Radiatively Driven Experiments on the MAGPIE Pulsed-Power Generator

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[1] University of Oxford; [2] Imperial College London; [3] University of Nevada, Reno; [4] Technische Universität München;

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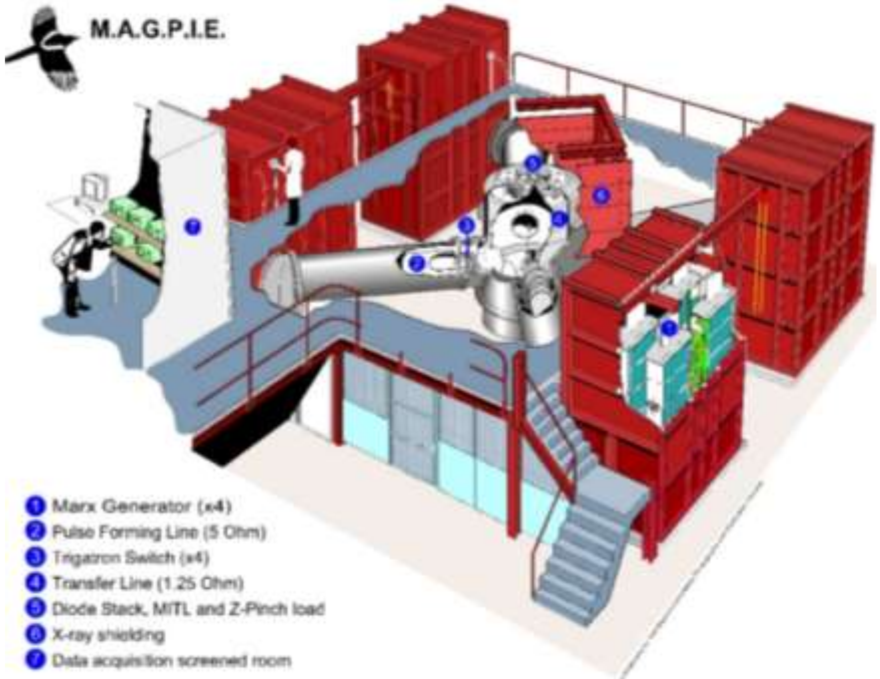
Imperial College London | UNIVERSITY OF OXFORD | MAGPIE | CIFS | University of Nevada, Reno

This work was supported by the US Department of Energy under Award Nos. DE-SC0020434 and DE-NA0003764, and by the US Defence Threat Reduction Agency under Award No. HDTRA1-20-1-0001. Some additional computing support was provided by the UK Central Laser Facility (CLF). My current position is supported by the UK Engineering and Physical Sciences Research Council under Award Nos. EP/X01133X/1 and EP/X010791/1.

