Radiatively driven plasma flows in experiments on the MAGPIE pulsed-power generator

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

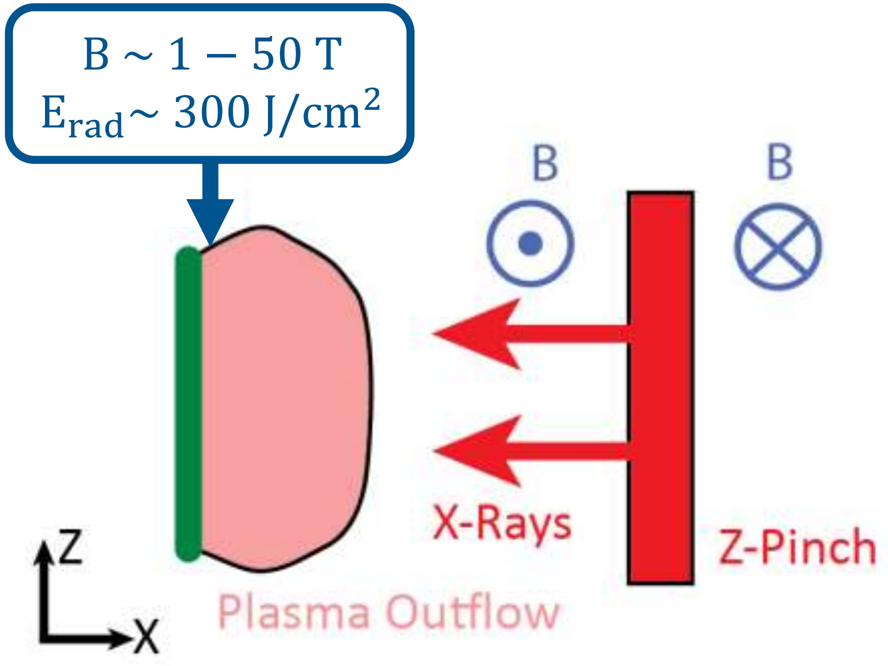
Imperial College (MAGPIE, Experimental): S. N. Bland, S. V. Lebedev, L. G. Suttle, D. R. Russell, V. Valenzuela Villaseca, S. Merlini

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

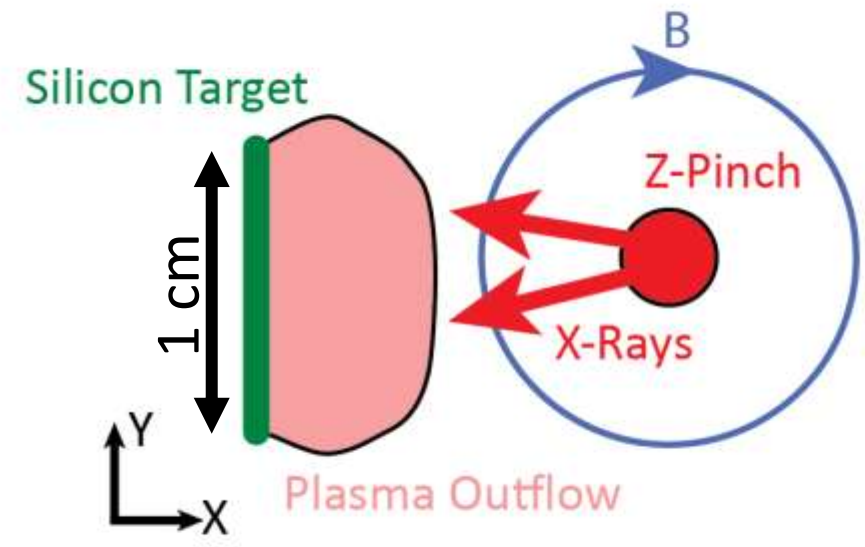
University of Nevada, Reno: R. C. Mancini

Imperial College London MAGPIE CIFS University of Nevada, Reno

Overview of experimental setup



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 magnetic field ($B \sim 10$ T)
- Target size ~ 1 cm^2, irradiated uniformly

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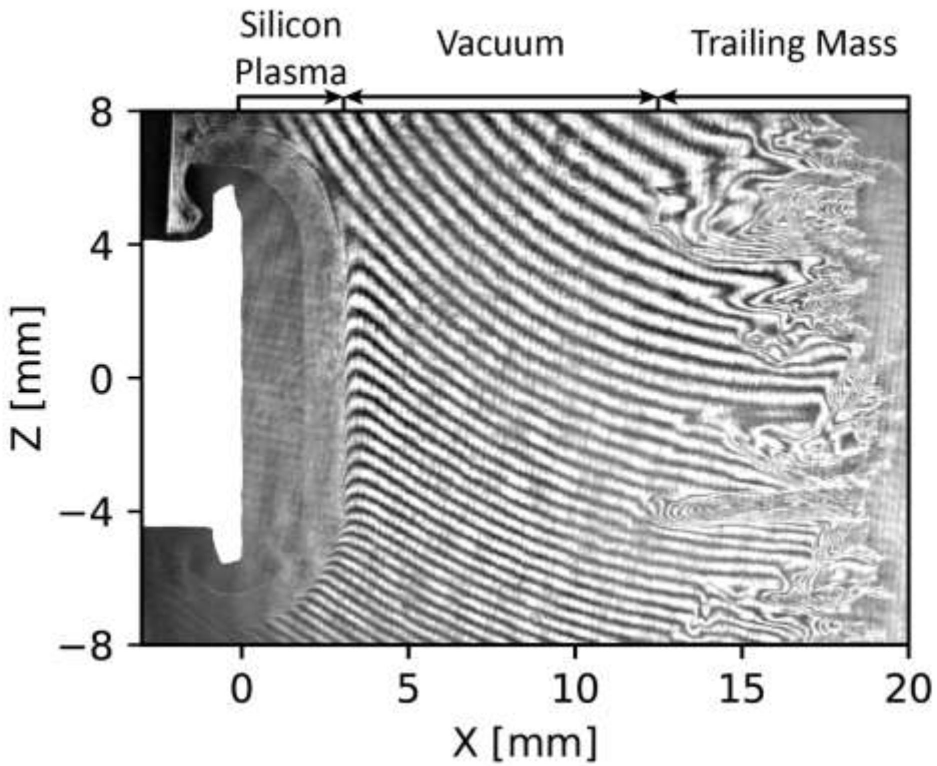

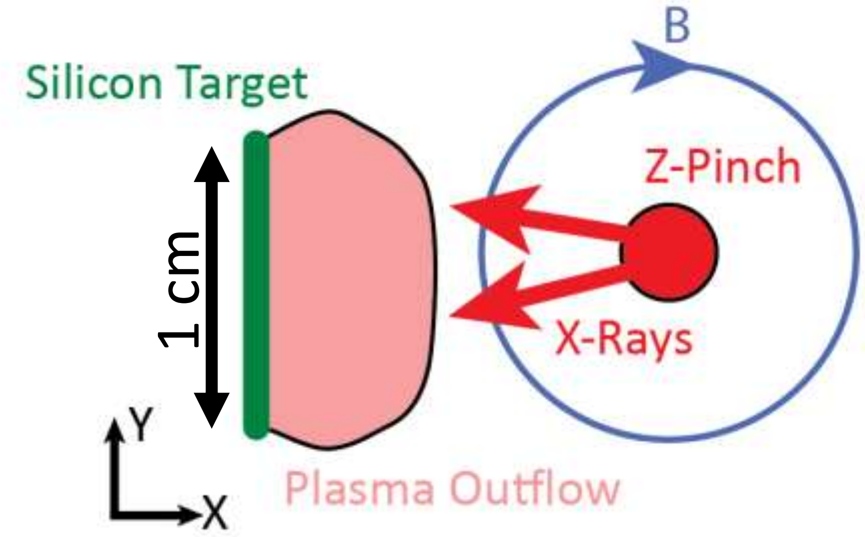

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Outline

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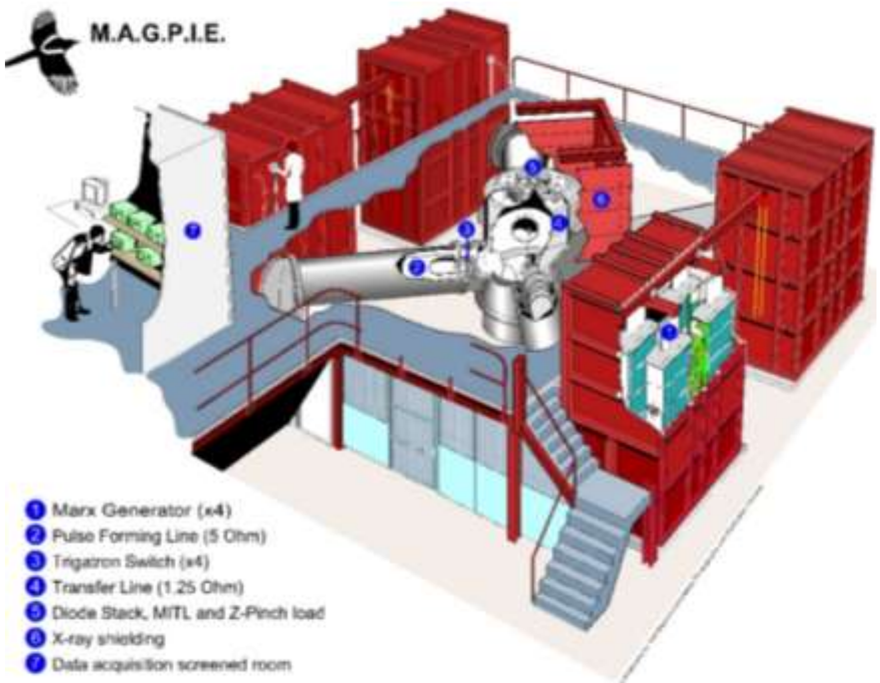
- Overview of the MAGPIE facility
- Wire array Z-pinches as X-Ray sources
- X-Ray ablated plasma:
  - Data from imaging diagnostics
  - Local V, T, Z profiles from TS

  } Compare with R-MHD simulations (Chimera)
- Measurement of magnetic flux penetration
- Future work and conclusions

Experimental facility and diagnostics

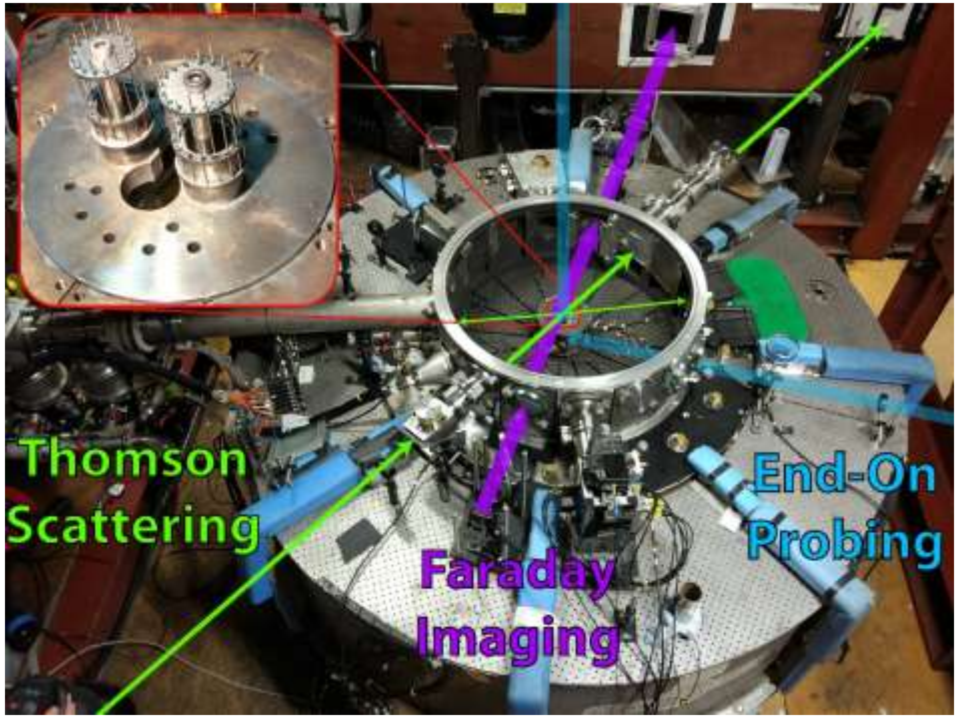
1.4MA, 1TW, 250kJ



$\sim$ 30 kJ delivered to a load

Plasma scales: $\begin{cases} L \sim 10 \text{ mm} \\ \tau \sim 400 \text{ ns} \end{cases}$

Load region



$\langle B_y \rangle$	Faraday rotation
$\overrightarrow{V_{fl}}$, $\overrightarrow{V_d}$, ZT_e, T_i	Thomson scattering
$n_e L$	Imaging interferometry

Slide credit: S. V. Lebedev

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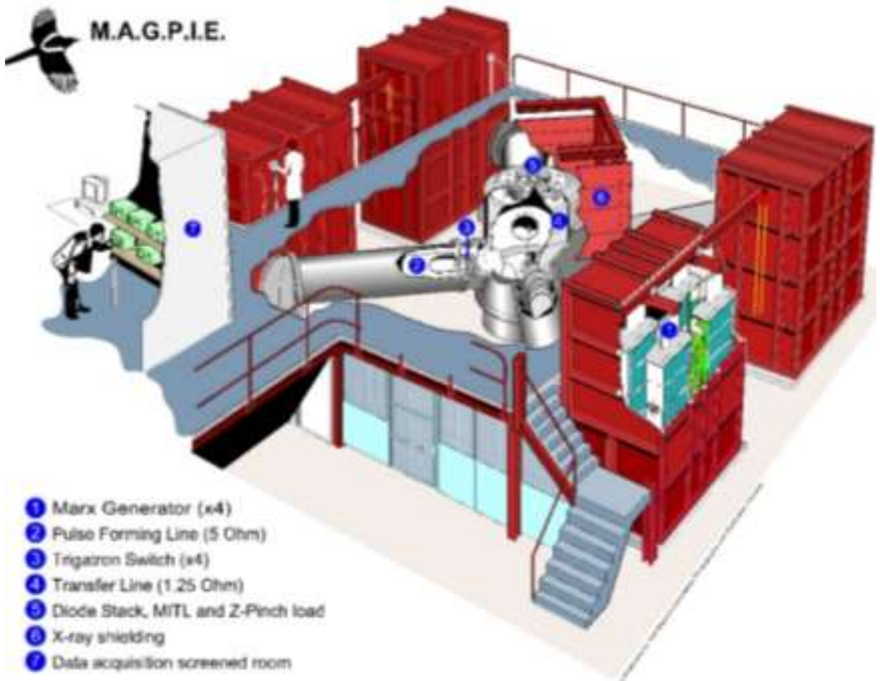

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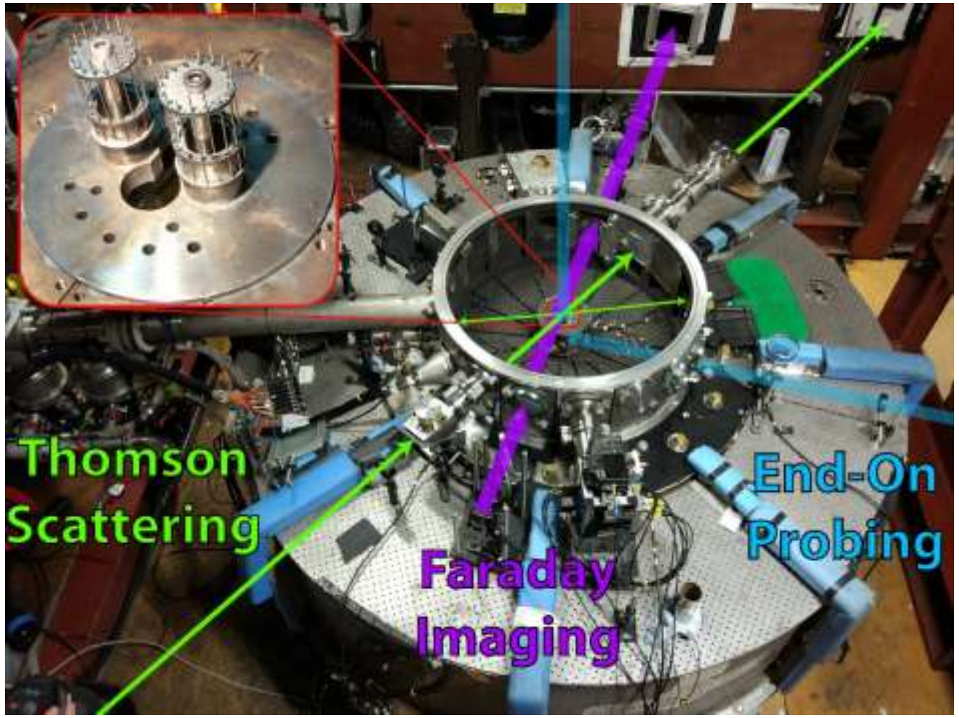

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An overview of other recent MAGPIE experiments

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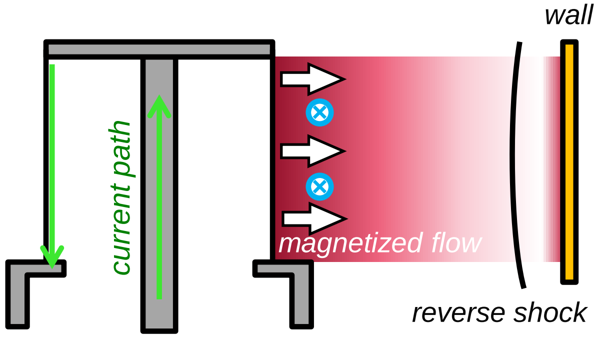
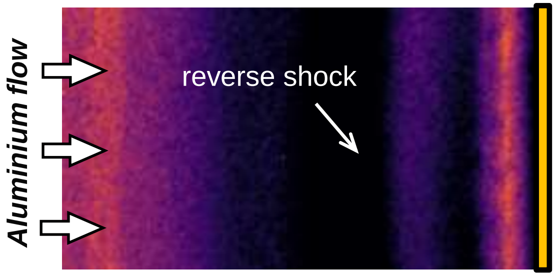
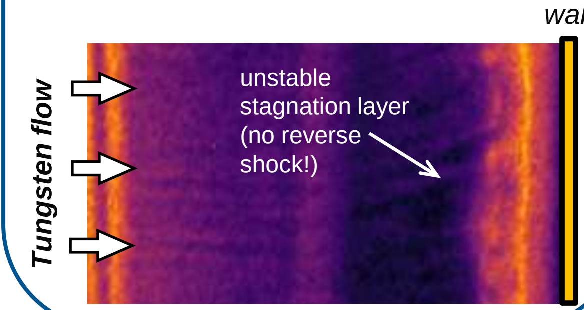
Instabilities in magnetized shock experiments

S. Merlini

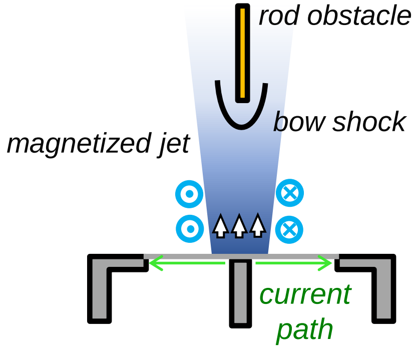


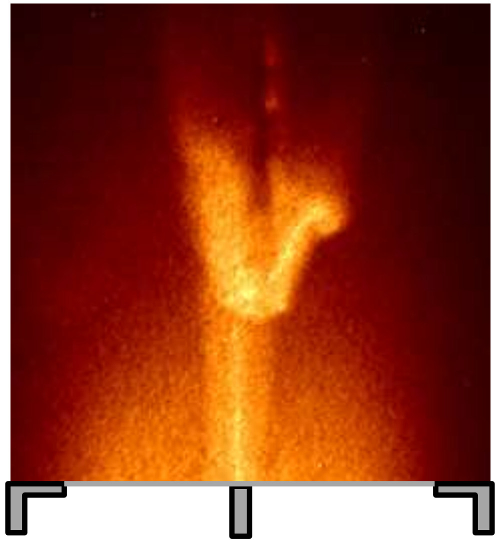




Shocks in magnetic tower jet experiments

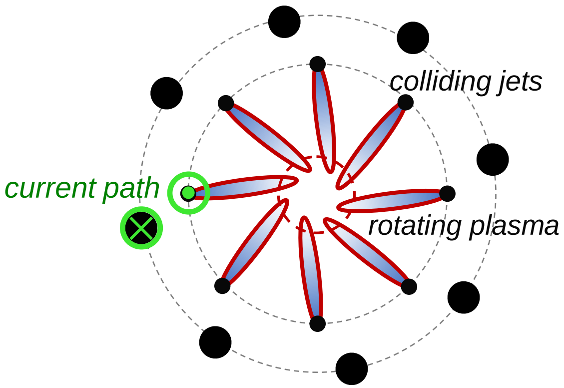
D. Russell / F. Suzuki Vidal

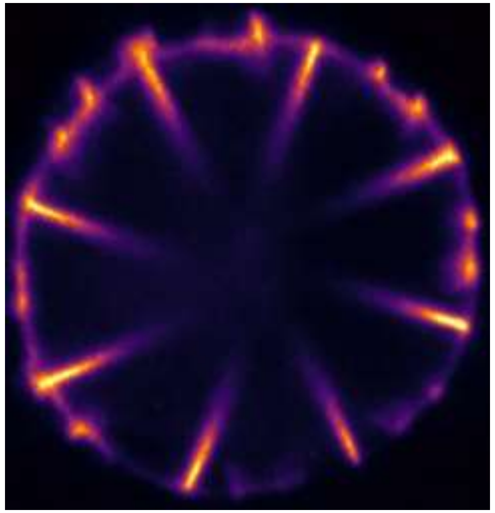




Differentially rotating plasmas

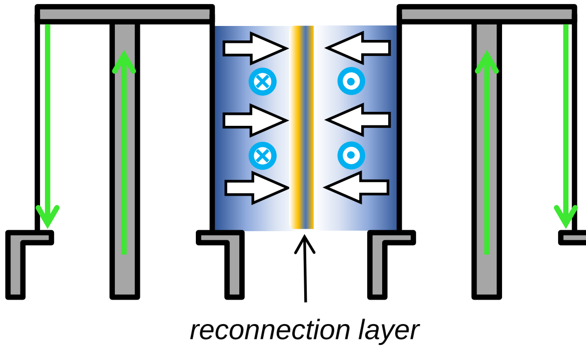
V. Valenzuela-Villaseca

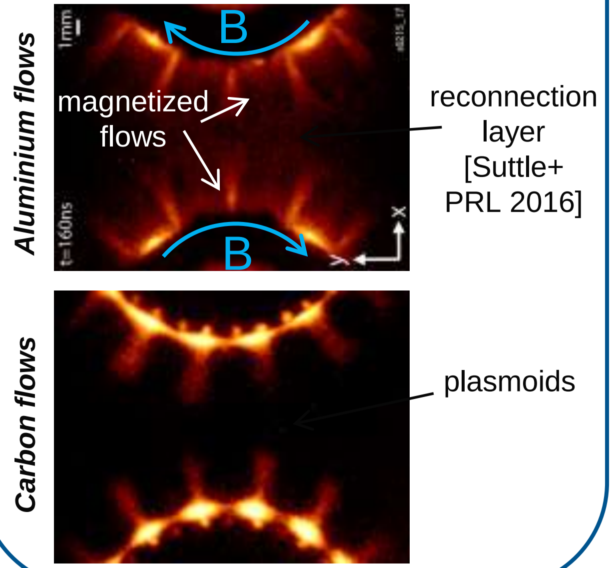




Magnetic reconnection experiments

L. Suttle / J. Hare





Slide credit: V. Valenzuela-Villaseca

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Wire-Array Z-pinches are versatile X-ray drivers

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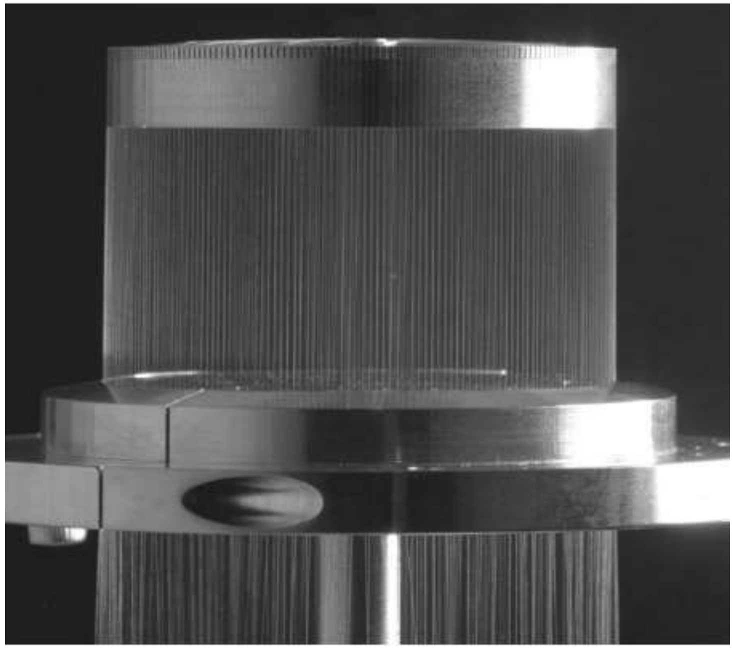


Photograph of a tungsten wire array, fielded on the Z-Machine (SNL)

