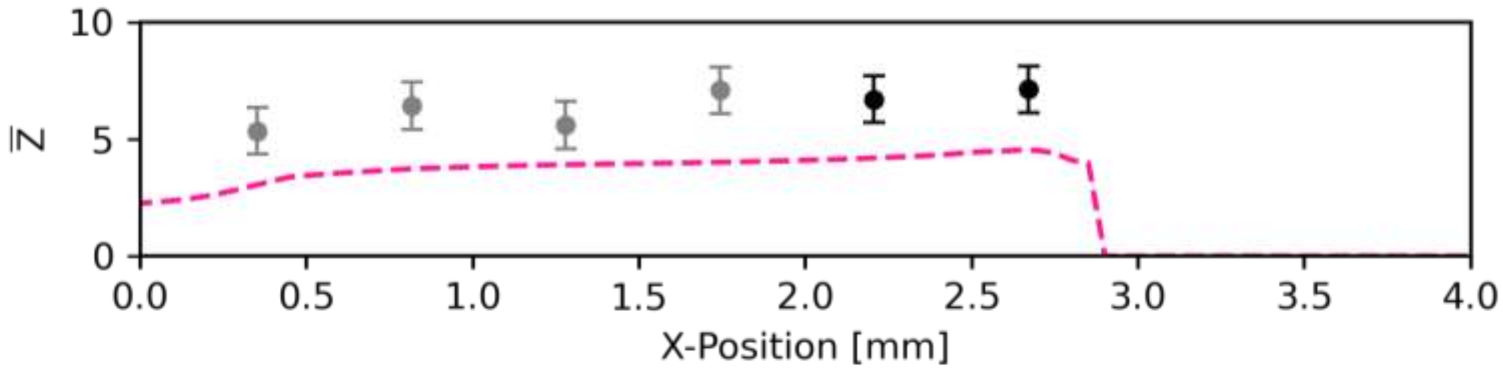


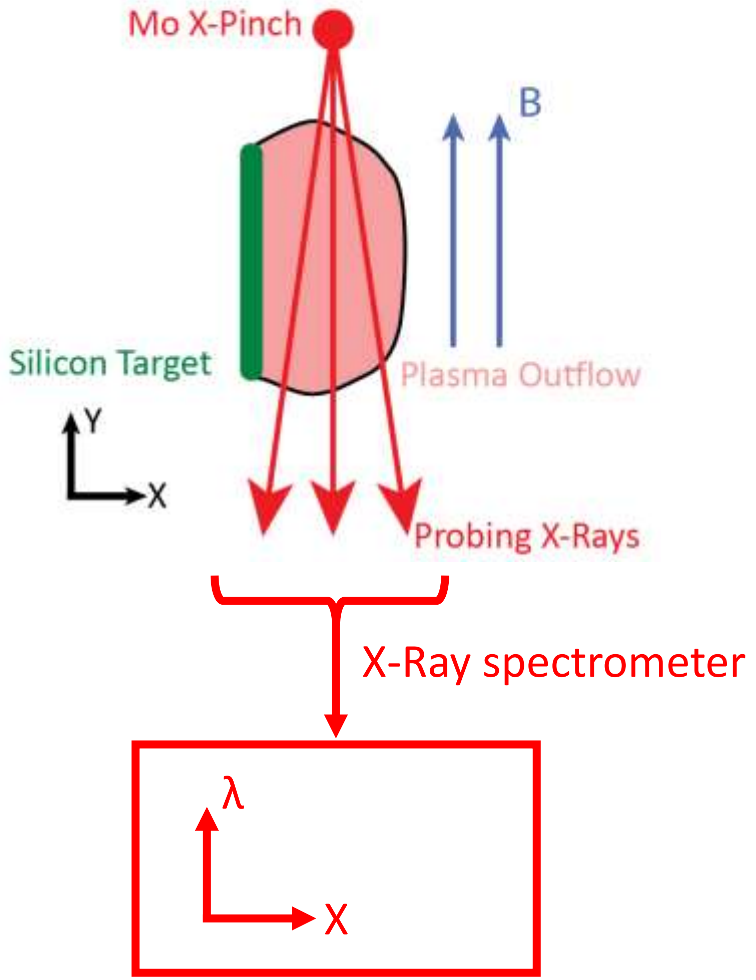
Future work – Diagnosis of Charge State Distribution



Silicon K-Shell absorption spectrum from Helios-CR.

(No MHD, inline atomic kinetics)





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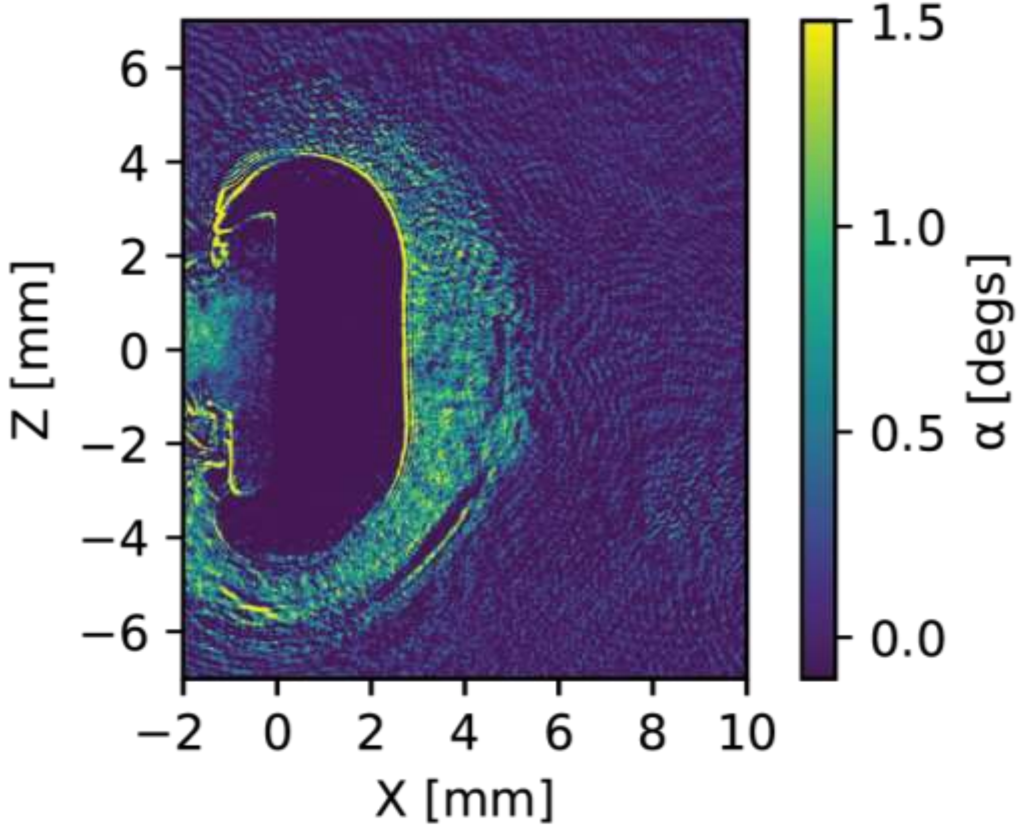
Faraday rotation imaging [weighted average of B_y]



- Measure rotation applied to laser polarisation:

$$\alpha \propto \lambda^2 \int n_e \vec{B}.d\vec{y}$$

- Obtain interferometry along same line of sight:

$$n_e L = \int n_e dy$$

- Combine data to back-out **weighted average** magnetic field:

$$\overline{B_y} = \frac{\alpha}{n_e L} \propto \frac{\lambda^2 \int n_e \vec{B}.d\vec{y}}{\int n_e dy}$$

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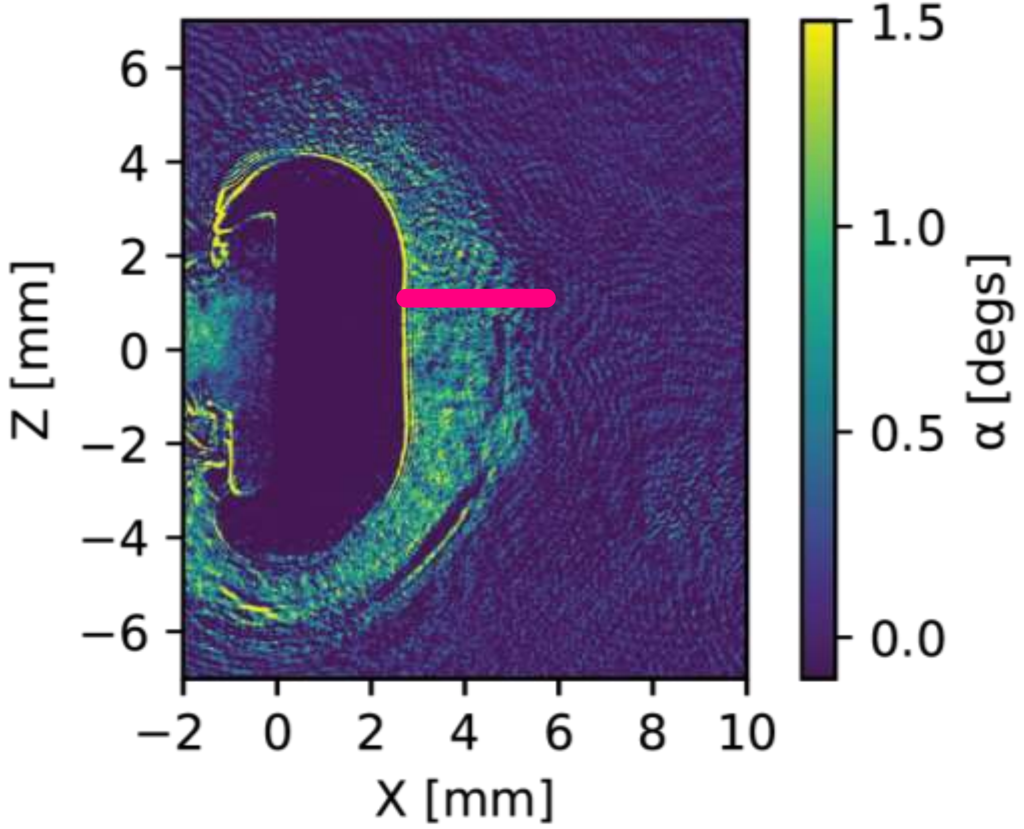