Experimental facility and diagnostics

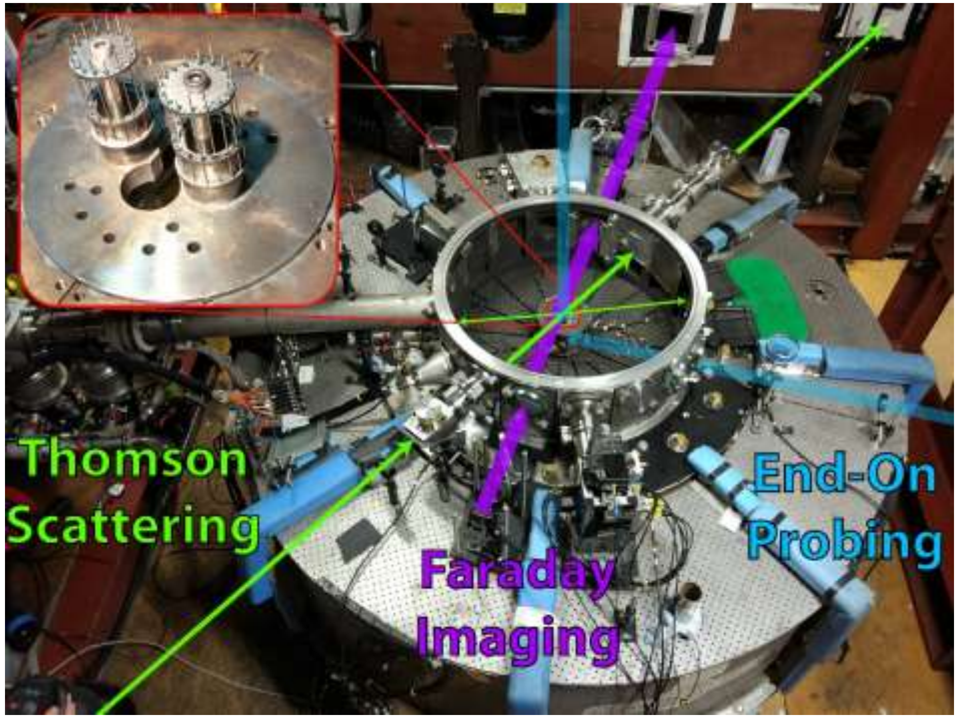
1.4 MA, 240 ns, 1 TW, 250 kJ



$\sim$ 30 kJ delivered to a load

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

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

Current driven laboratory astrophysics on MAGPIE

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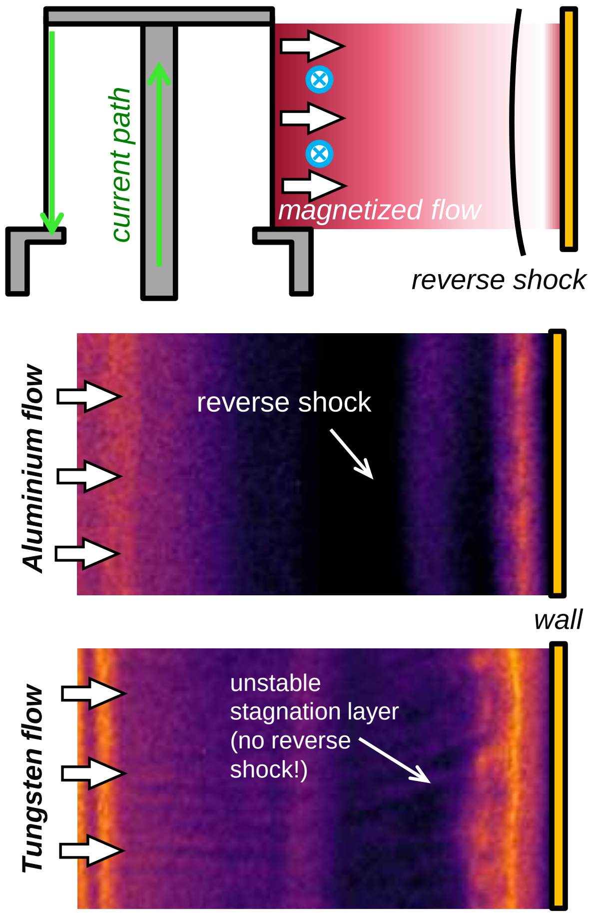
Instabilities in magnetized shock experiments