Credit: Spielman et al. PoP 1998

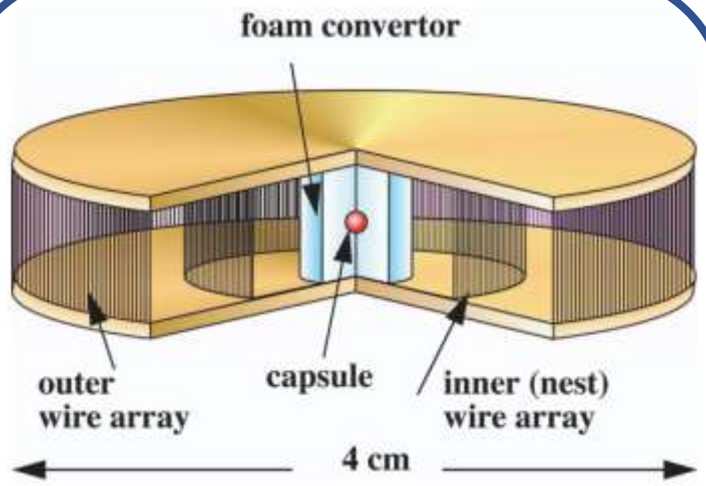
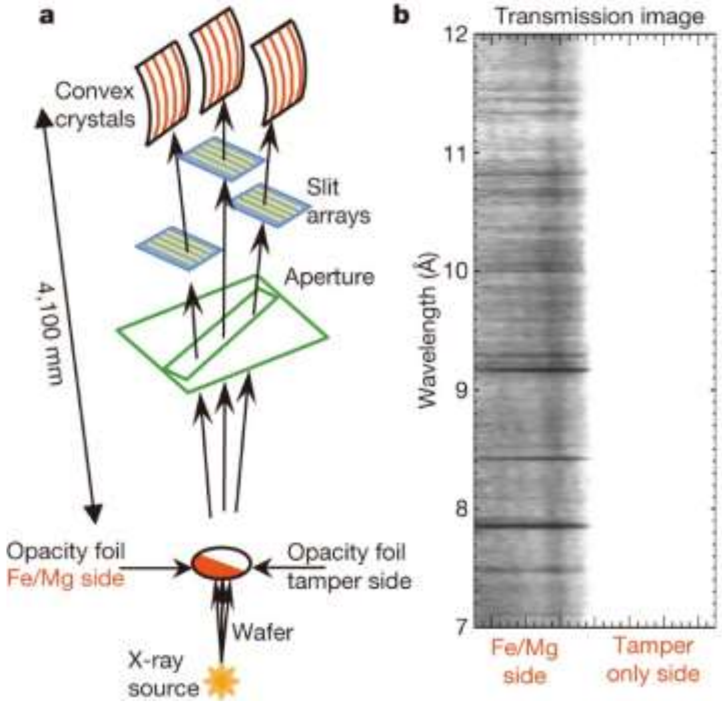


Diagram of a dynamic hohlraum ICF experiment

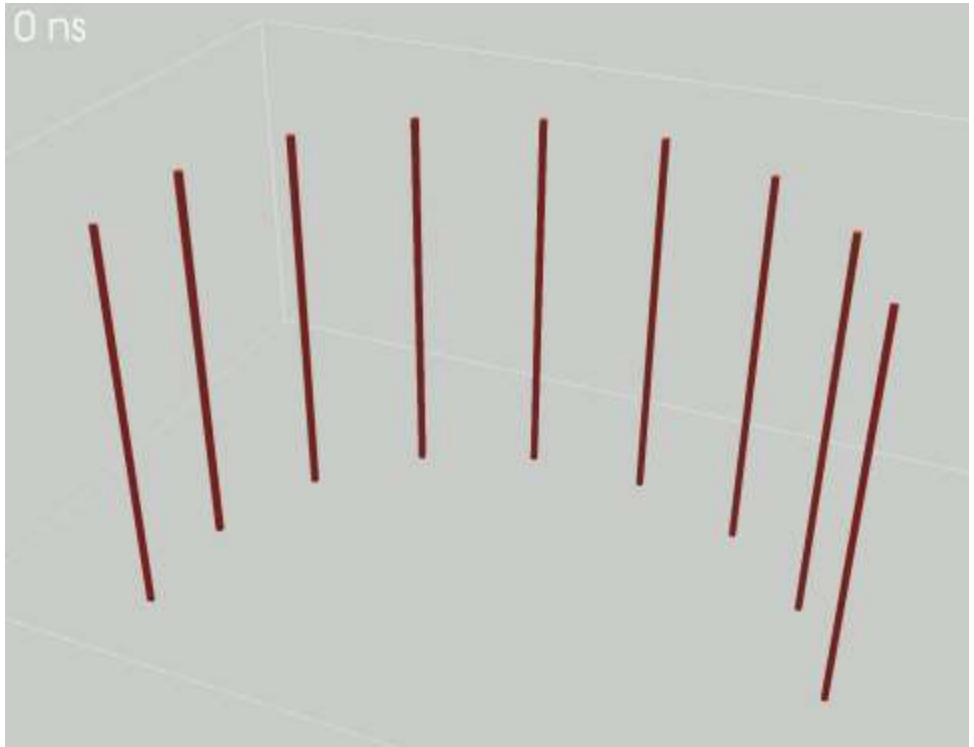
Credit: Slutz et al. PoP 2006



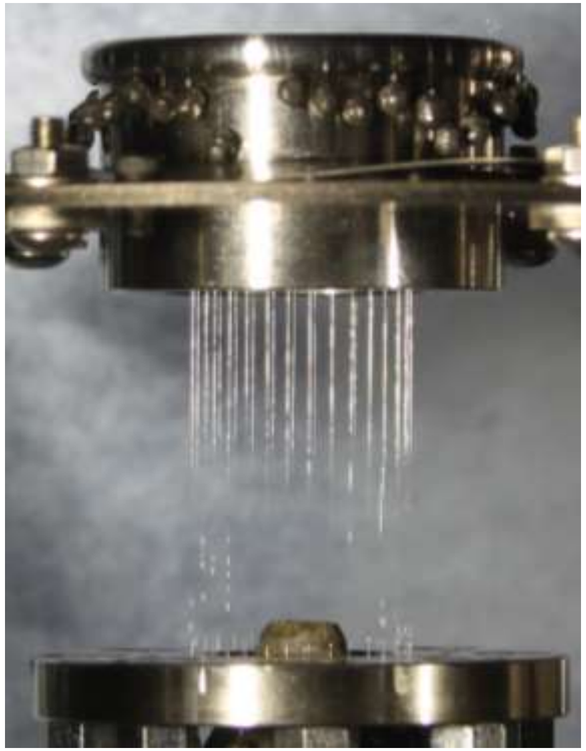
Experimental schematic of an iron opacity experiment

Credit: Bailey et al. Nature 2015

Wire array Z-pinch experiments on MAGPIE



Mass density from Gorgon (MHD) simulation



A 32-wire aluminium array used in MAGPIE experiments

Spectral Character of Radiation at ~1 MA Level

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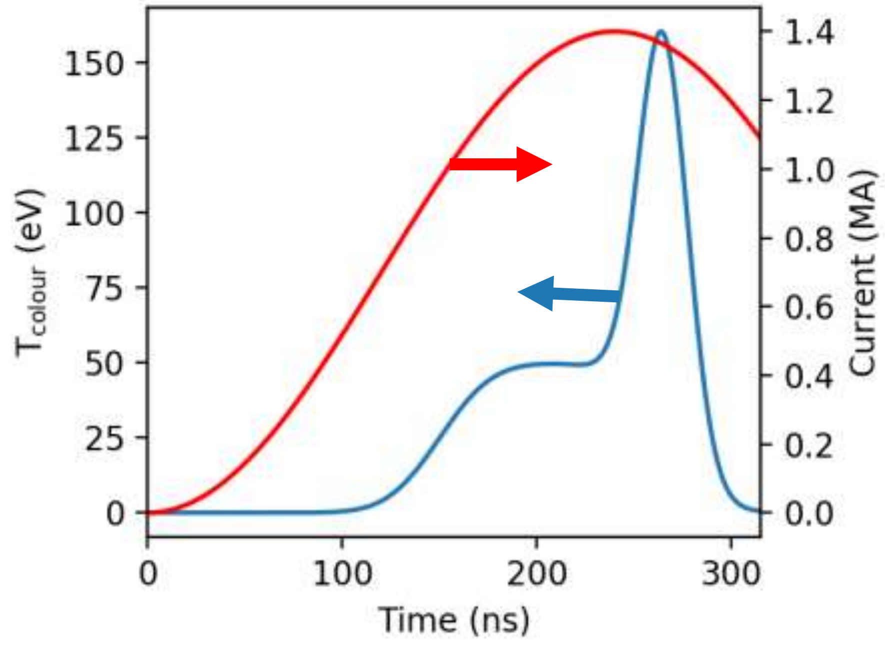
- **Precursor:**
  - Longer pulse
  - Colder spectral character ($T_c \sim 30$ eV)
  - Radiates ~ 400 J in total
- **Implosion:**
  - Emitted radiation ~ 15 kJ over ~ 30 ns
  - Non-thermal: forest of L shell lines
  - Some K-Shell radiation also
  - Estimate $T_c \sim 150$ eV



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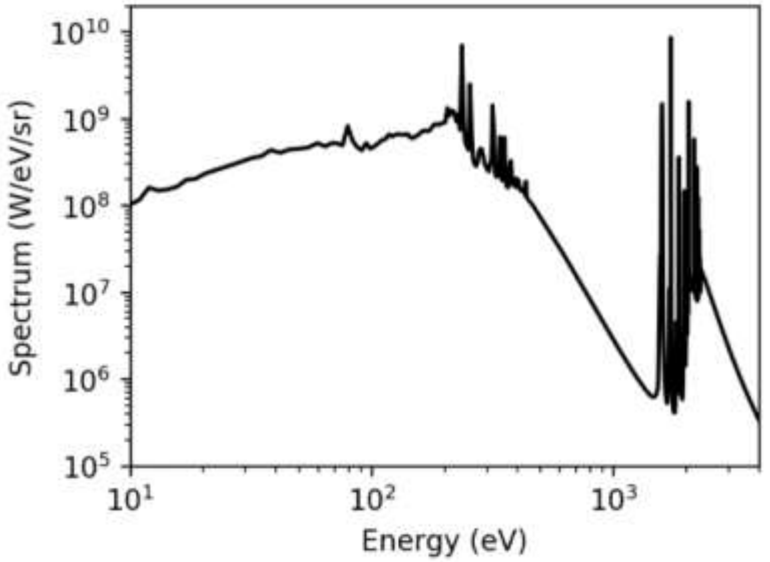

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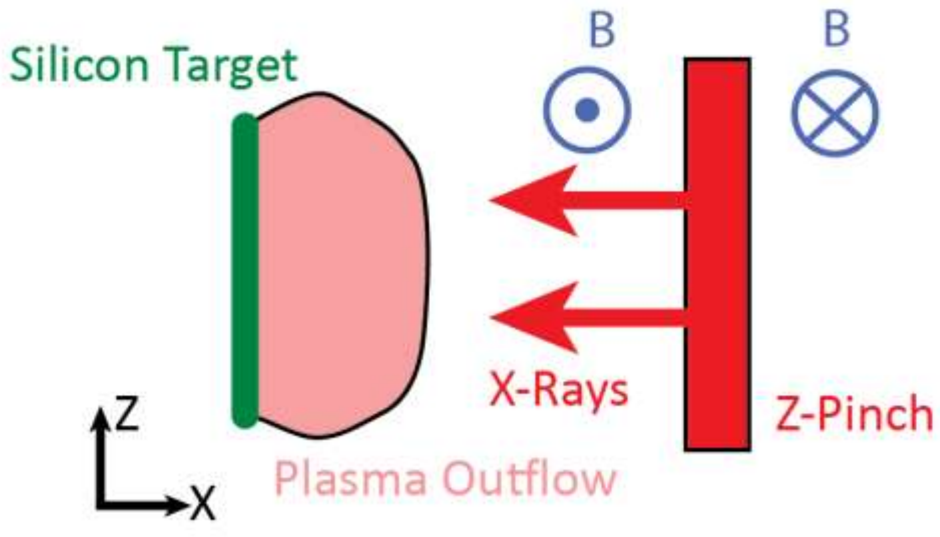

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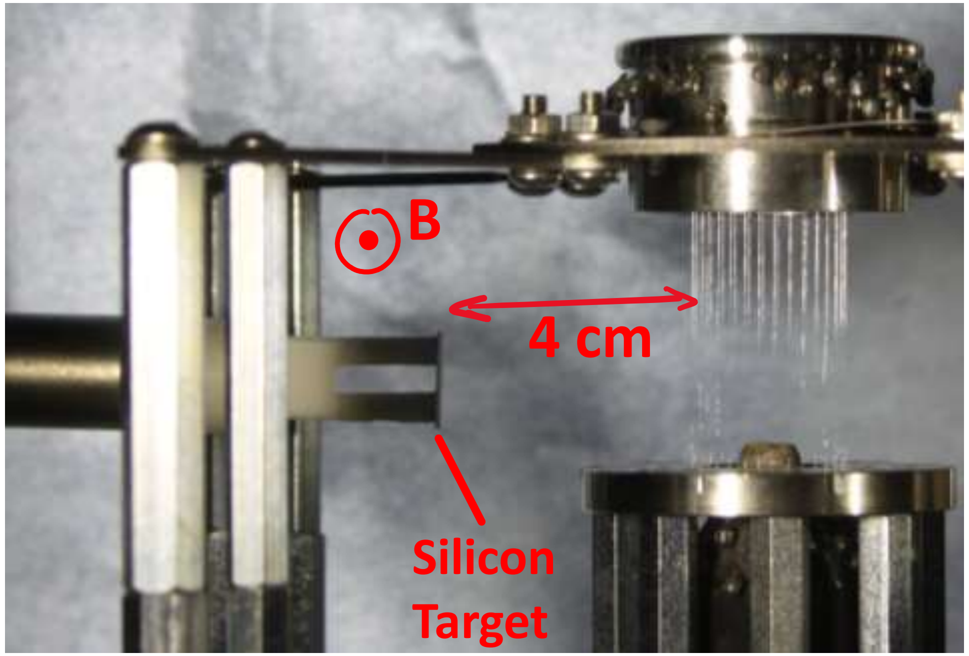

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Optical self emission images [qualitive dynamics]

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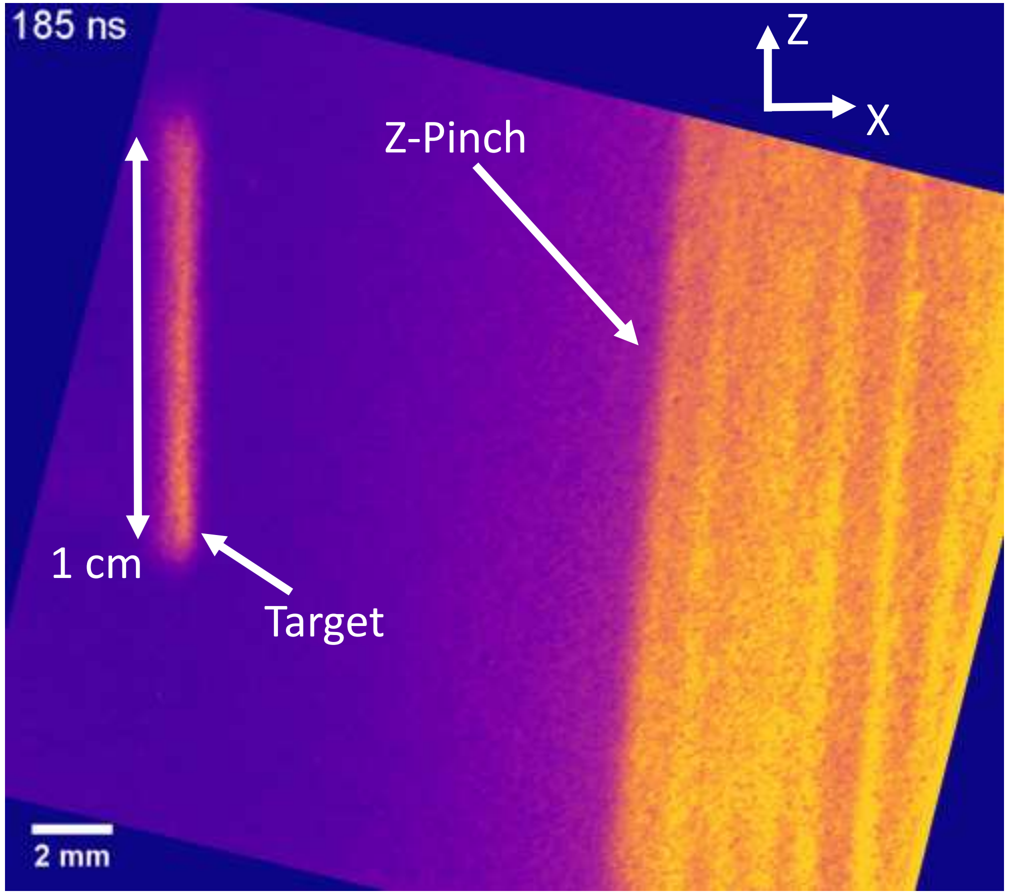
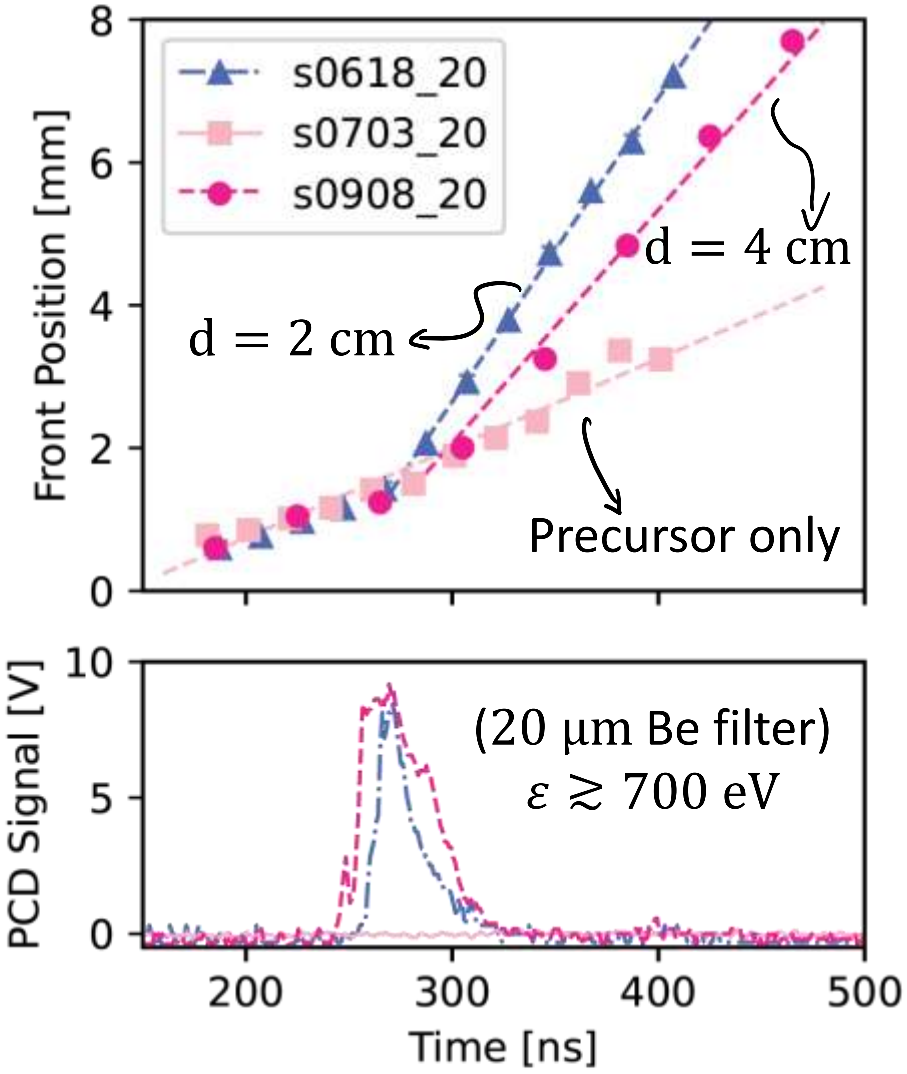


Self emission images [$600 \lesssim \lambda \lesssim 900$ nm]



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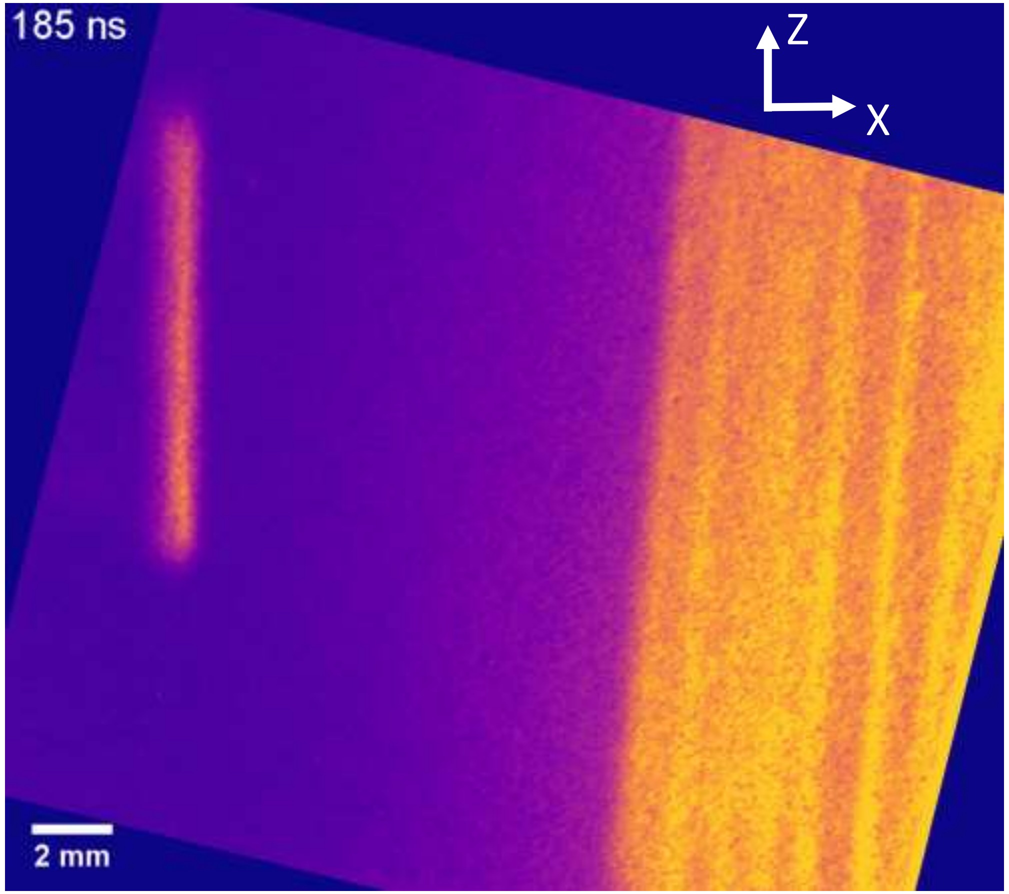

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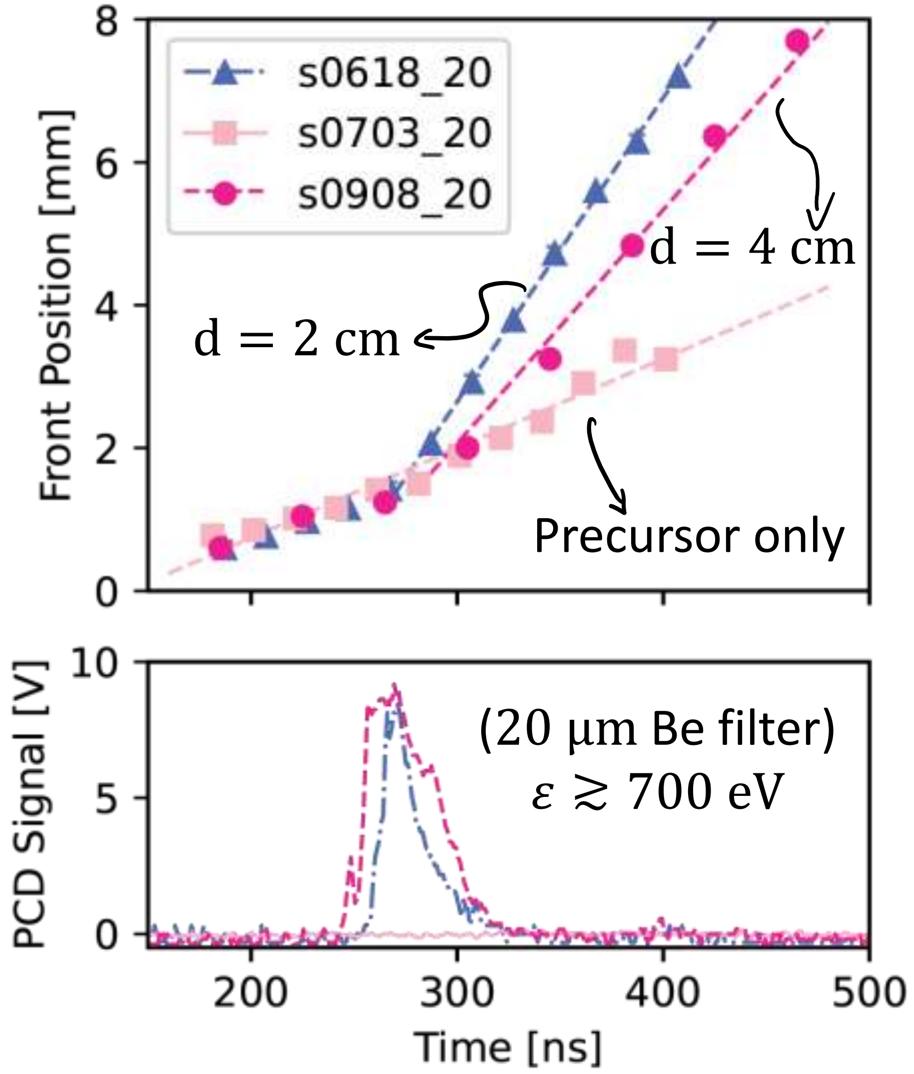