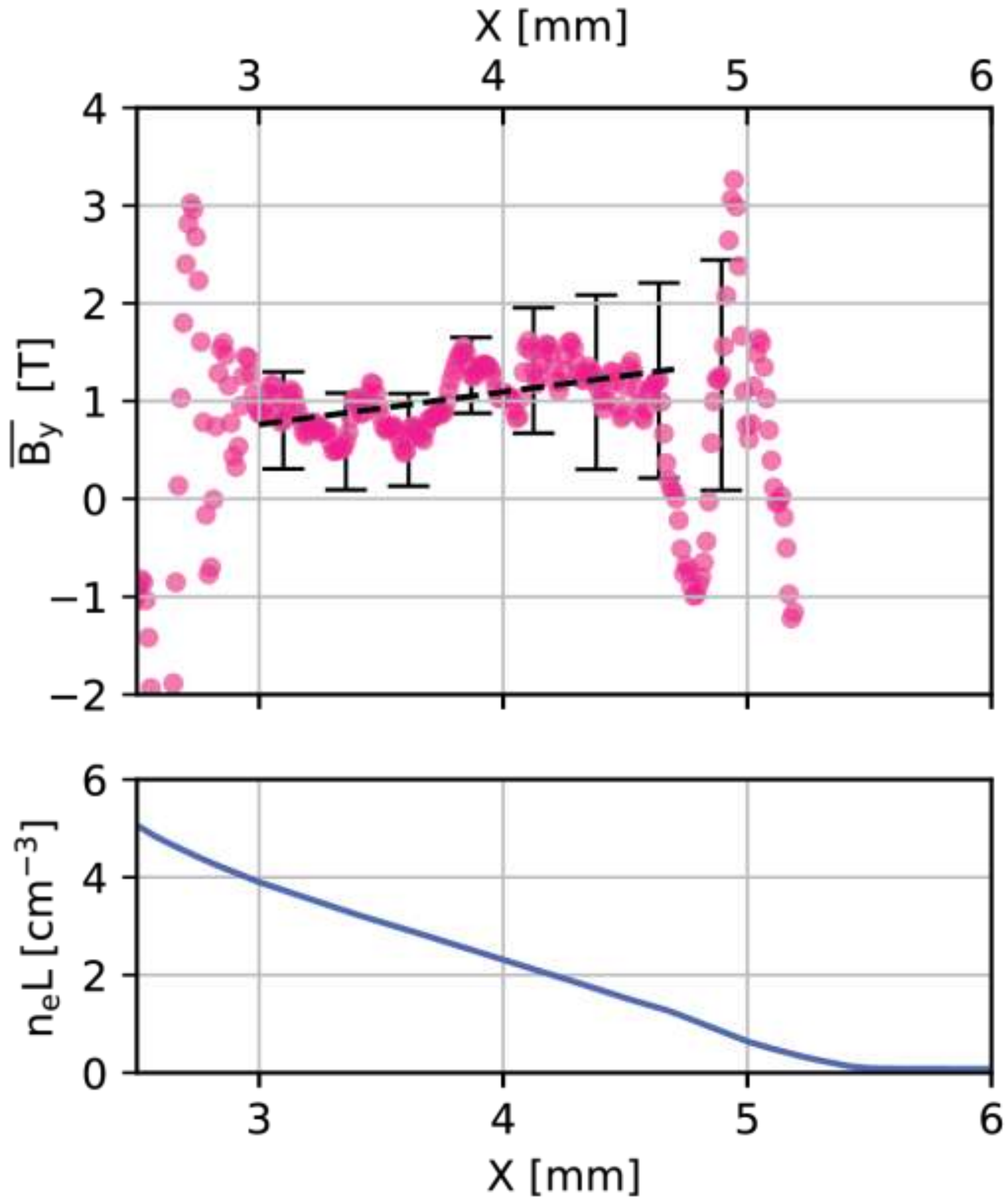

Faraday rotation imaging [weighted average of B_y]

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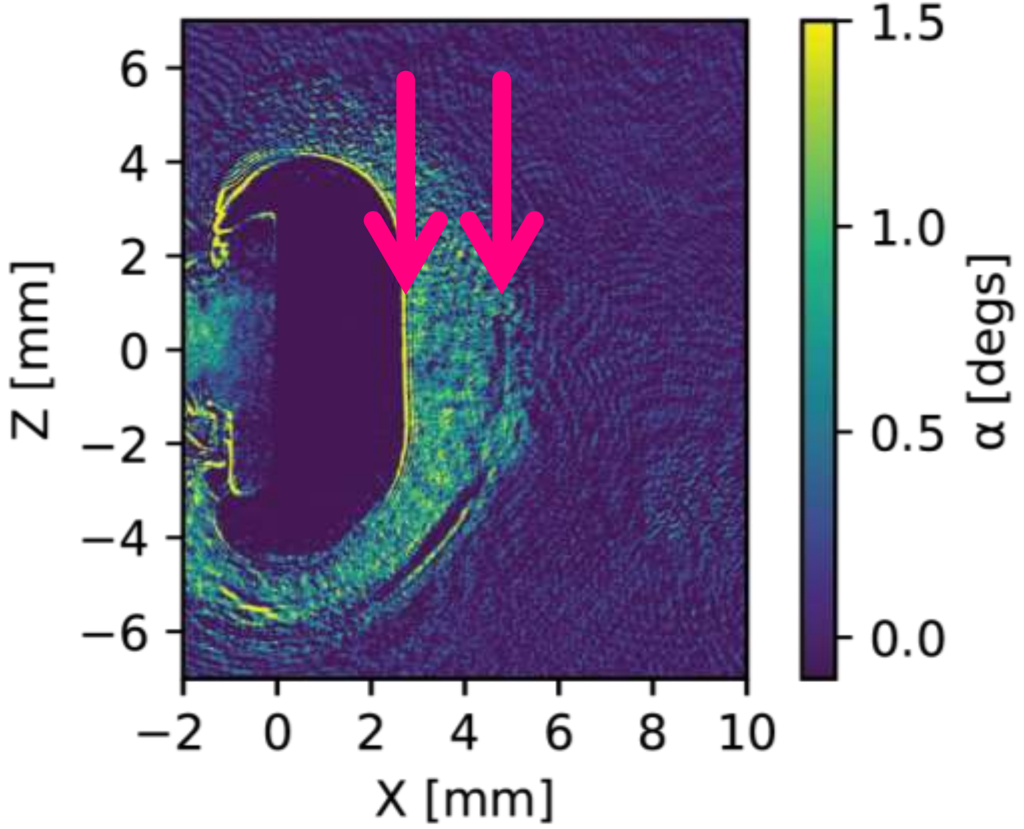
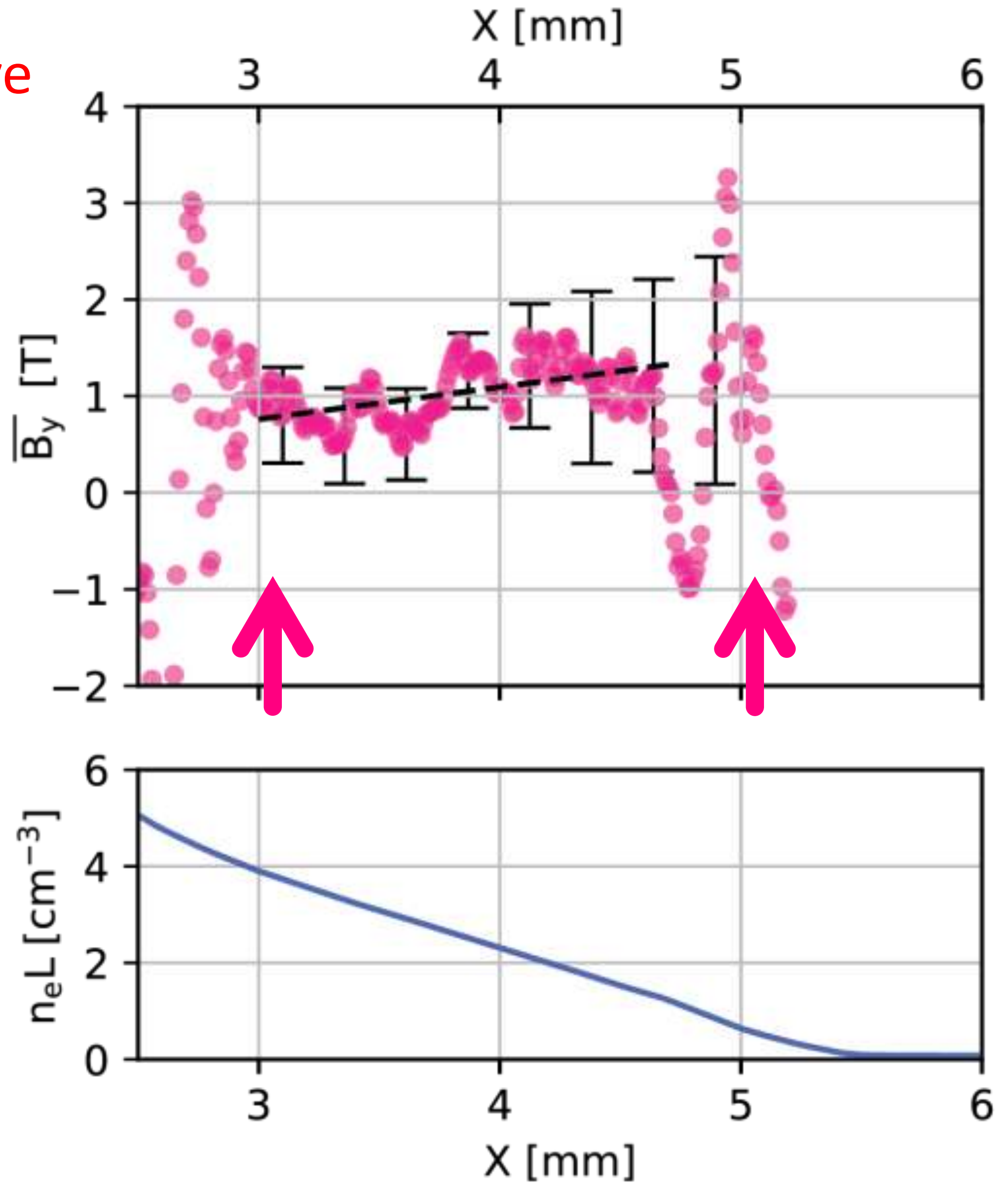
Arrows indicate caustics ⟹ B field not representative