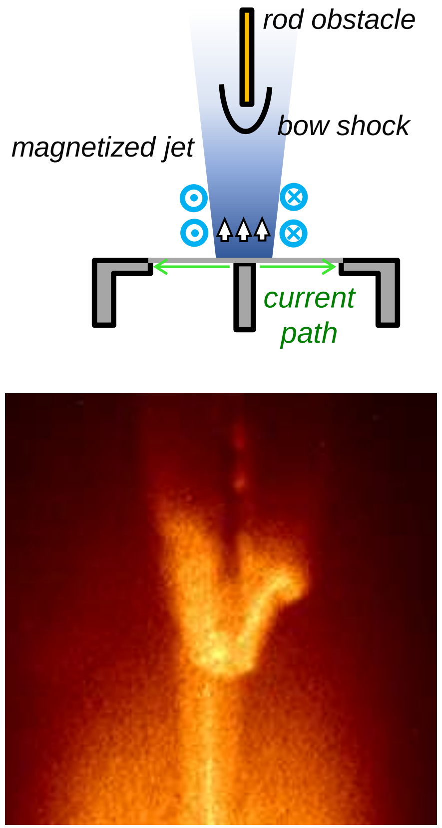
S. Merlini



S. Merlini+ arXiv:2306.01847

Shocks in magnetic tower jet experiments

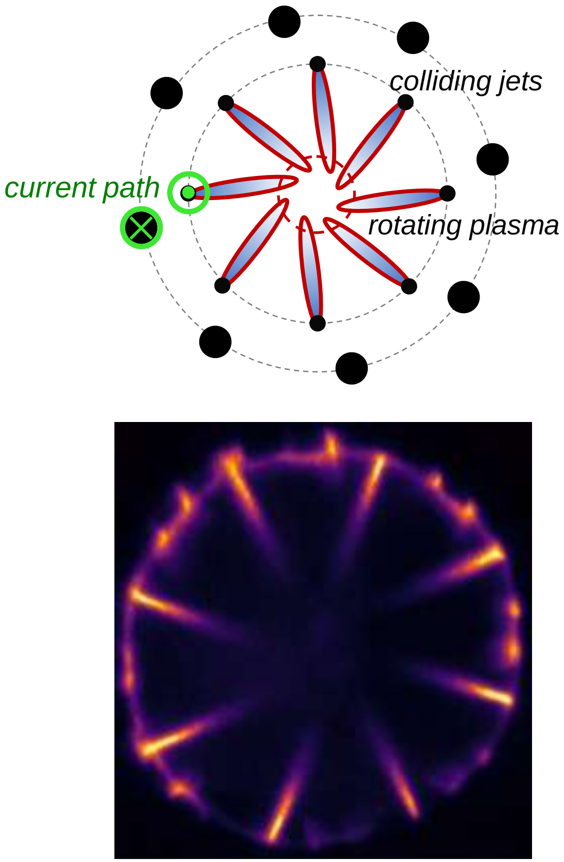
D. Russell / F. Suzuki Vidal



D. R. Russell+ PRL 2022

Differentially rotating plasmas

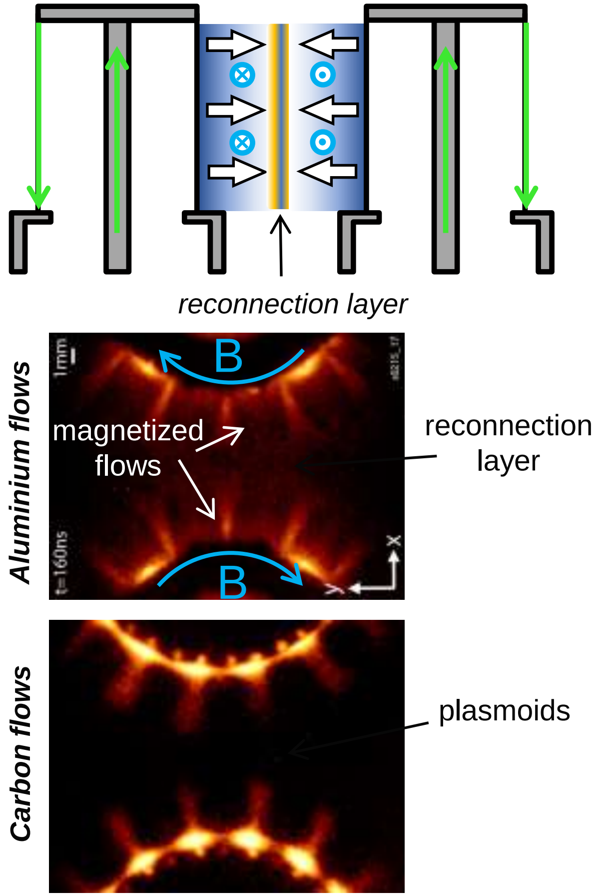
V. Valenzuela-Villaseca



V. Valenzuela-Villaseca+ PRL 2023

Magnetic reconnection experiments

L. Suttle / J. Hare



L. G. Suttle+ PRL 2016

Slide credit: V. Valenzuela-Villaseca

