Diagnosis of magnetic flux penetration in radiatively driven plasma flows

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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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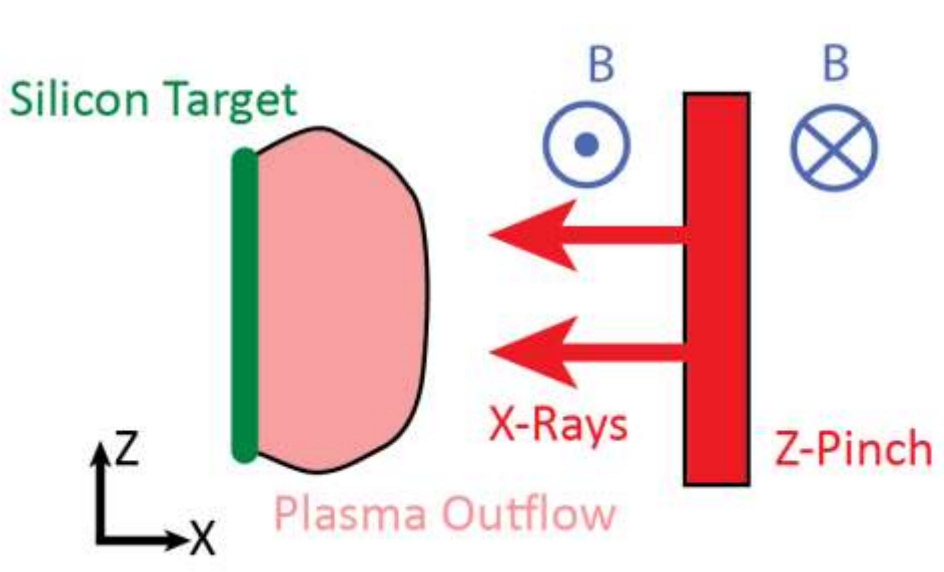
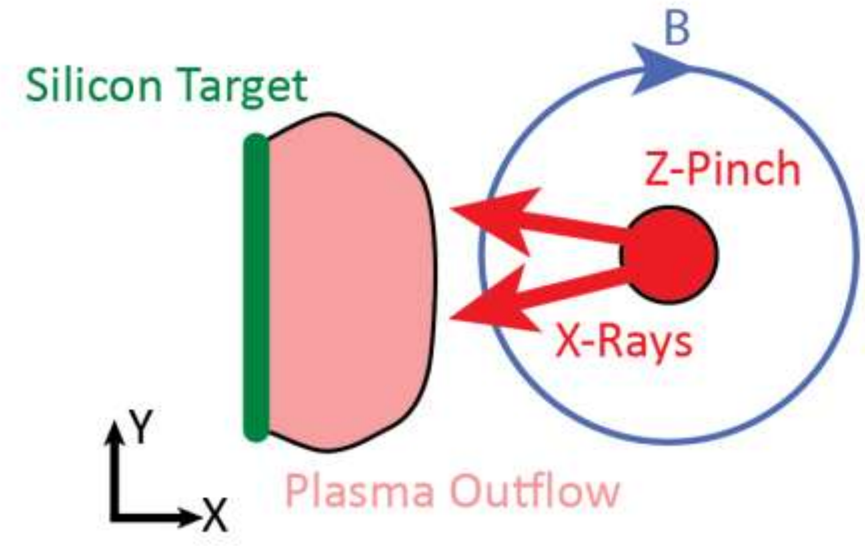


Side-On (X-Z plane) view of the experiment



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 $\sim 10\ \mathrm{T}$ magnetic field
- Target positioned $1.5 - 4$ cm from pinch

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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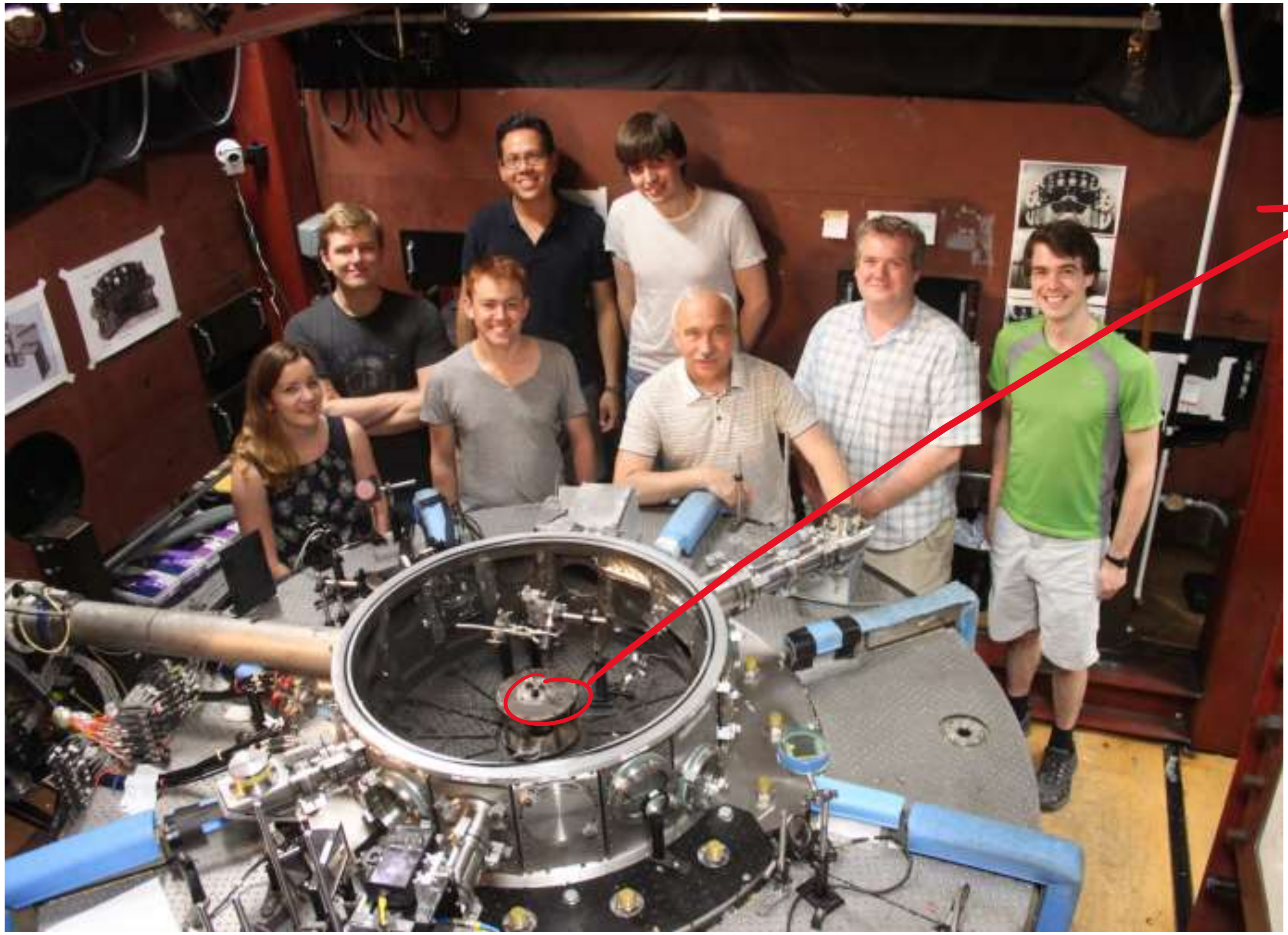
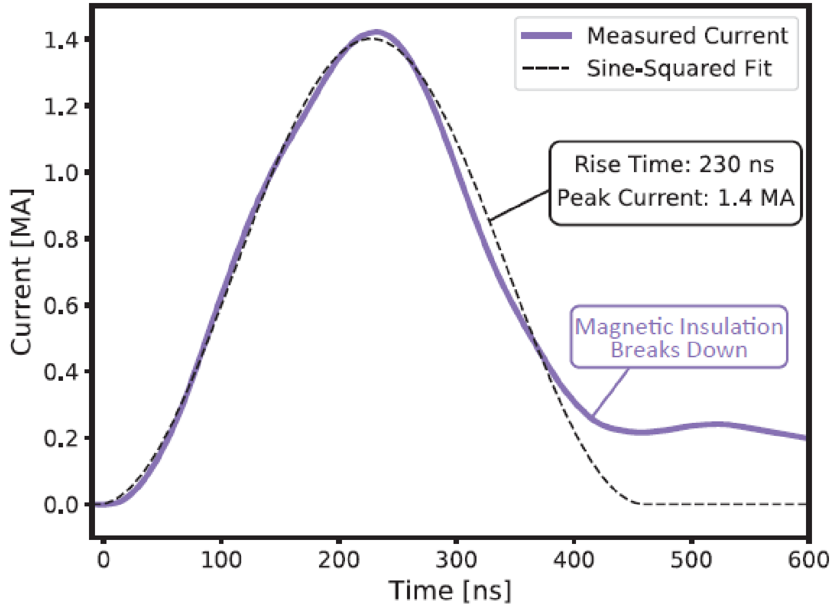
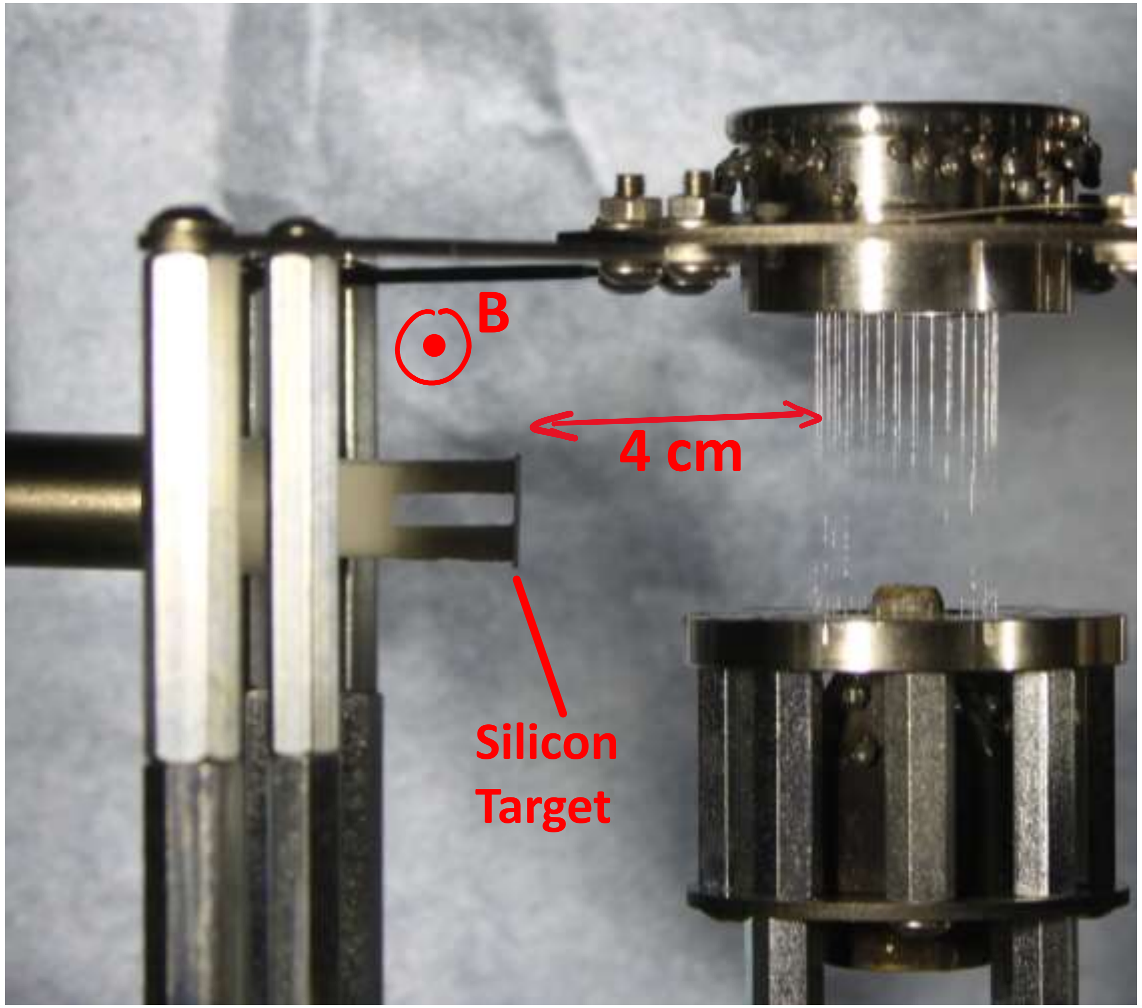


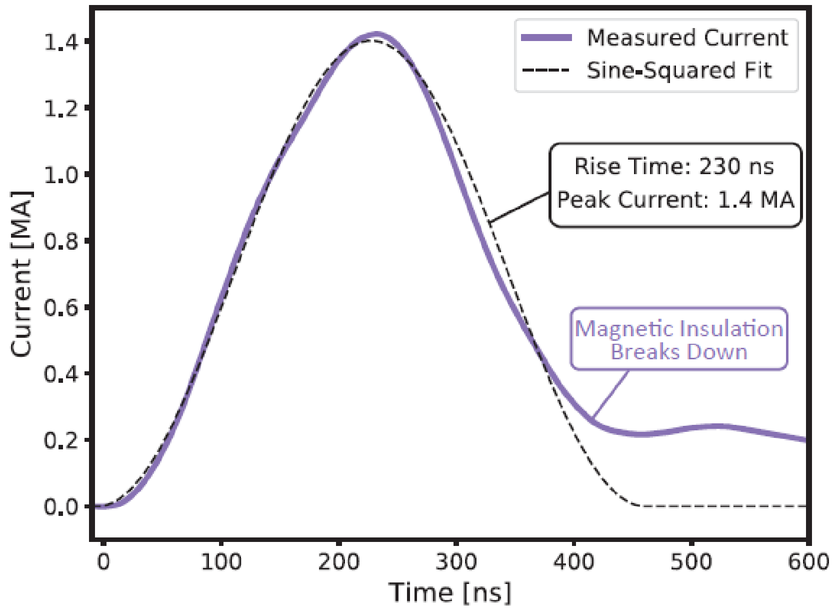


1.4 MA, 240 ns Current Pulse

X-Ray Pulse ~ 1 TW

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

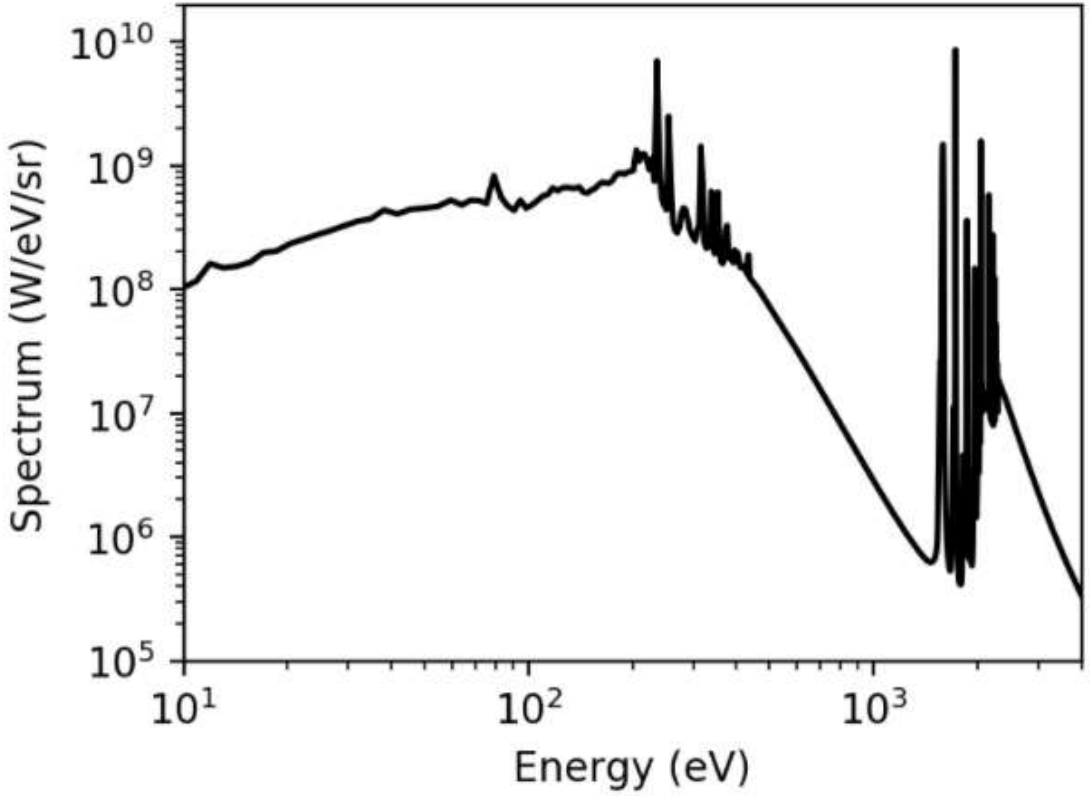




1.4 MA, 240 ns Current Pulse

X-Ray Pulse ~ 1 TW

Spectral Character of Radiation at ~1 MA Level



- Aluminium wire array
- Emits ~15 kJ over ~30 ns
- Color temperature $T_c \sim 150$ eV