Faraday rotation imaging [weighted average of B_y]

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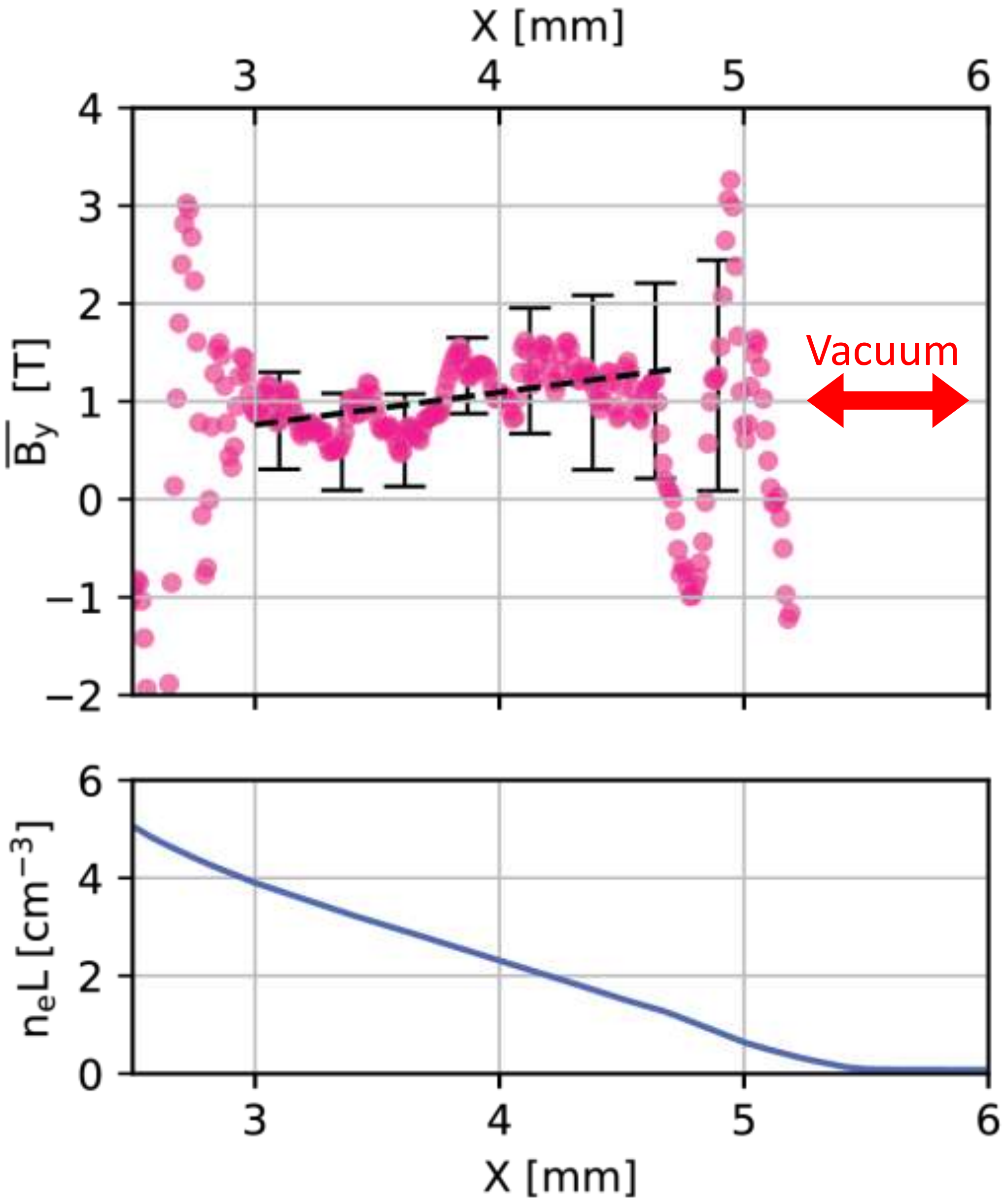
- Diagnostic measures weighted average magnetic field:

$$\overline{B_y} = \frac{\alpha}{n_e L} \propto \frac{\lambda^2 \int n_e \vec{B}.d\vec{y}}{\int n_e dy}$$

- Cannot diagnose field in the vacuum ($n_e = 0$)

- Within region which can be probed, the field is approximately constant ($\sim 1\ \mathrm{T}$)



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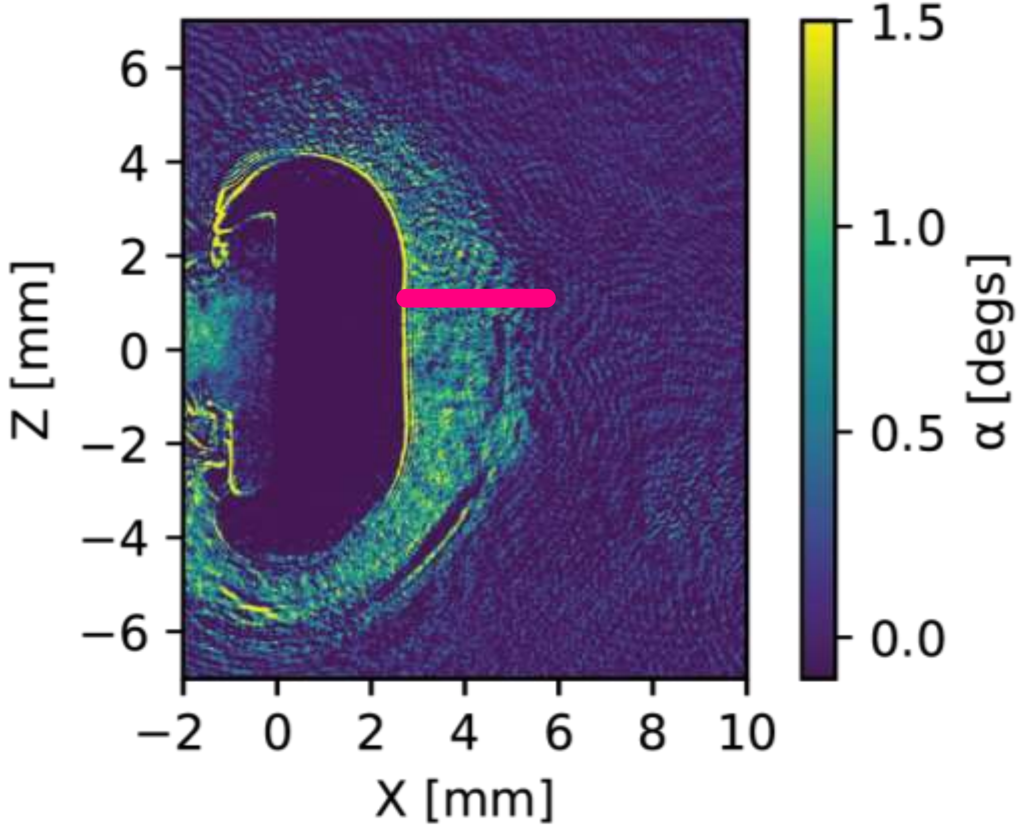

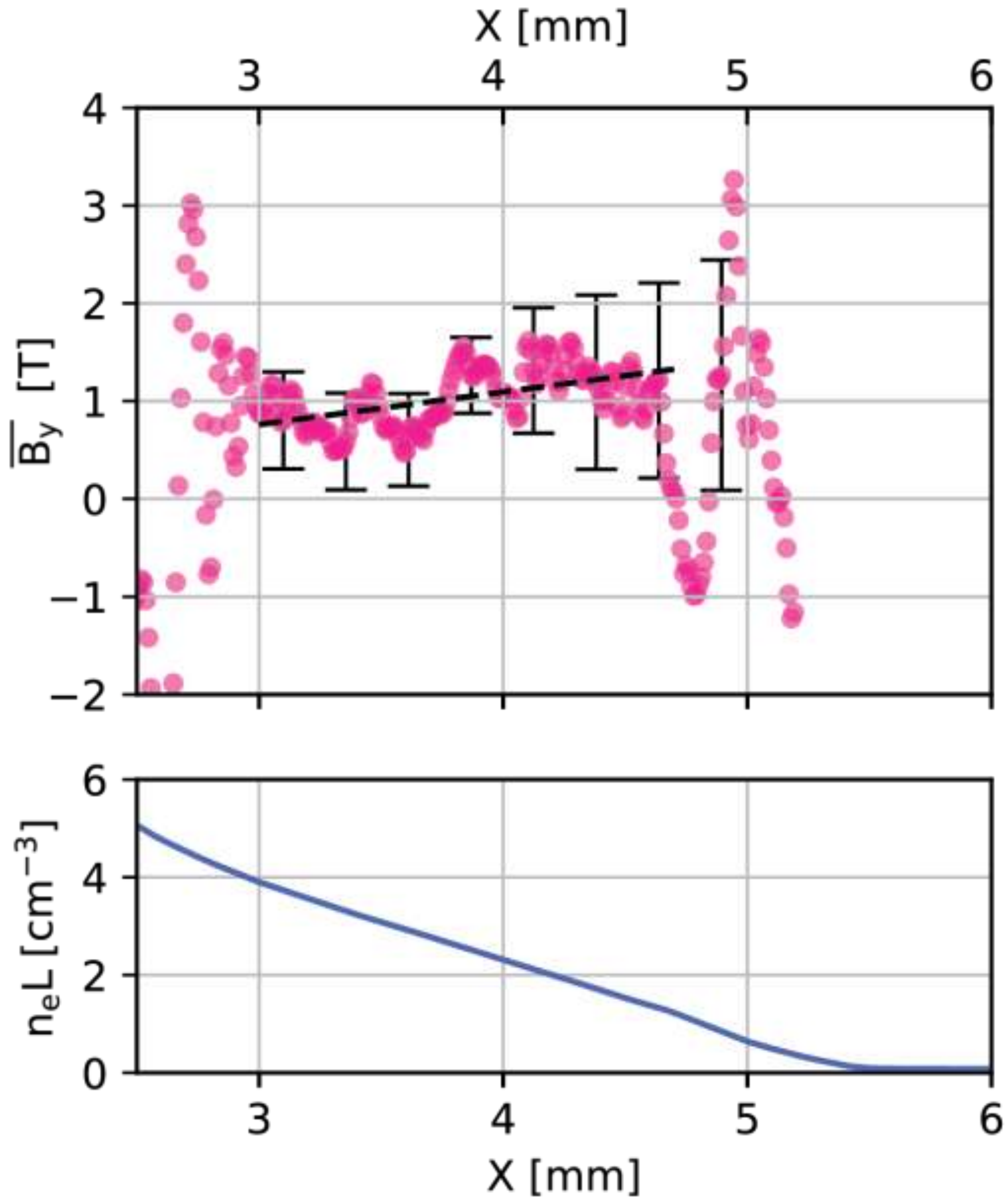

Faraday rotation imaging [weighted average of B_y]