Overview of experimental setup

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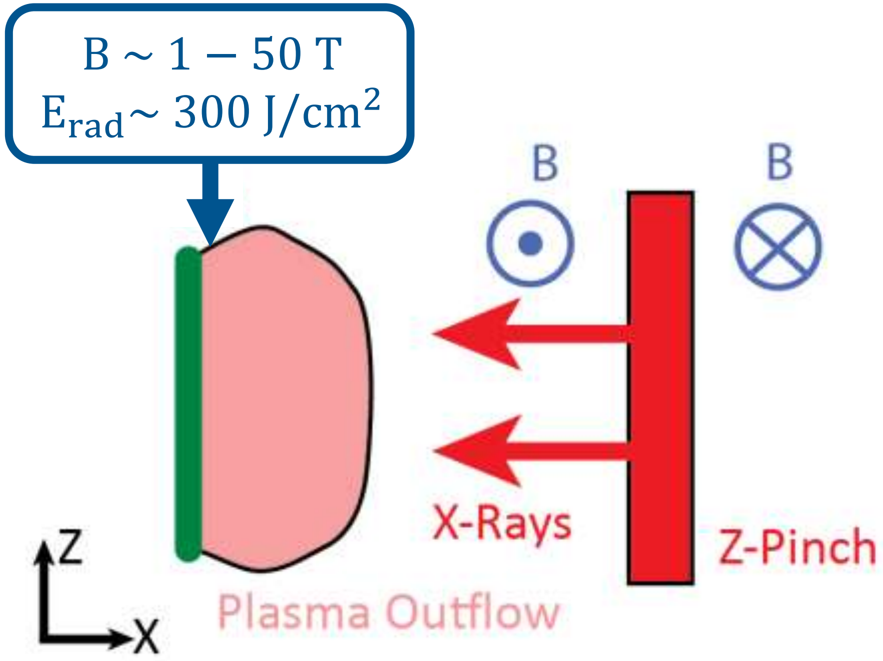
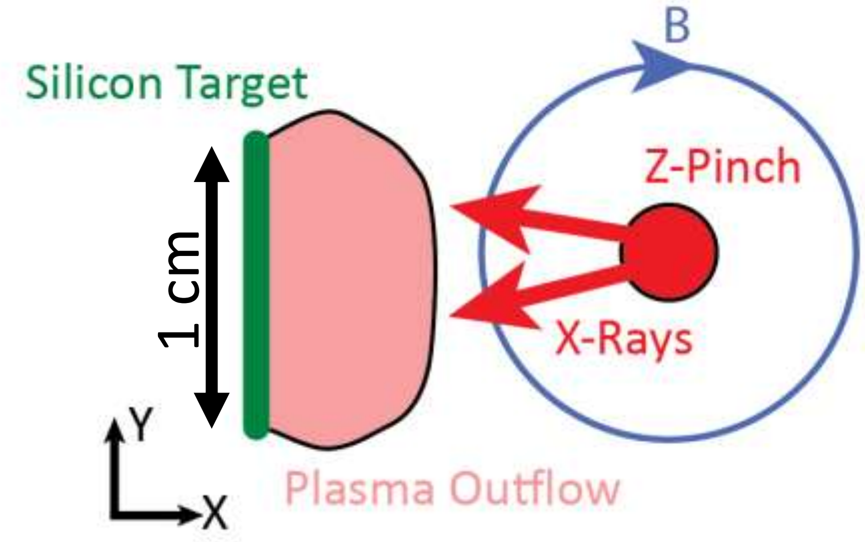


Side-On (X-Z plane) view of the experiment



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

- X-Rays from aluminium wire array Z-Pinch
- $T_B \sim 10$ eV on target
- Ablated silicon plasma expands into magnetic field ($B \sim 10$ T)
- Target size ~ 1 cm^2, irradiated uniformly