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Optical self emission images [qualitive dynamics]

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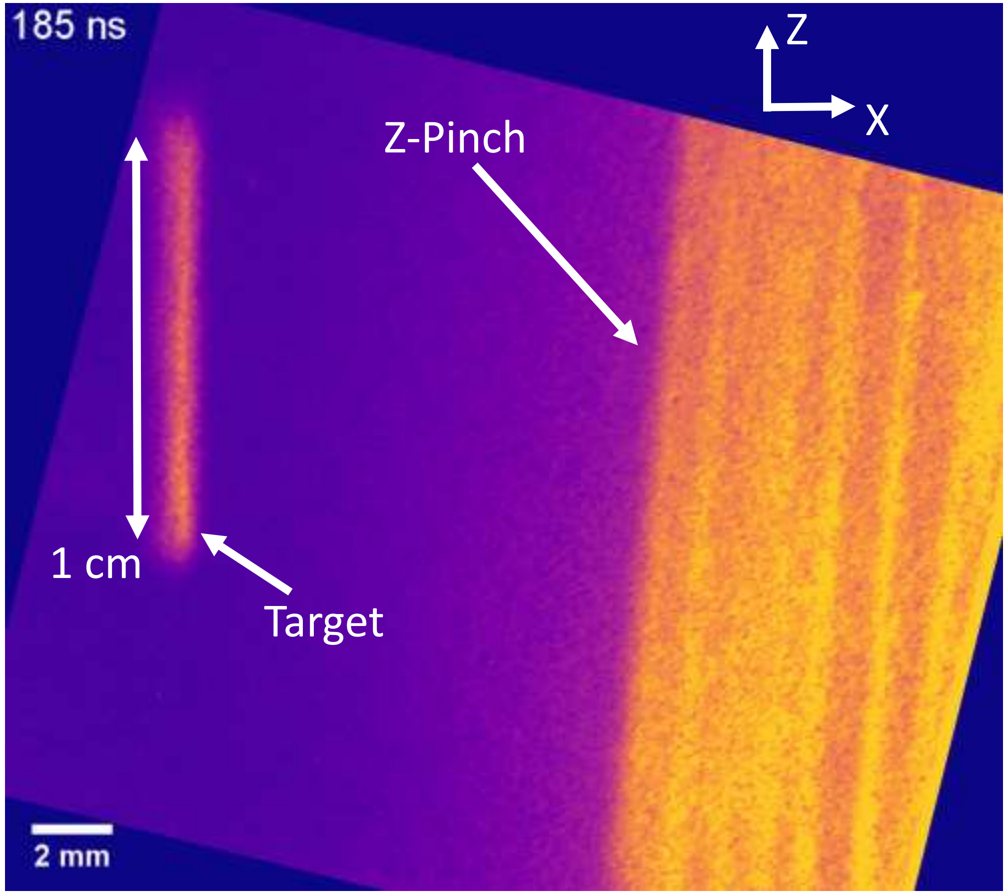

Self emission images [$600 \lesssim \lambda \lesssim 900$ nm]

Optical self emission images [qualitive dynamics]

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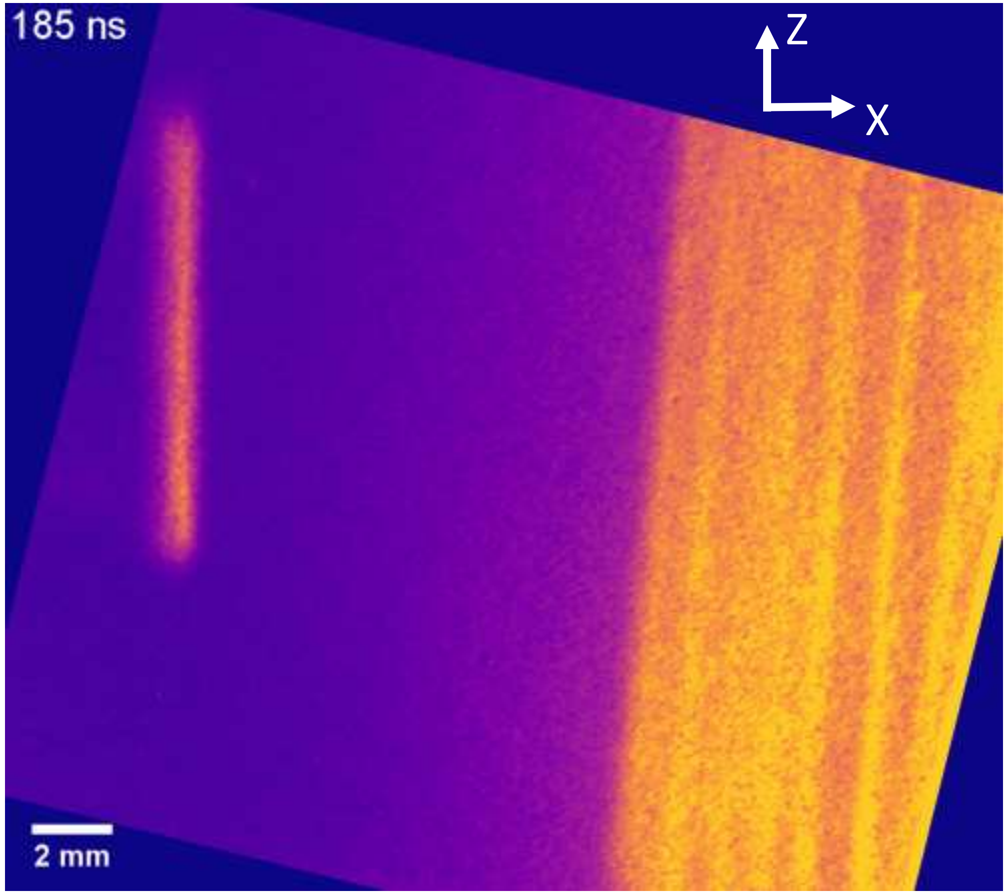

Self emission images [$600 \lesssim \lambda \lesssim 900$ nm]

Interferometry [line integrated electron density]

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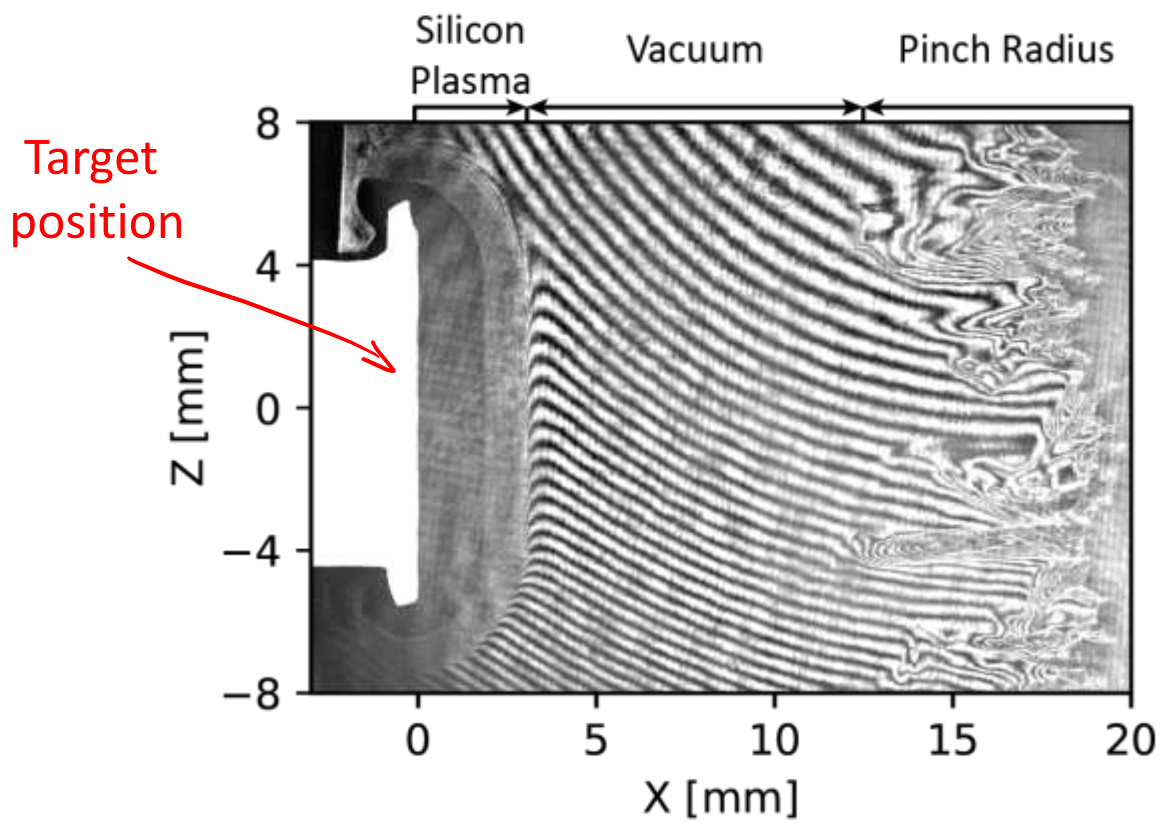

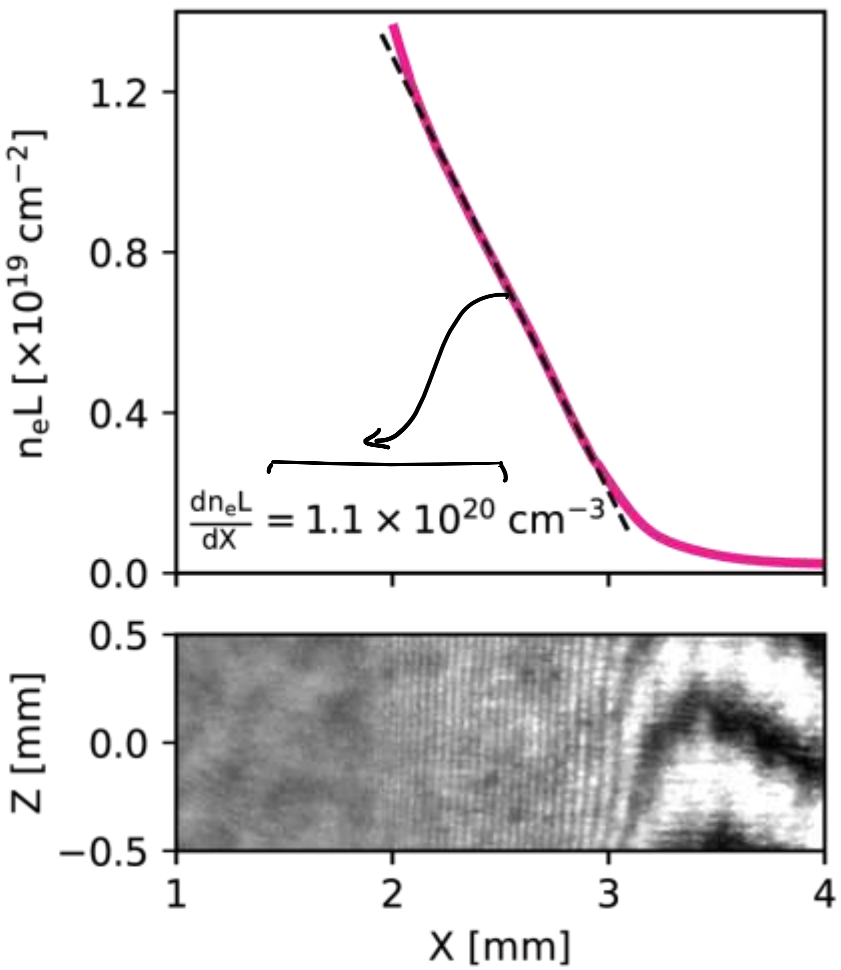

- Interferogram captured at $t = 320$ ns
- Smooth $\sim$1D expansion profile confirmed by orthogonal laser probing

Radiative MHD simulations [Chimera]

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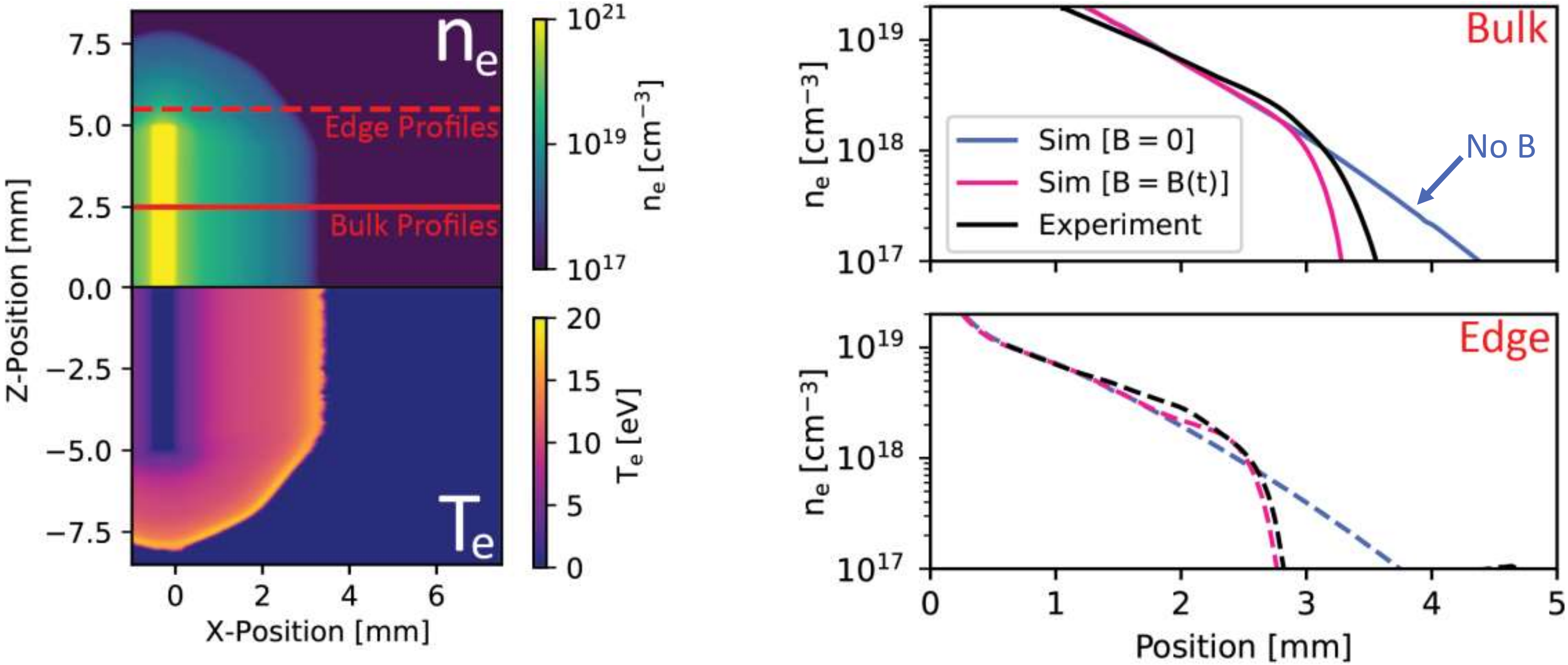

Density profile is affected by B-Field.