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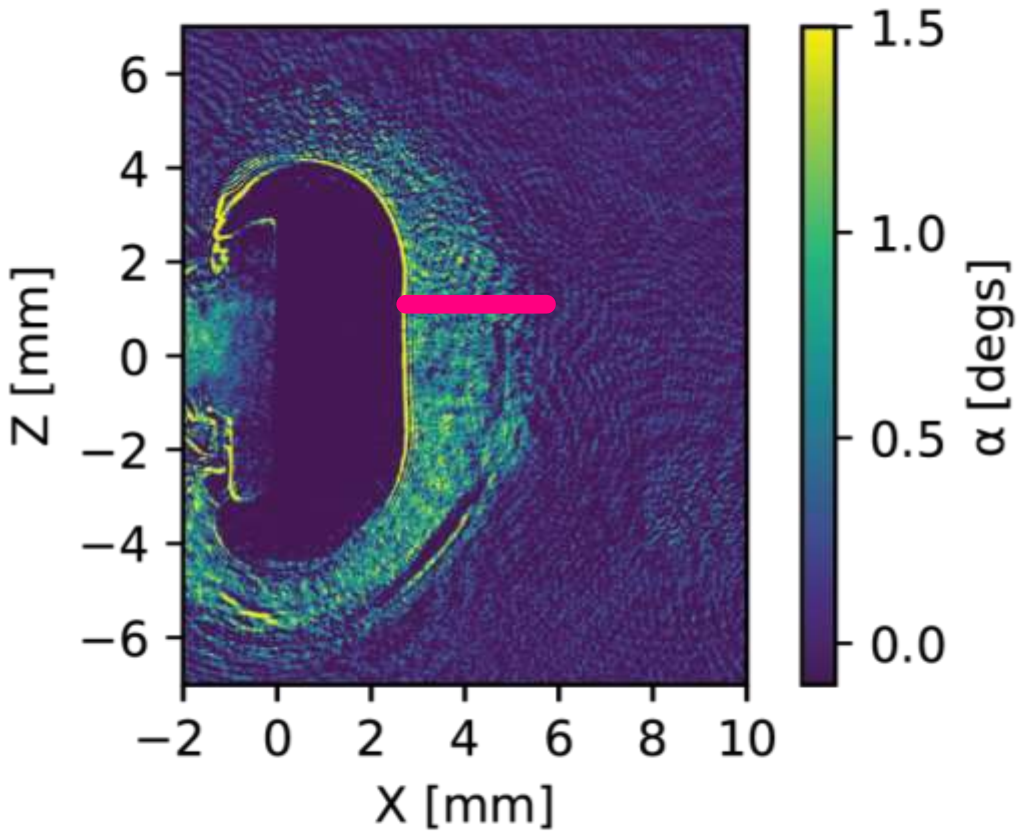
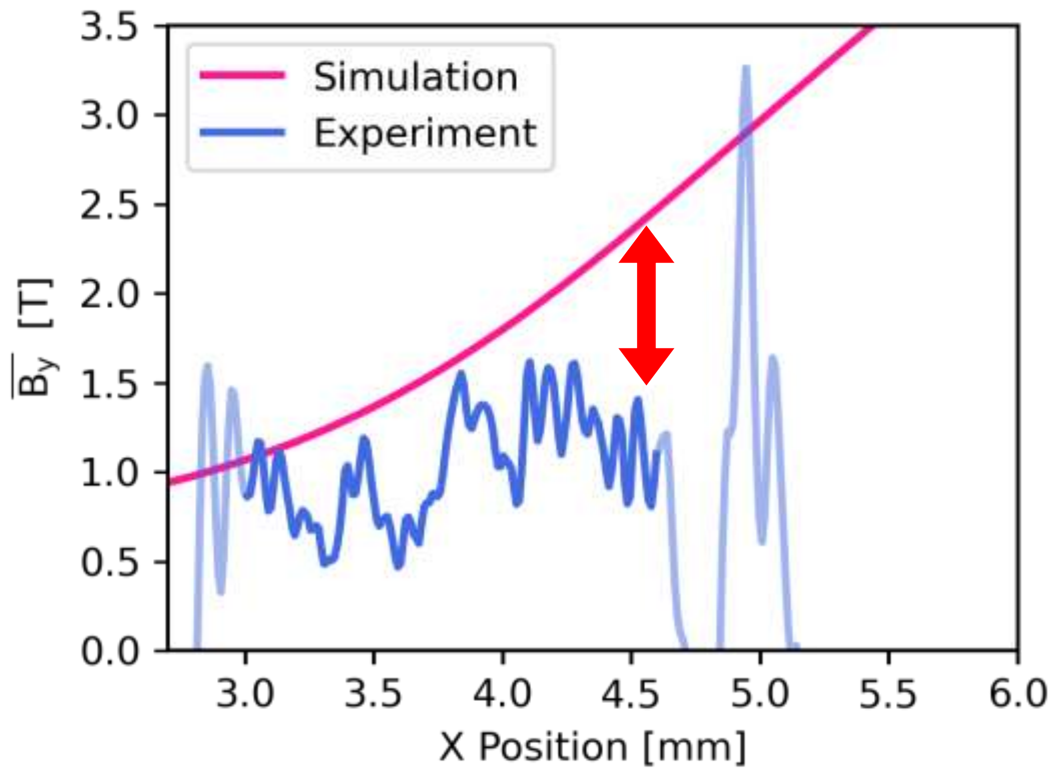
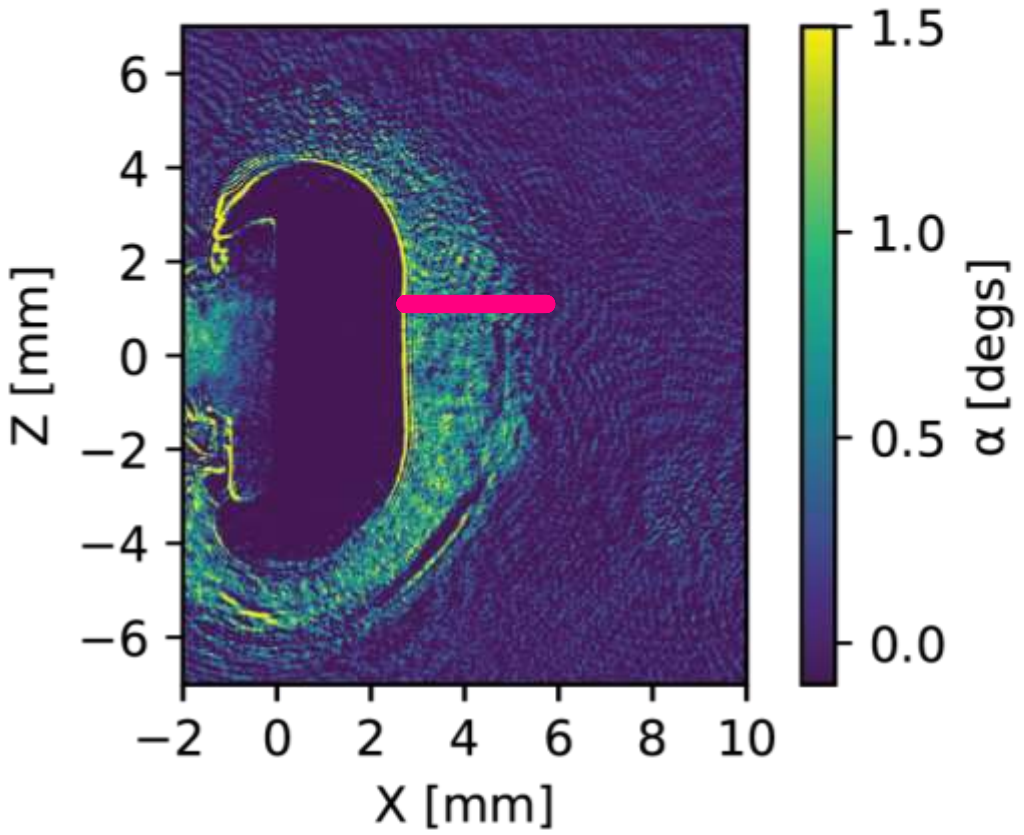
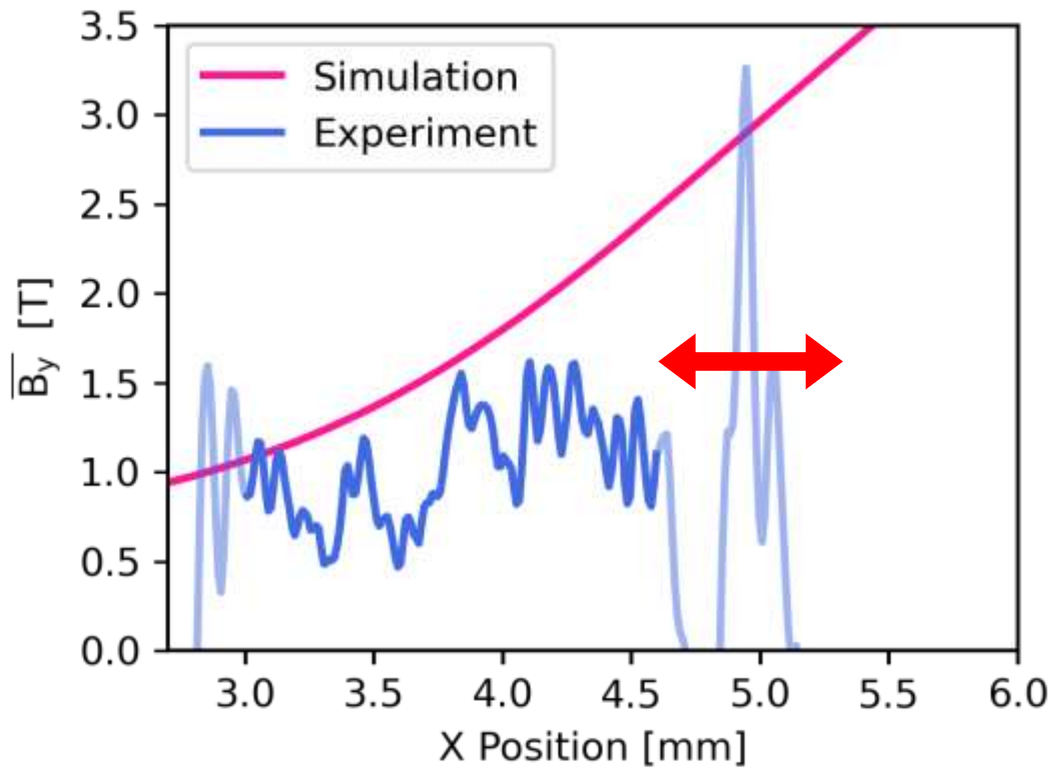




Simulated profile is more diffusive

Faraday rotation imaging [weighted average of B_y]





Need to diagnose vacuum boundary!