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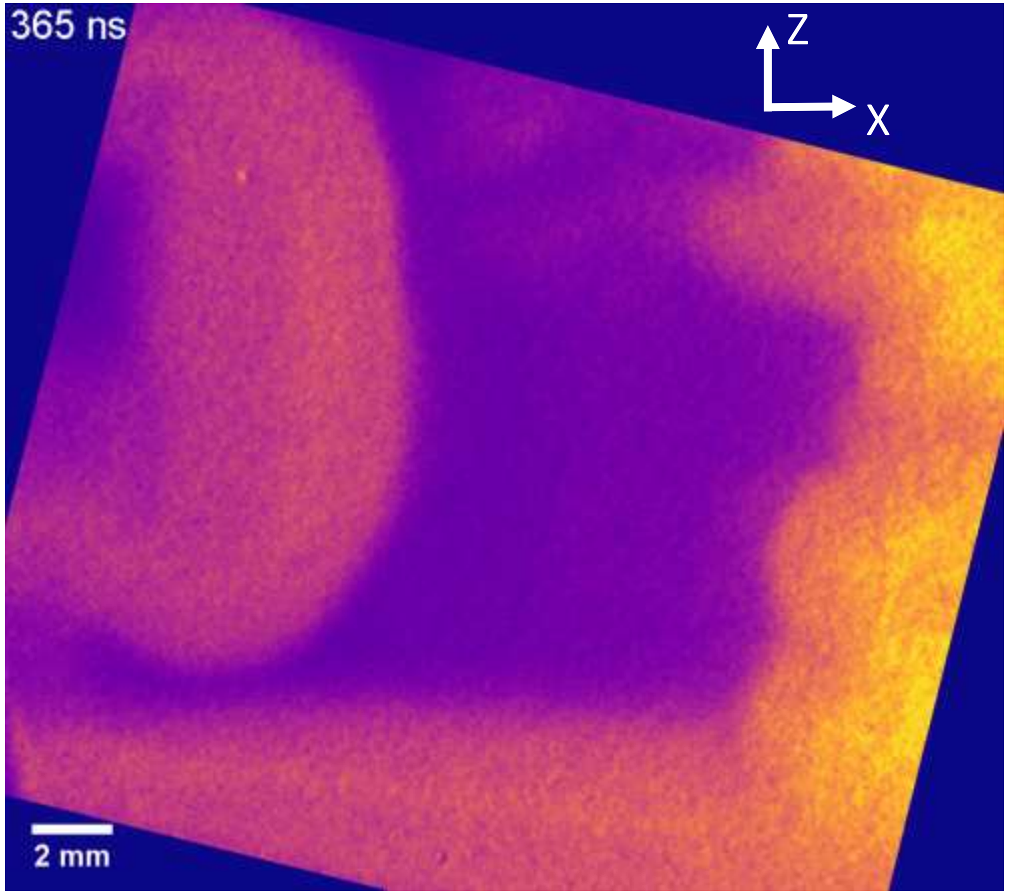

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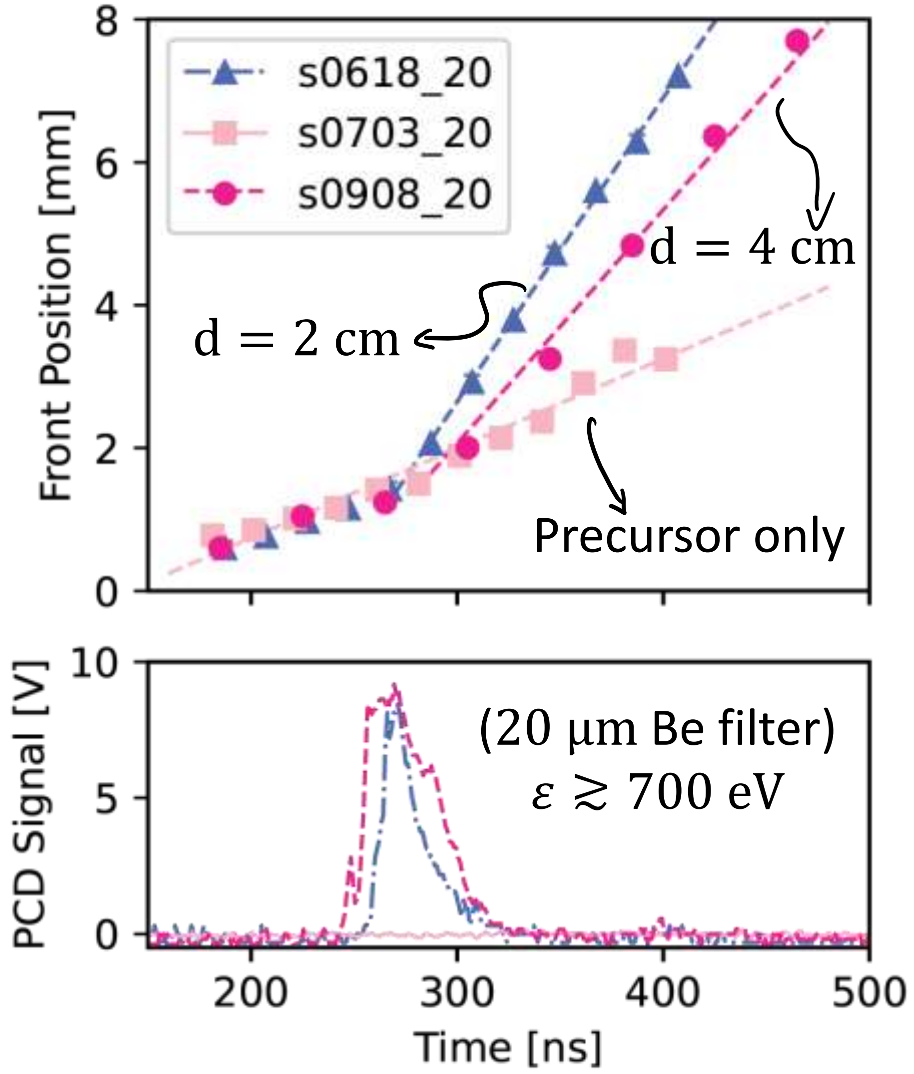
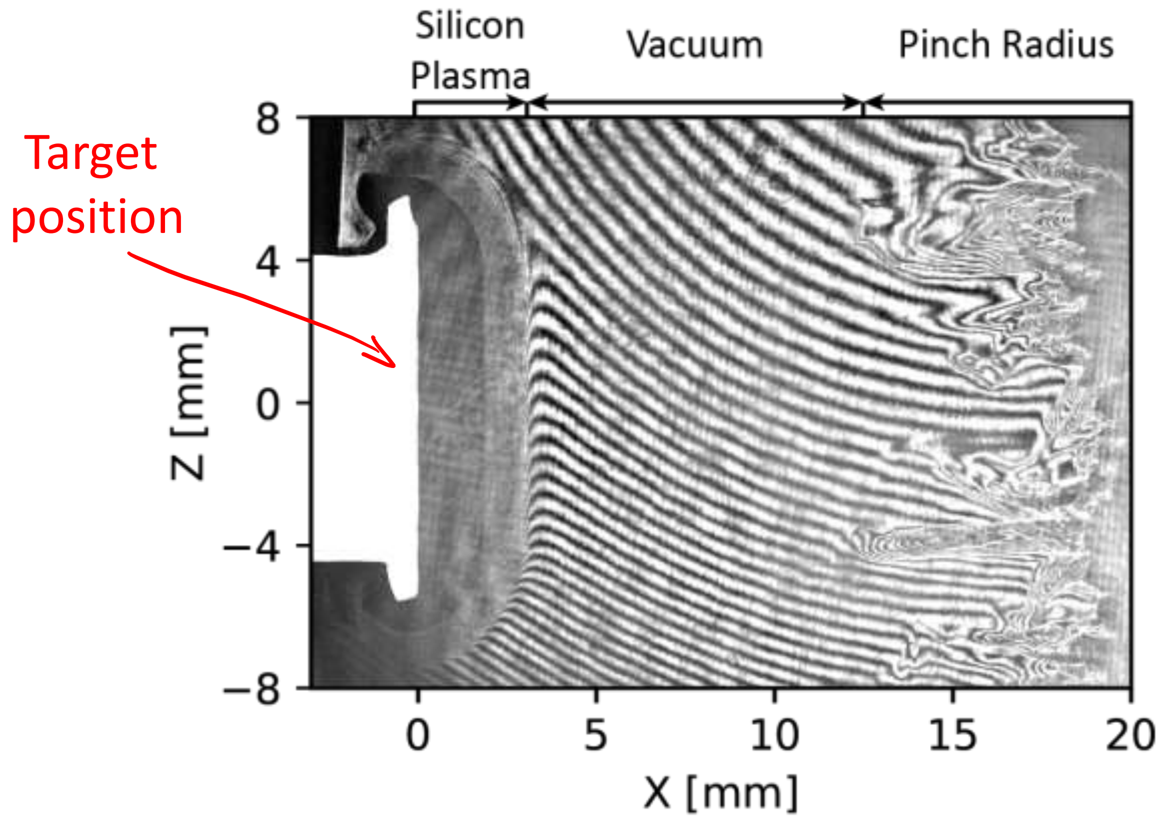
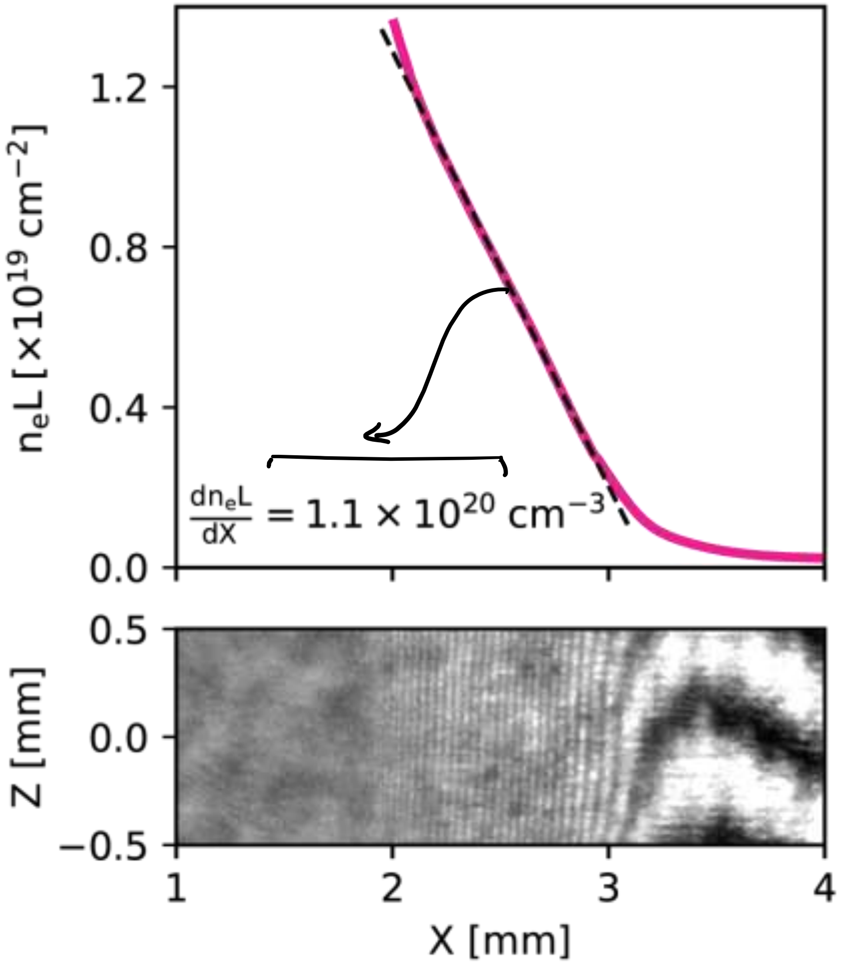


Interferometry [line integrated electron density]





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

Radiative MHD simulations [Chimera]

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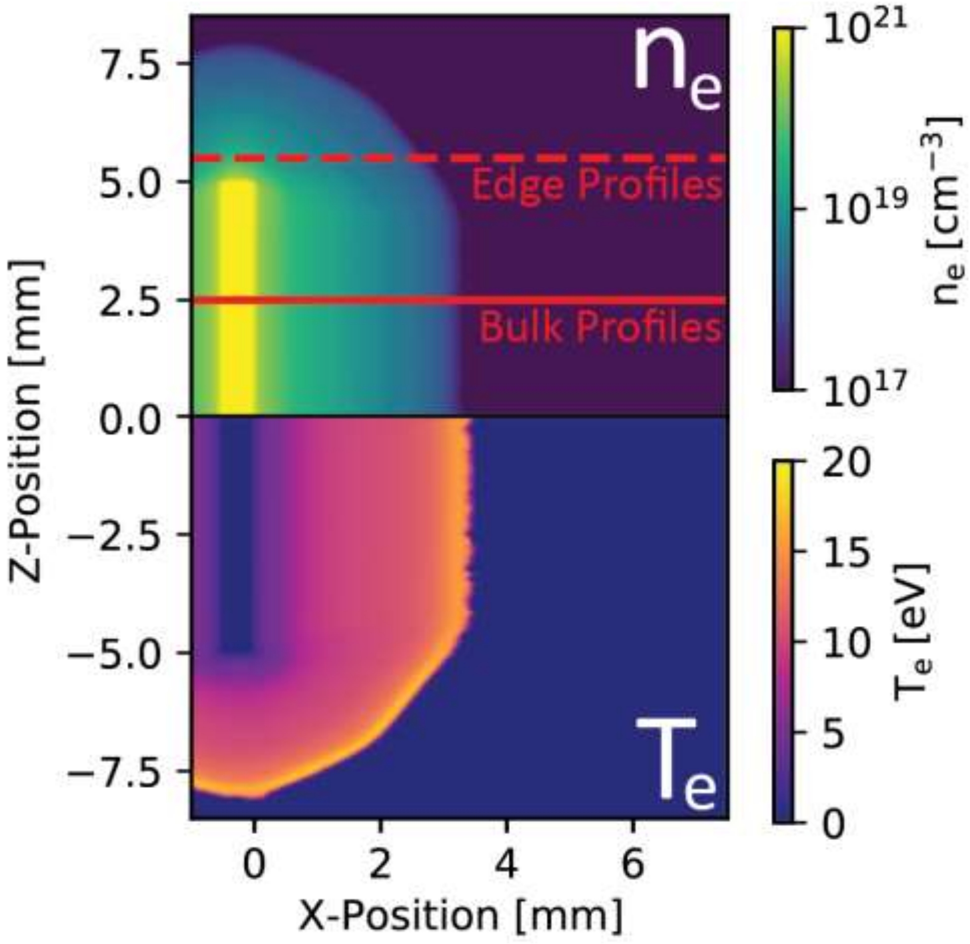
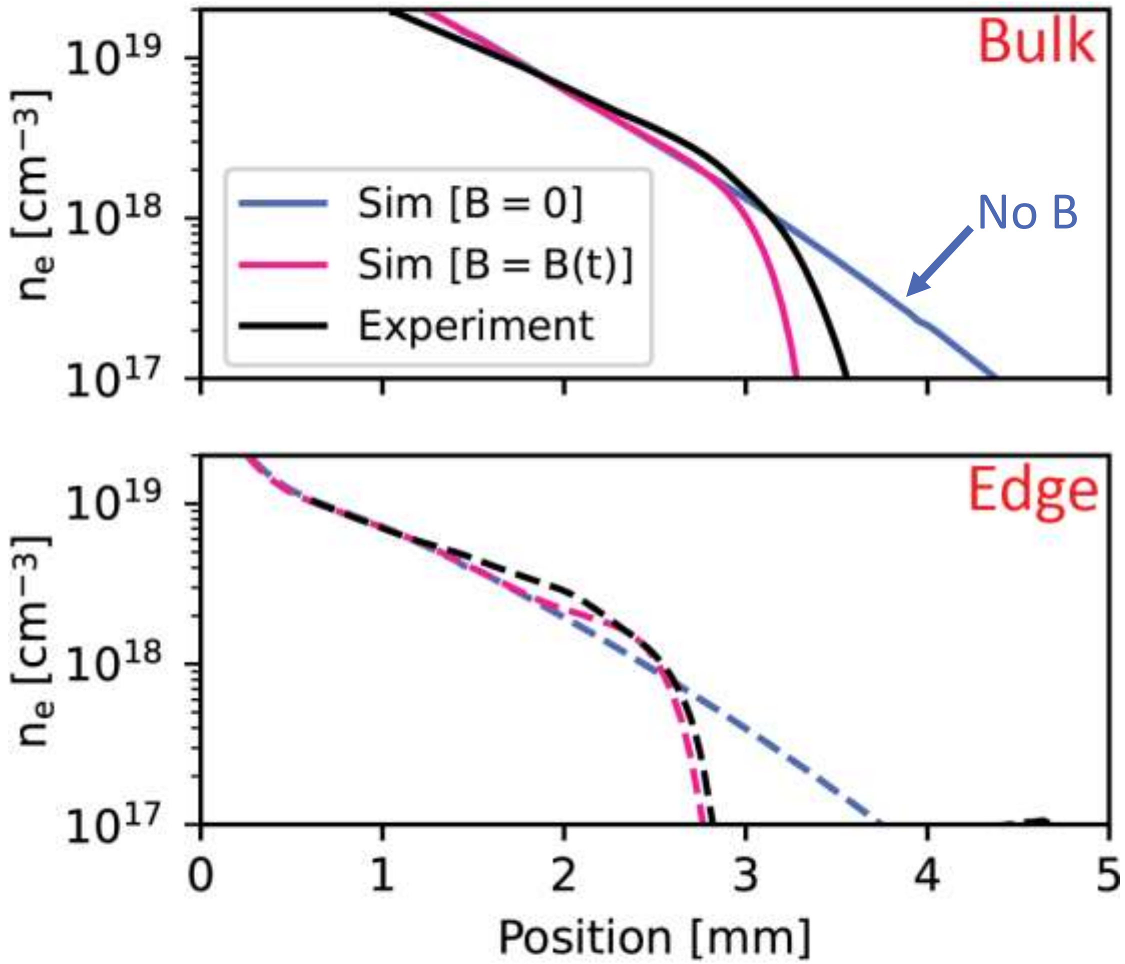
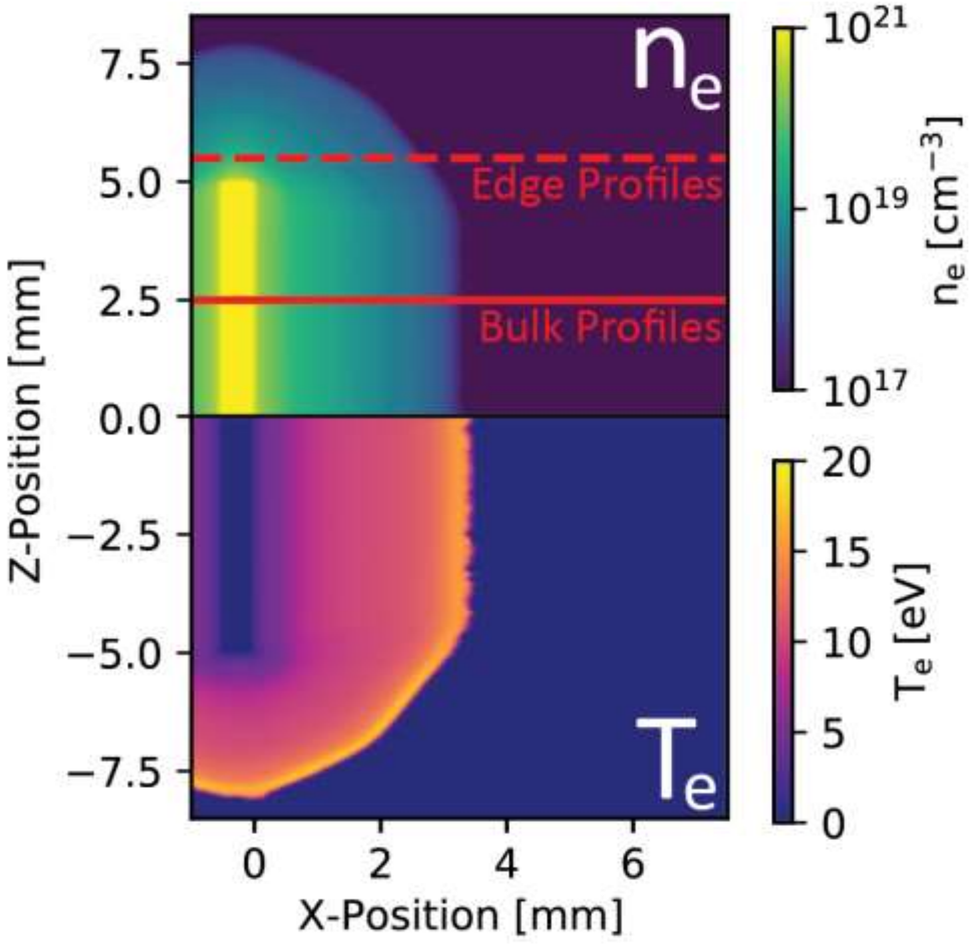
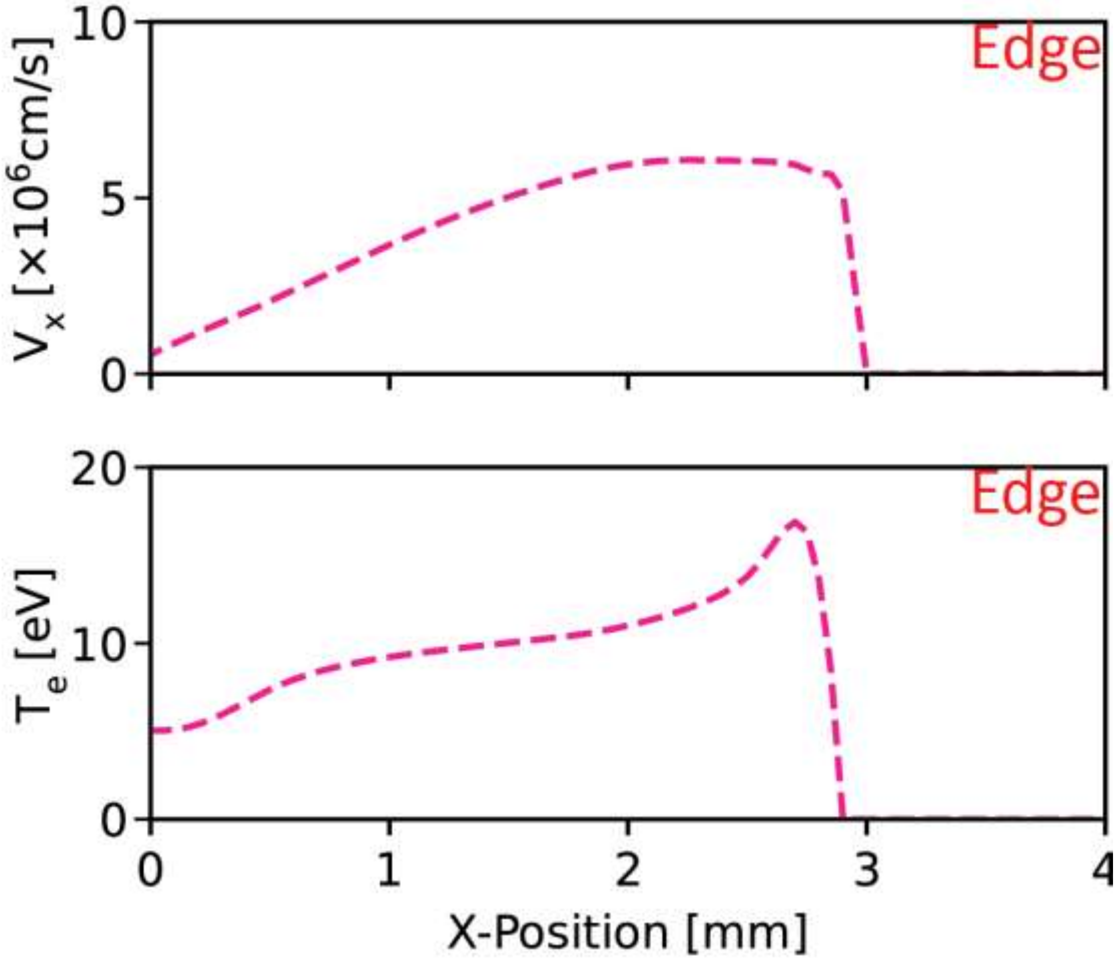




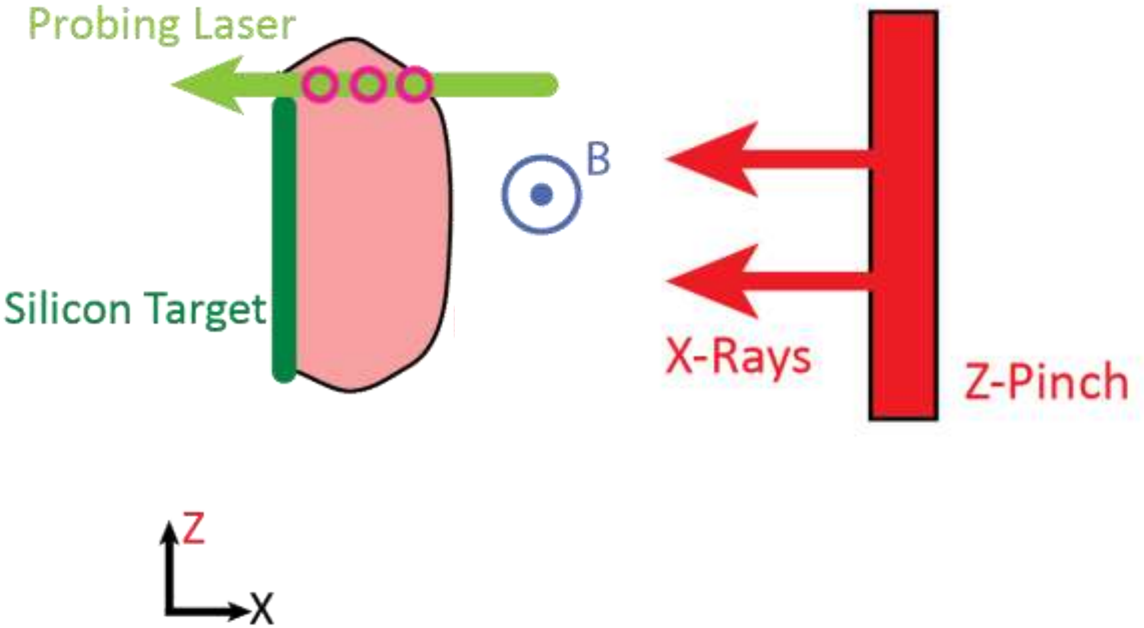
Density profile is affected by B-Field.