Radiative MHD simulations [Chimera]

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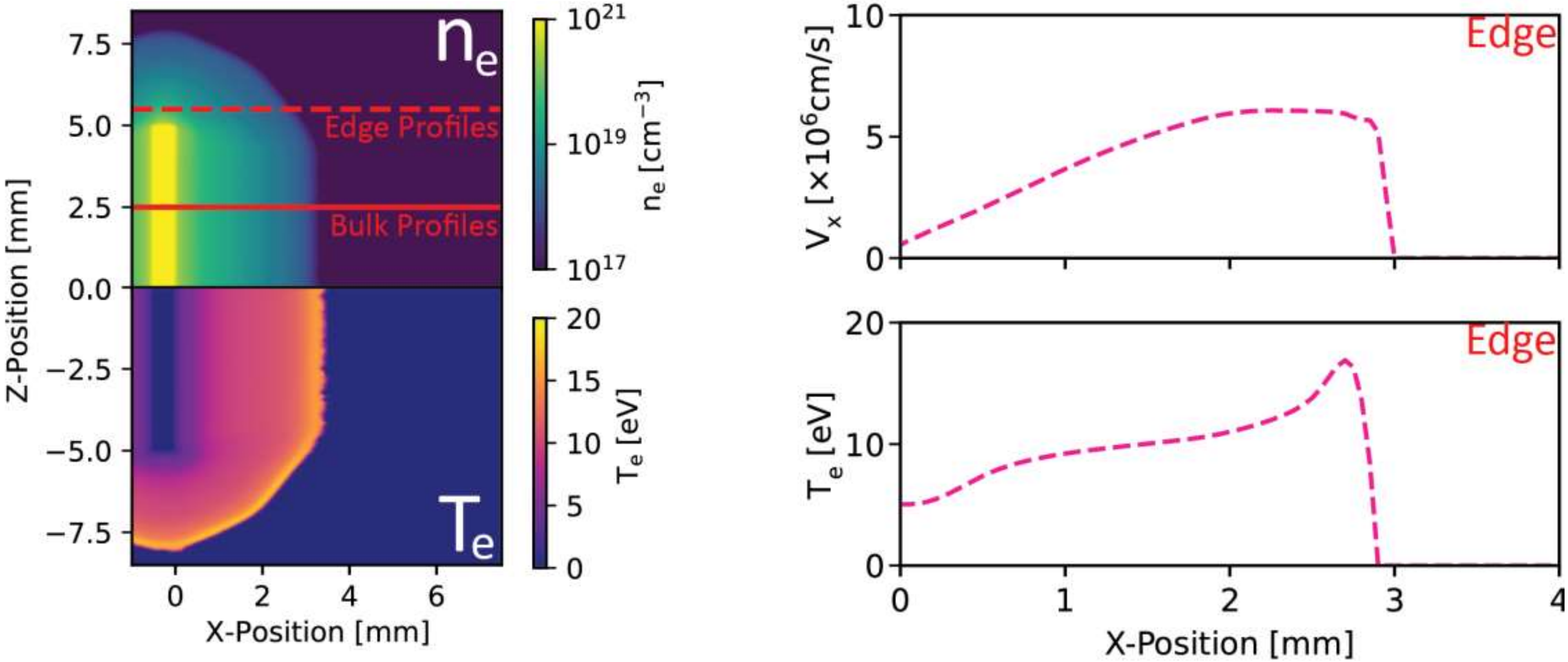

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Thomson scattering [localised diagnosis of T, V, Z]

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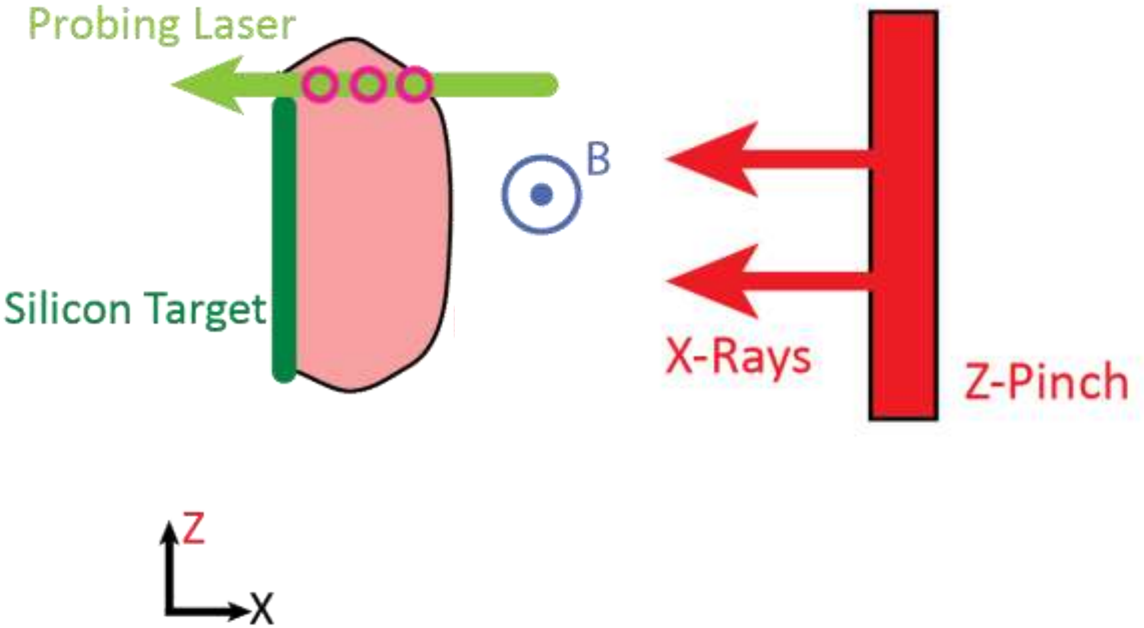

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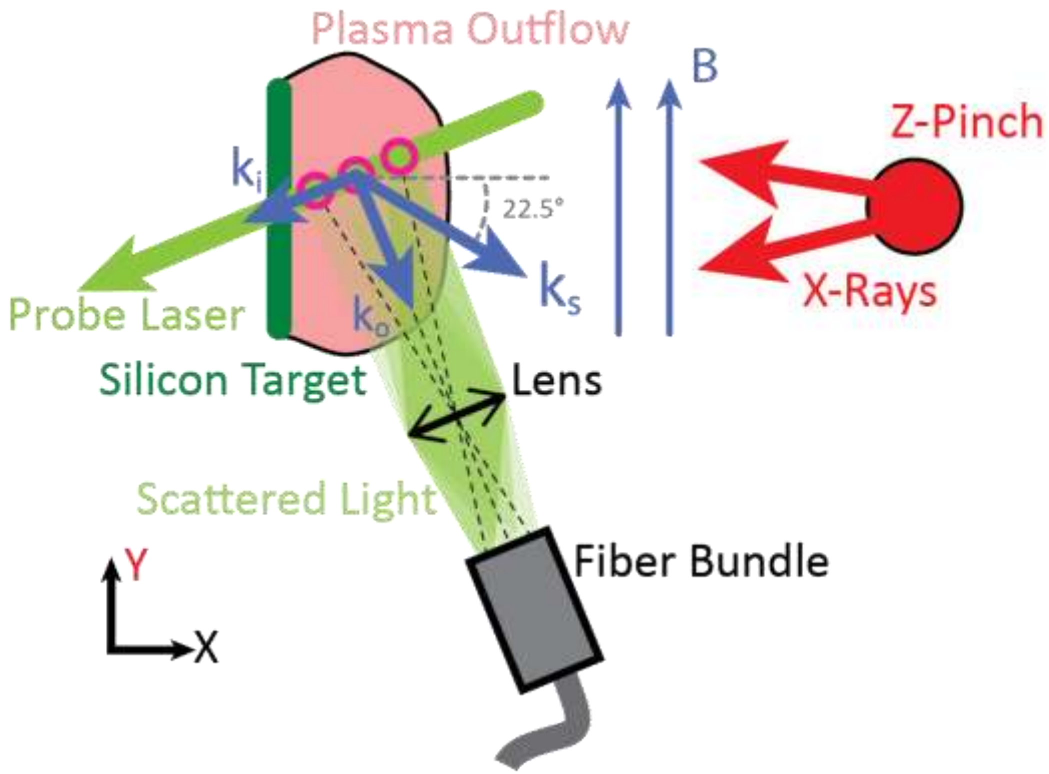
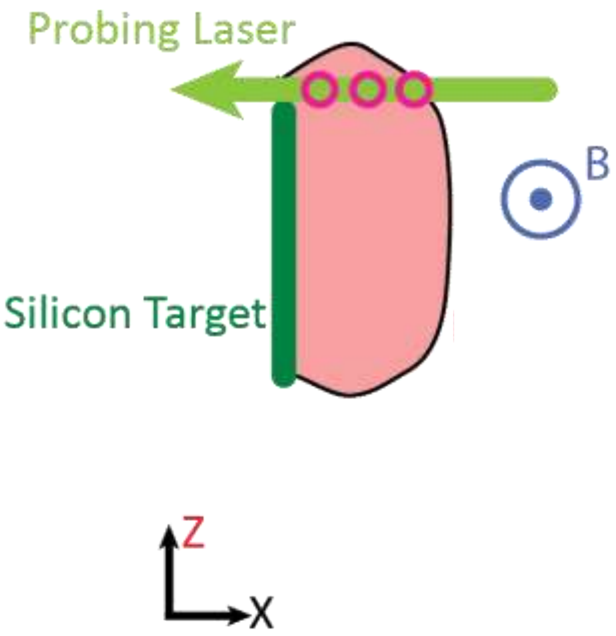
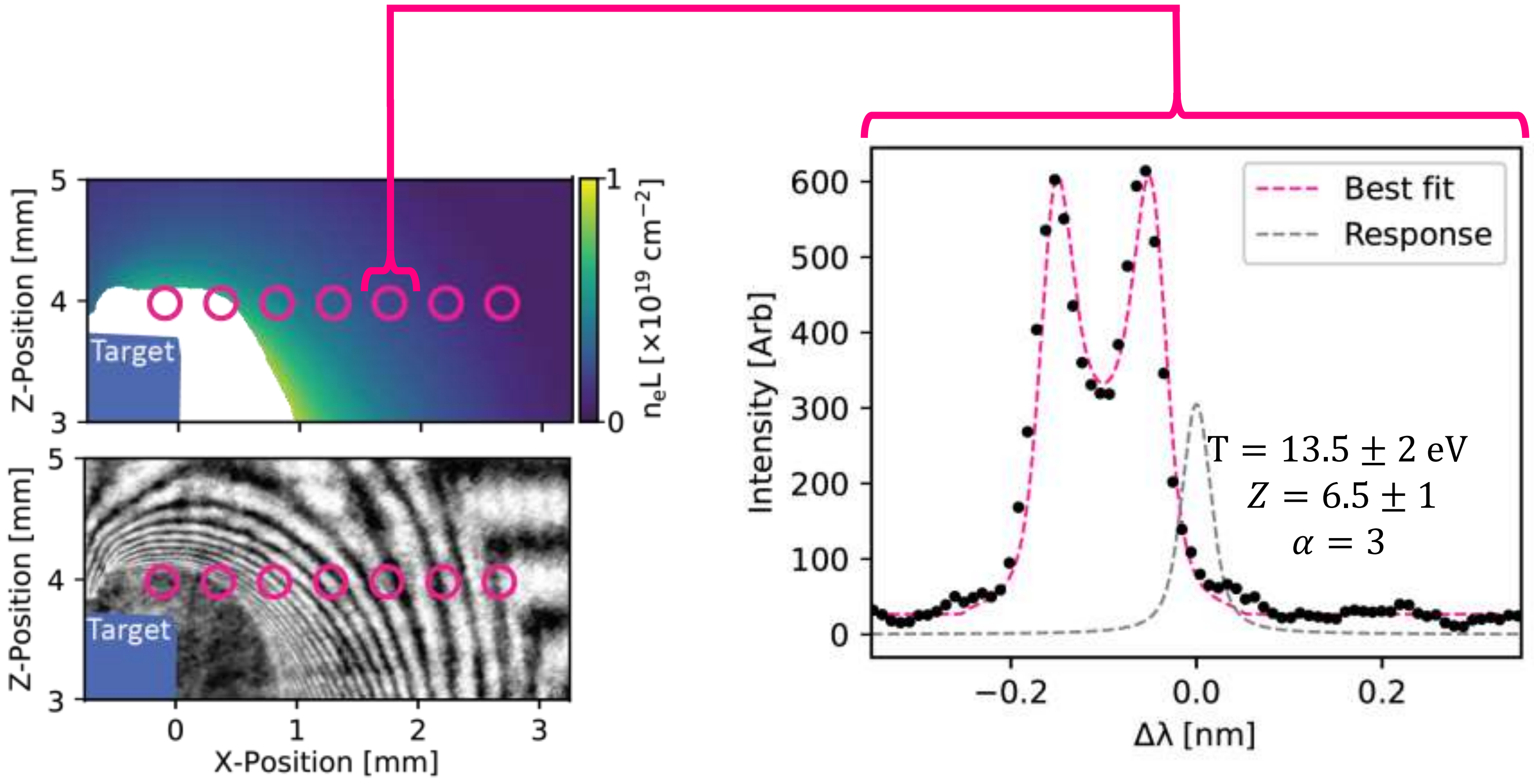