Future work – Local Current Density Measurement

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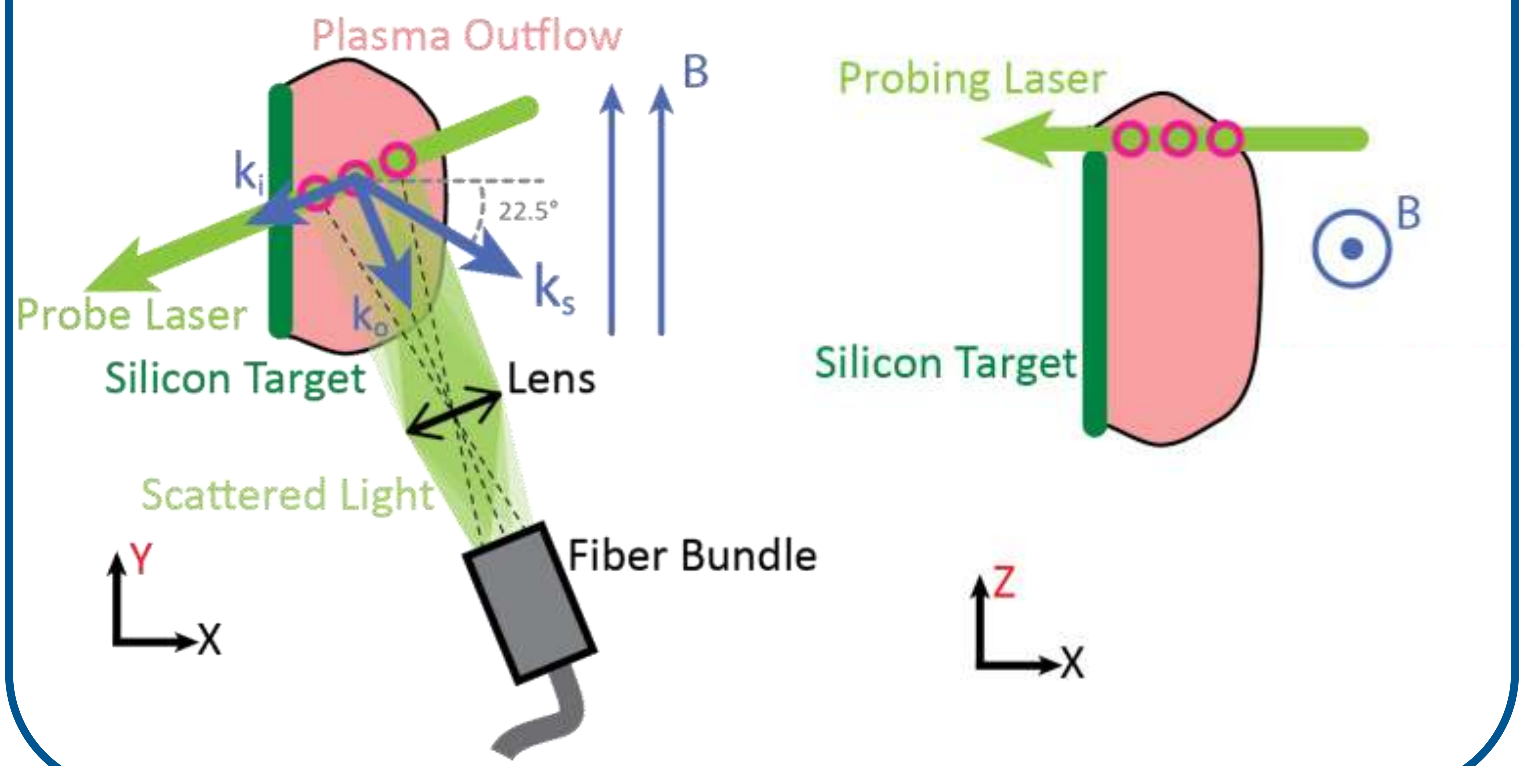
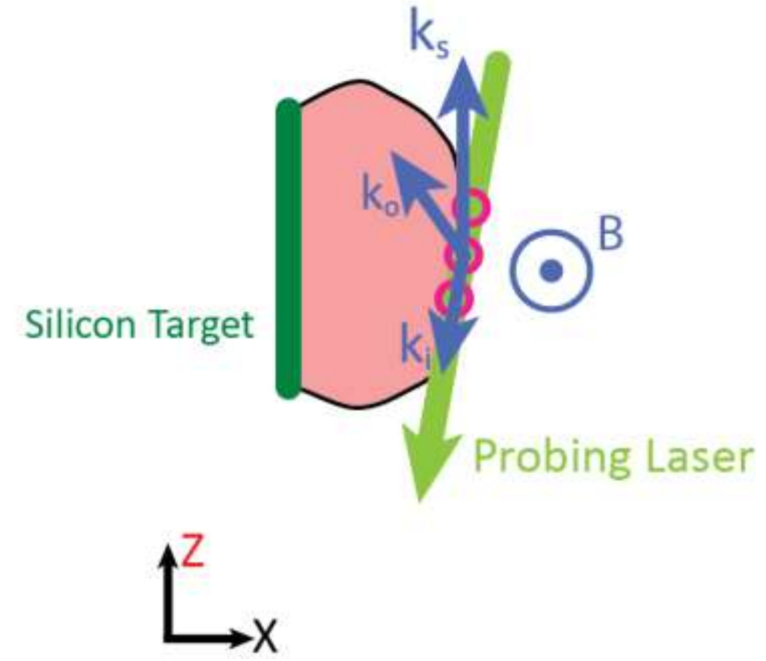
Existing setup $\Rightarrow k_s \perp J$



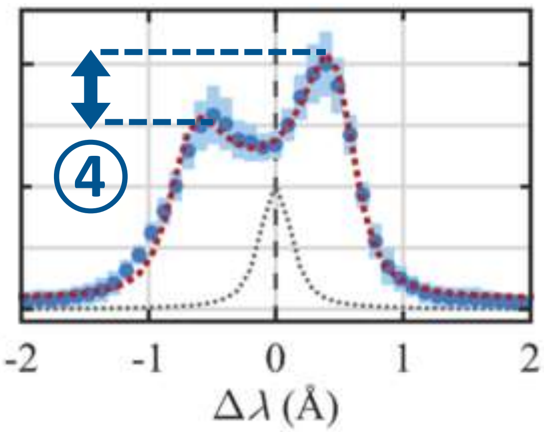
New setup $\Rightarrow k_s \parallel J$



Future work – Local Current Density Measurement

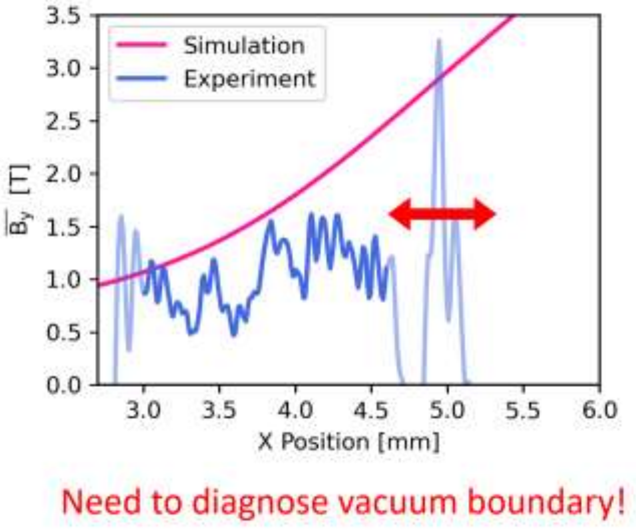
④: Peak **asymmetry** depends on $\widehat{k_s}.V_d$

L. G. Suttle *et al* "Collective Thomson scattering in pulsed-power driven HED experiments" RSI 2021.

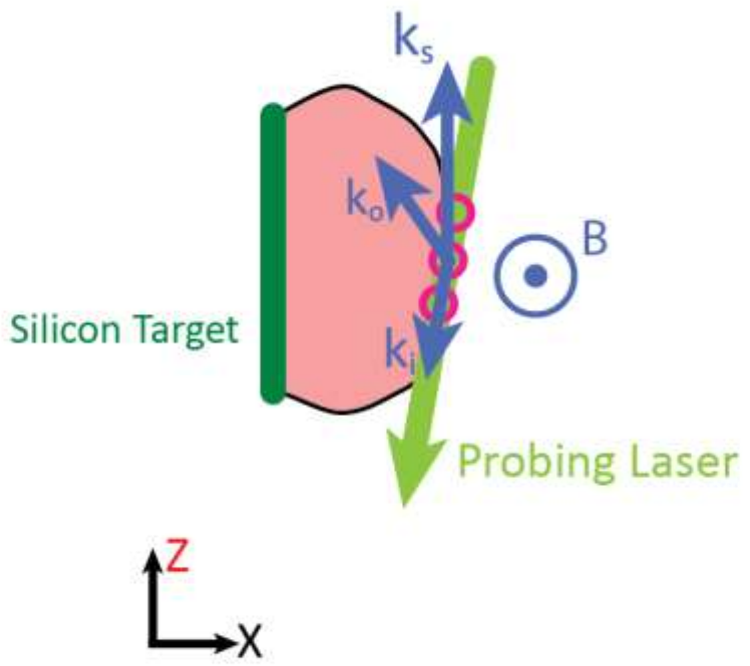


Diagnose current at vacuum boundary with Thomson:

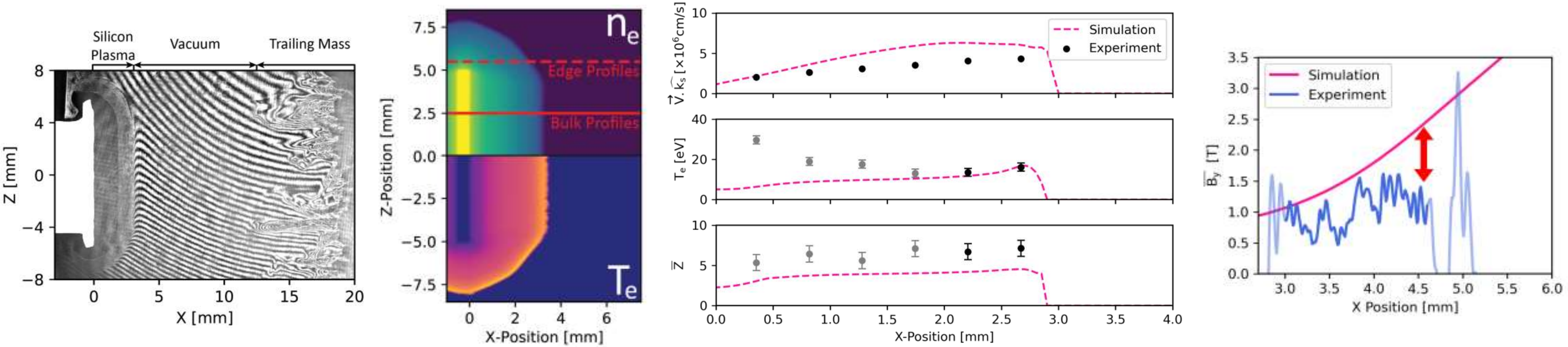
- Can probe smaller n_e
- Reduce λ for less diffraction



New setup ⇒ $k_s \parallel J$



Summary



- Experimental morphology well reproduced by simulations
- Saw influence of Thomson probe heating
- Radiation field plays a role in charge state distribution (?)
- Simulated B field is more diffusive than experiment

Chimera: external radiation drive & imposed field

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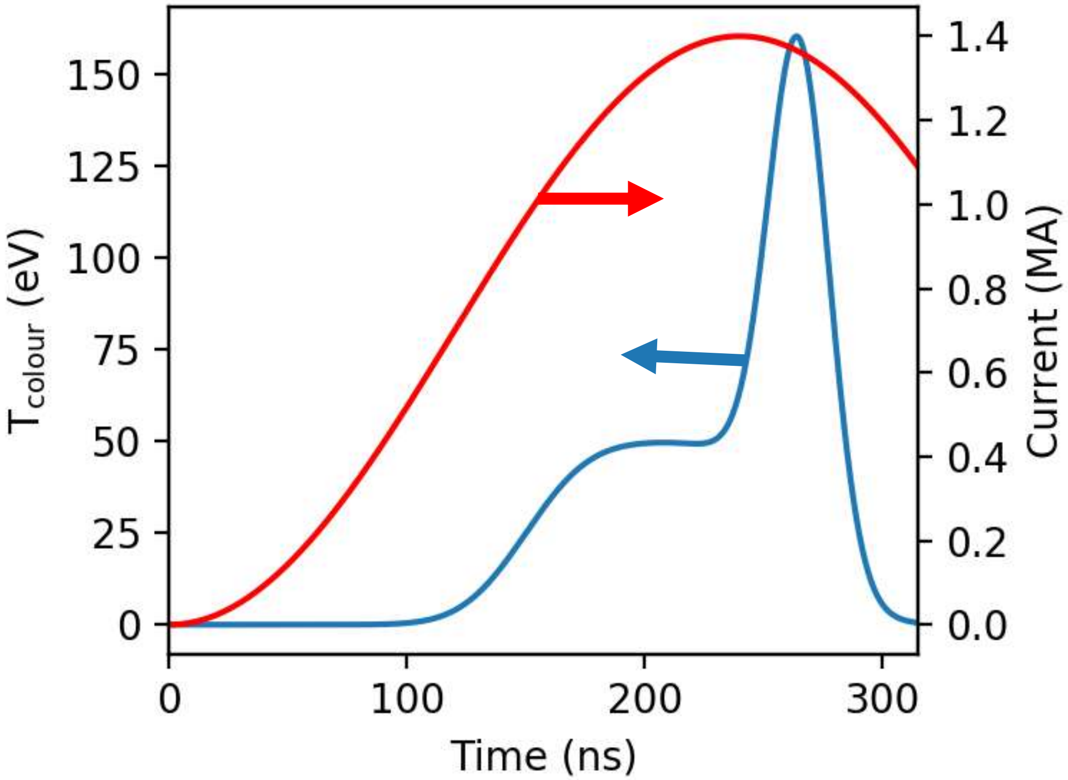
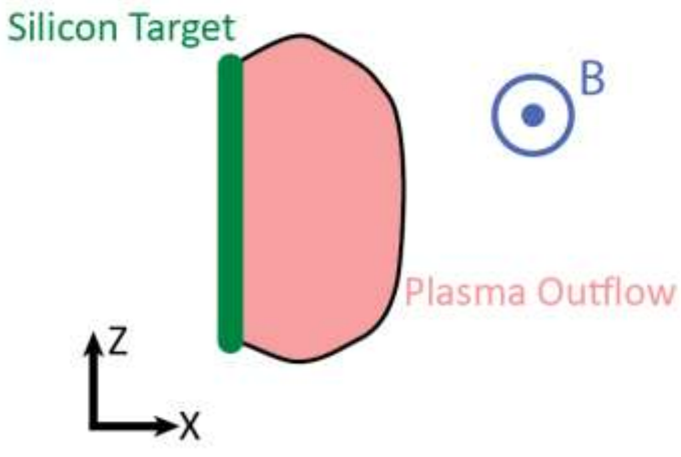
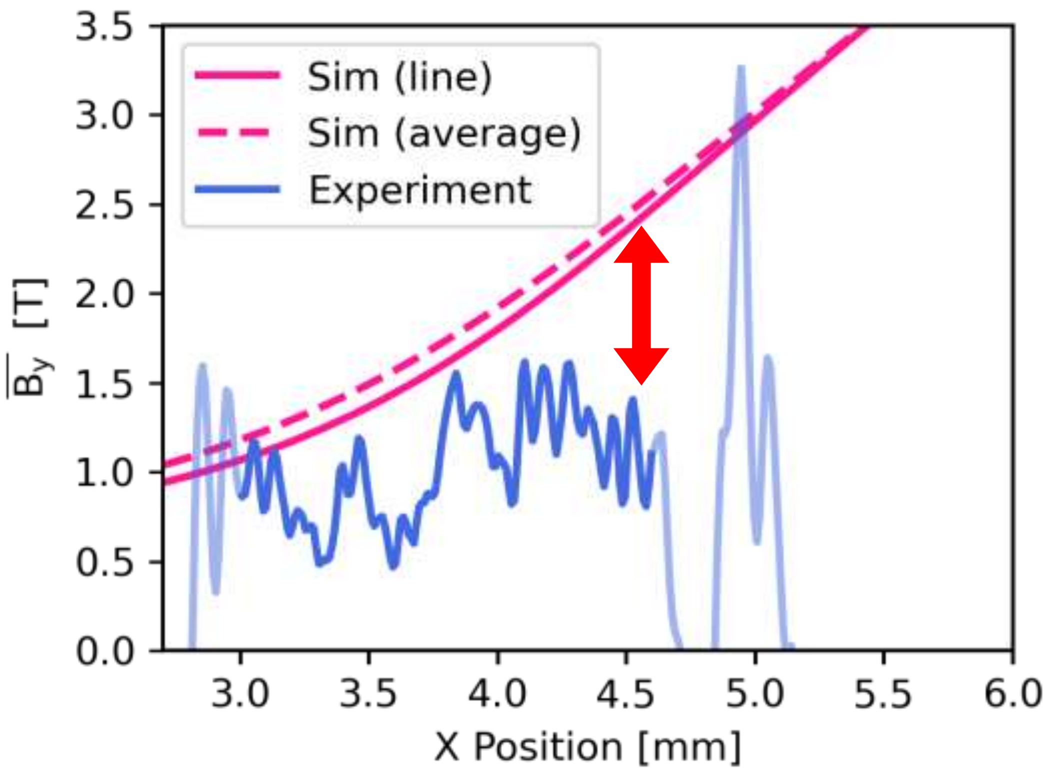


Faraday rotation imaging [weighted average of B_y]