Radiative MHD simulations [Chimera]





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



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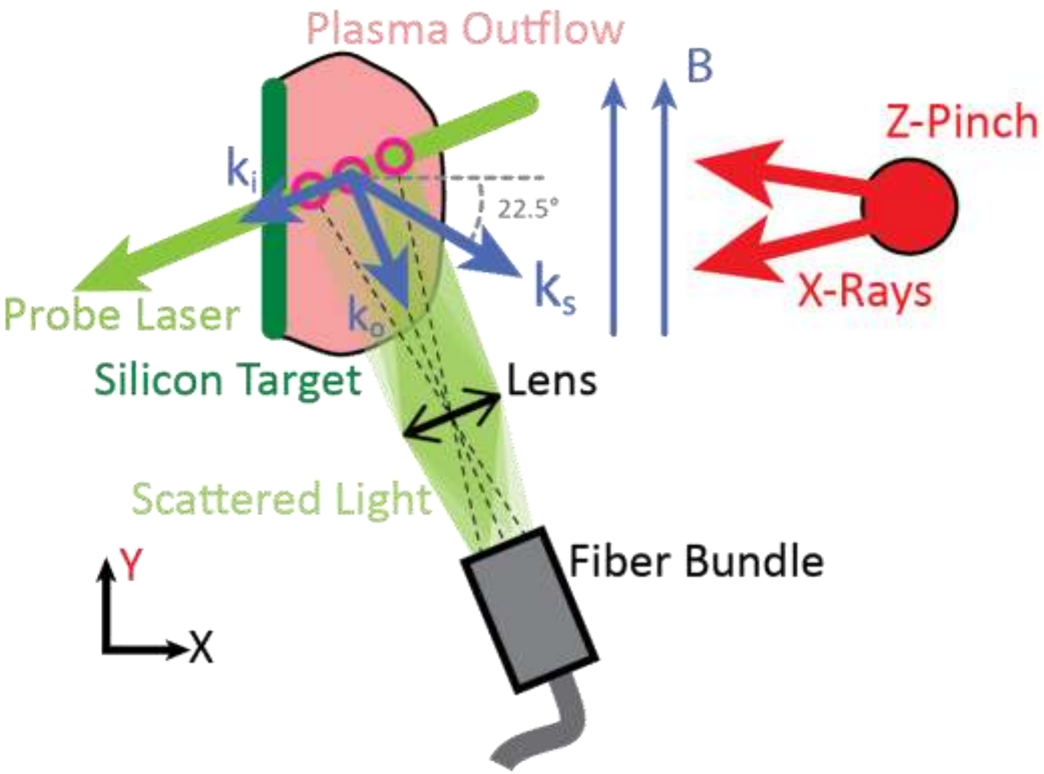

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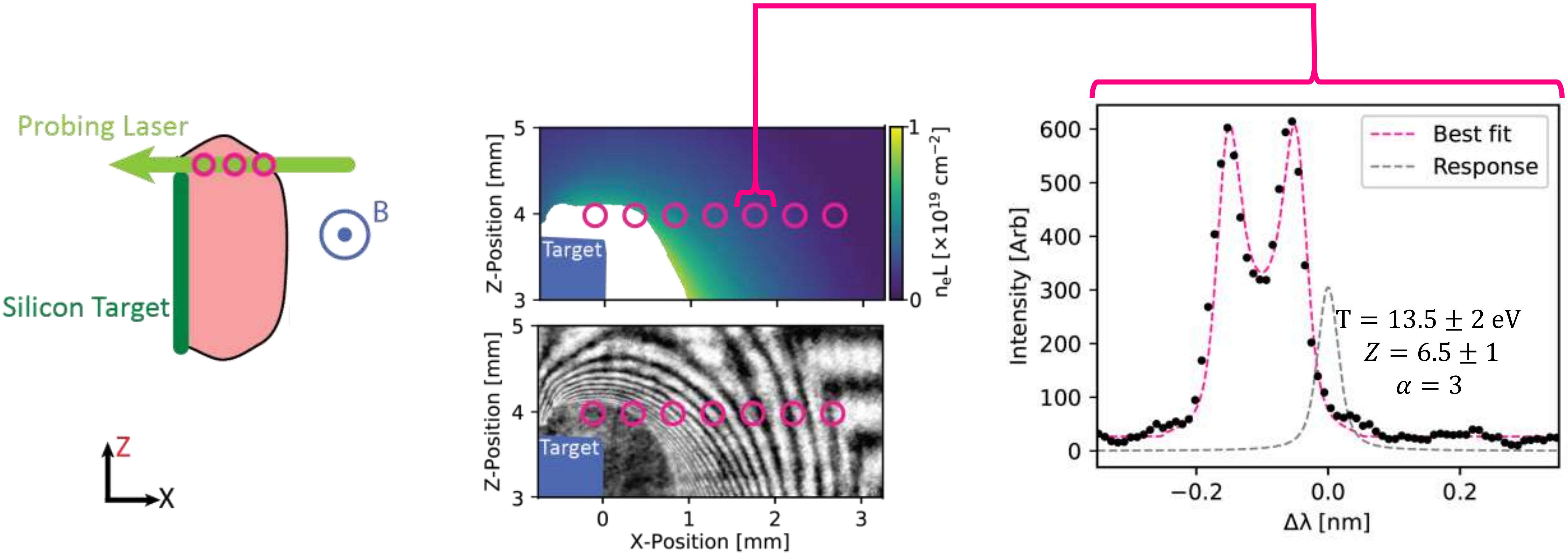


Analysis of Ion-Acoustic Thomson Scattering Data

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

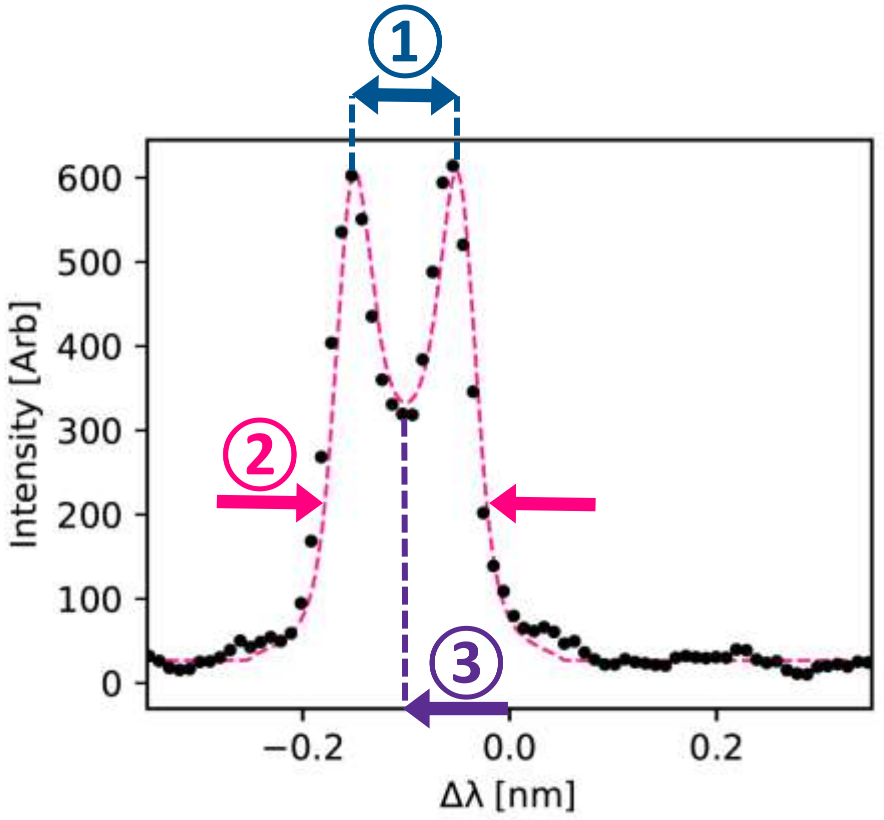
②: Feature **width** depends on n_e, T_i, and spectral response

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

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

Convolved calculated spectra with measured spectral response.

Constrained value of n_e from (near simultaneous) interferometry.



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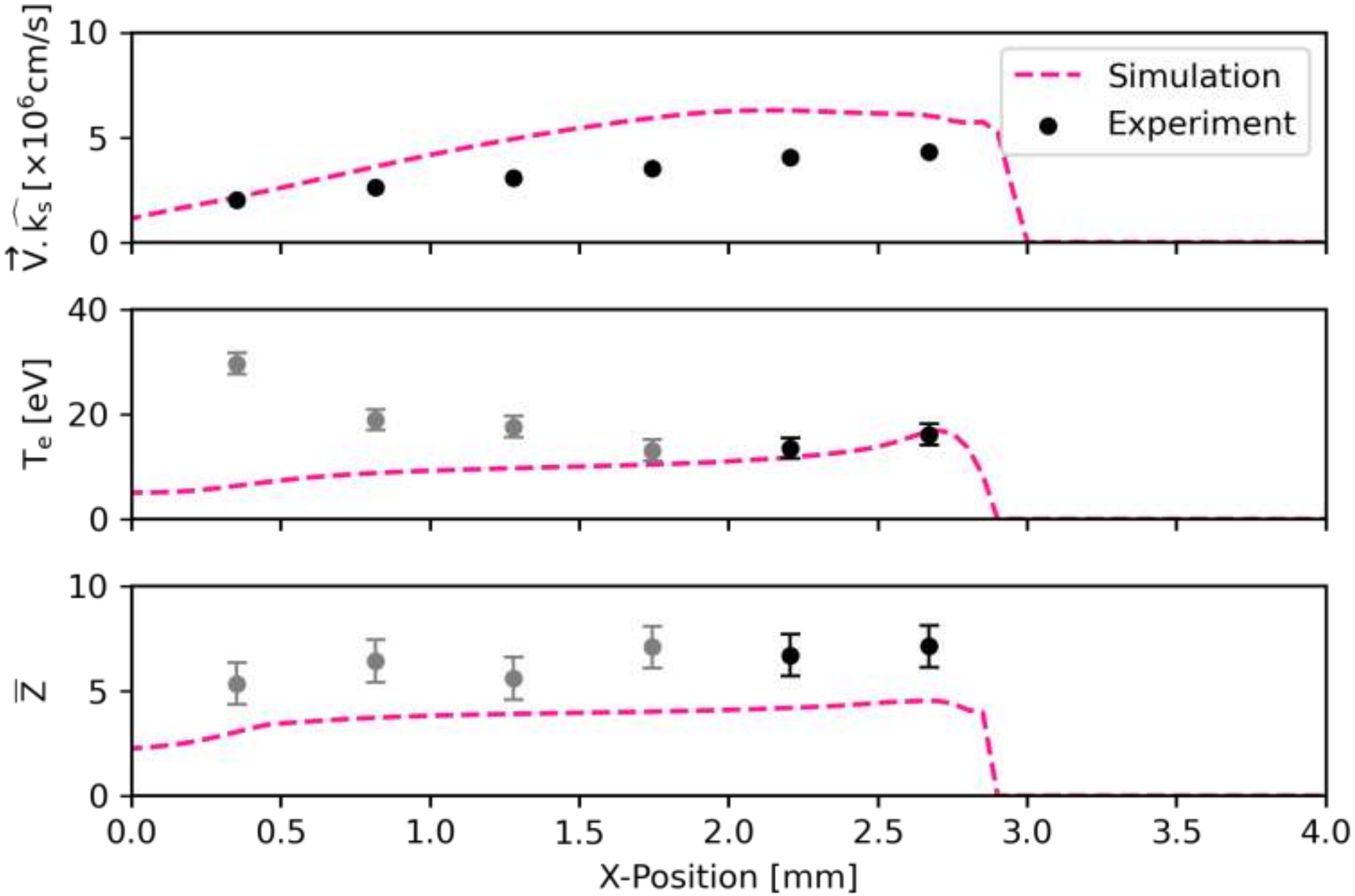

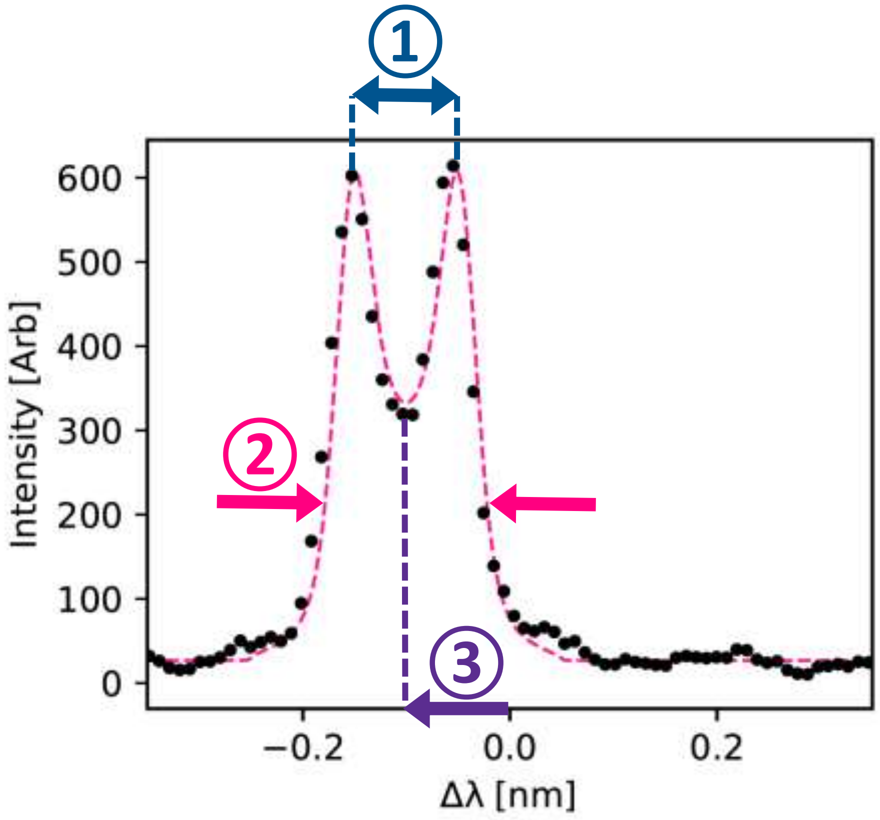

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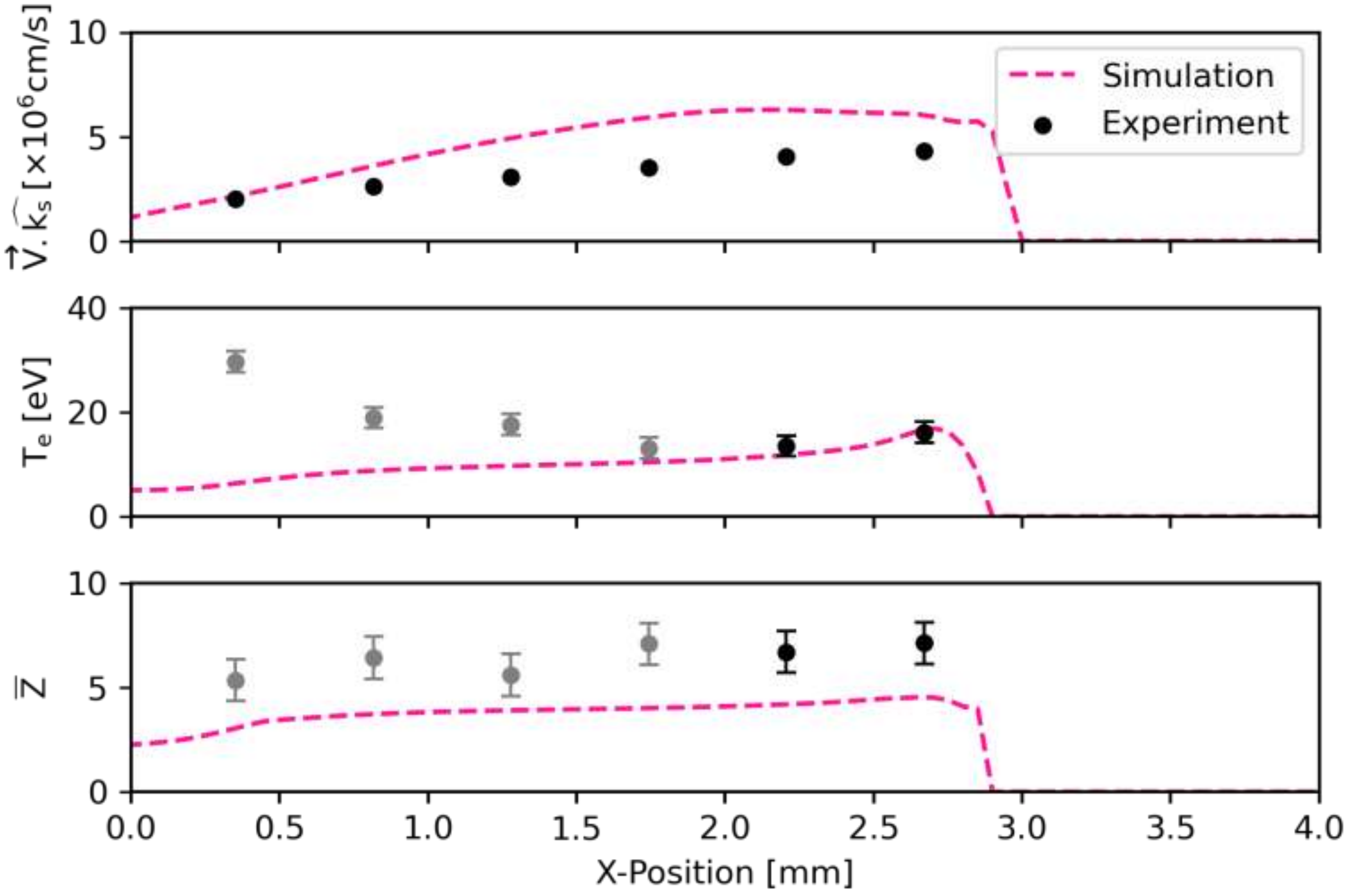
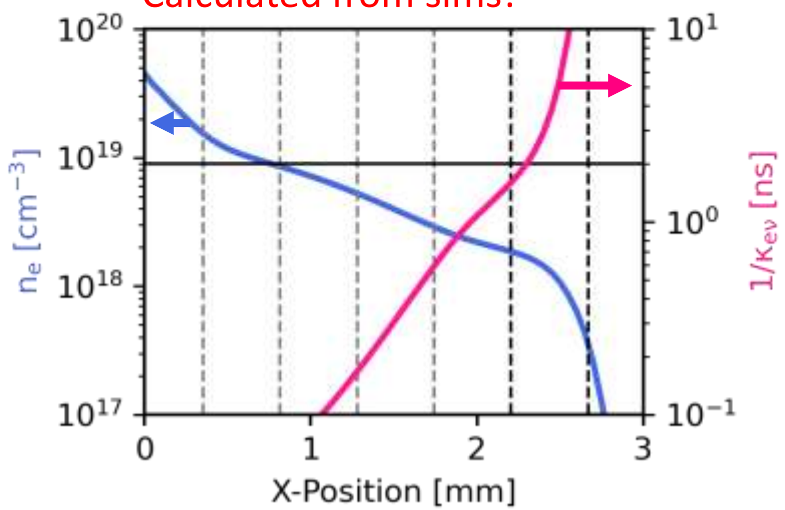
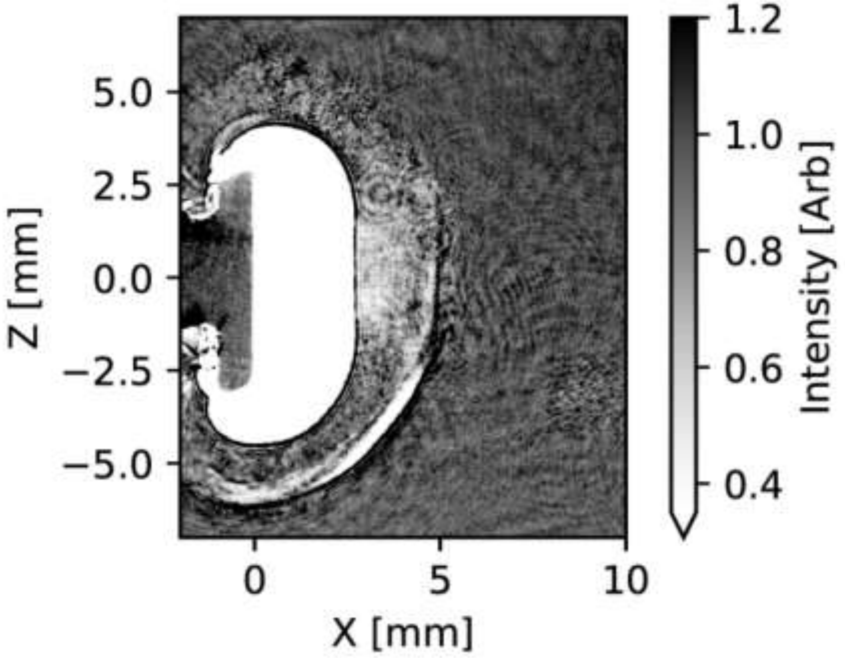




$$\kappa_{ve} \propto \frac{Z n_e^2 \ln(\Lambda) T_e^{-\frac{3}{2}}}{\sqrt{\omega^2\left(1-\omega_p^2/\omega^2\right)}}$$

N. R. L. plasma physics formulary

Measurement of Inverse Bremsstrahlung Coefficient



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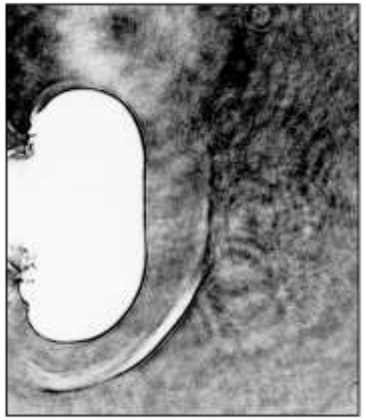
N. R. L. plasma physics formulary

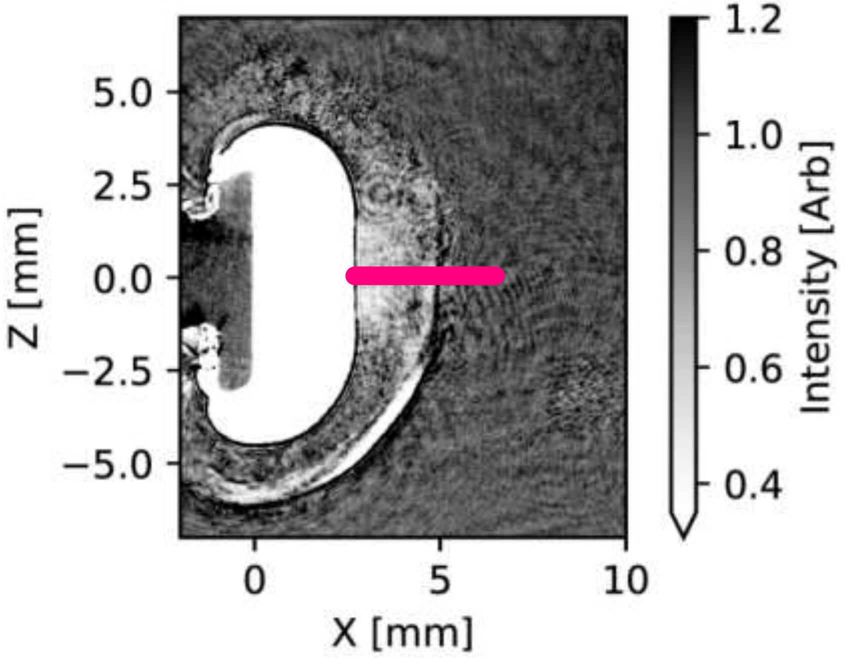
$$I = I_0 e^{-\kappa_{ve} x} \Rightarrow \kappa_{ve} = \frac{-\ln(I/I_0)}{x}$$