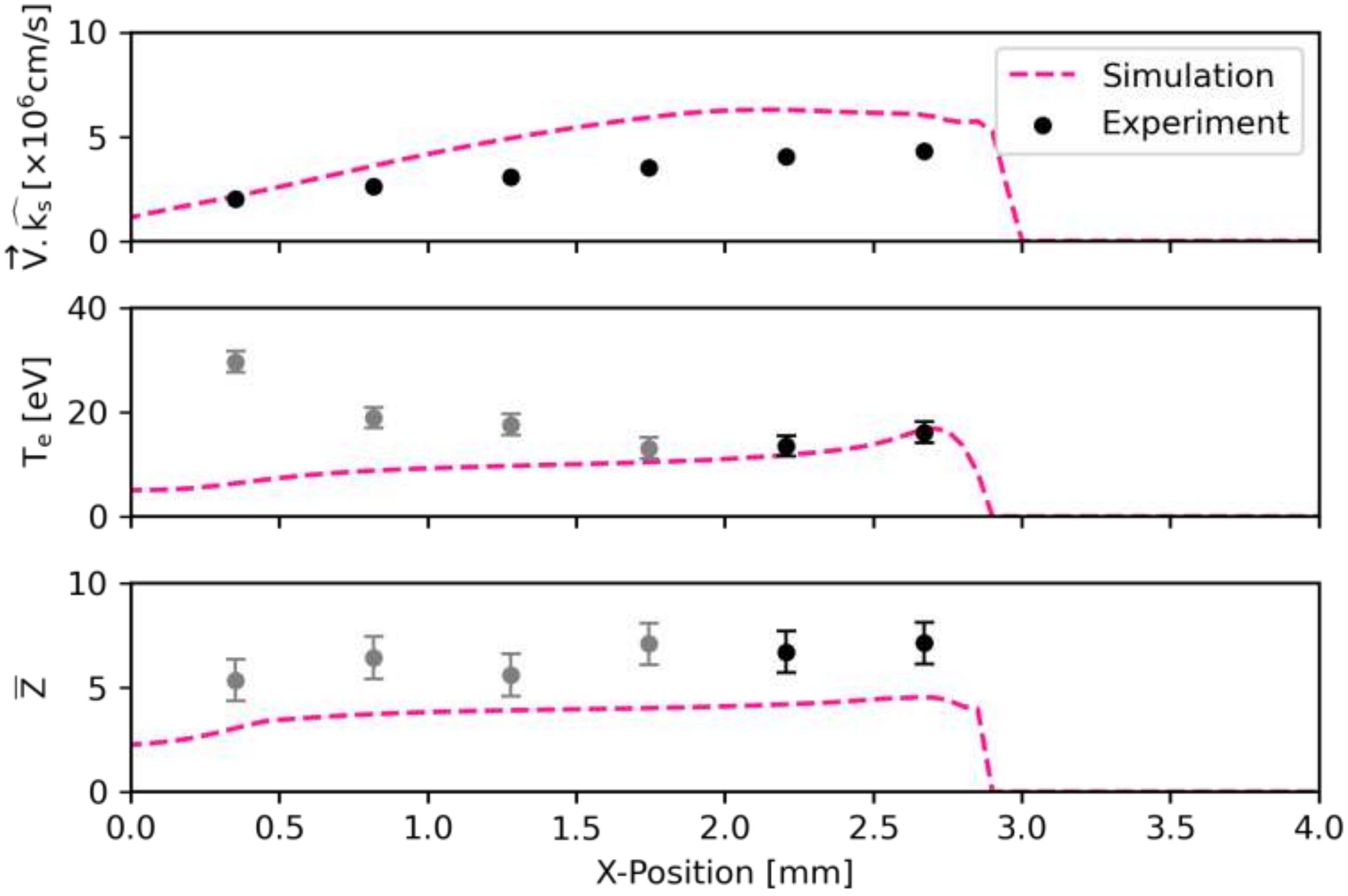
End-On (X-Y plane) view of the experiment

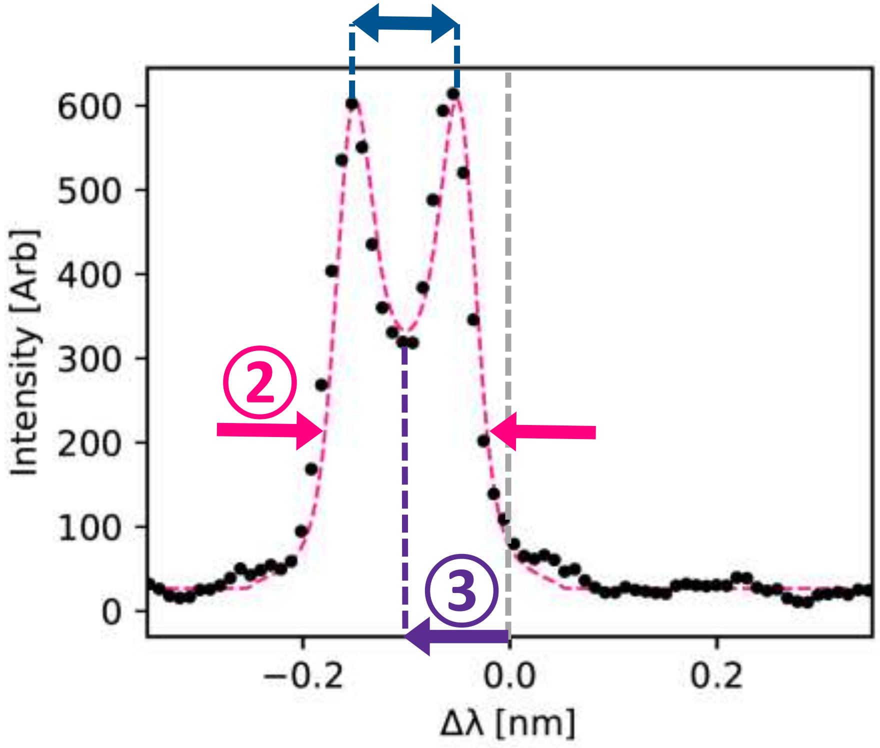
Thomson scattering [localised diagnosis of T, V, Z]





Analysis of Ion-Acoustic Thomson Scattering Data





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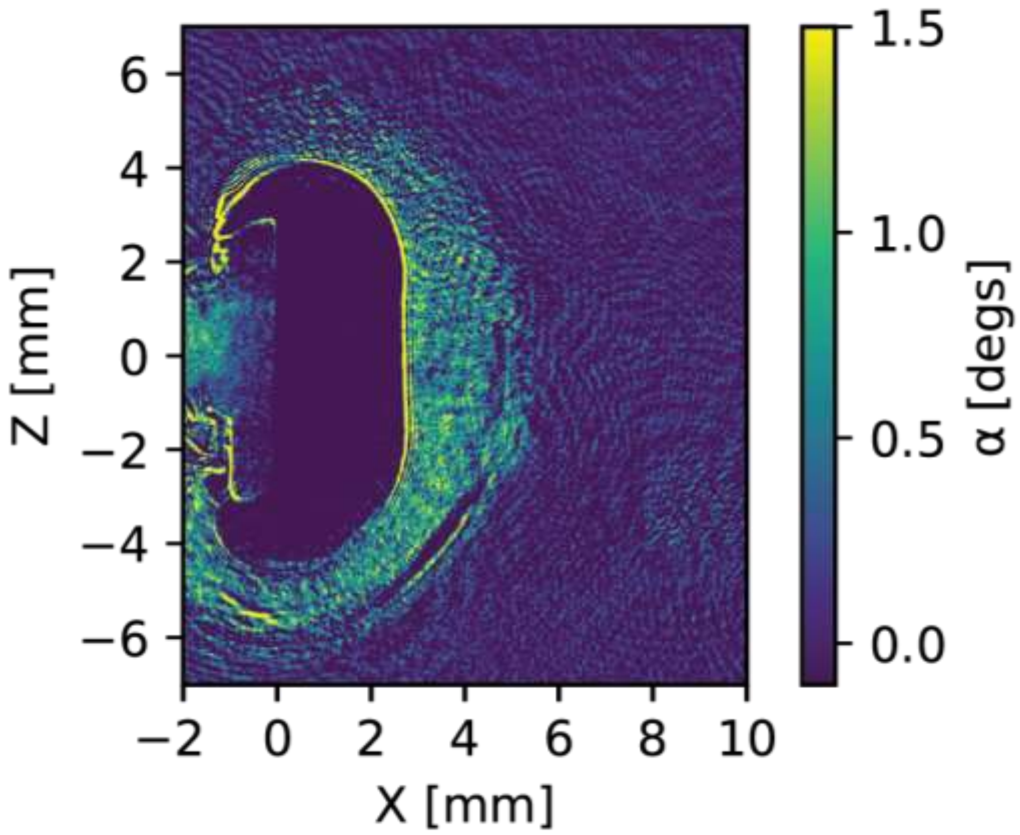
Faraday rotation imaging [weighted average of B_y]



- Measure rotation applied to laser polarisation:

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

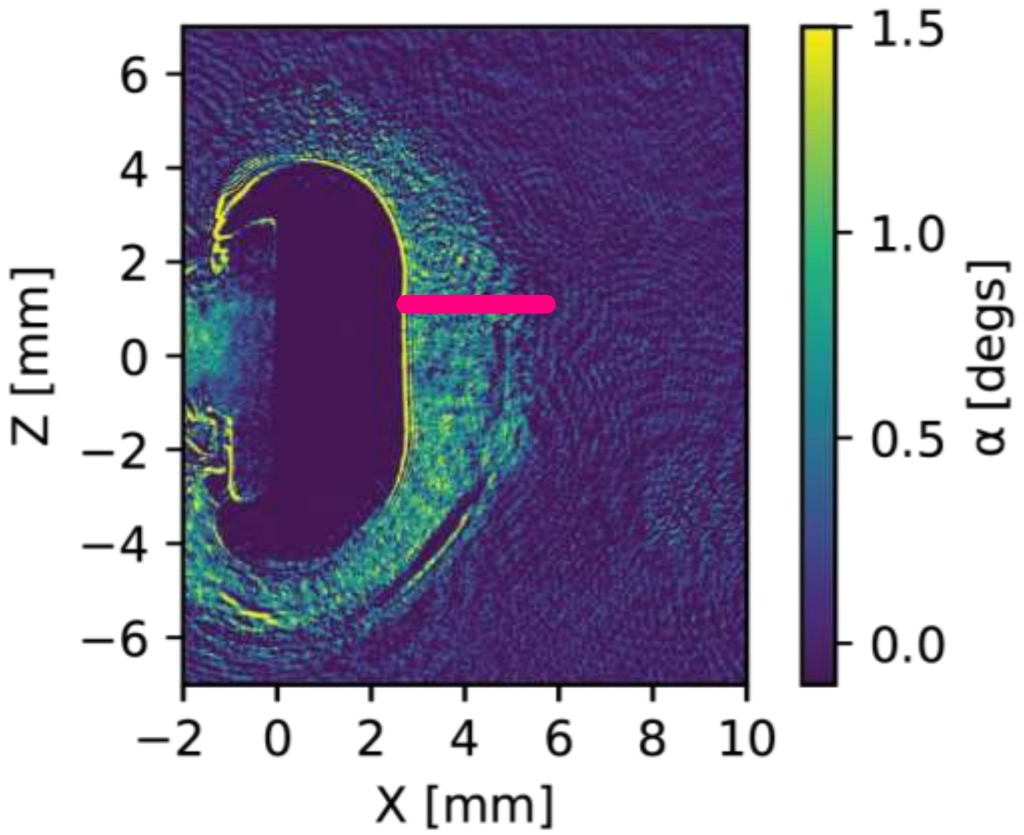
- Obtain interferometry along same line of sight:

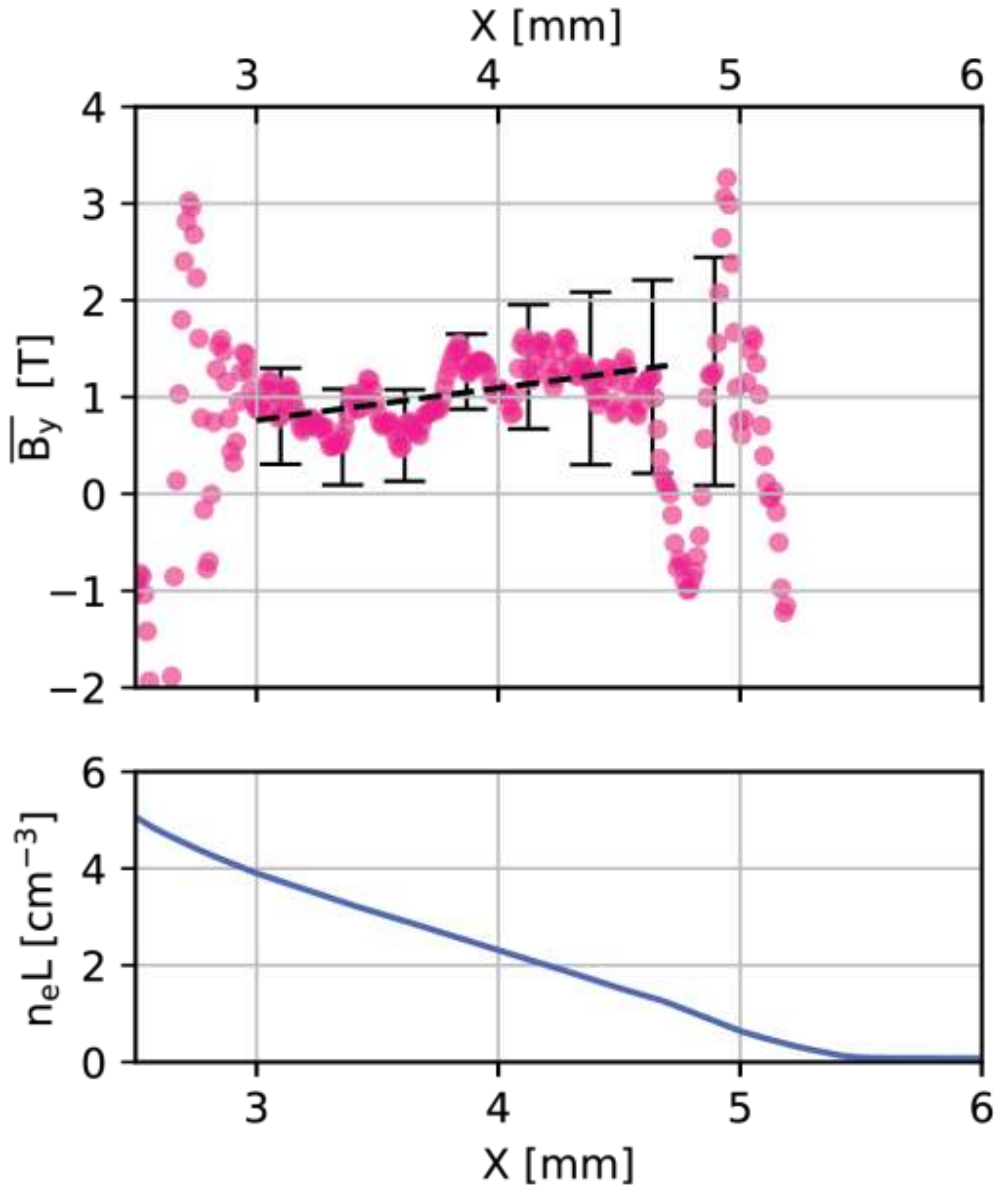
$$n_e L = \int n_e dy$$

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

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

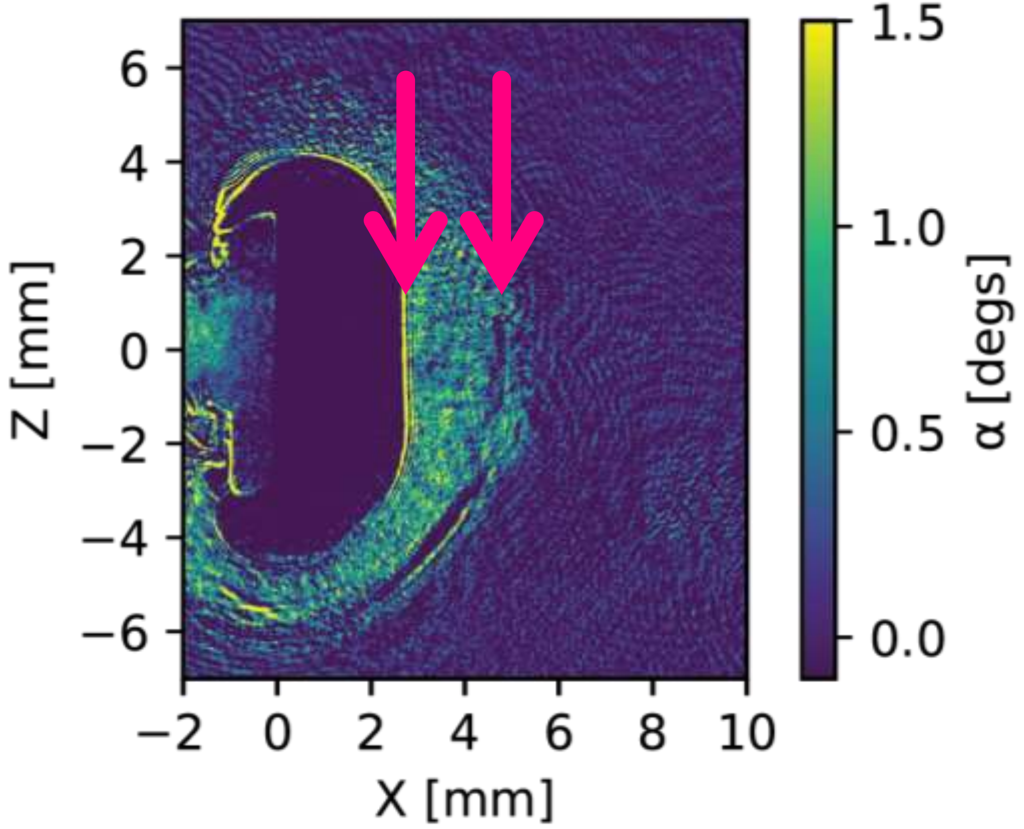
Faraday rotation imaging [weighted average of B_y]

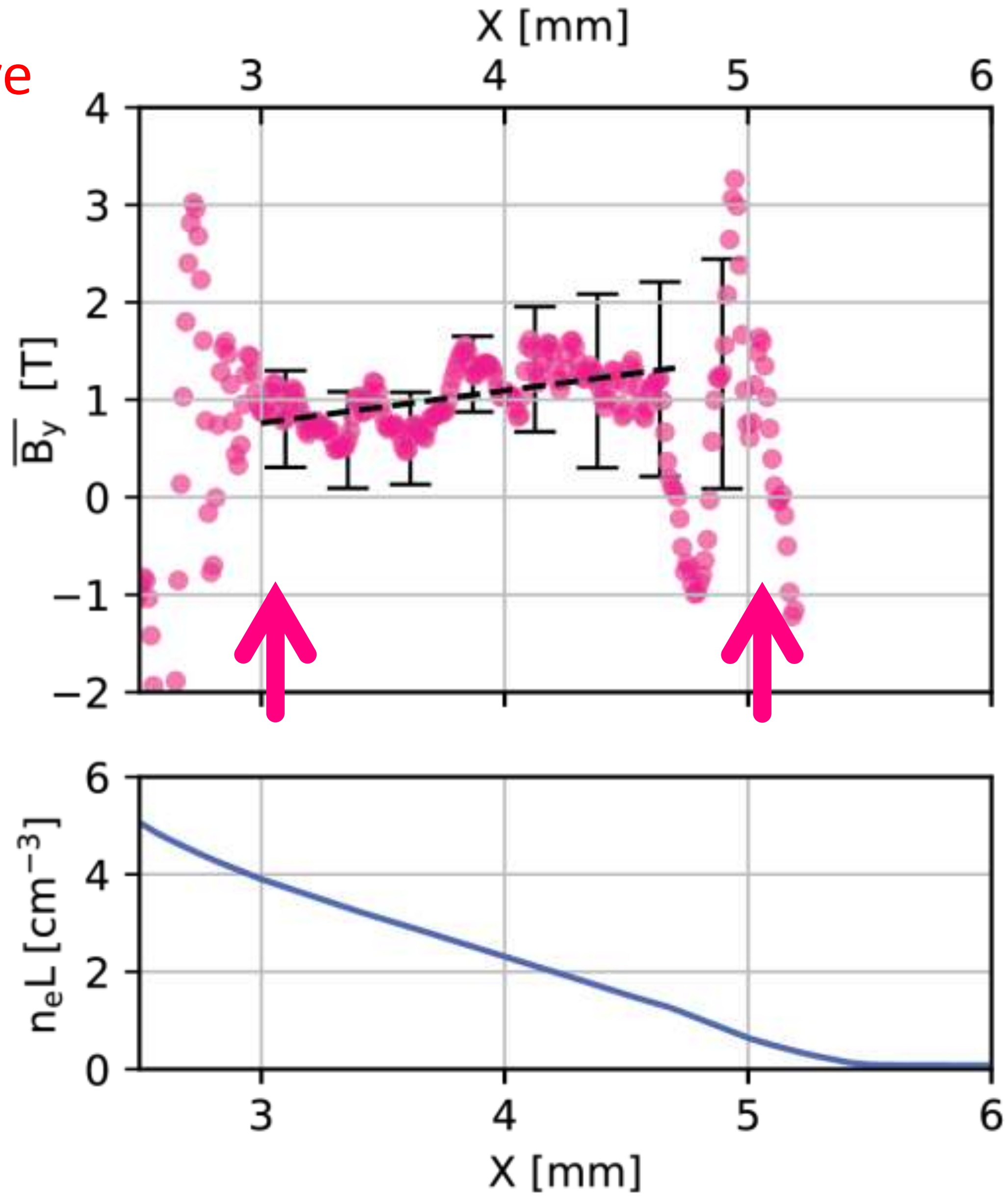




Faraday rotation imaging [weighted average of B_y]

Arrows indicate caustics ⟹ B field not representative





Faraday rotation imaging [weighted average of B_y]

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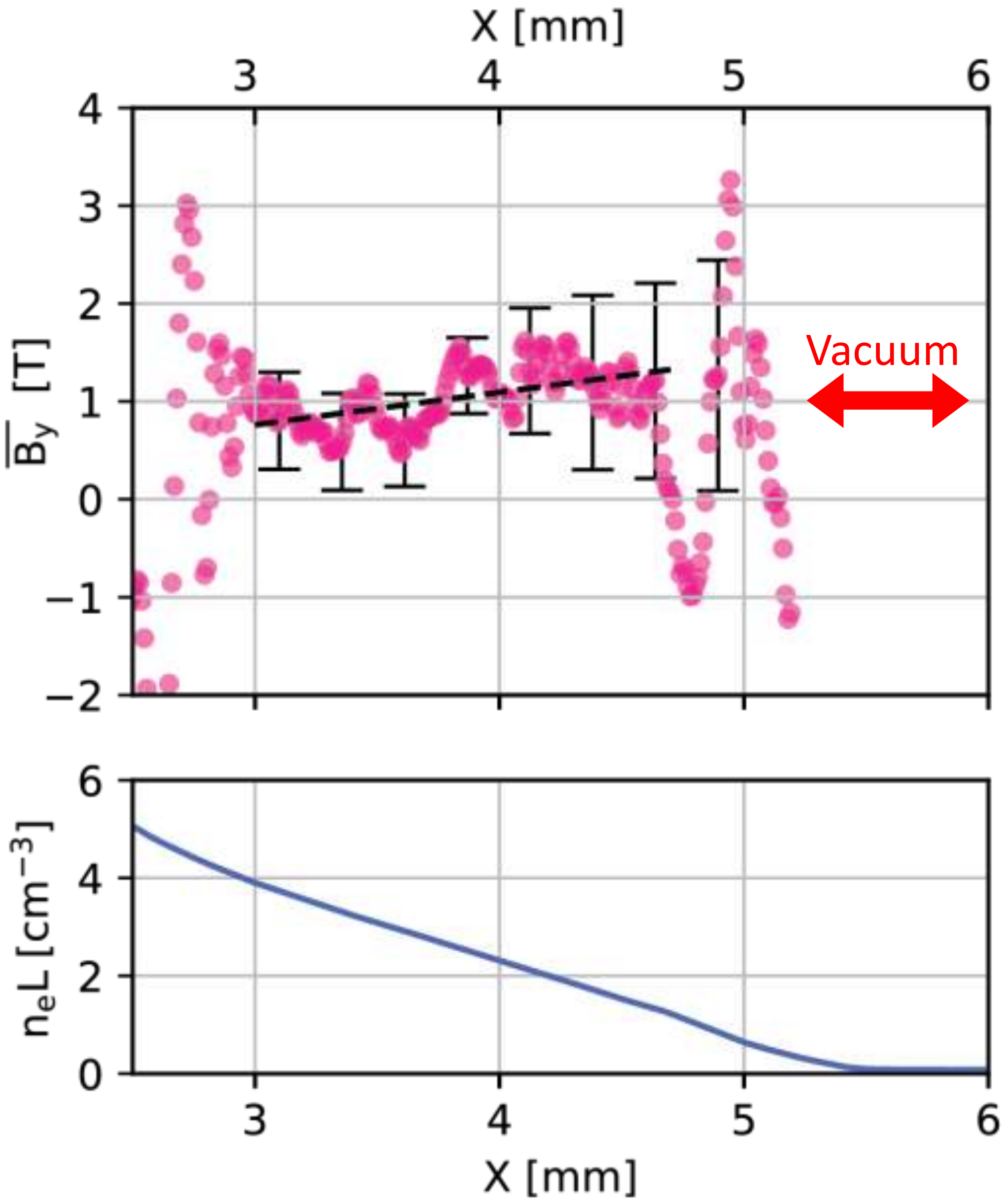
- Diagnostic measures weighted average magnetic field:

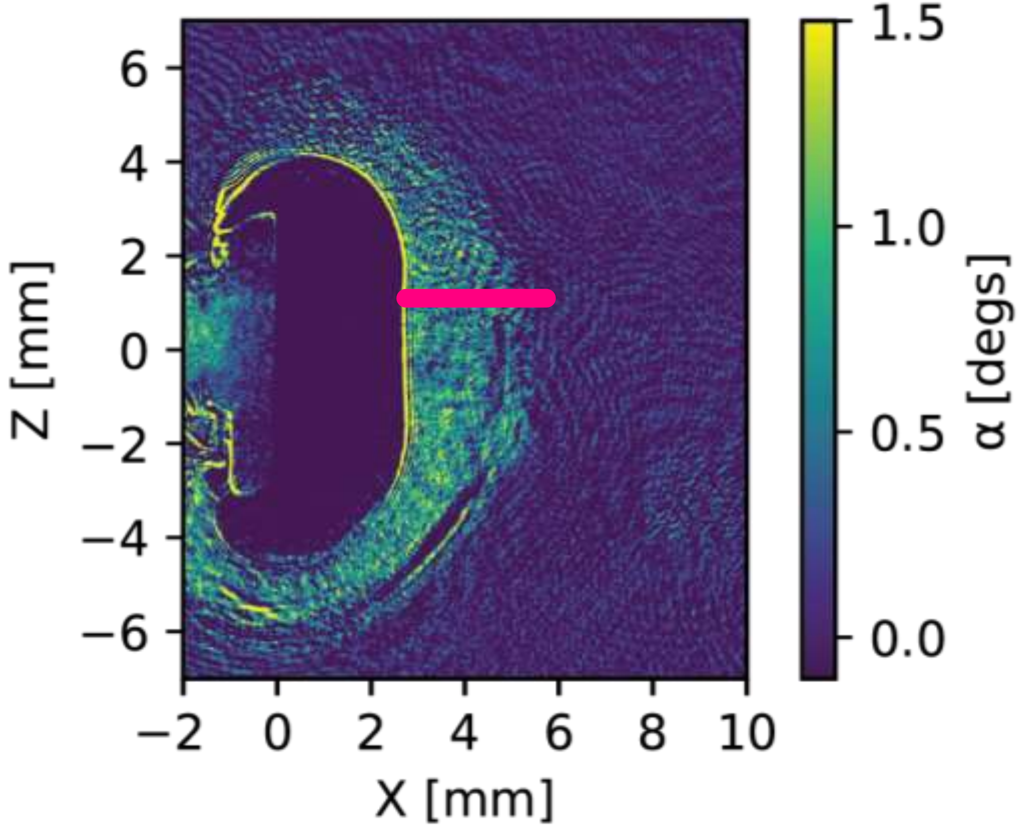
$$\overline{B_y} = \frac{\alpha}{n_e L} \propto \frac{\lambda^2 \int n_e \vec{B}.d\vec{y}}{\int n_e dy}$$