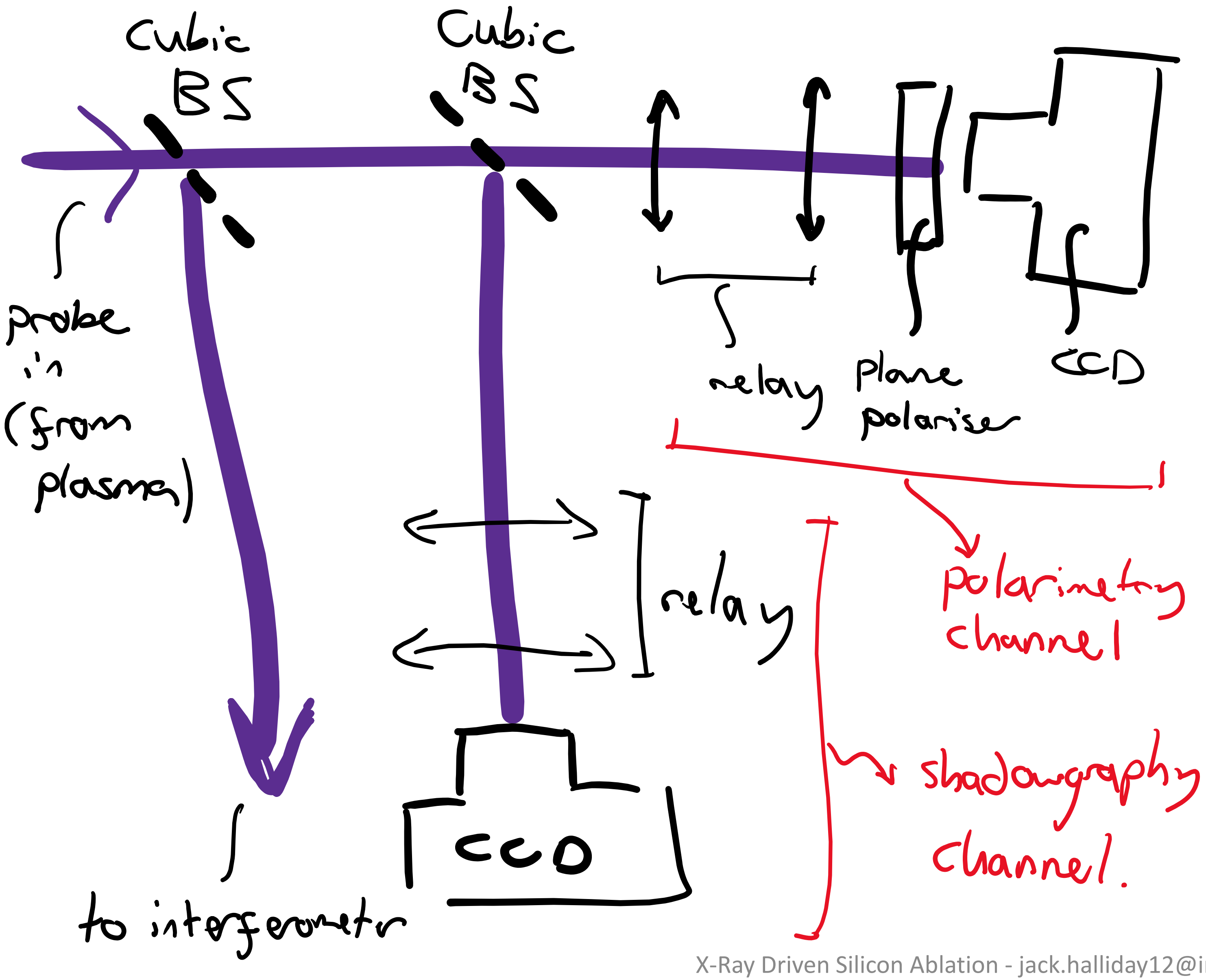
$$\overline{B_y} = \frac{\alpha}{n_e L} \propto \frac{\lambda^2 \int n_e \vec{B}.d\vec{y}}{\int n_e dy}$$

$$B_{y,av} = \frac{\int n_e B_y dz}{\int n_e dz}$$



Simulated profile is more diffusive

Faraday rotation imaging [weighted average of B_y]



In the absence of shadowgraphy effects, during the experiment, the signal measured at position x, z in the shadowgram is given by

$$I_s(x,z) = R_s(x,z)T(x,z)I_0(x,z), \qquad (5)$$

where R_s is the response of the shadowgraphy camera; T is the fraction of laser light which is transmitted through the plasma; and I_0 is the initial intensity of the probe. For an image taken with the same optical setup but *in the absence of plasma*, the signal measured is given by

$$I_s^*(x,z) = R_s(x,z)I_0^*(x,z). \qquad (6)$$

For the polarogram, the signal during the experiment is given by

$$I_p(x,z) = R_p(x,z)T(x,z)\sin^2[\beta - \alpha(x,z)]I_0(x,z), \qquad (7)$$

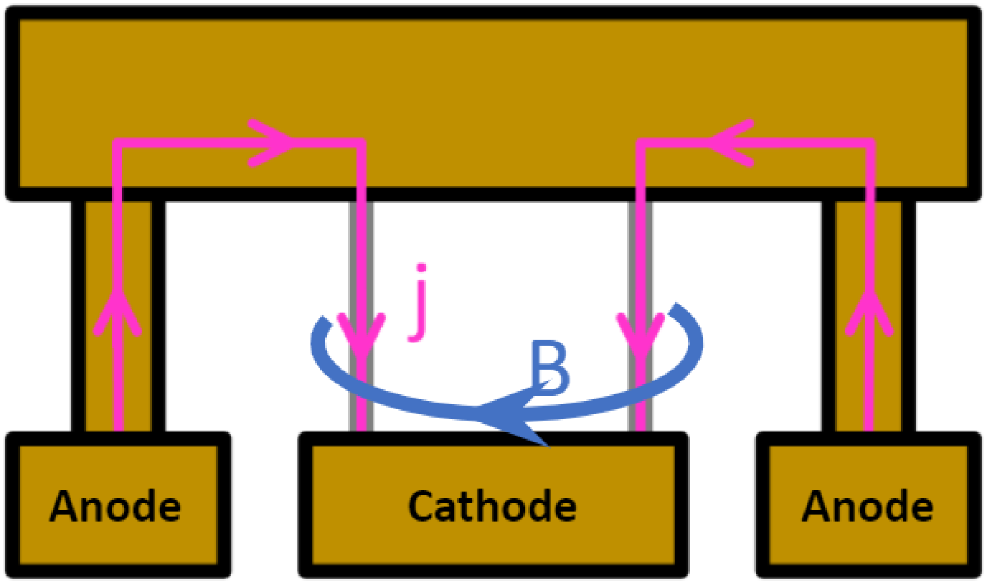
and the signal in the absence of plasma is

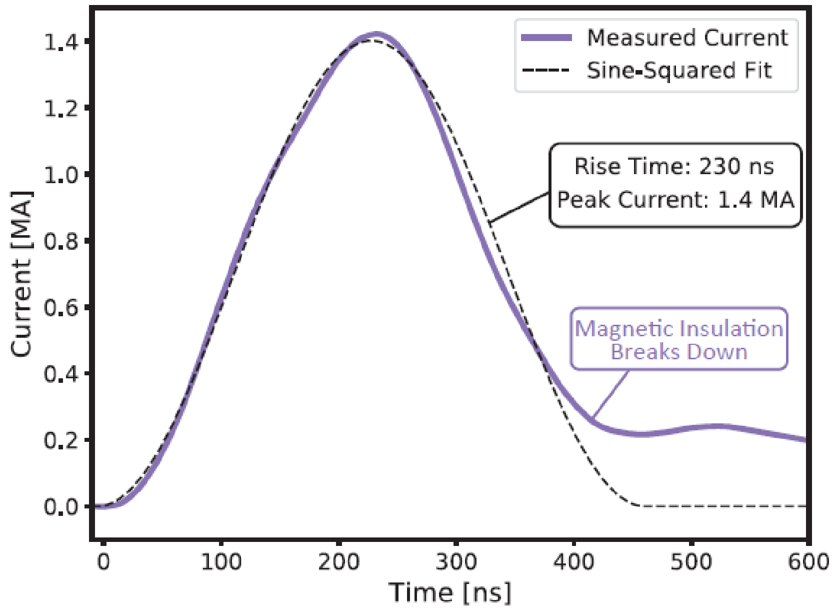
$$I_p^*(x,z) = R_p(x,z)\sin^2(\beta)I_0^*(x,z). \qquad (8)$$

Combining these four equations, and solving for α, yields

$$\alpha(x,z) = \beta - \arcsin\left(\sqrt{\frac{I_p(x,z)I_s^*(x,z)}{I_p^*(x,z)I_s(x,z)}}\sin(\beta)\right). \qquad (9)$$