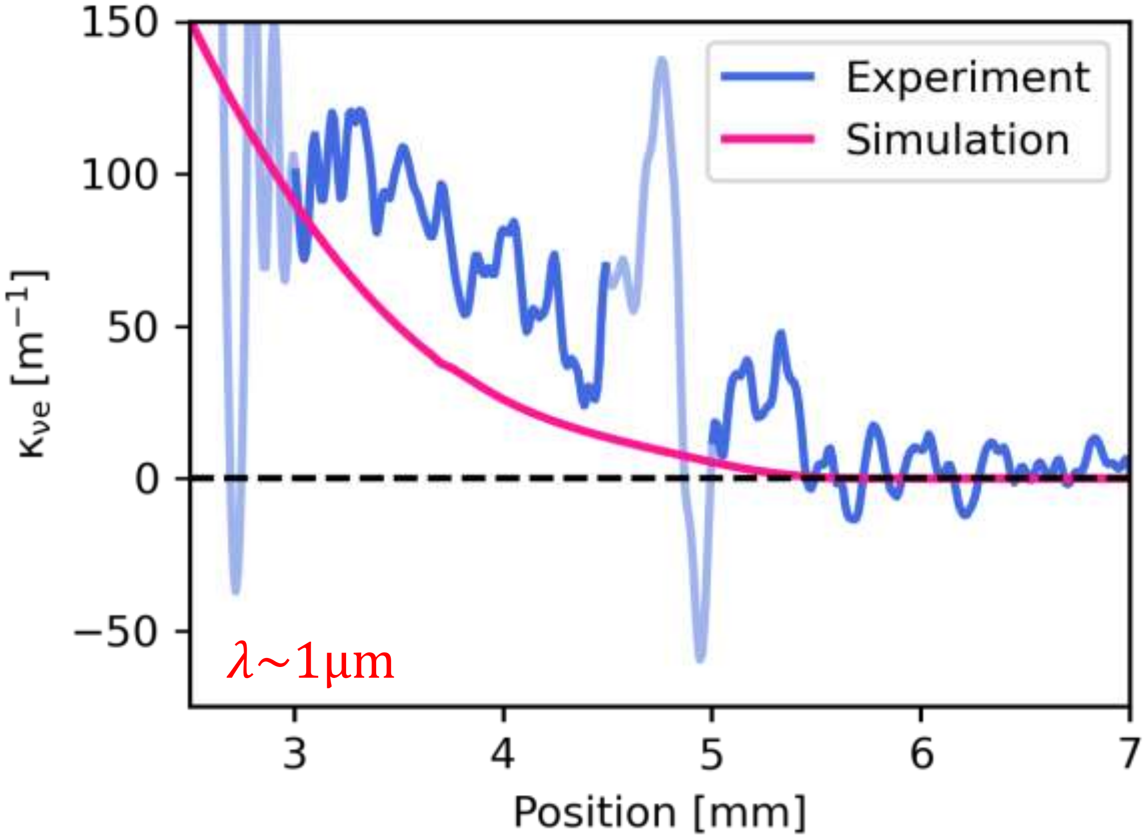
Background Image (I_0)



Shot Image (I)

Measurement of Inverse Bremsstrahlung Coefficient





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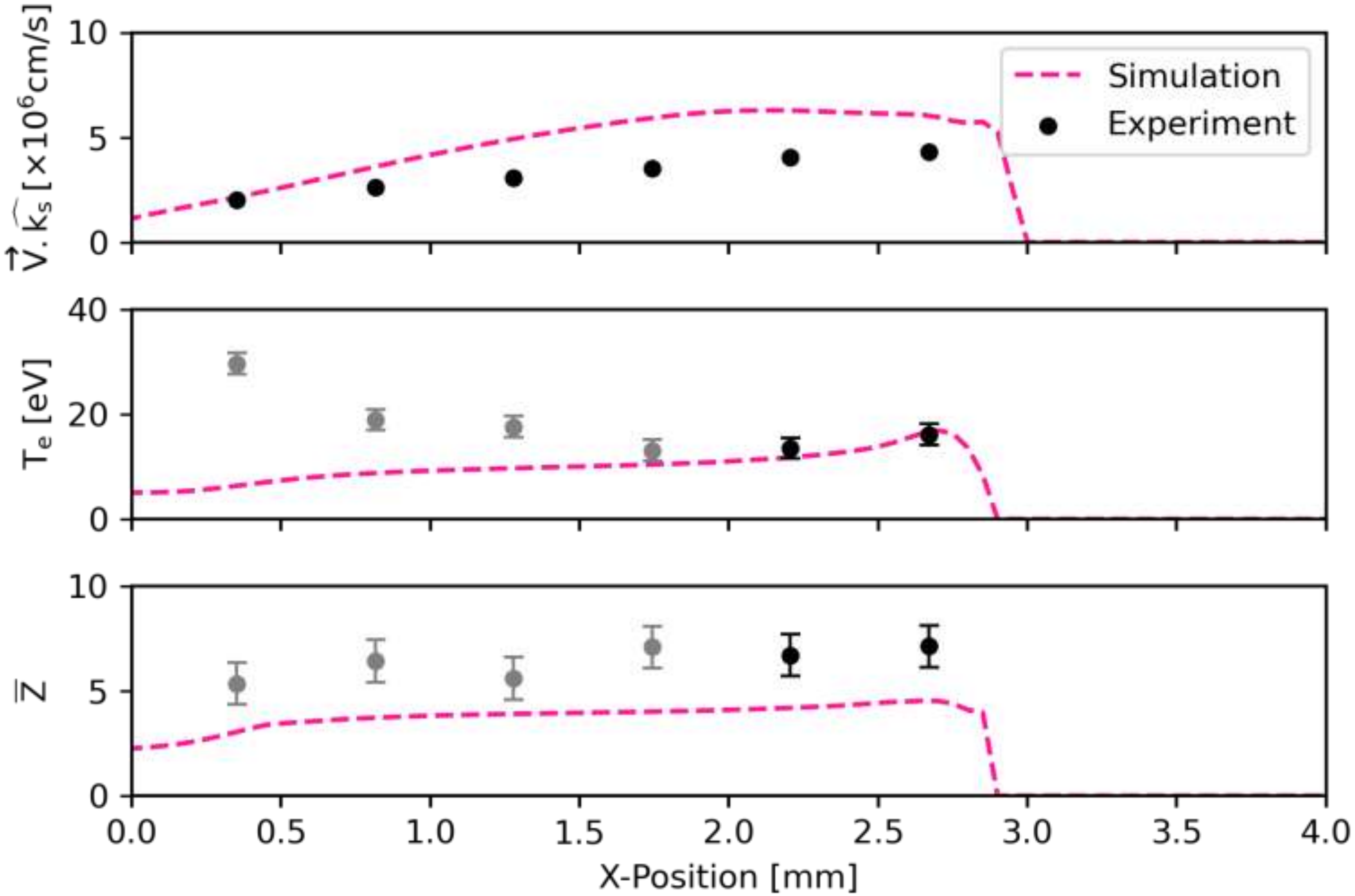
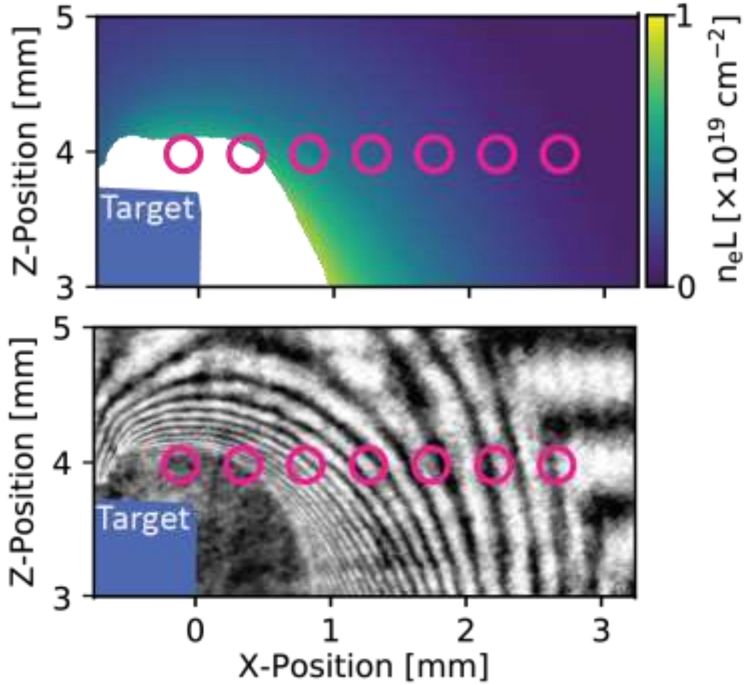
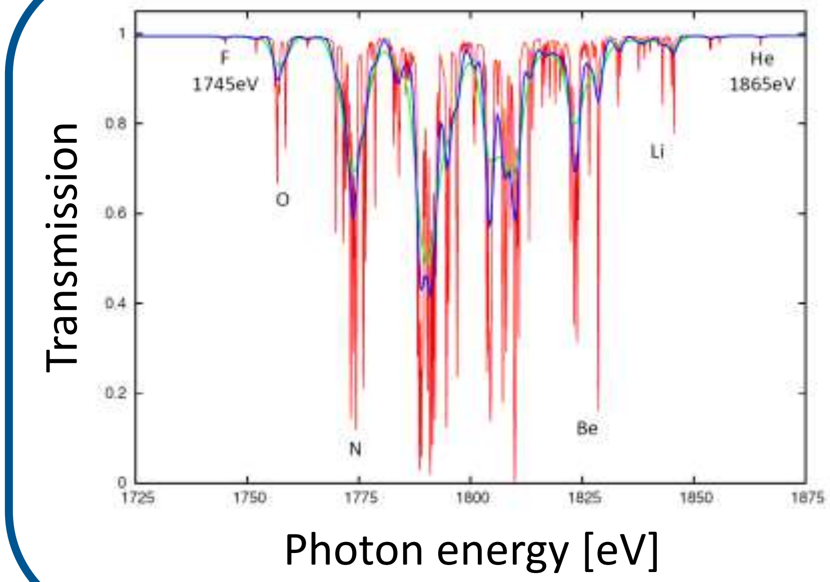


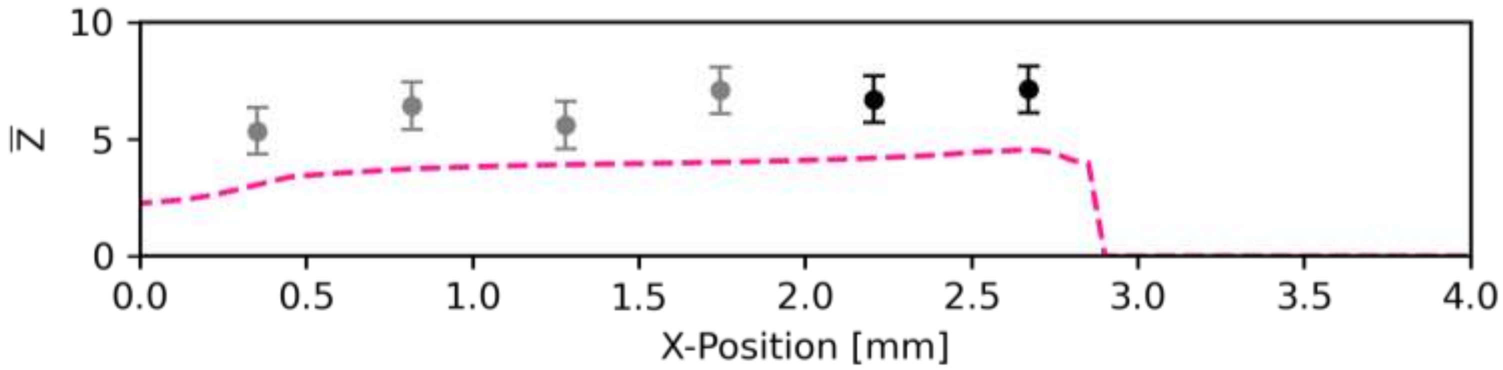


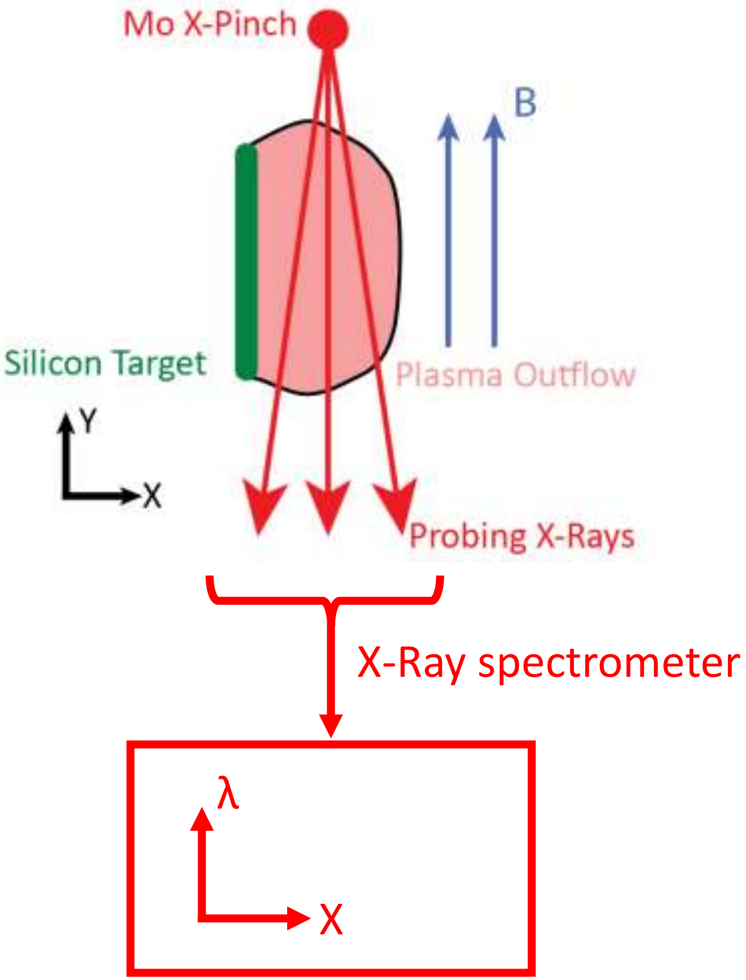
Next step – Diagnosis of Charge State Distribution



Silicon K-Shell absorption spectrum from Helios-CR.

(No MHD, inline atomic kinetics)





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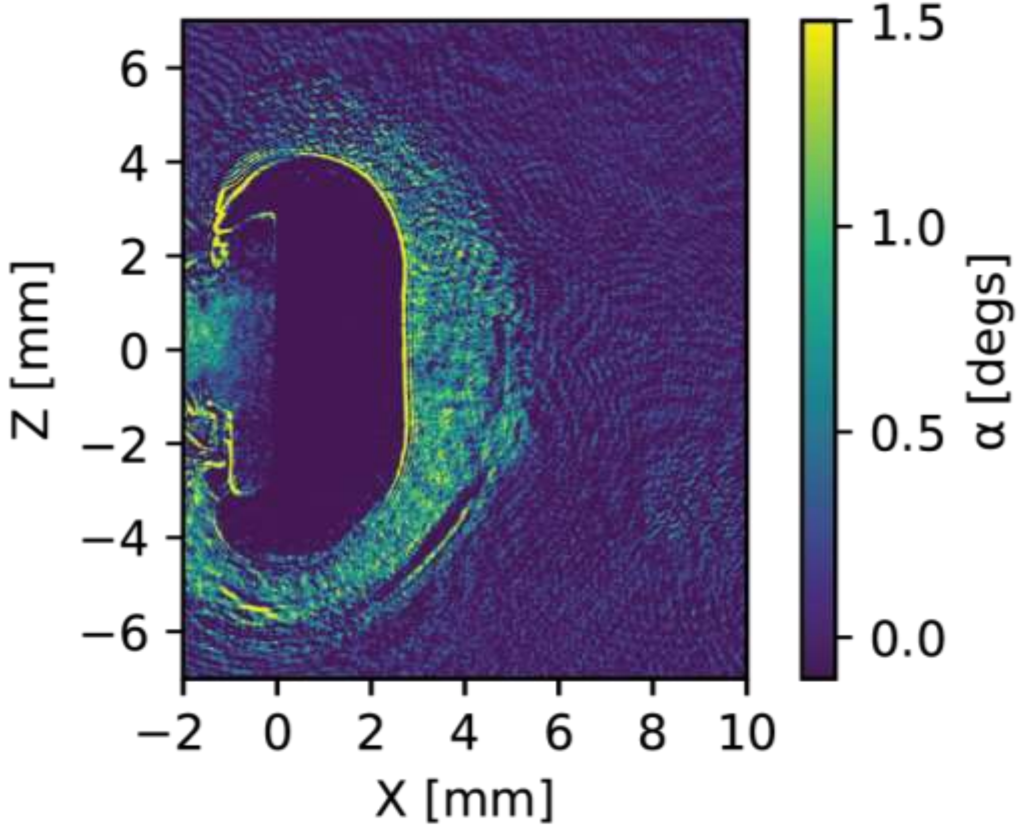
- Future work and conclusions

Faraday rotation imaging [weighted average of B_y]



- Measure rotation applied to laser polarisation:

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

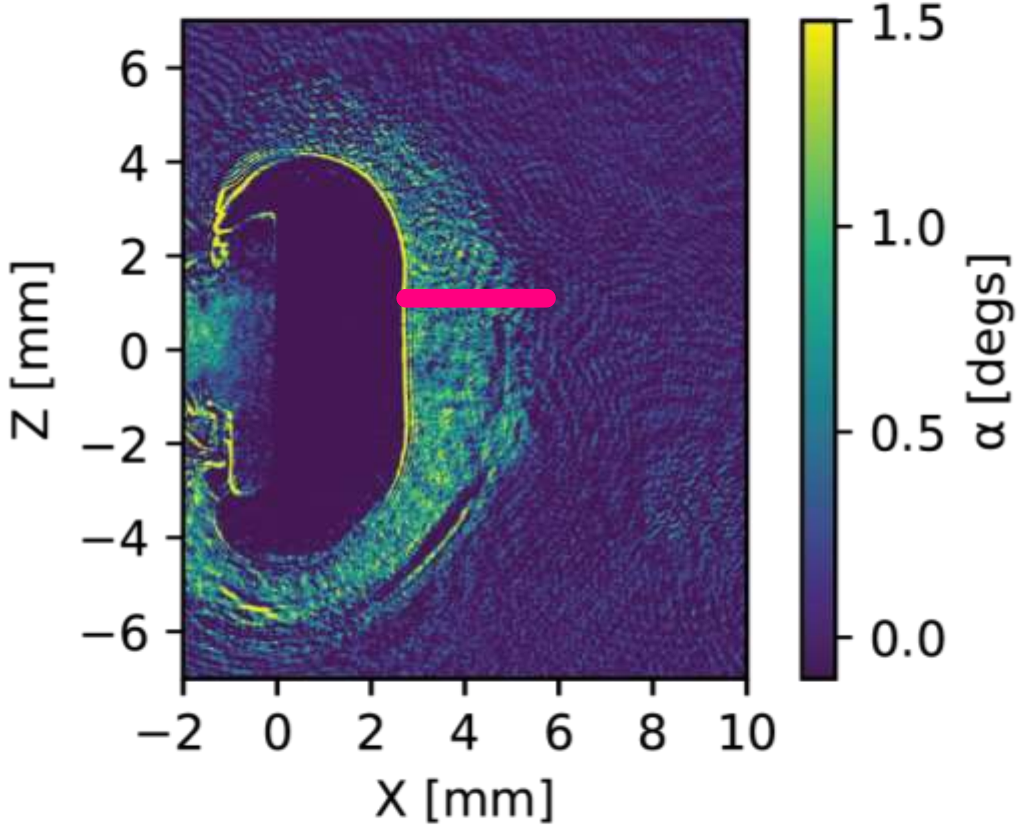
- Obtain interferometry along same line of sight:

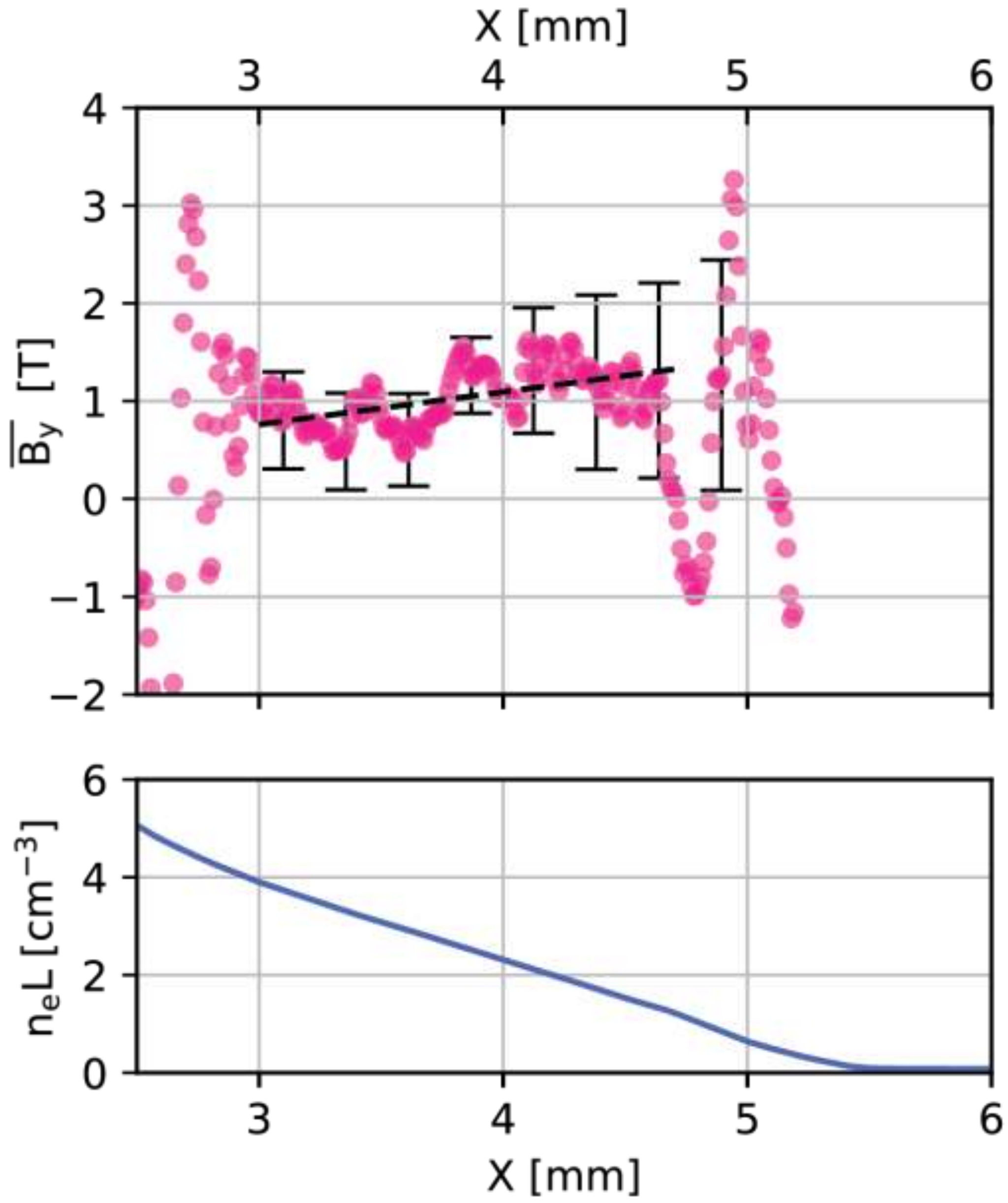
$$n_e L = \int n_e dy$$

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

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

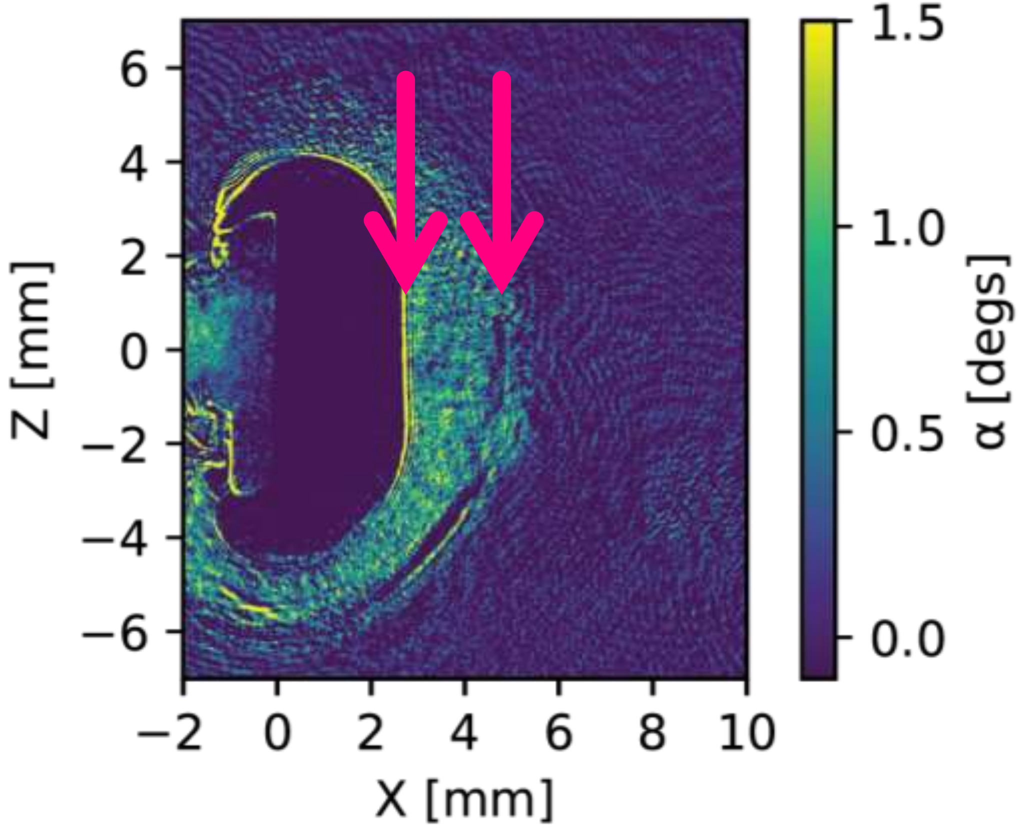
Faraday rotation imaging [weighted average of B_y]