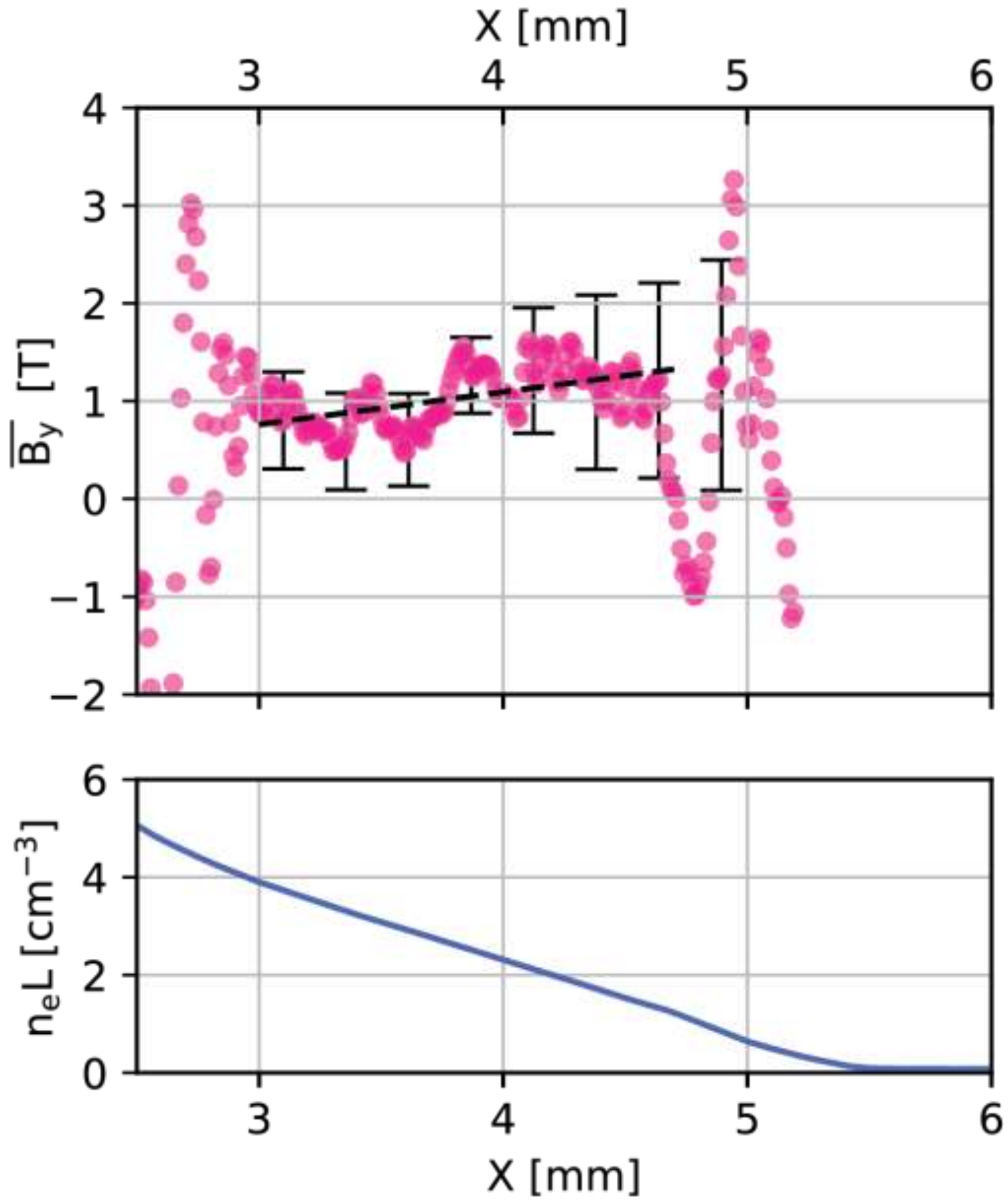
- Cannot diagnose field in the vacuum ($n_e = 0$)

- Within region which can be probed, the field is approximately constant (~ 1 T)

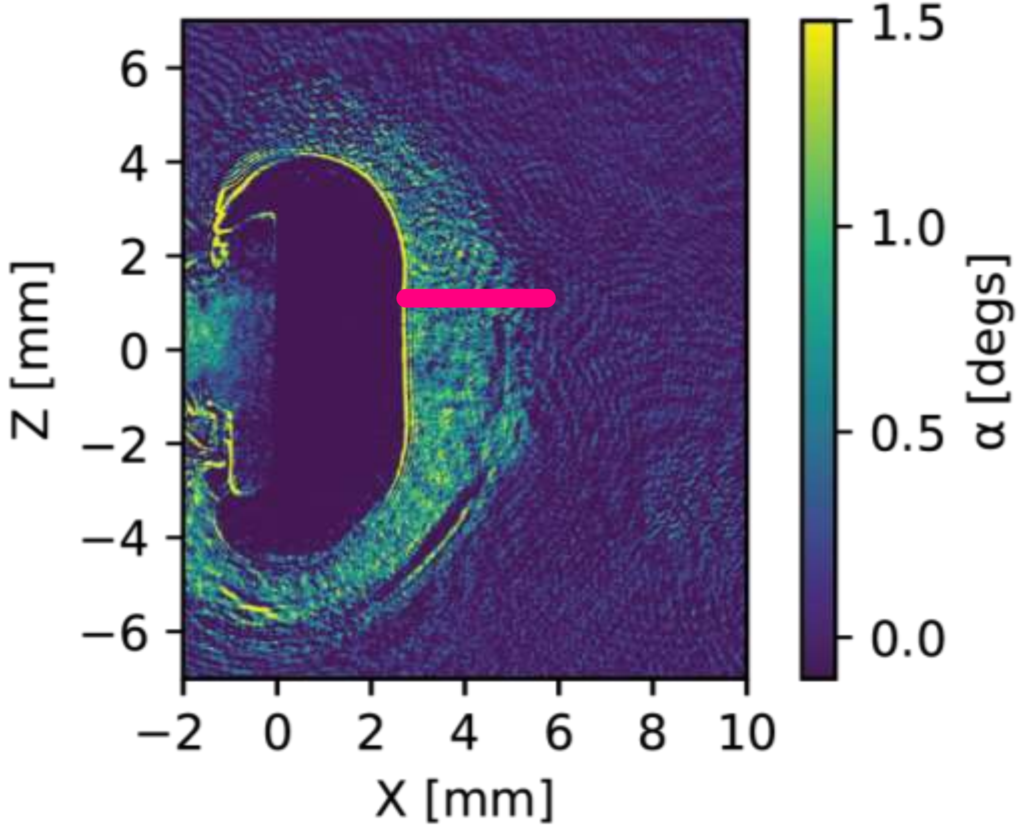


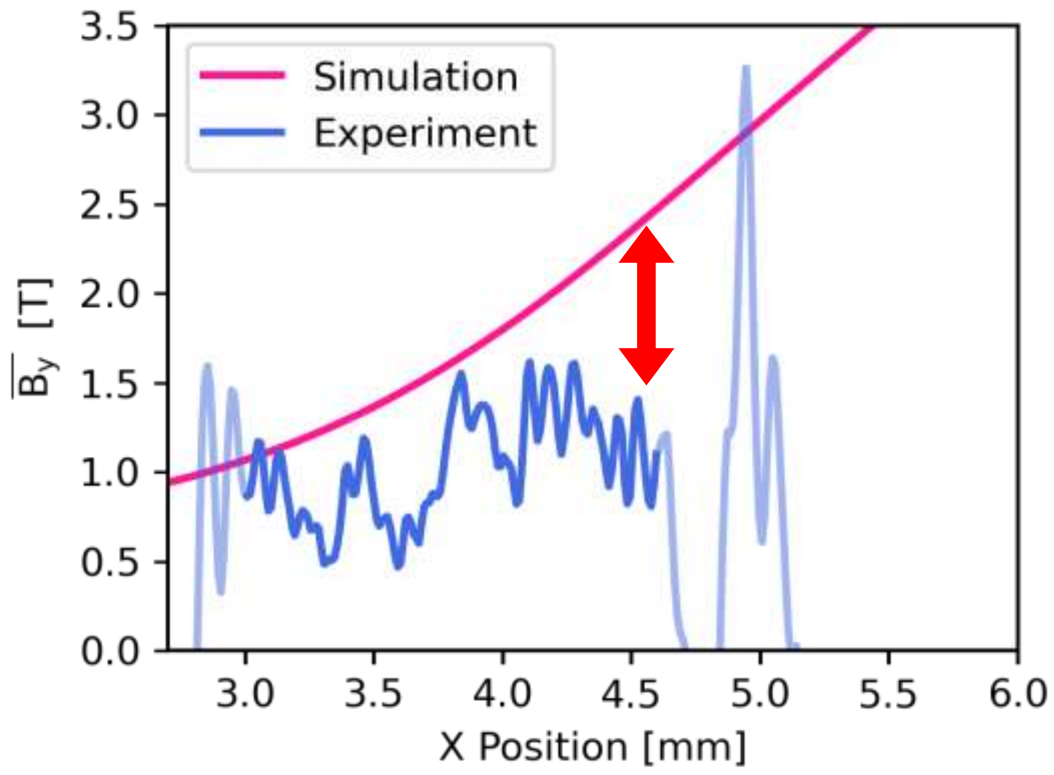
Faraday rotation imaging [weighted average of B_y]





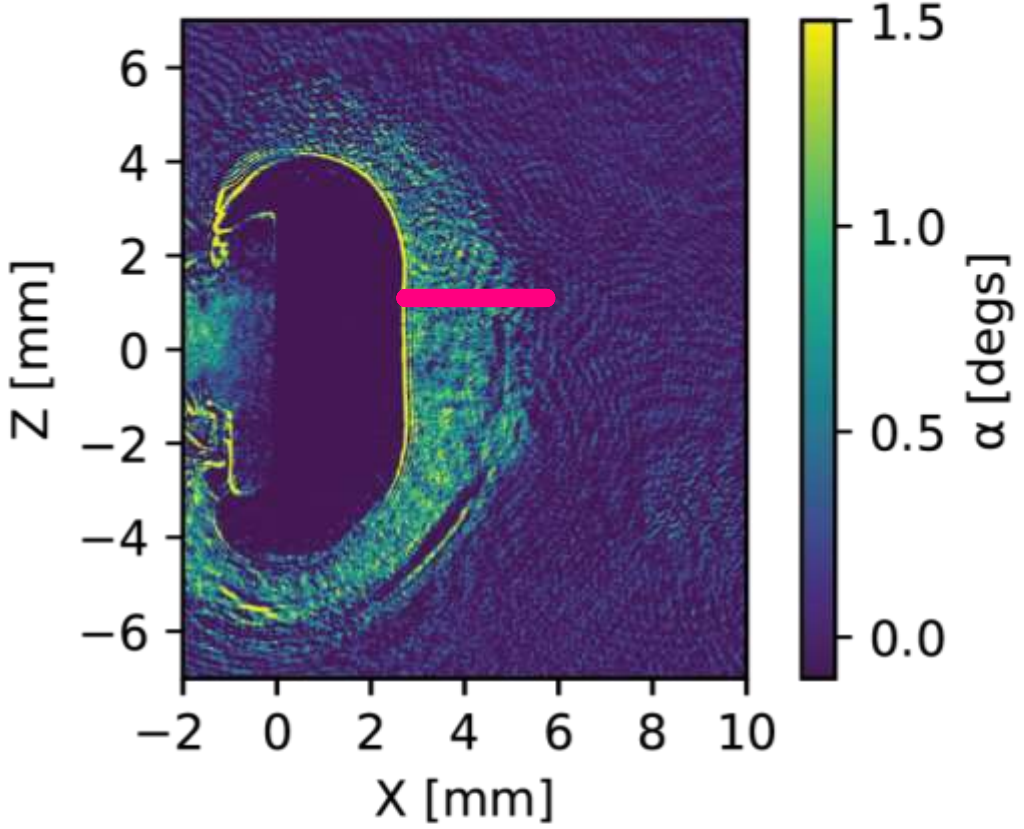
Faraday rotation imaging [weighted average of B_y]

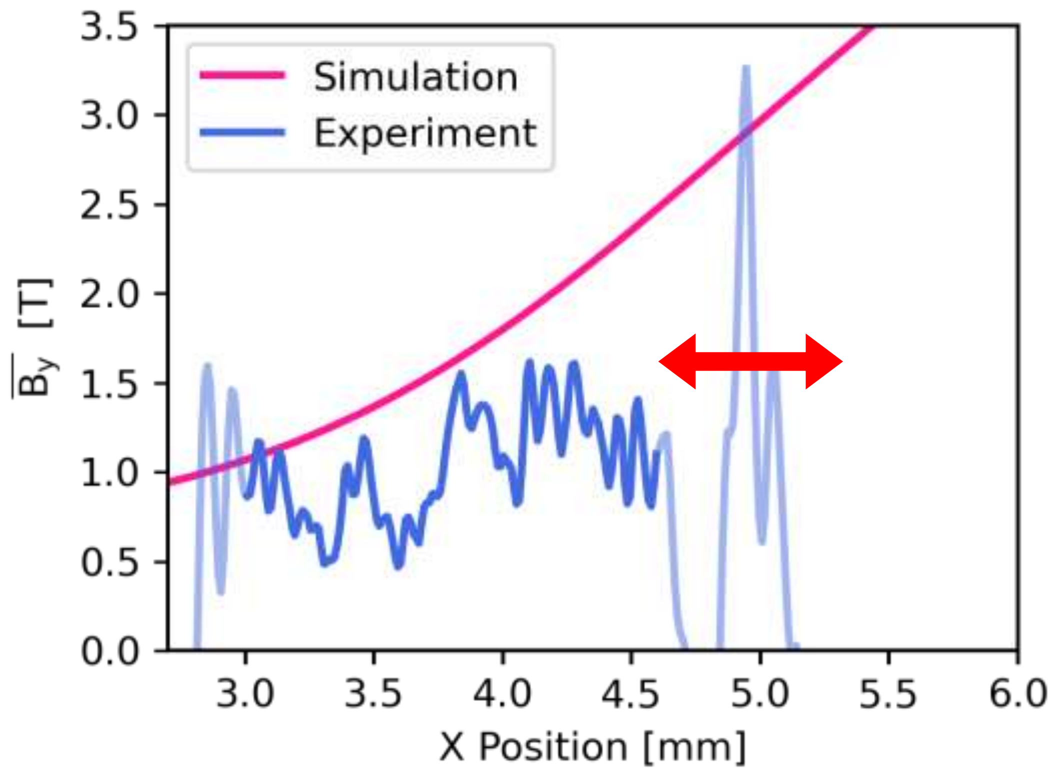




Simulated profile is more diffusive

Faraday rotation imaging [weighted average of B_y]





Need to diagnose vacuum boundary!