Imploding Wire Array Z-Pinches

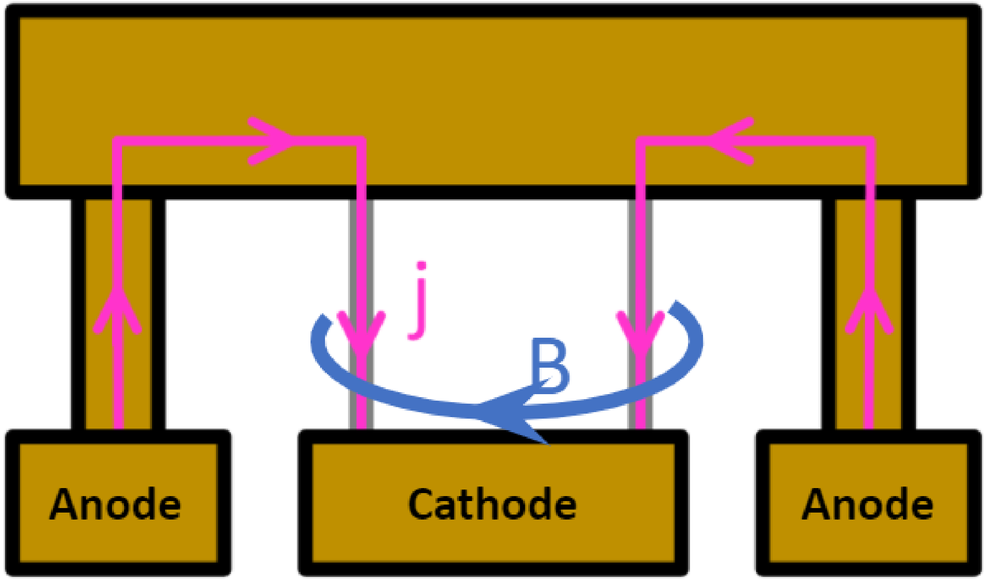


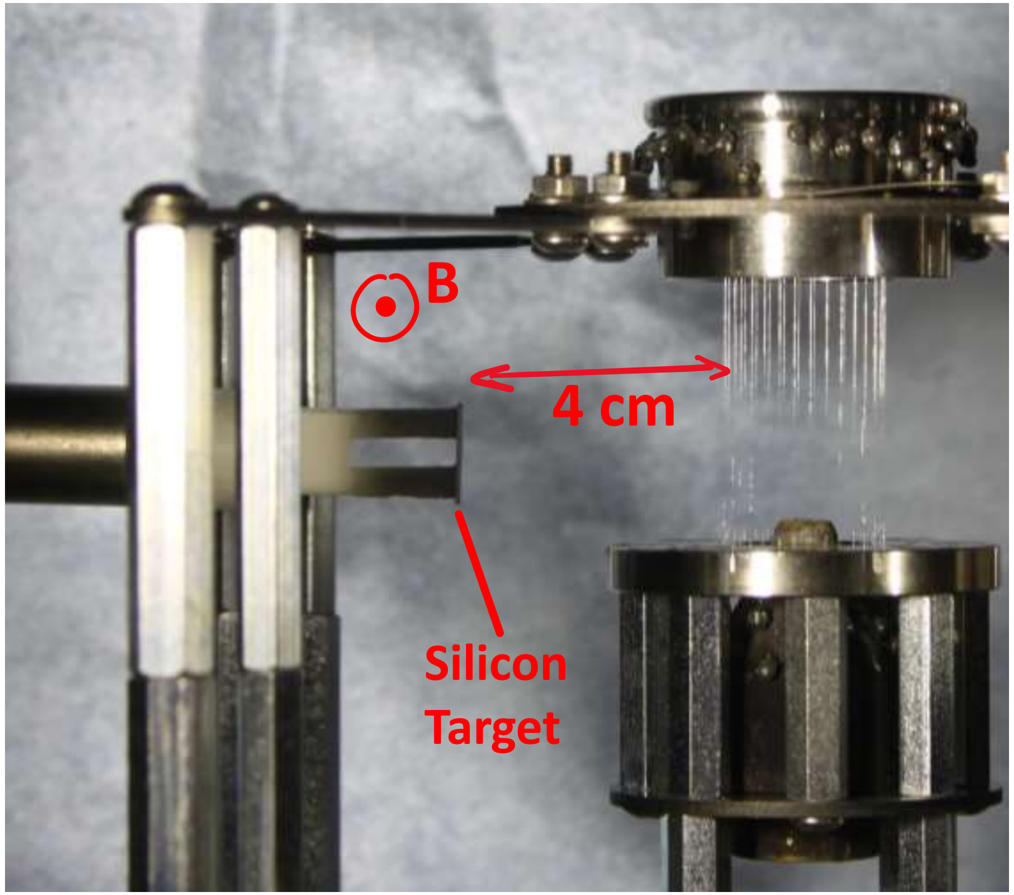


1.4 MA, 240 ns Current Pulse

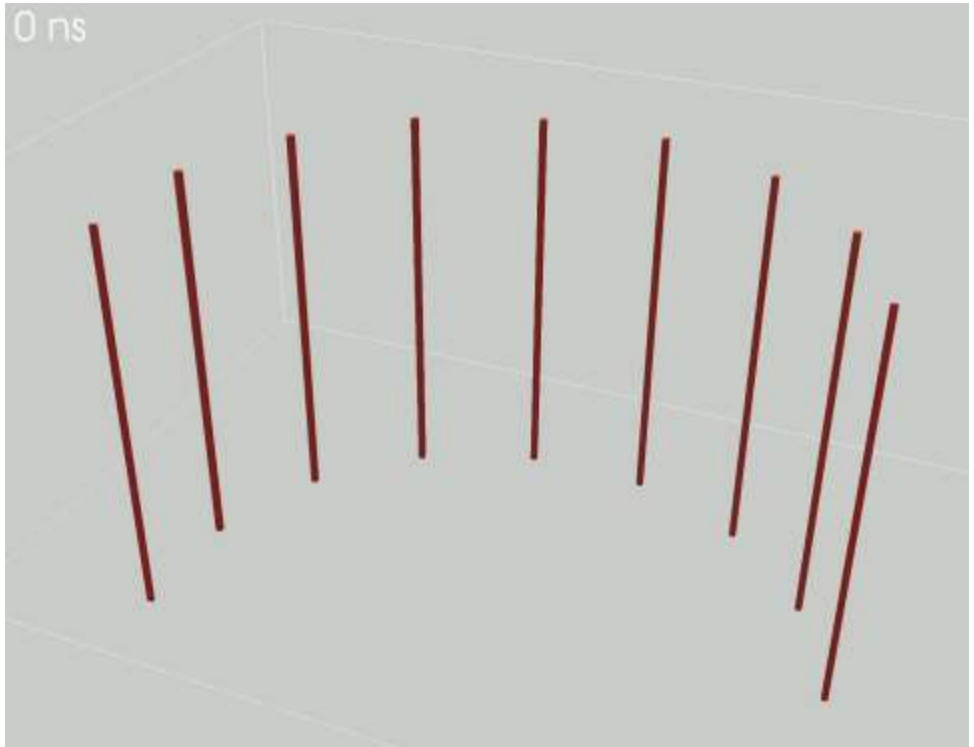
X-Ray Pulse ~ 1 TW

Imploding Wire Array Z-Pinches

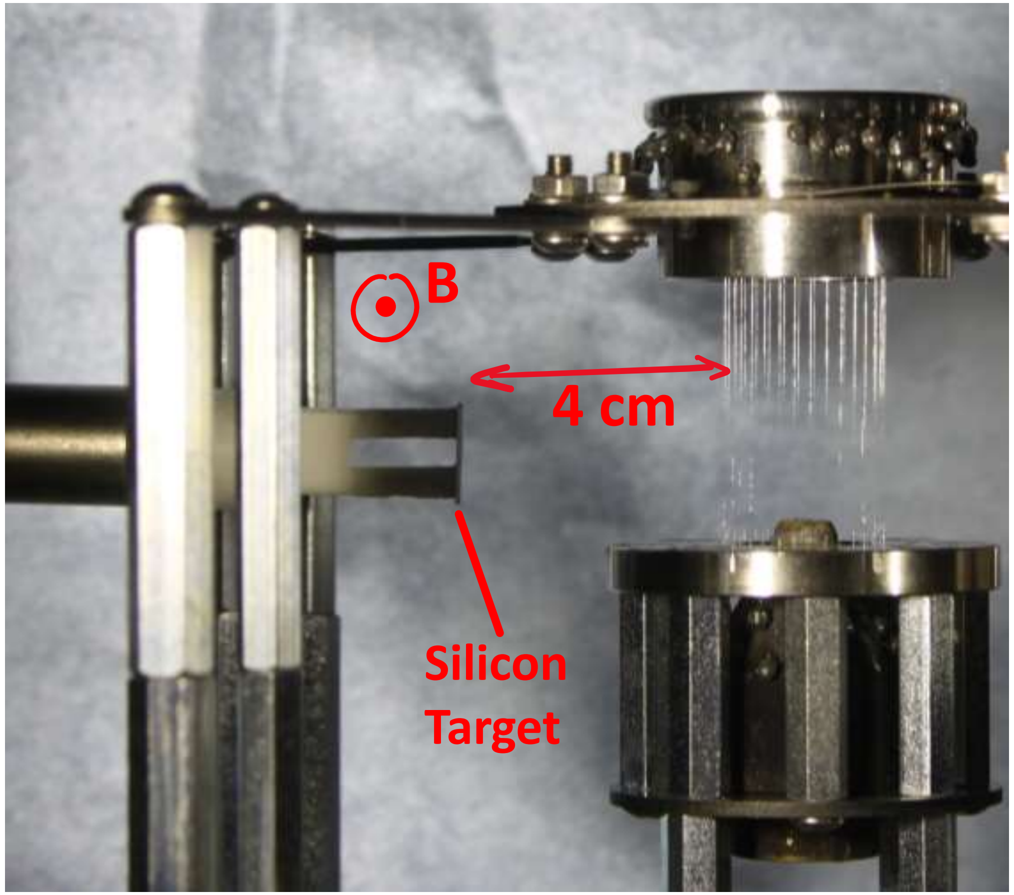




Wire array Z-pinch experiments on MAGPIE



Mass density from Gorgon (MHD) simulation



Wire array Z-pinch experiments on MAGPIE

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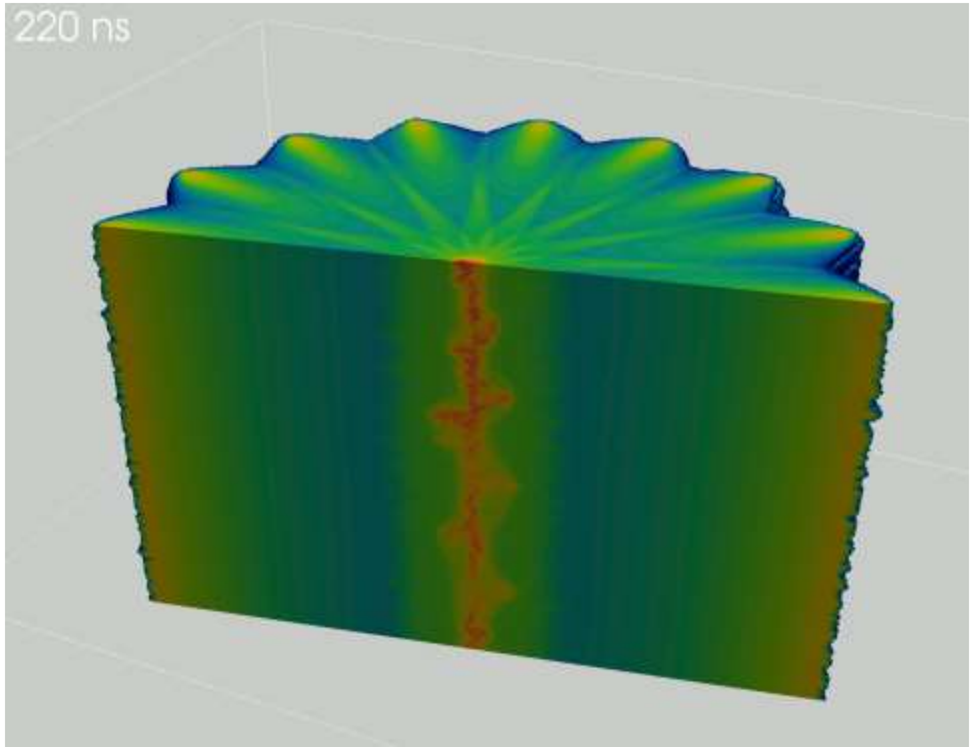

Mass density from Gorgon (MHD) simulation