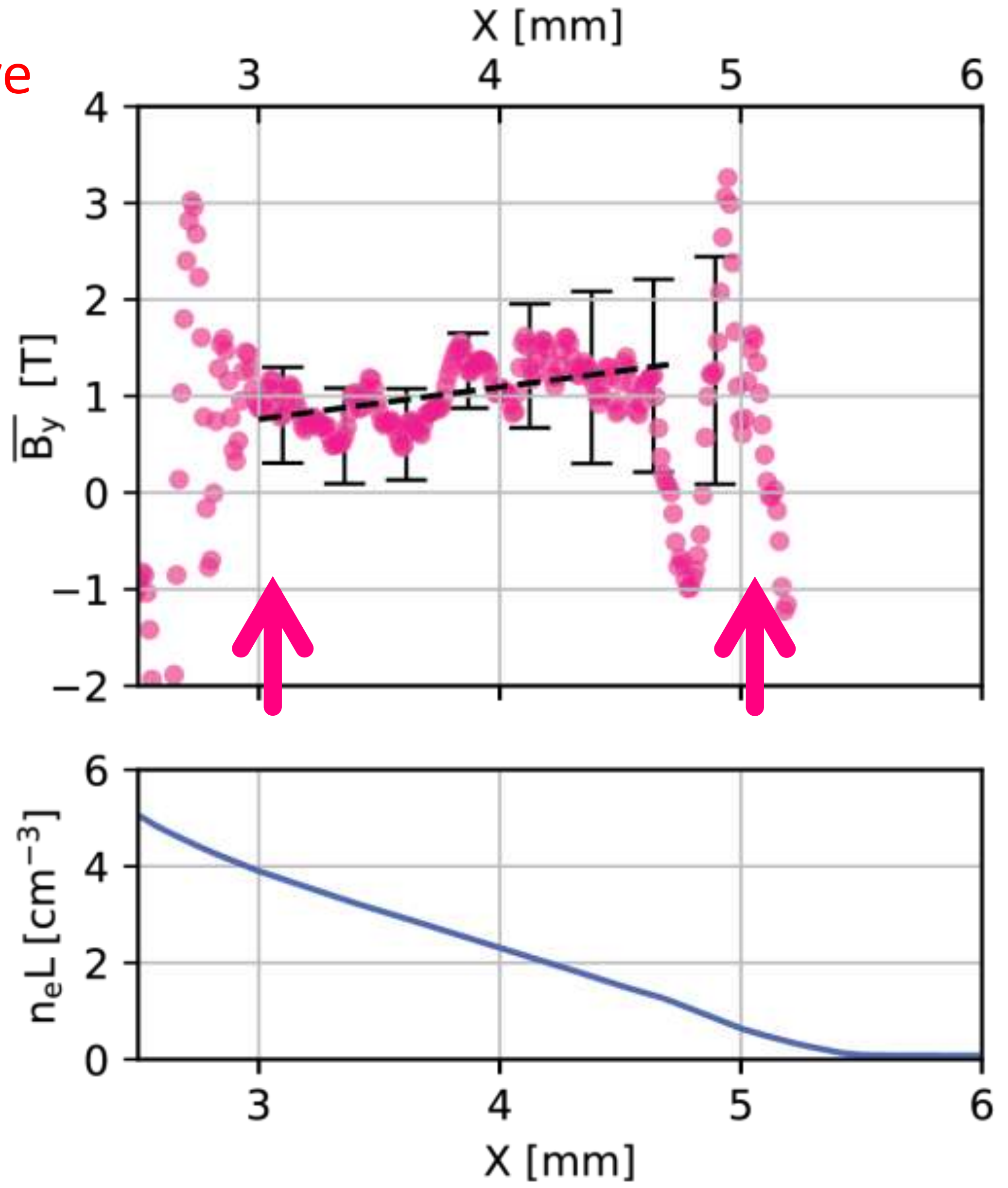




Faraday rotation imaging [weighted average of B_y]

Arrows indicate caustics $\Longrightarrow$ B field not representative





Faraday rotation imaging [weighted average of B_y]

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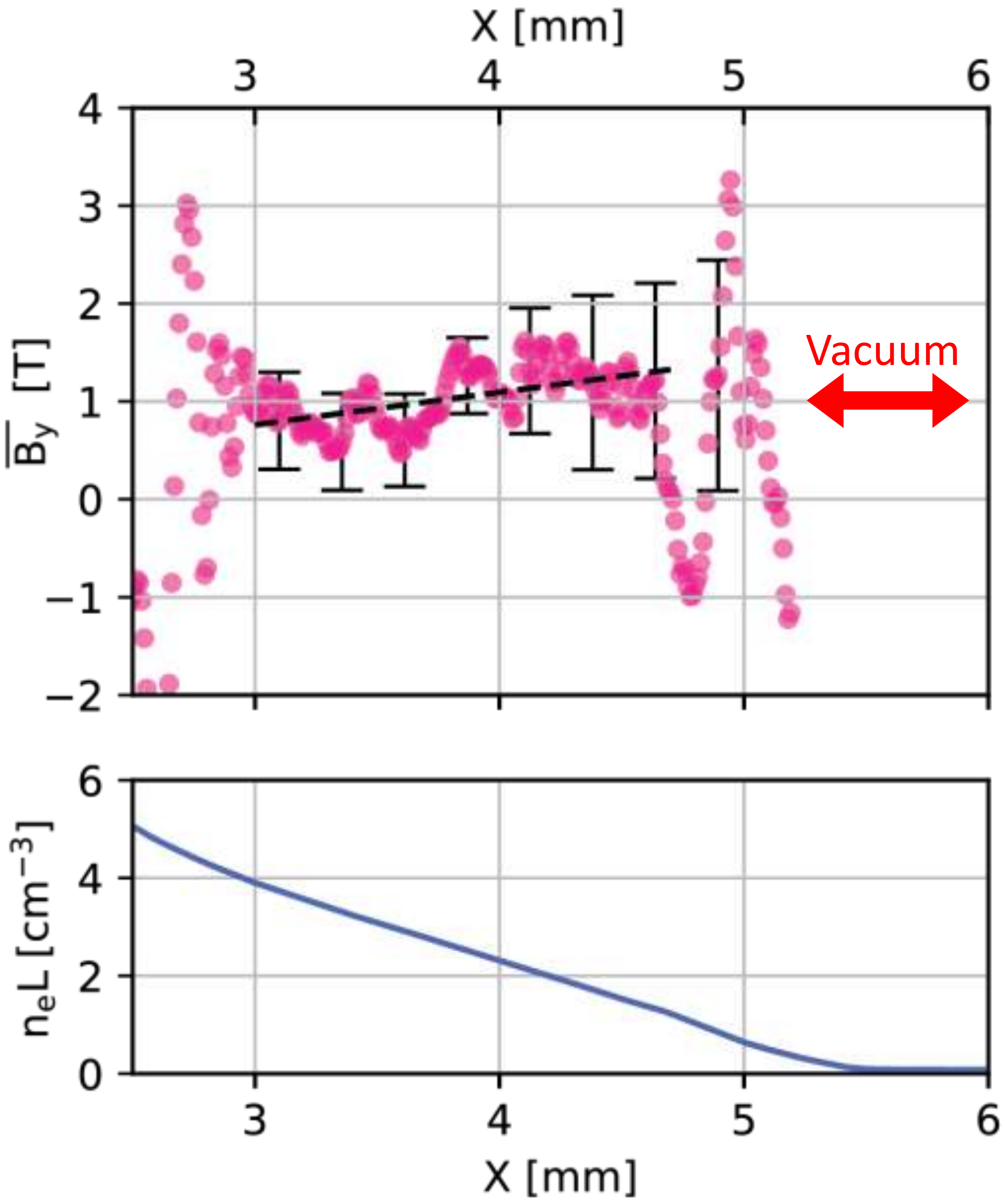
- Diagnostic measures weighted average magnetic field:

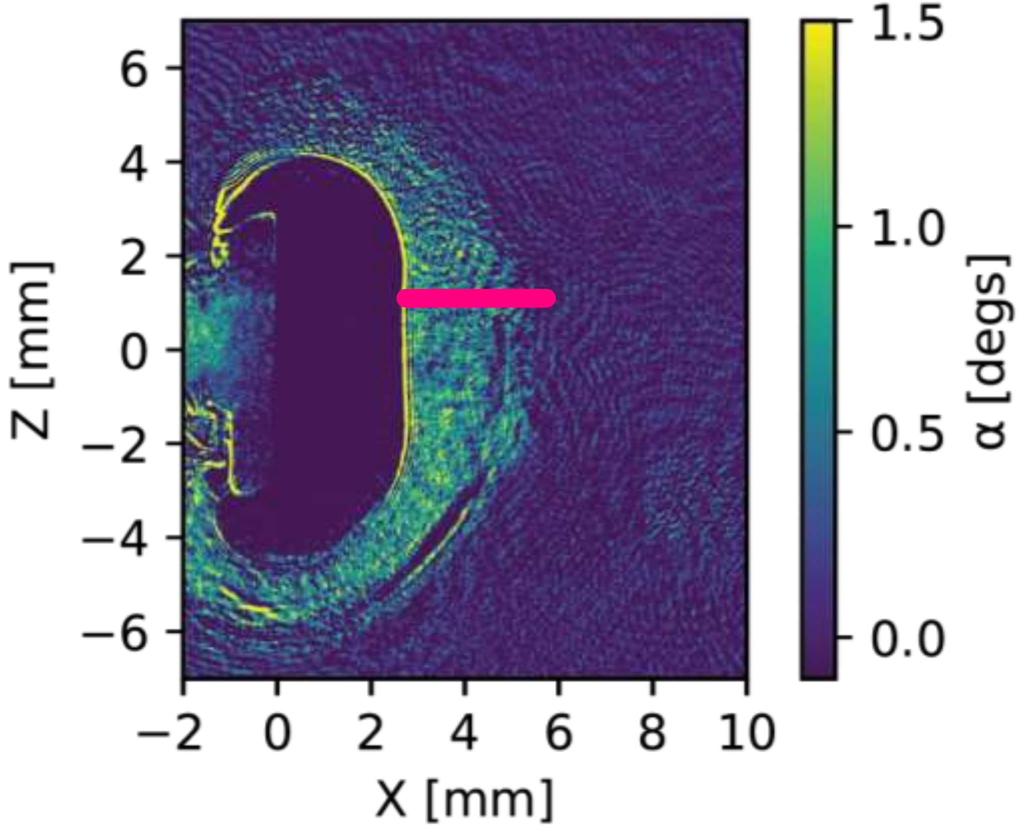
$$\overline{B_y} = \frac{\alpha}{n_e L} \propto \frac{\lambda^2 \int n_e \vec{B}.d\vec{y}}{\int n_e dy}$$

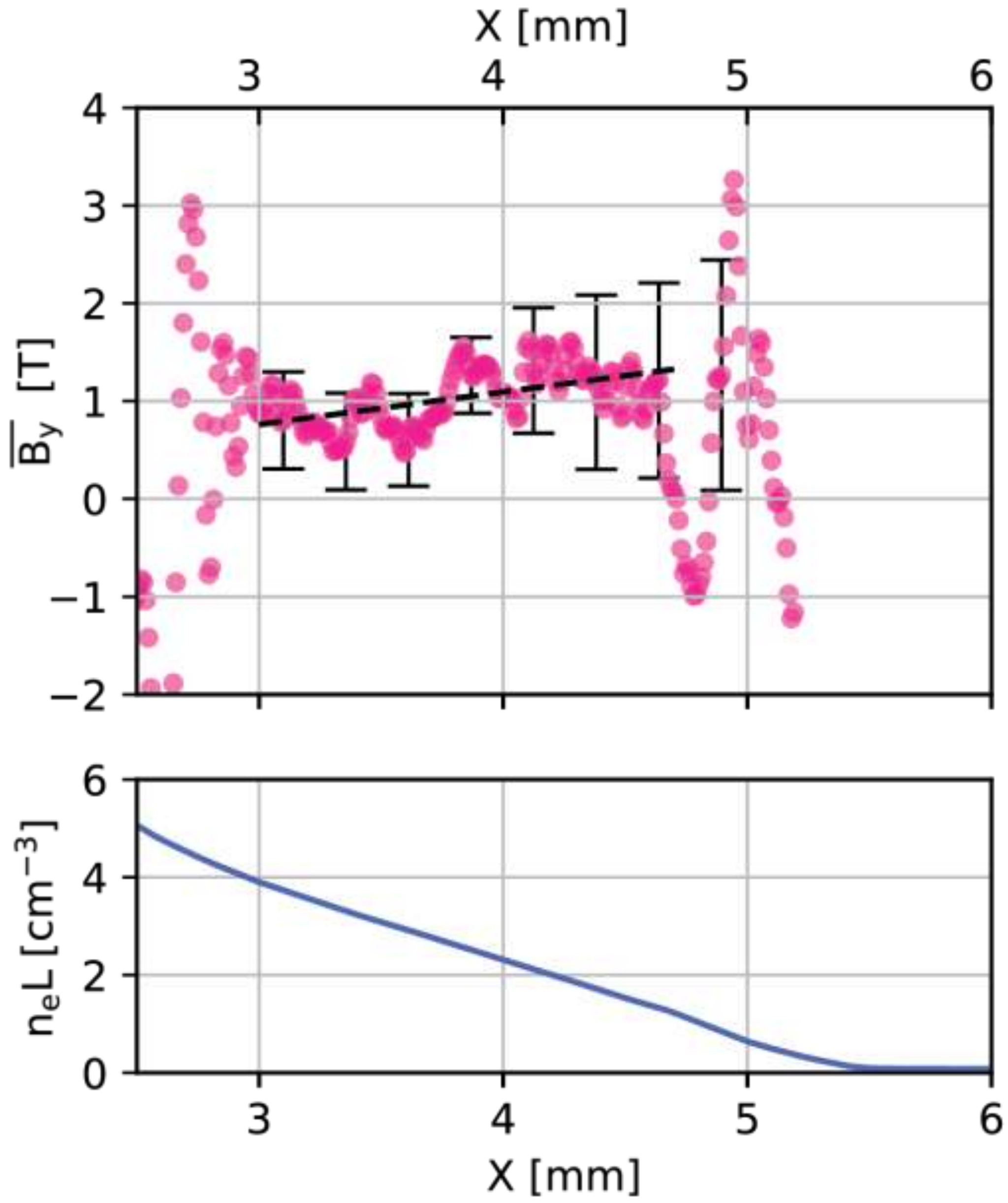
- Cannot diagnose field in the vacuum ($n_e = 0$)

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

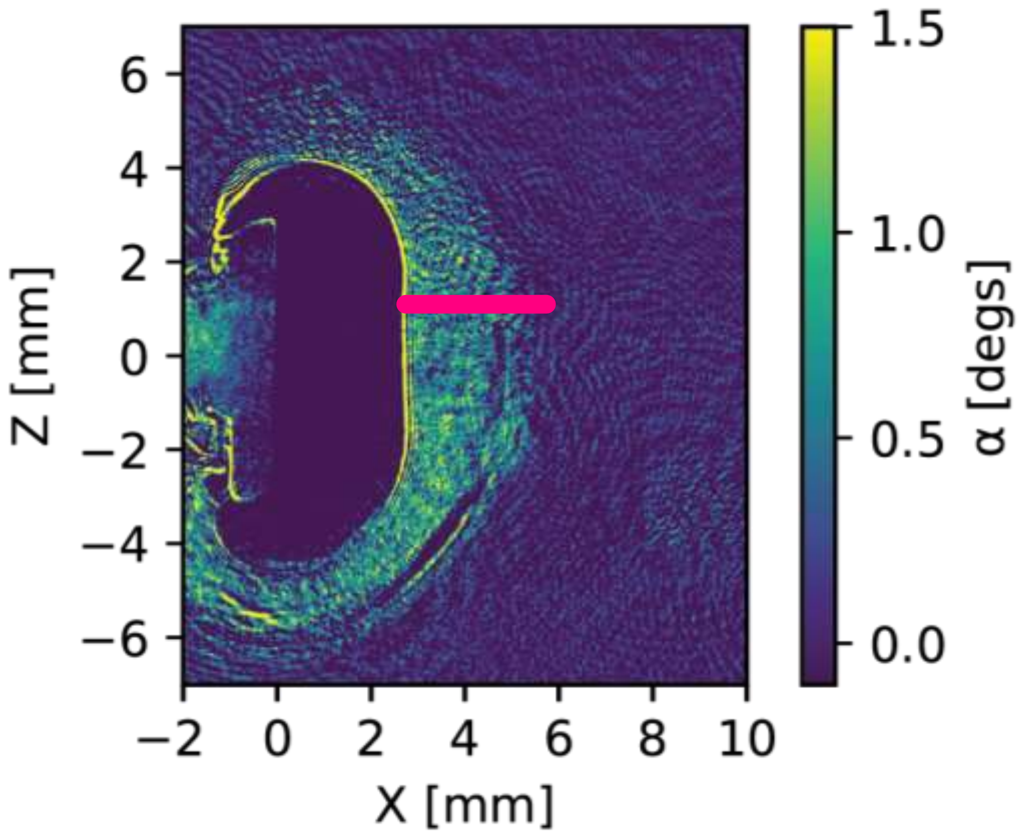


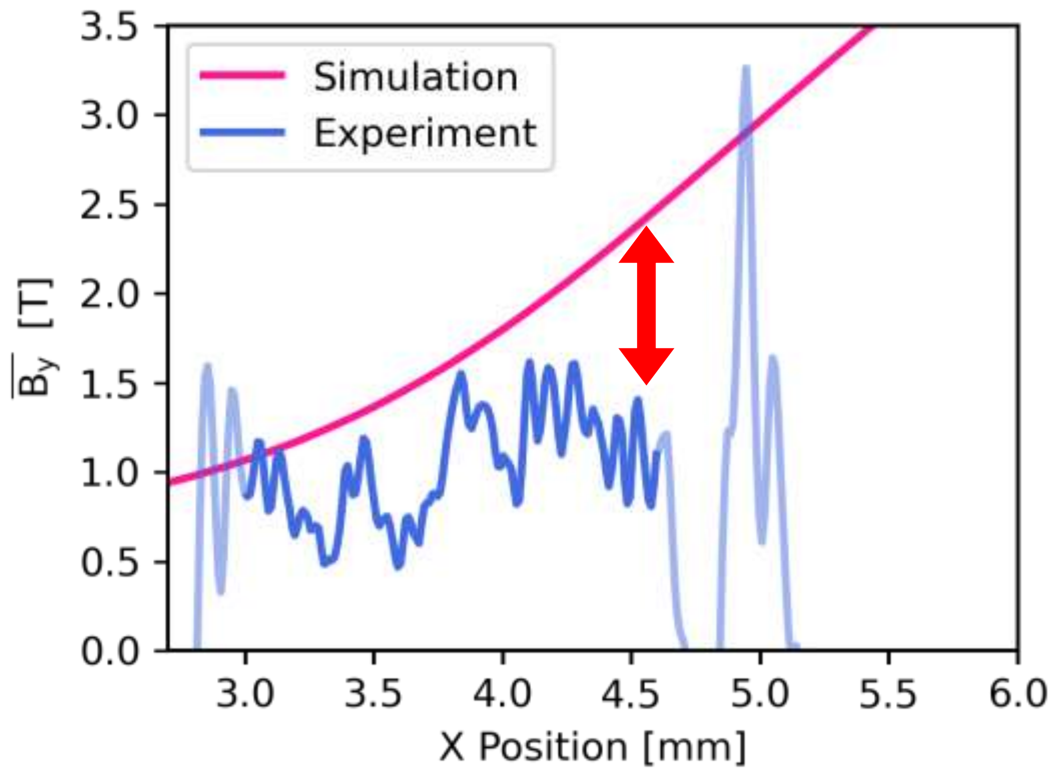
Faraday rotation imaging [weighted average of B_y]





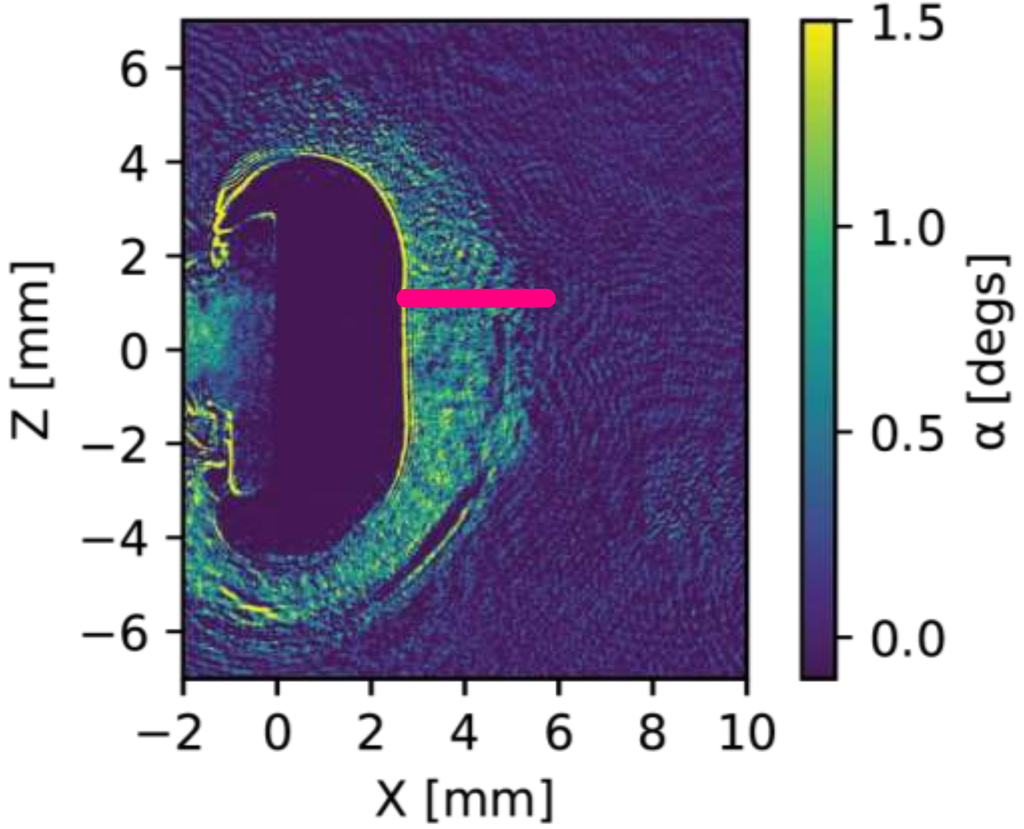
Faraday rotation imaging [weighted average of B_y]

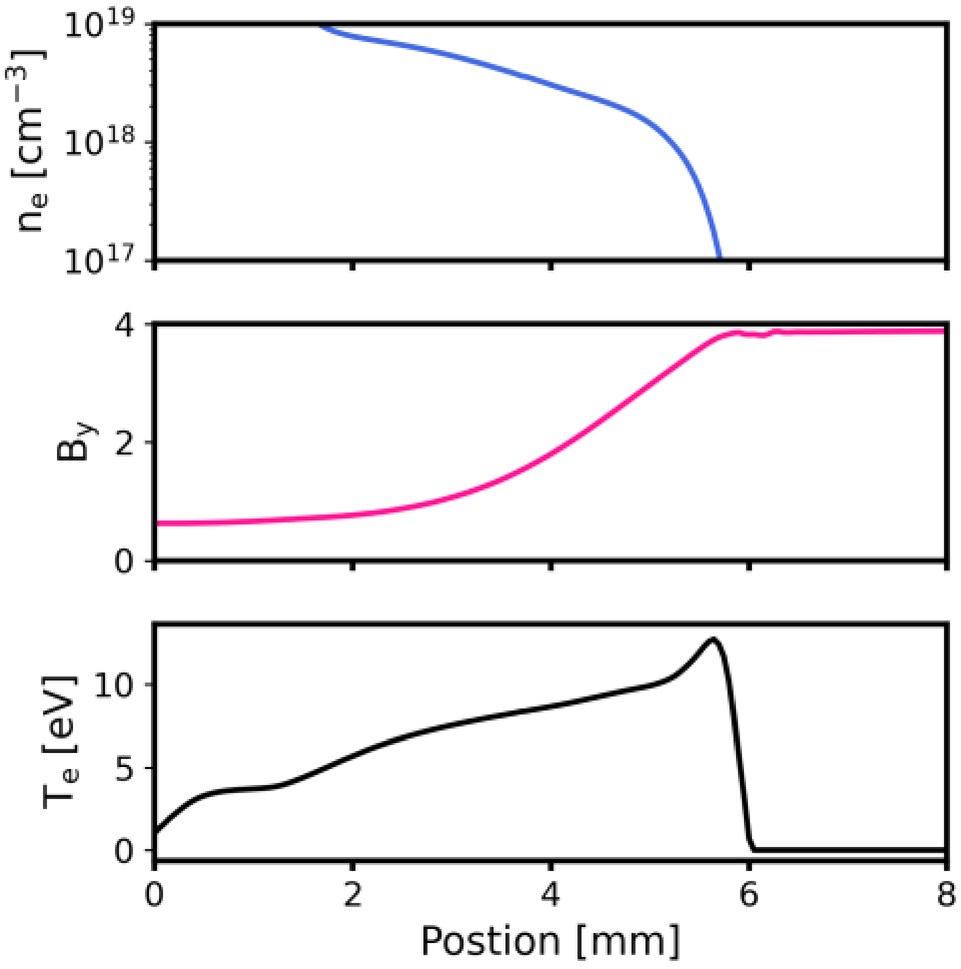




Simulated profile is more diffusive

Faraday rotation imaging [weighted average of B_y]