Future work – Local Current Density Measurement

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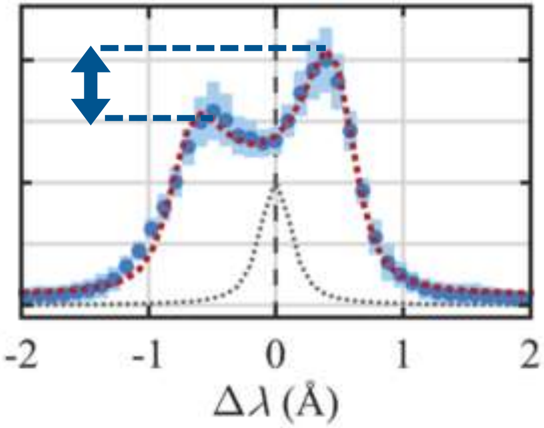
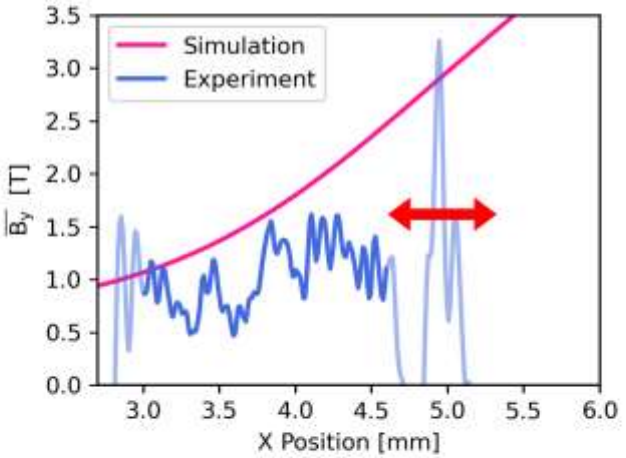
Peak **asymmetry** depends on $\widehat{\boldsymbol{k_s}}.\boldsymbol{V_d}$

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



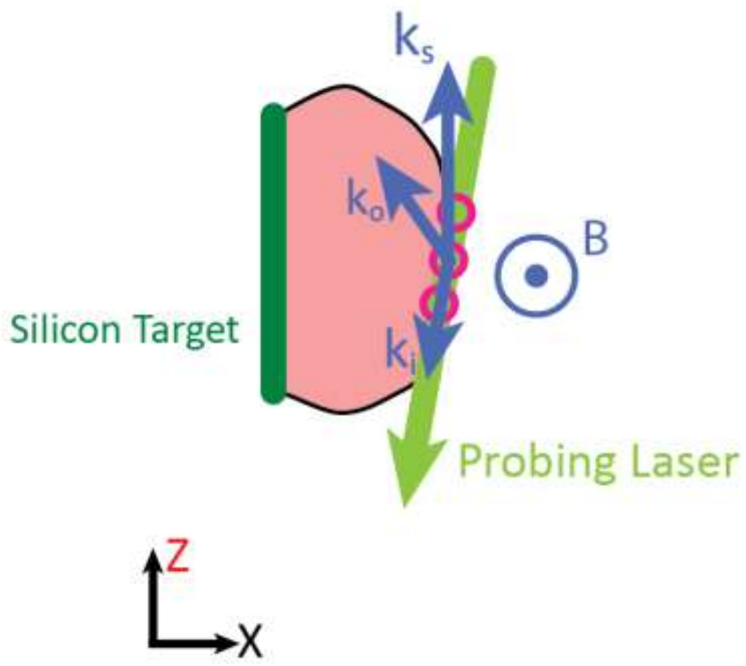
Diagnose current at vacuum boundary with Thomson:

- Can probe smaller n_e
- Reduce λ for less diffraction



Need to diagnose vacuum boundary!

New setup ⇒ $k_s \parallel J$



Summary

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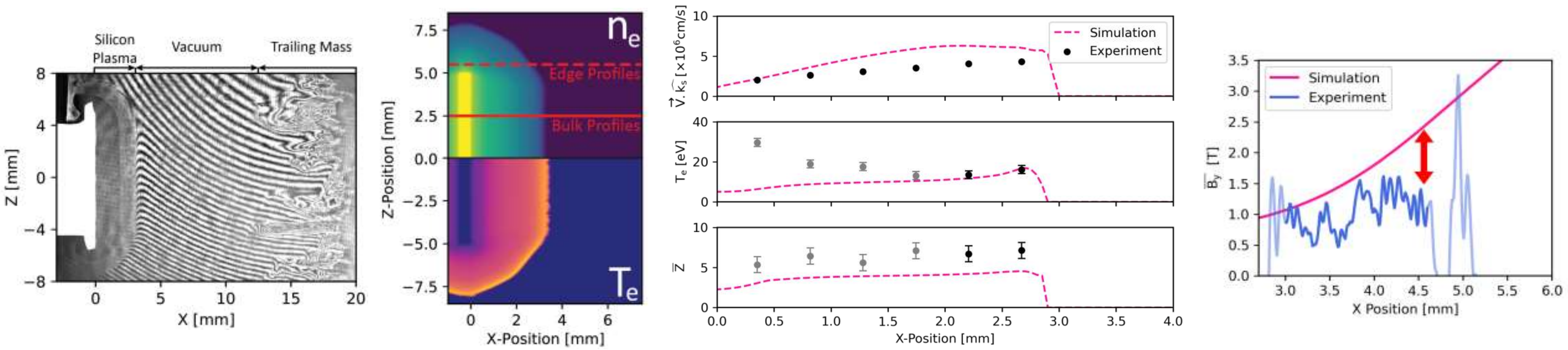

J. W. D. Halliday et al. Physics of Plasmas (2022):

Experimental morphology well reproduced by simulations

Probe heating perturbs temperature in Thomson scattering data

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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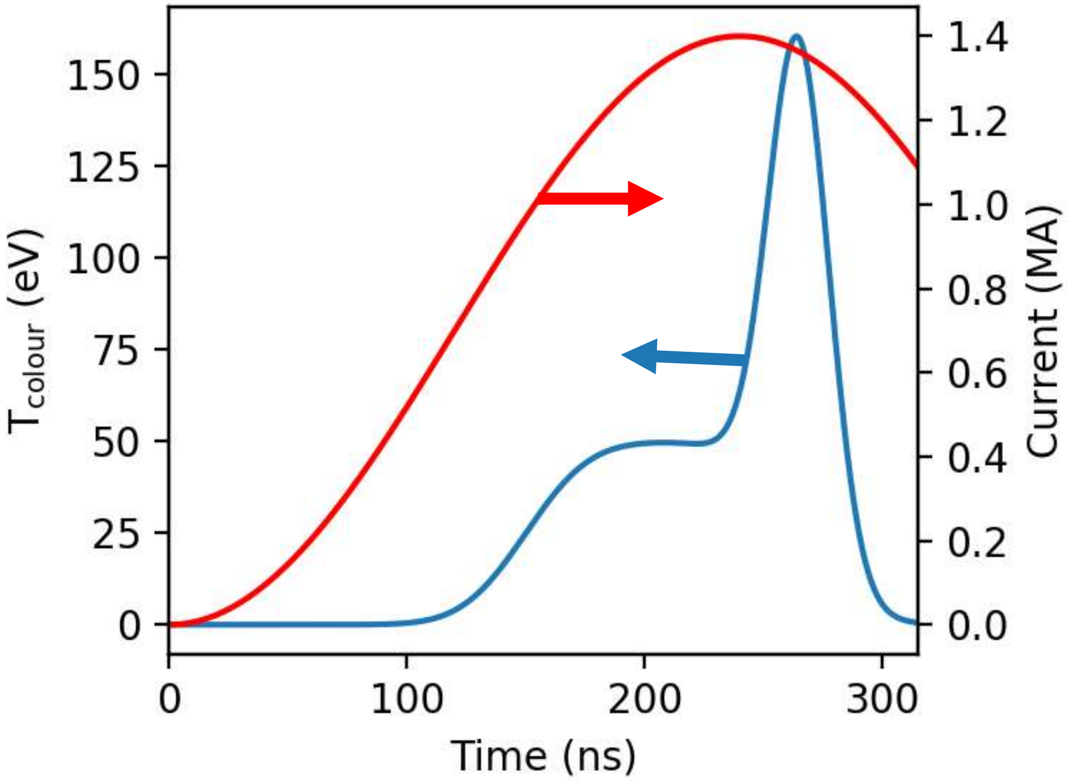
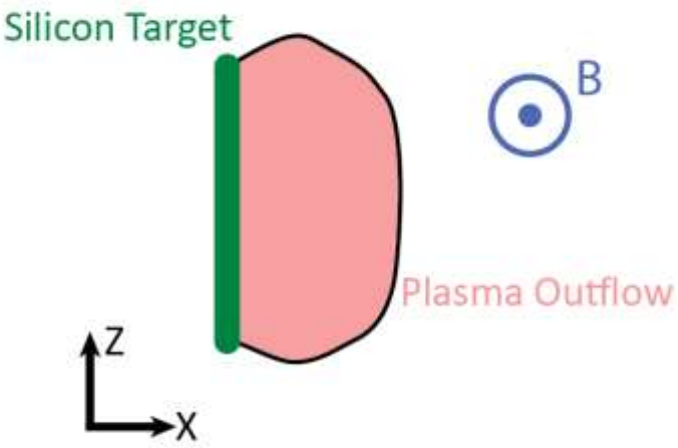
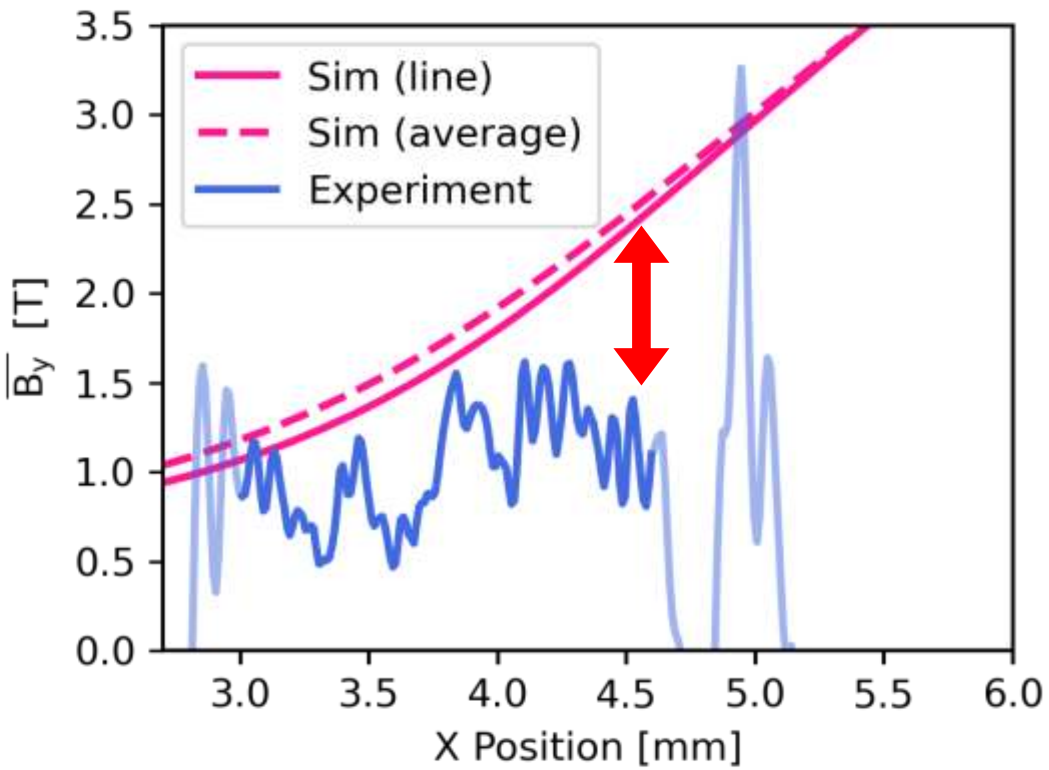


Faraday rotation imaging [weighted average of B_y]



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

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



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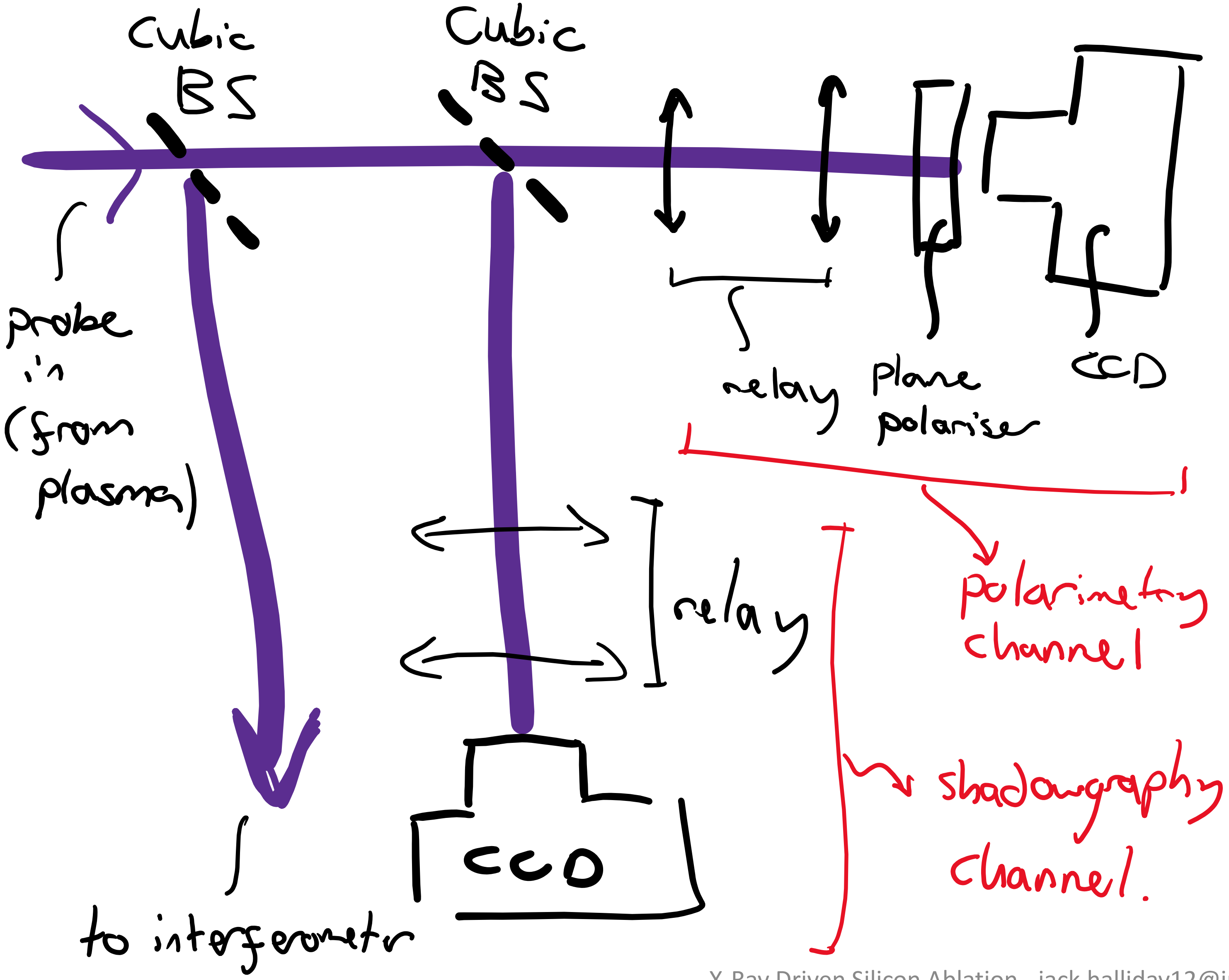


In the absence of shadowgraphy effects, during the experiment, the signal measured at position x, z in the shadowgram is given by

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

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

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

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

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

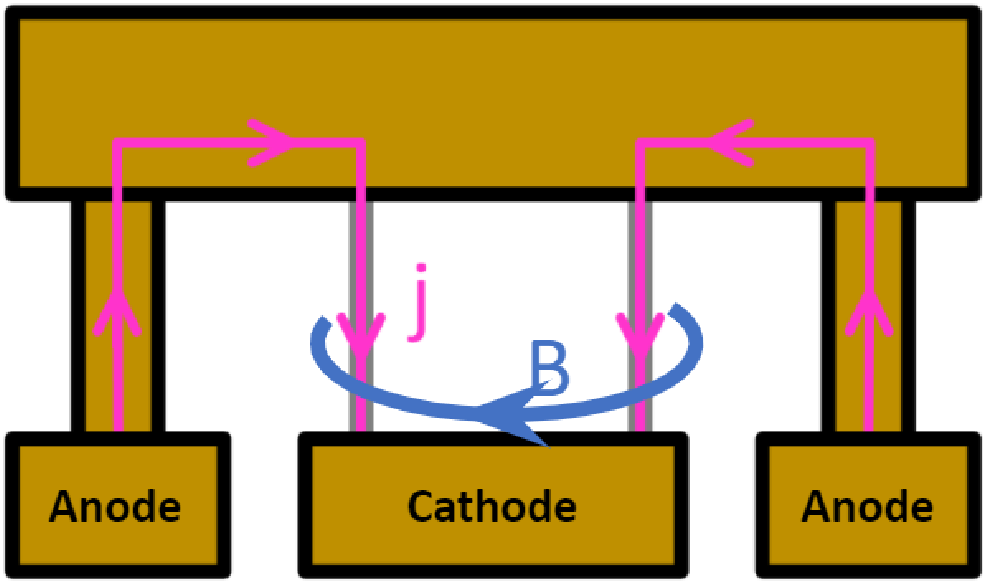
and the signal in the absence of plasma is