Overview & Motivation

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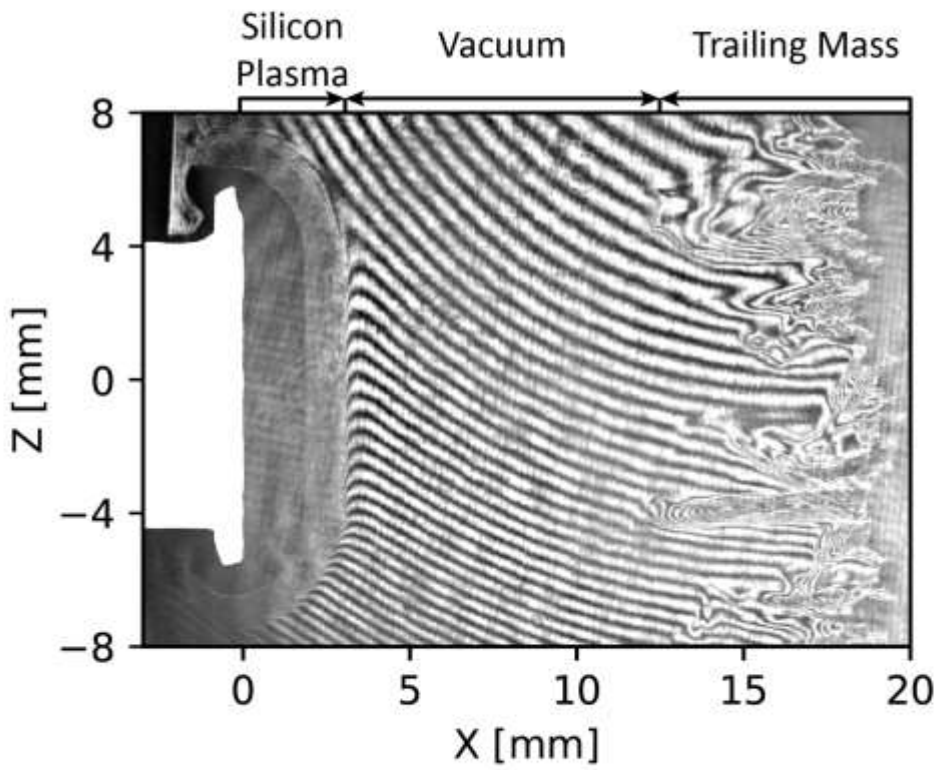
Wire arrays at 1 MA

Laser probing measurements [Halliday+ PoP 2022] characterize hydrodynamics

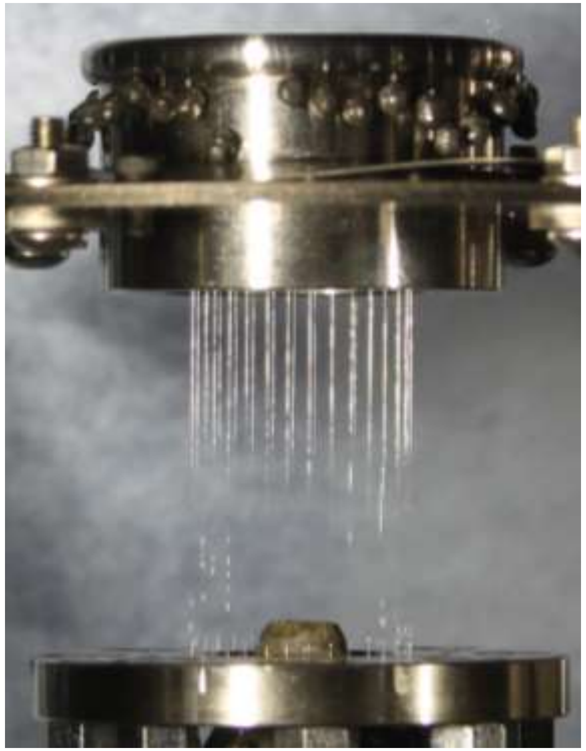
Single target experiments: Cold plasma, large system size – platform is a great testbed for problems in atomic kinetics

Two target experiments: Potential to study radiative instabilities using colliding flows