Plasma parameters relevant to B-field transport

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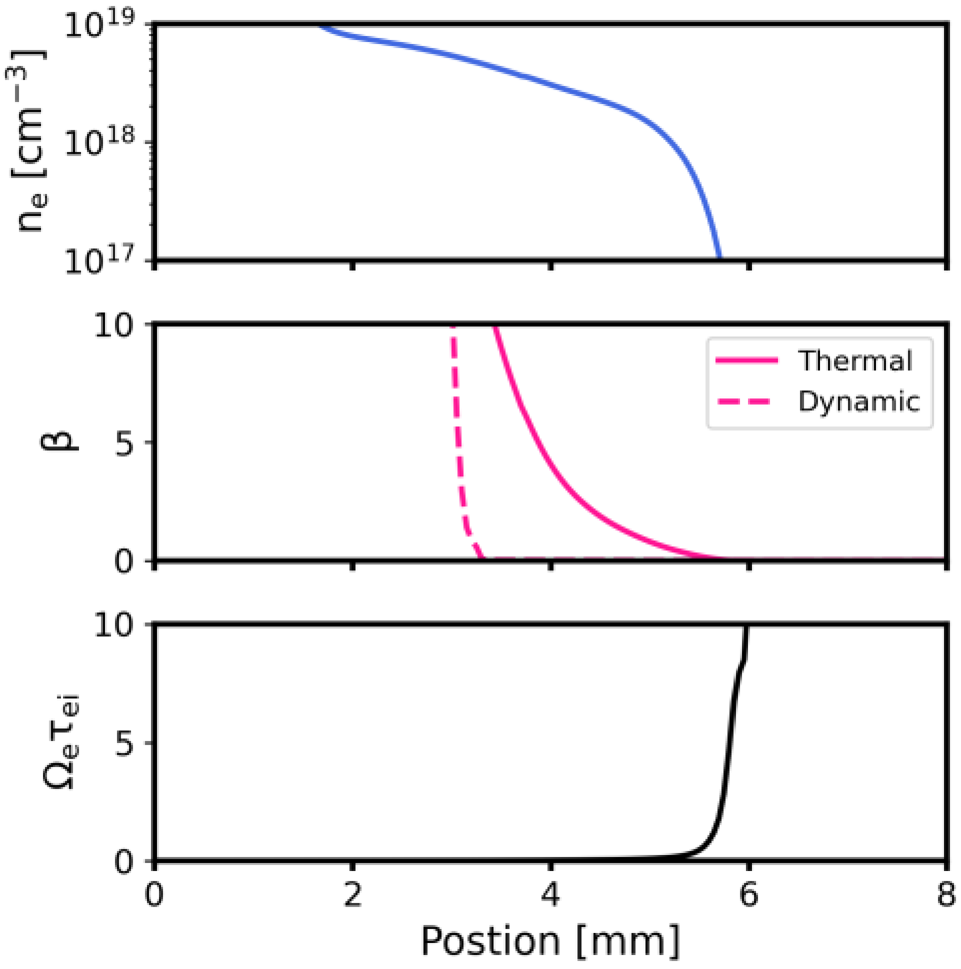
- Use simulated conditions to calculate dimensionless parameters

$$\beta_{th} = \frac{2\mu_0 n_e \left(T_e + \frac{Ti}{Z}\right)}{B^2} \qquad \beta_{dyn} = \frac{2\mu_0 \rho u^2}{B^2}$$

- At the leading edge:

$$\beta_{th} \sim \beta_{dyn} \lesssim 1 \qquad \Omega_e \tau_{ei} \gtrsim 1$$

- Magnetisation may be important in low density region



Anomalous resistivity may be driven by the LHDI

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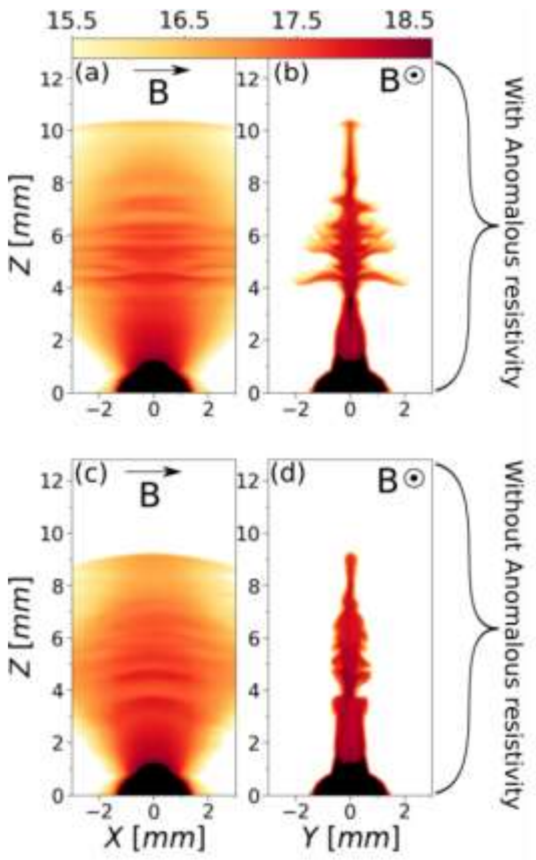
- Additional dissipation associated with the Lower Hybrid Drift Instability (LHDI) reported to cause anomalous resistivity

- Gorgon / Chimera includes a model [1] for anomalous resistivity of the form :

$$\nu_{ei} \rightarrow \nu_{ei} + \nu_A, \qquad \nu_A = \sqrt{\frac{\pi}{8}} \omega_{LH} \left(\frac{v_d}{c_s}\right)^2$$

- Simulations of X-ray ablated plasmas run with classical (Epperlein-Haines) transport only

[1] – Chittingden et al. PoP 1995



Plots of Log(n_e) from Gorgon simulations of a laser driven plasma jet experiment

Credit: Khiar et al. PRL 2019

Flux exclusion is not explained by anomalous resistivity

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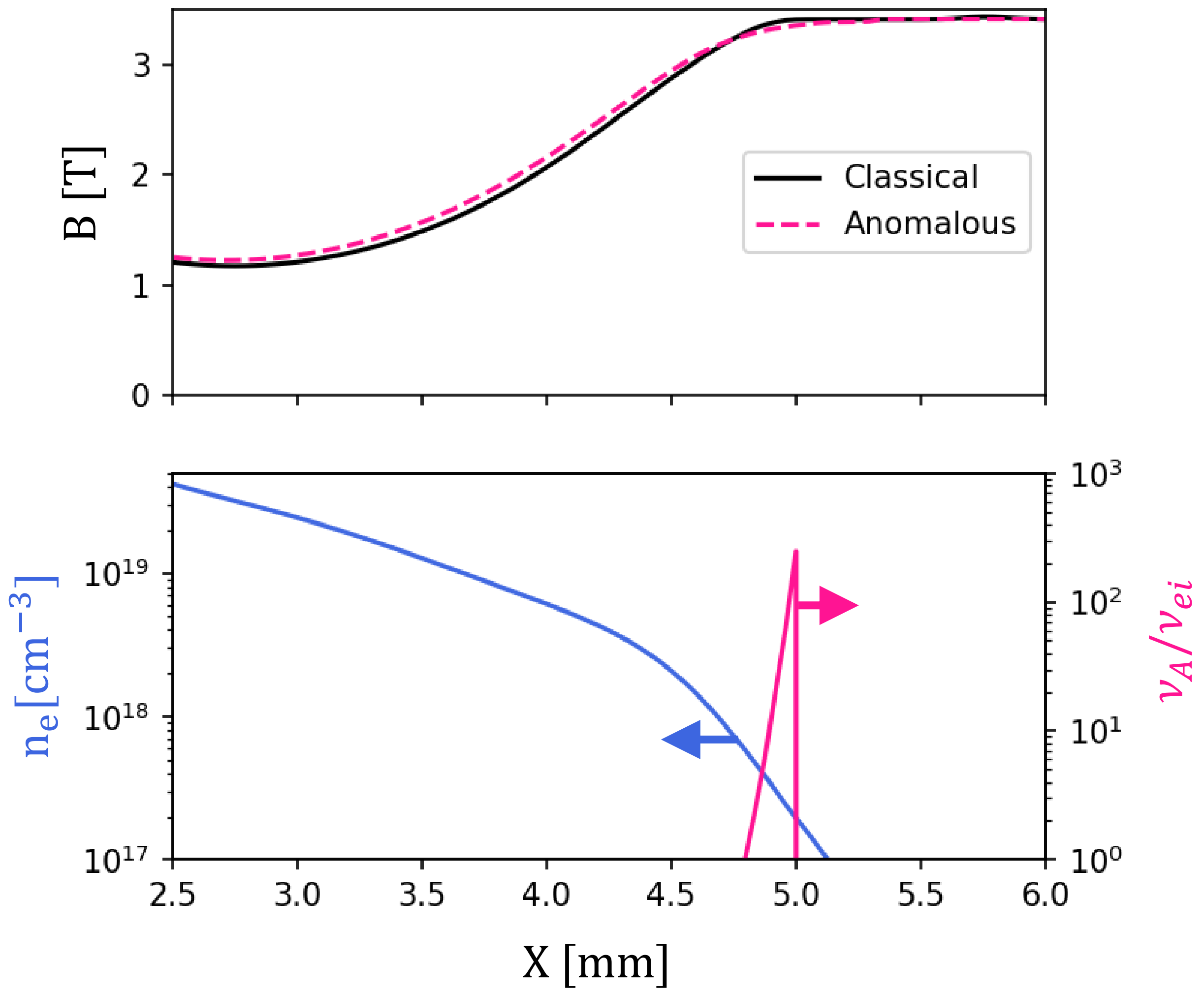
- Difficult to see how anomalous resistivity can exclude B-field from experiment:
  - Additional diffusion should allow magnetic flux to penetrate further
  - Thickness of anomalous region is small so overall effect is negligible
- Results are from a 1D simulation
- Impact of ν_A is increased by a factor of 100 for the profile of B(x)



Faraday rotation imaging [weighted average of B_y]

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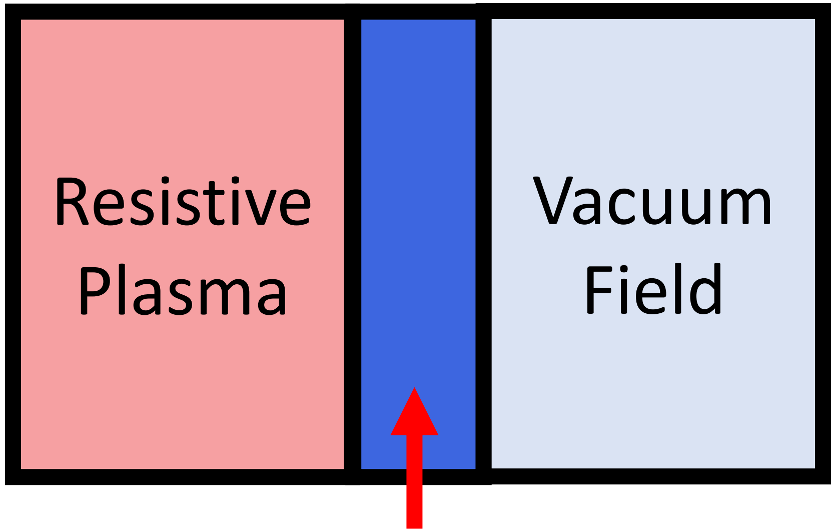
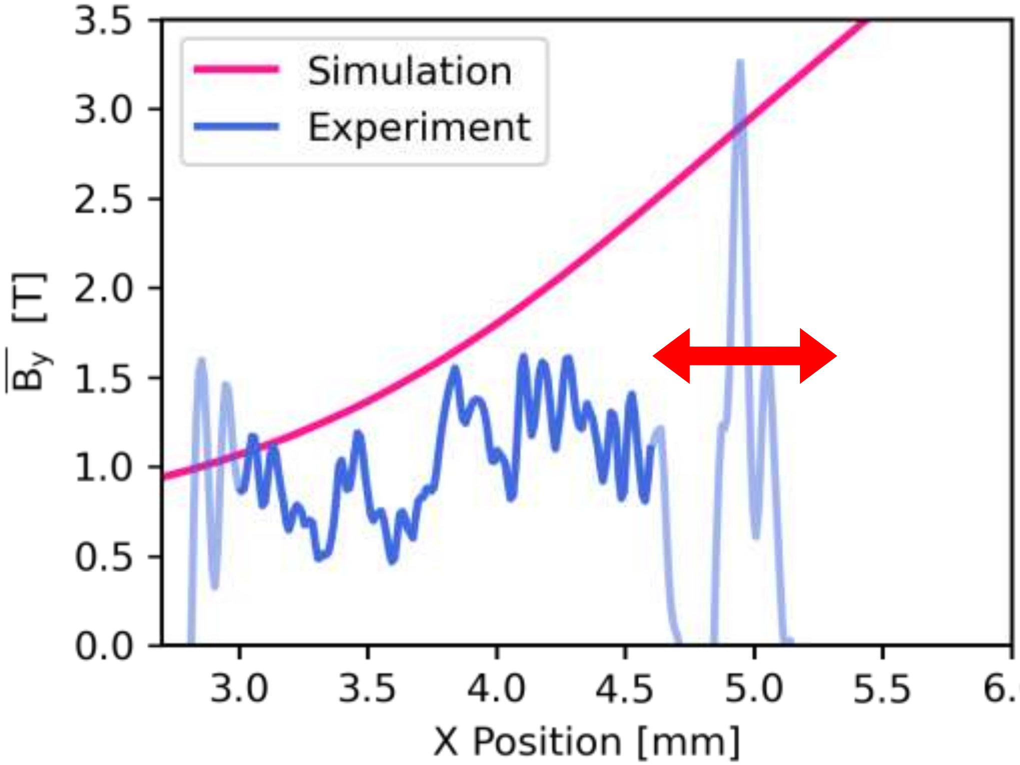
A layer of enhanced conductivity may better explain the experimental result:

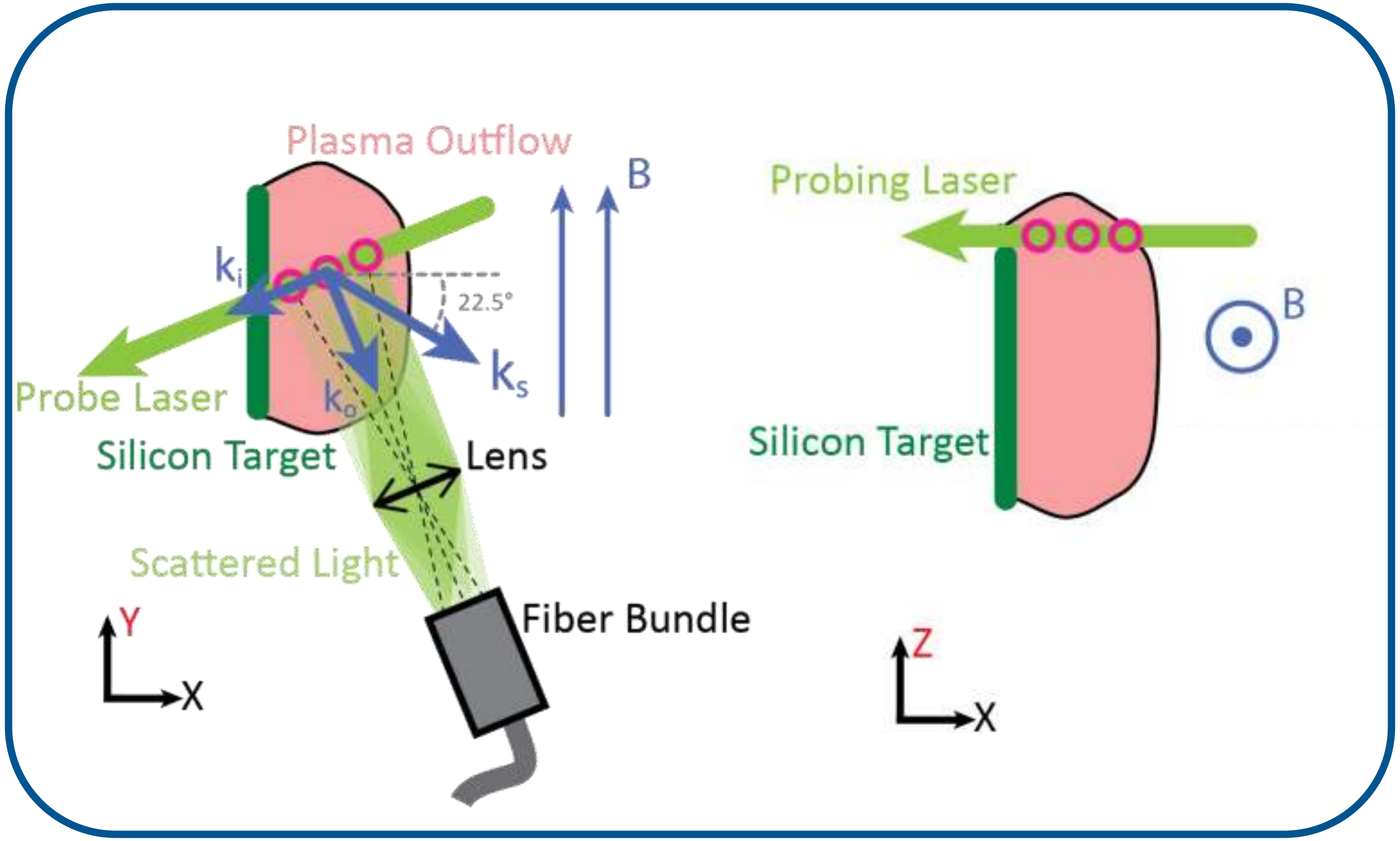




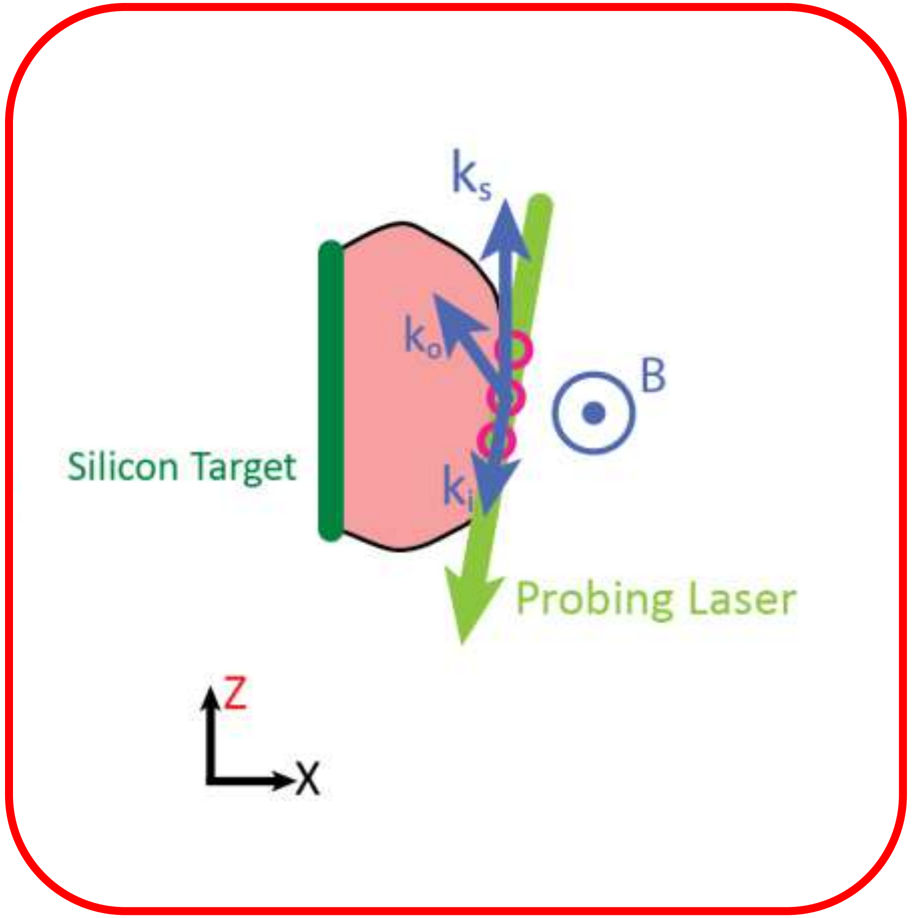
Need to diagnose vacuum boundary!

Next step – Local Current Density Measurement

Existing setup ⇒ $k_s \perp J$



New setup ⇒ $k_s \parallel J$

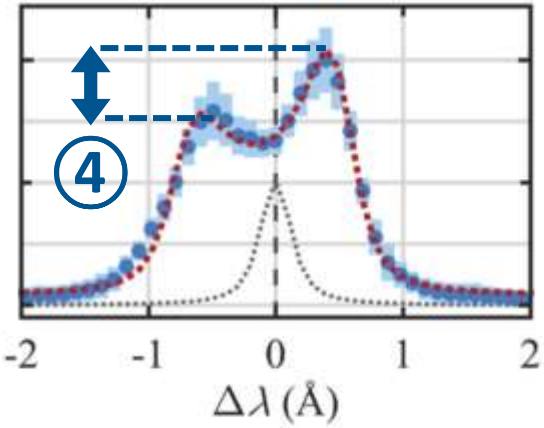


Next step – Local Current Density Measurement

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

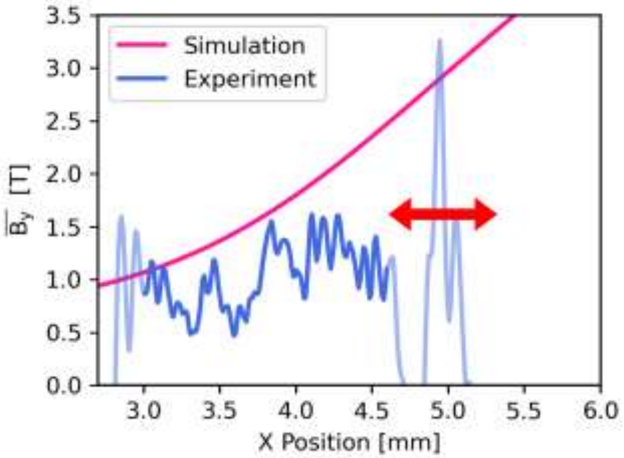
L. G. Suttle *et al* RSI 2021 (MAGPIE experiments)

C. Bruulsema *et al* PoP 2020 (Current in Weibel unstable plasmas)



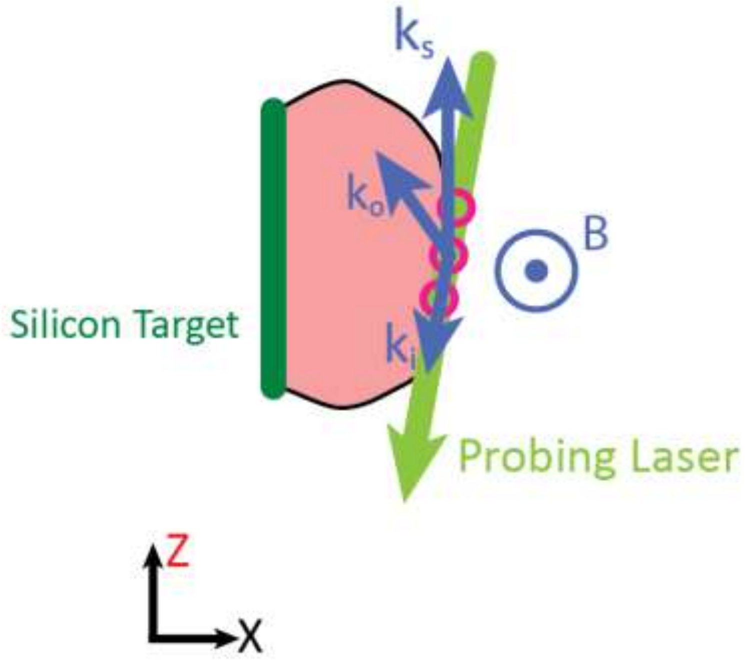
Diagnose current at vacuum boundary with Thomson:

- Can probe smaller n_e
- Reduce λ for less diffraction



Need to diagnose vacuum boundary!