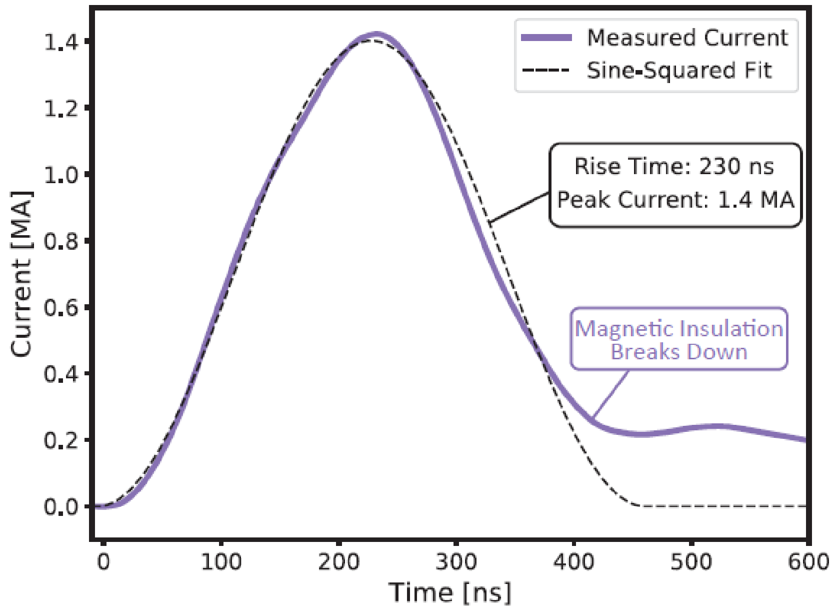
$$I_p^*(x,z) = R_p(x,z)\sin^2(\beta)I_0^*(x,z). \quad (8)$$

Combining these four equations, and solving for α, yields

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

Imploding Wire Array Z-Pinches





1.4 MA, 240 ns Current Pulse

X-Ray Pulse ~ 1 TW

Imploding Wire Array Z-Pinches

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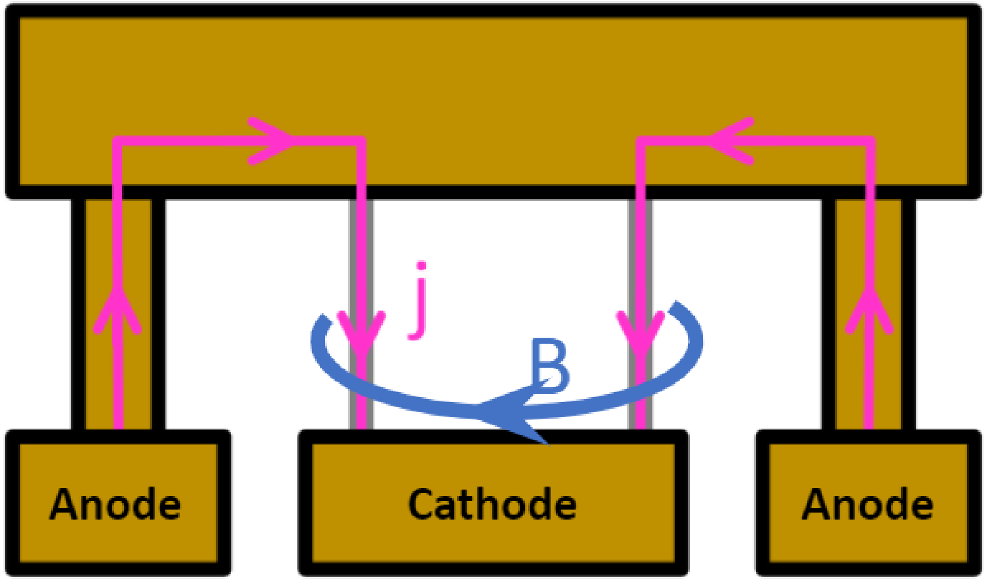
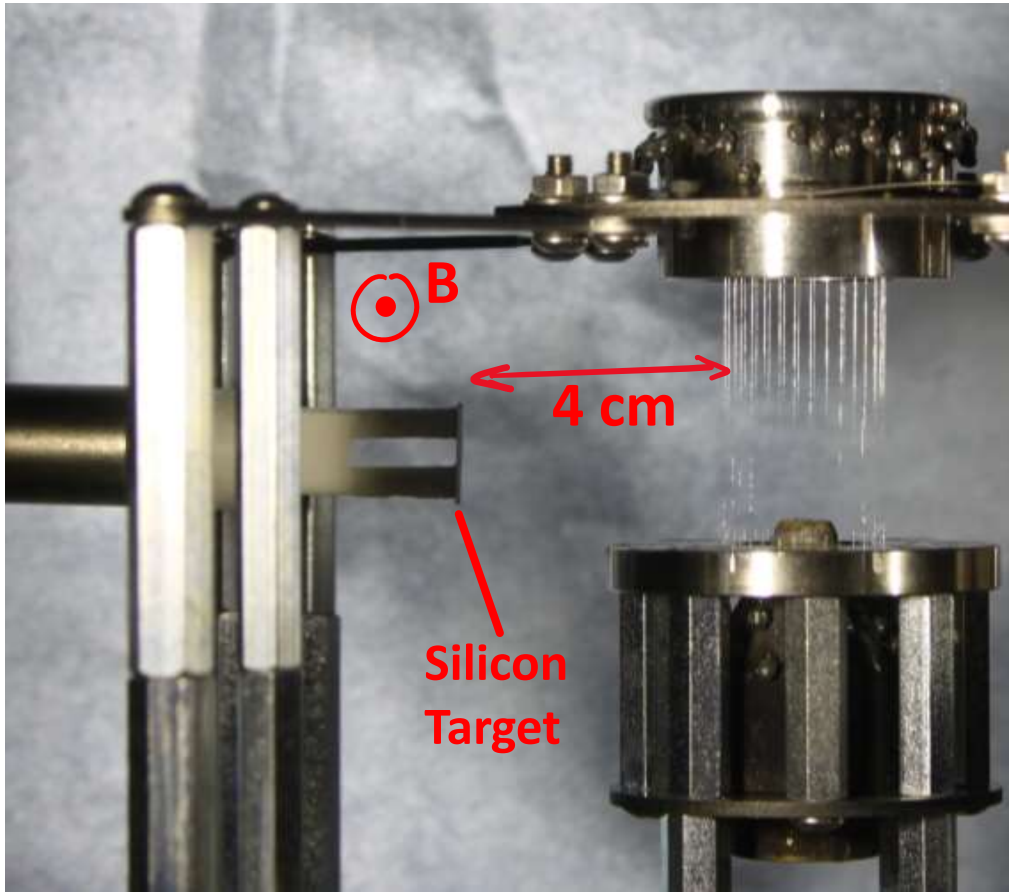
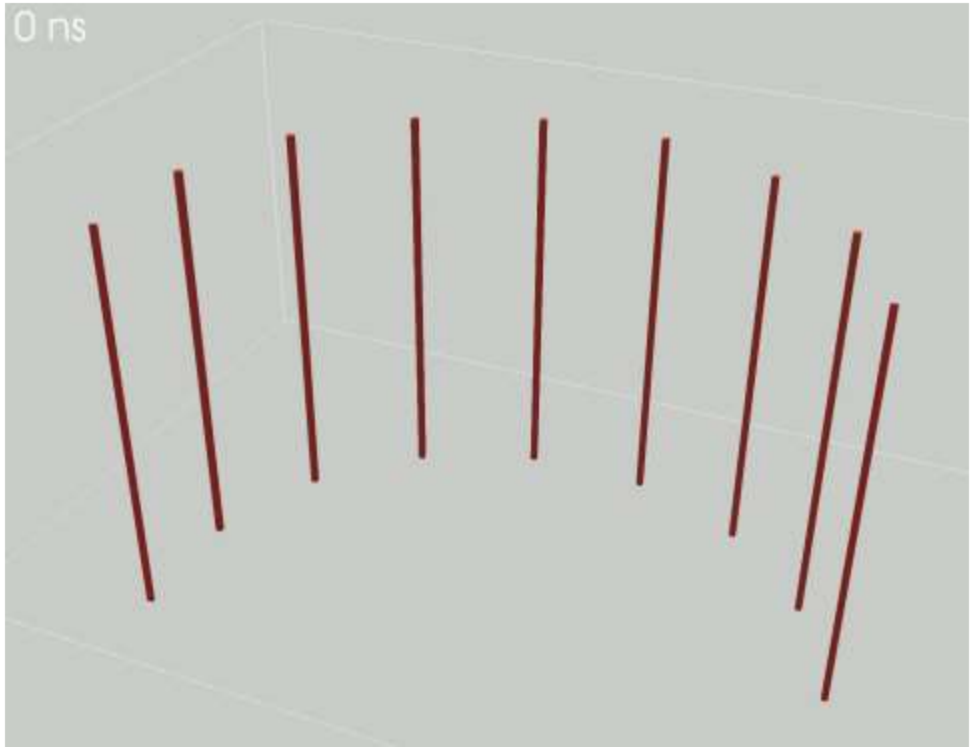
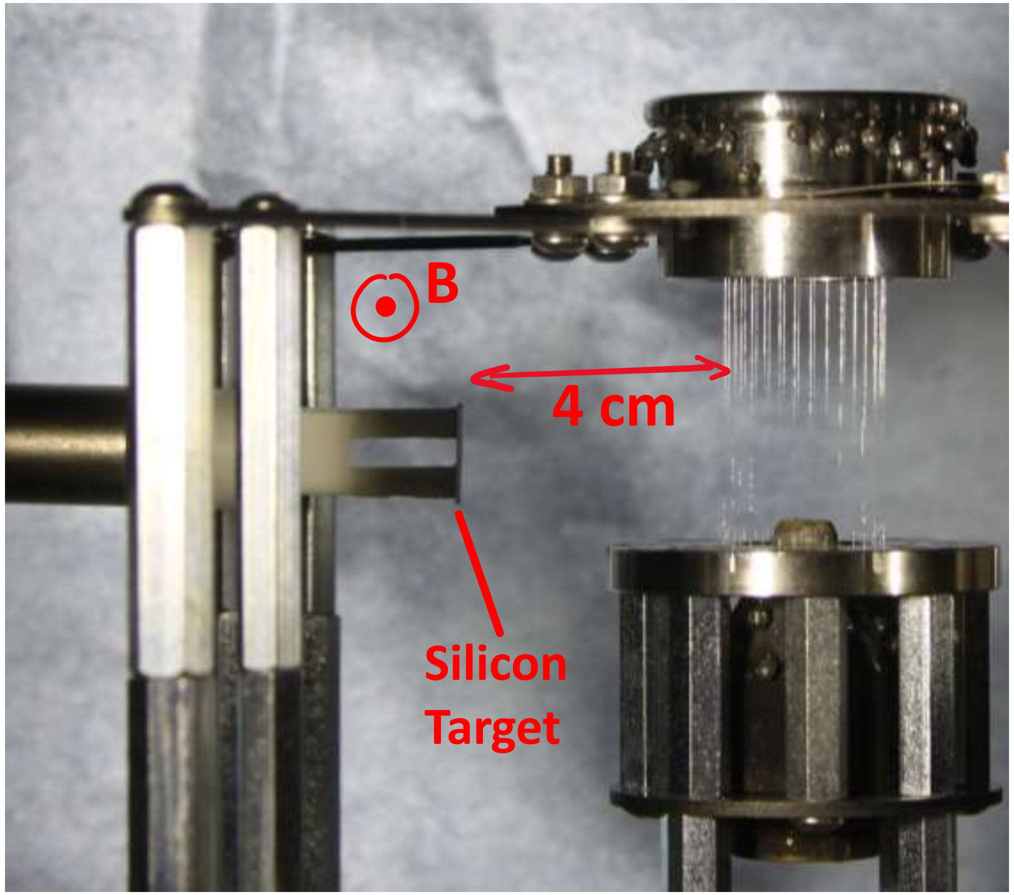




Wire array Z-pinch experiments on MAGPIE



Mass density from Gorgon (MHD) simulation



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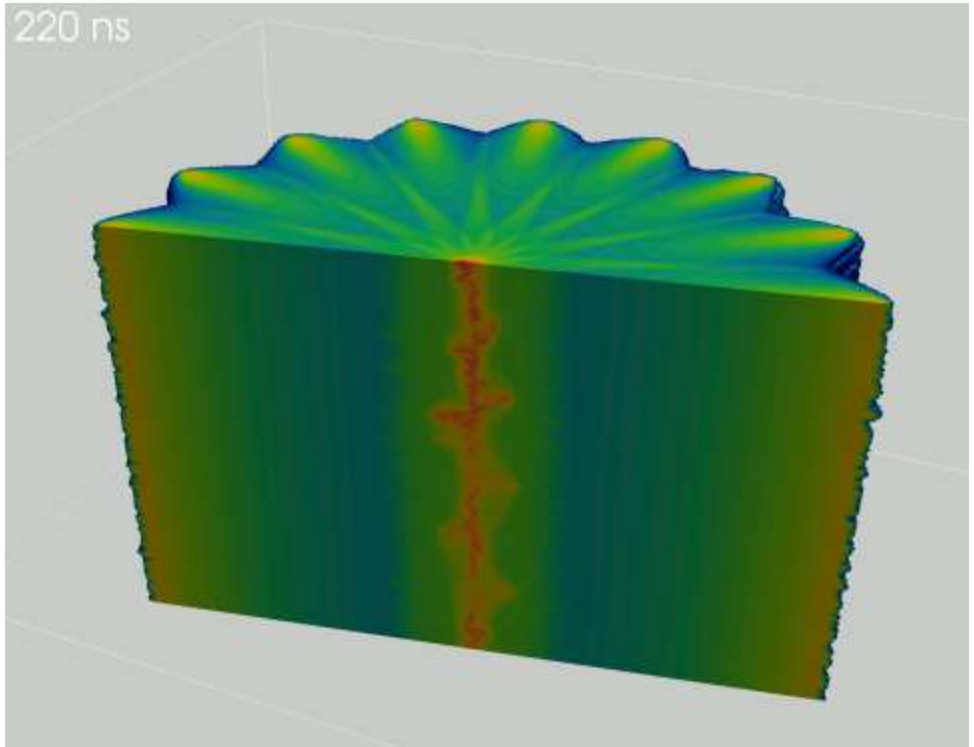

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