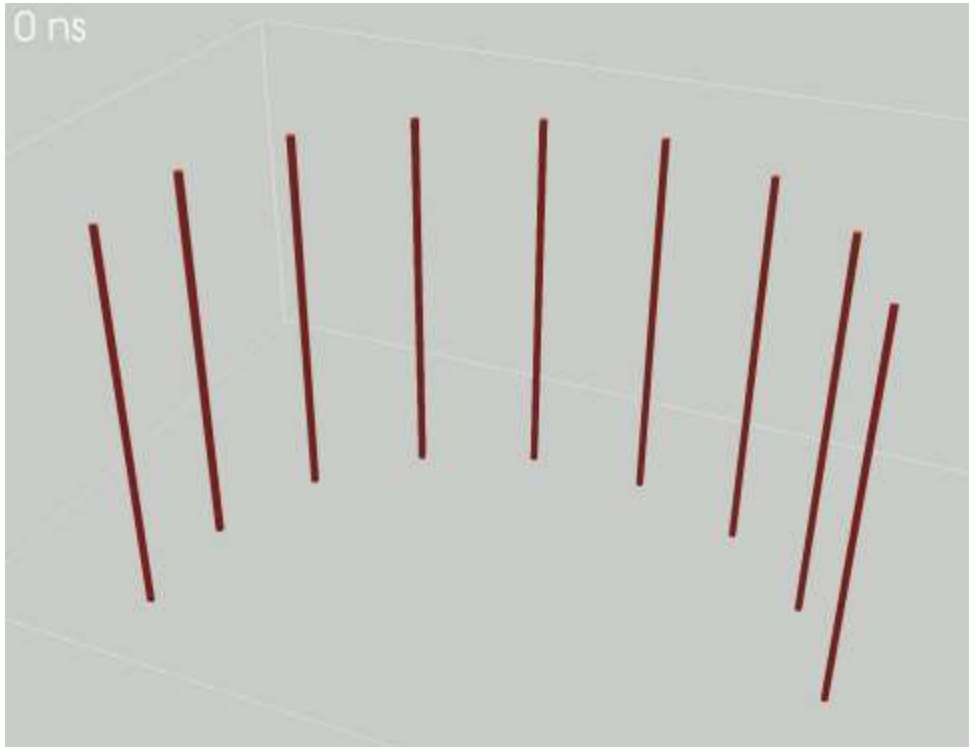


Motivation: Understand how satellites are damaged during nuclear weapon tests in the upper atmosphere.

Wire array Z-pinch experiments on MAGPIE



A 32-wire aluminium array used in MAGPIE experiments



Mass density from Gorgon (MHD) simulation

Spectral Character of Radiation at ~1 MA Level

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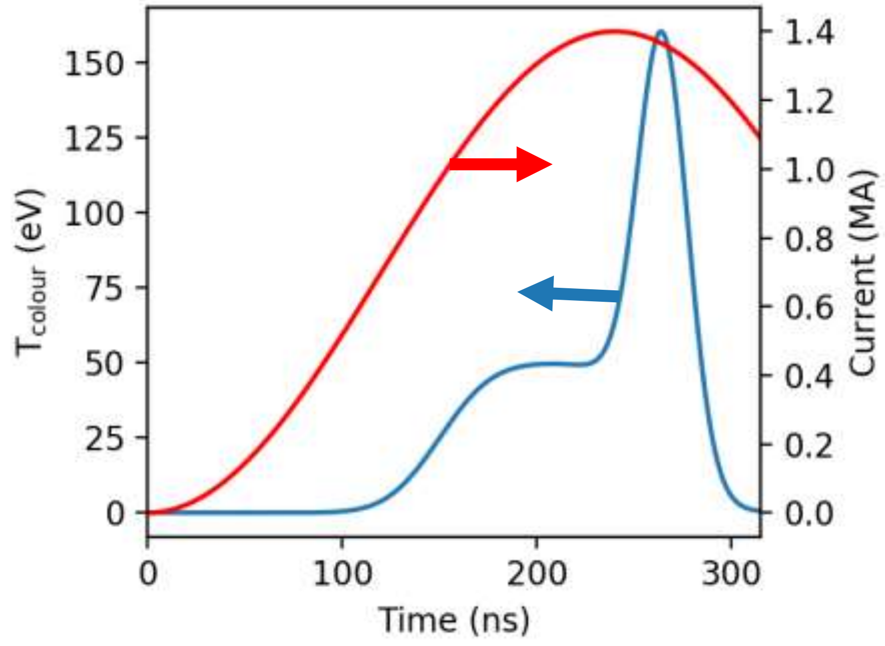
- **Precursor:**
  - Longer pulse
  - Colder spectral character ($T_c \sim 30$ eV)
  - Radiates ~ 400 J in total
- **Implosion:**
  - Emitted radiation ~ 15 kJ over ~ 30 ns
  - Non-thermal: forest of L shell lines
  - Some K-Shell radiation also
  - Estimate $T_c \sim 150$ eV