New setup ⇒ $k_s \parallel J$

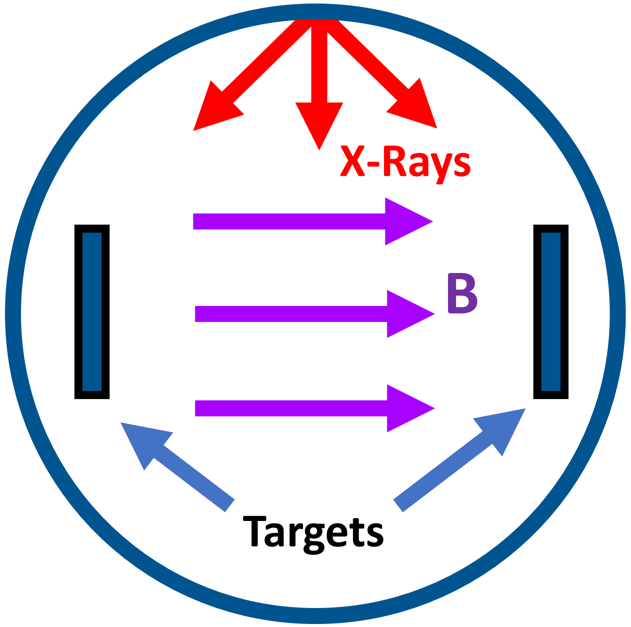


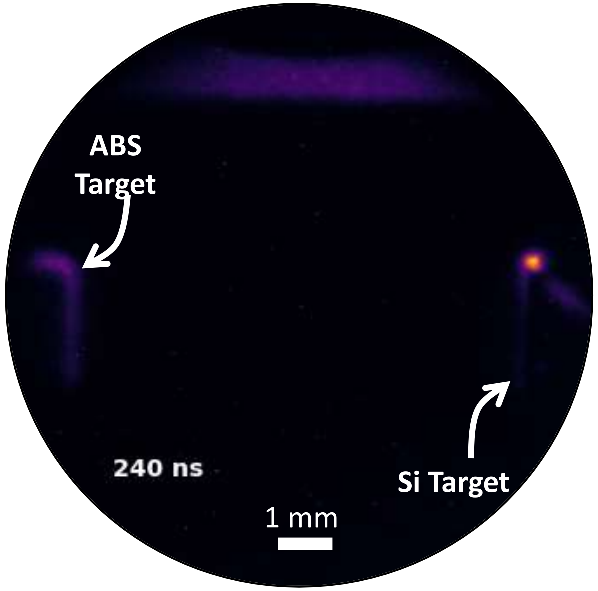
Outline

- Overview of the MAGPIE facility
- Wire array Z-pinches as X-Ray sources
- X-Ray ablated plasma:
  - Data from imaging diagnostics
  - Local V, T, Z profiles from TS

  } Compare with R-MHD simulations (Chimera)
- Measurement of magnetic flux penetration
- Future work and conclusions

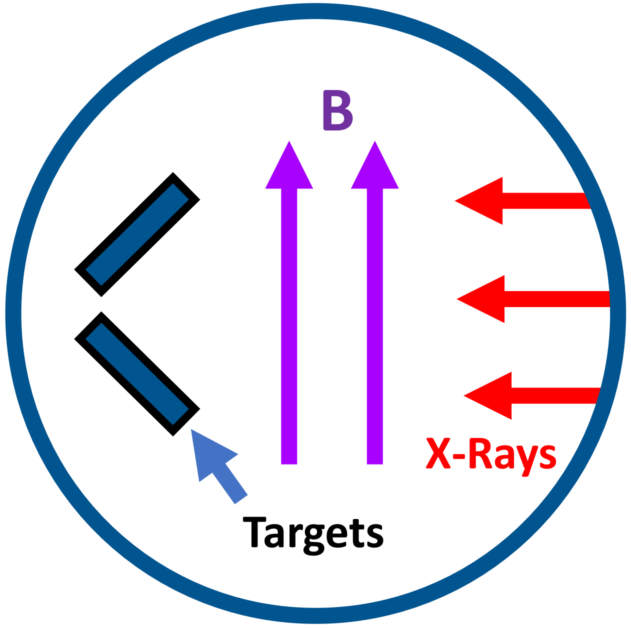
Future work – X-Ray ablated plasma collisions

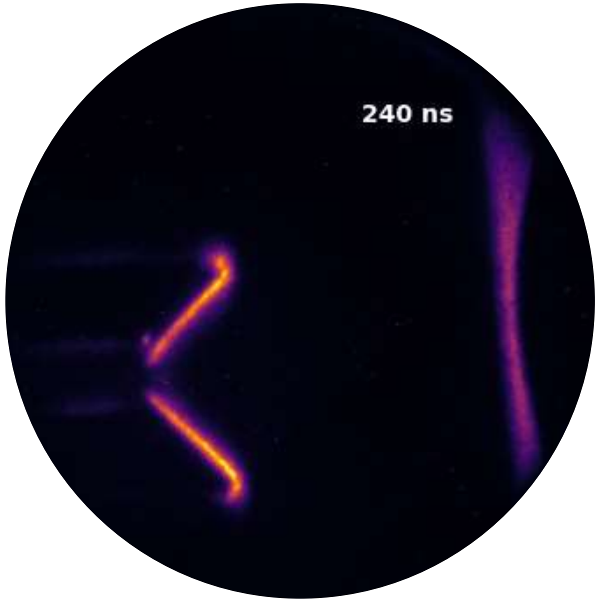




Normal incidence

- Structure of stagnated layer determined by radiative cooling
- Use targets of two different materials to investigate mix
- Large system sizes $(L \sim 10\ \mathrm{mm})$

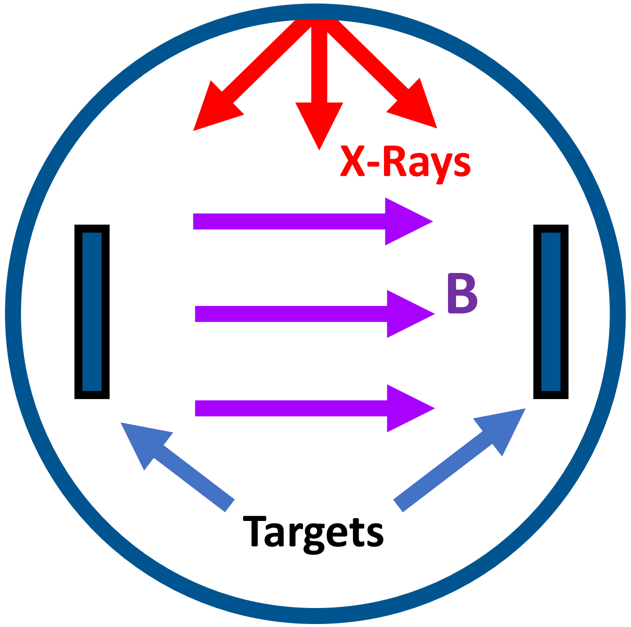


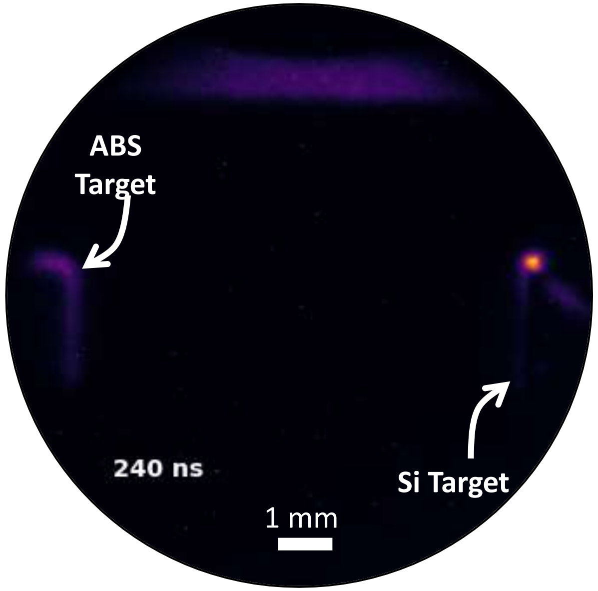


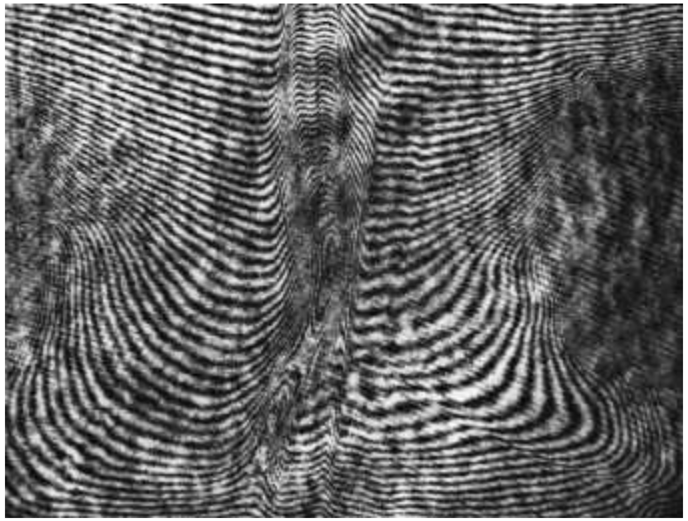
Oblique incidence

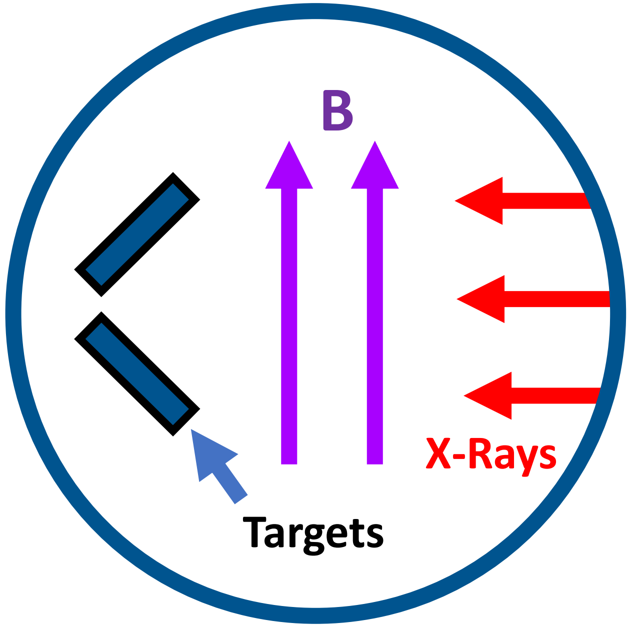
- Radiatively cooled jet is produced
- Vacuum-plasma interface with stark difference in morphology

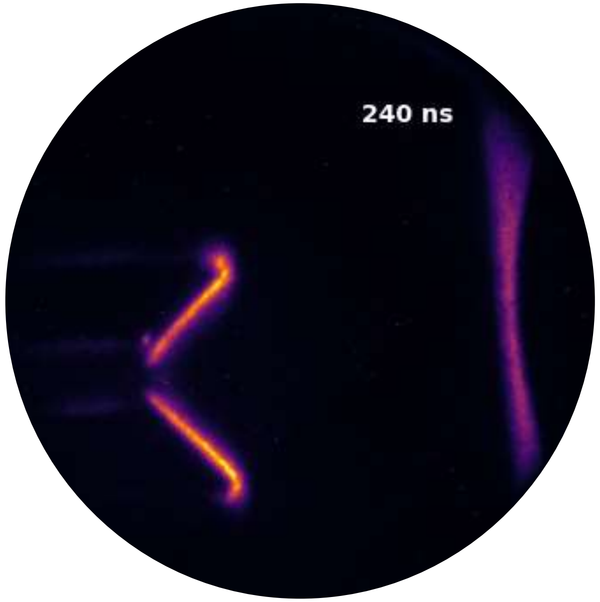
Future work – X-Ray ablated plasma collisions

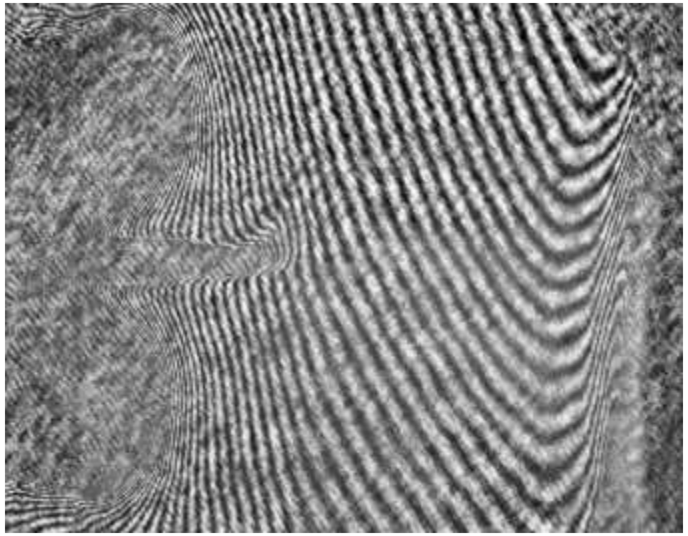




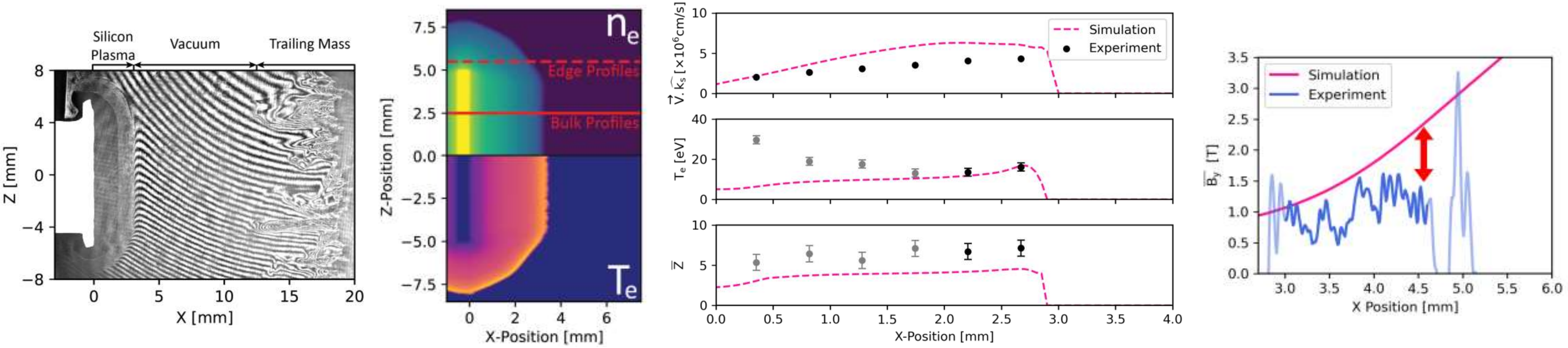








Conclusions



- Density profiles strongly influenced by ambient B field
- Saw influence of Thomson probe heating
- Radiation field perturbs the charge state distribution (?)
- Magnetic flux was excluded from expanding silicon plasma

Stagnation layer: Thomson measurements

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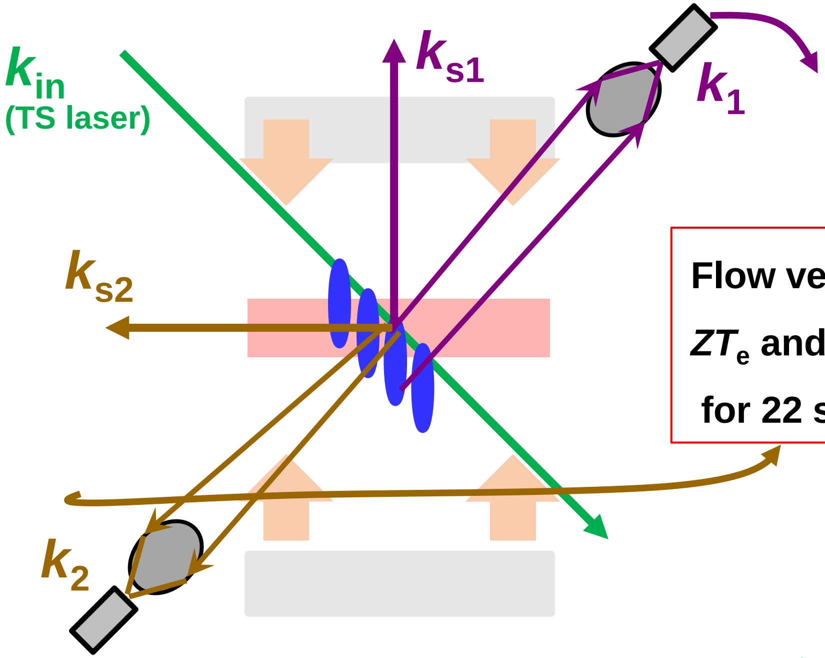
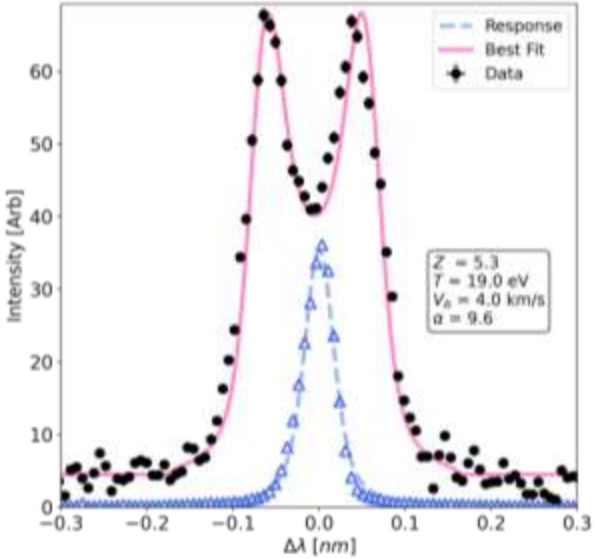


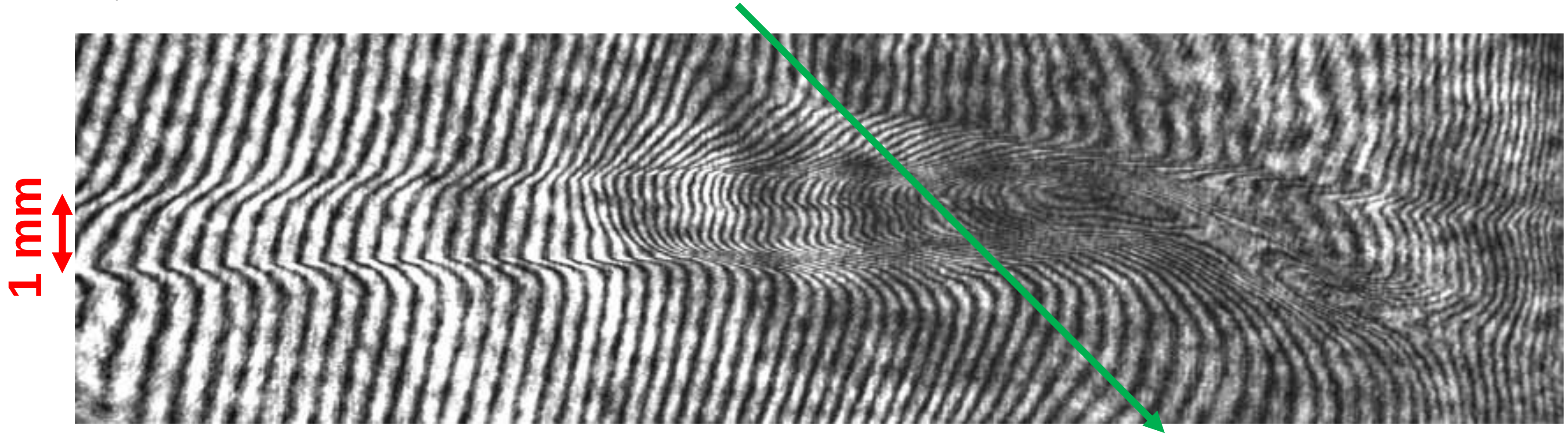
Collective scattering from Ion Acoustic Waves



Flow velocities (V_x , V_y)

ZT_e and T_i

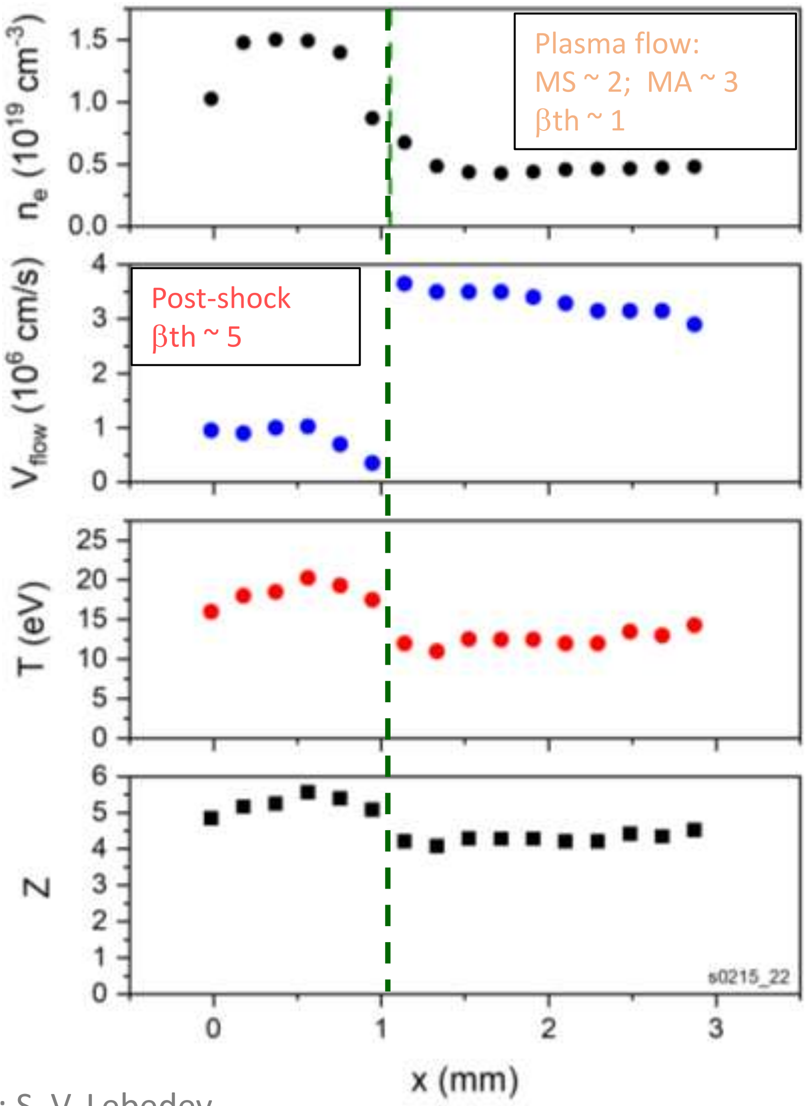
for 22 spatial positions



Slide credit: S. V. Lebedev

Stagnation layer parameters

Flow velocity and temperature profiles



Initial ion temperature:

$$E_{ion} = \frac{m_i V_{flow}^2}{2} \approx 250eV \Rightarrow T_{ion} \approx 90\,eV$$

Fast Ti – Te equilibration:

$$\tau_{ei}^{E} \approx 5\,ns \Rightarrow C_S \cdot \tau_{ei}^{E} \approx 0.1mm$$

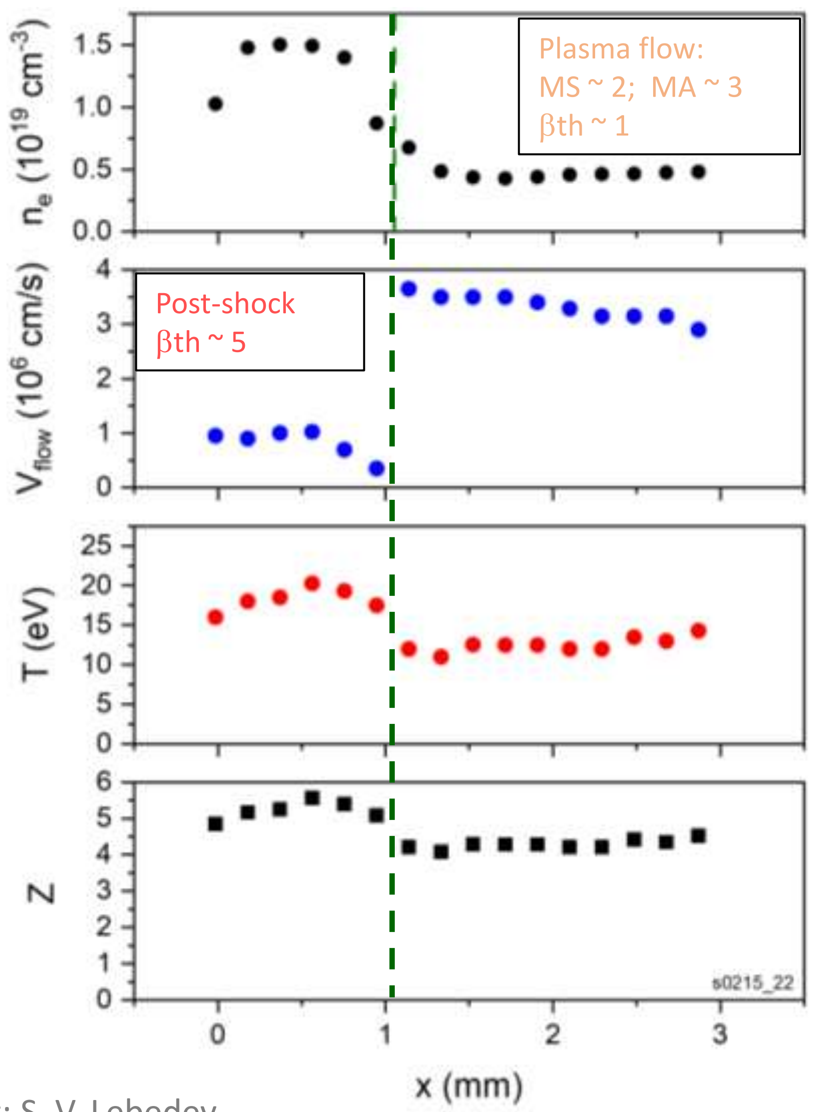
$$\Rightarrow \Delta T \approx 15\,eV \quad for\, T_e = T_i \quad and\; Z = 5$$

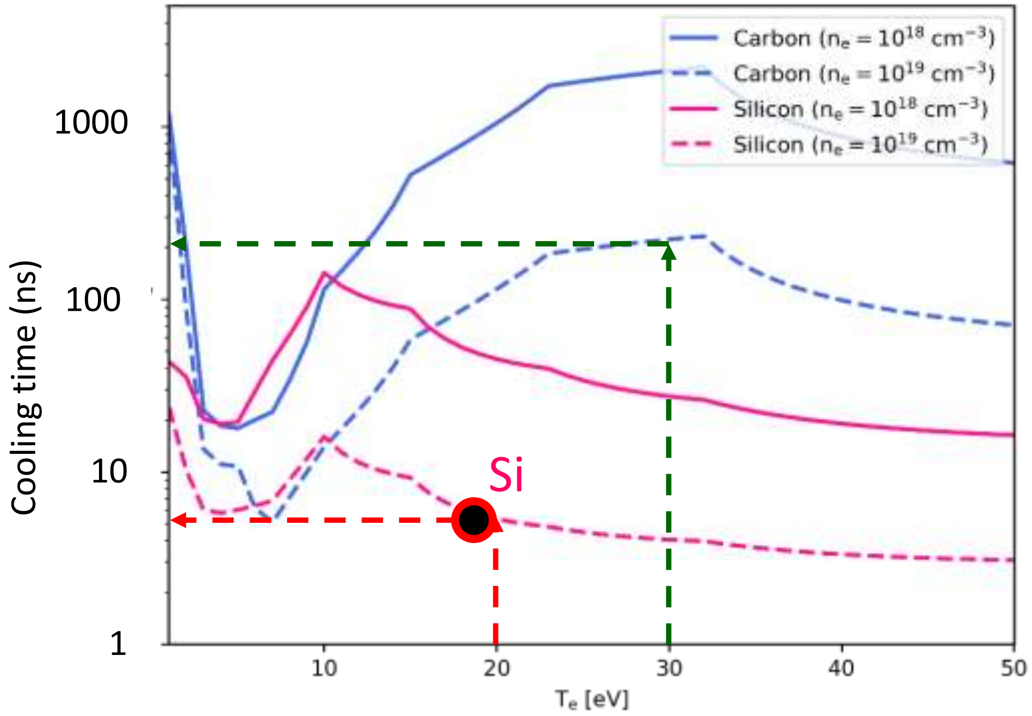
Radiative cooling time ?

Slide credit: S. V. Lebedev

Stagnation layer parameters

Flow velocity and temperature profiles





Radiative cooling time for Si:

$$\tau_{cool} \approx 5\,ns \Rightarrow \chi = \tau_{cool} / \tau_{hydr} < 0.1$$

For Carbon at 30 eV:

$$\tau_{cool} \approx 200\,ns \Rightarrow \chi \sim 10$$

Slide credit: S. V. Lebedev