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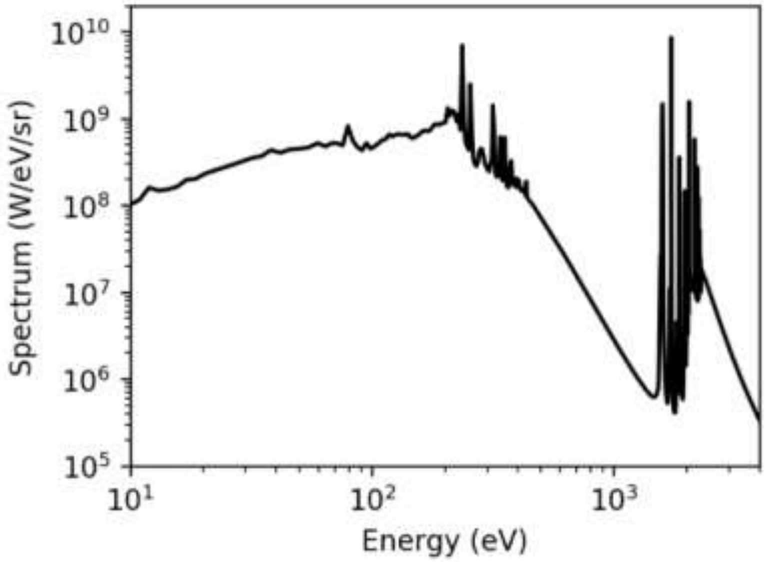

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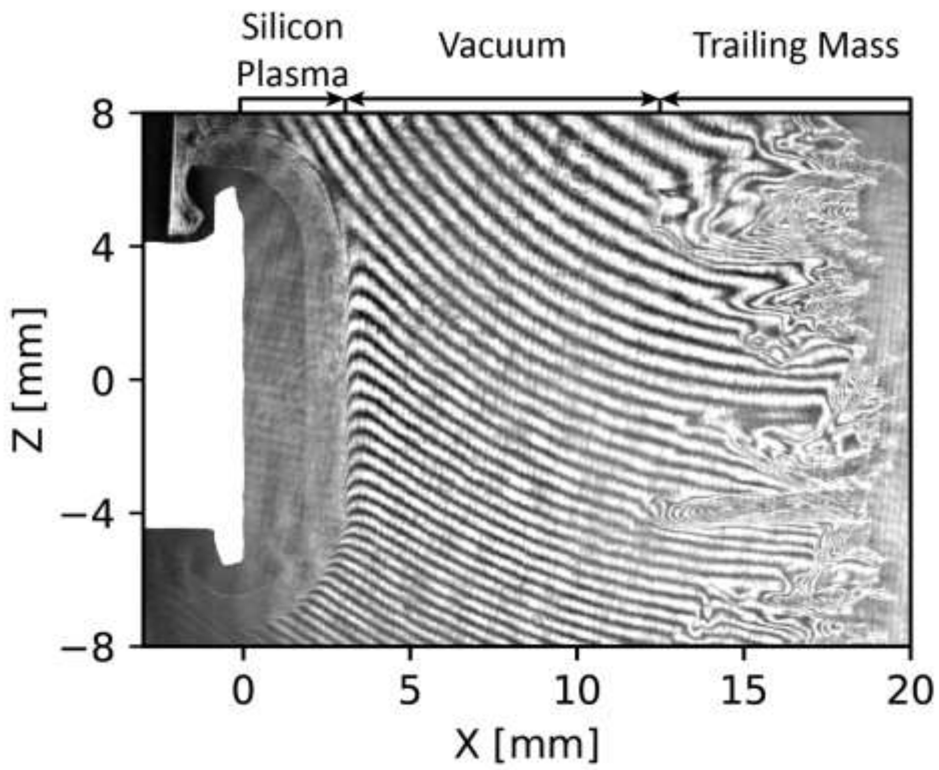
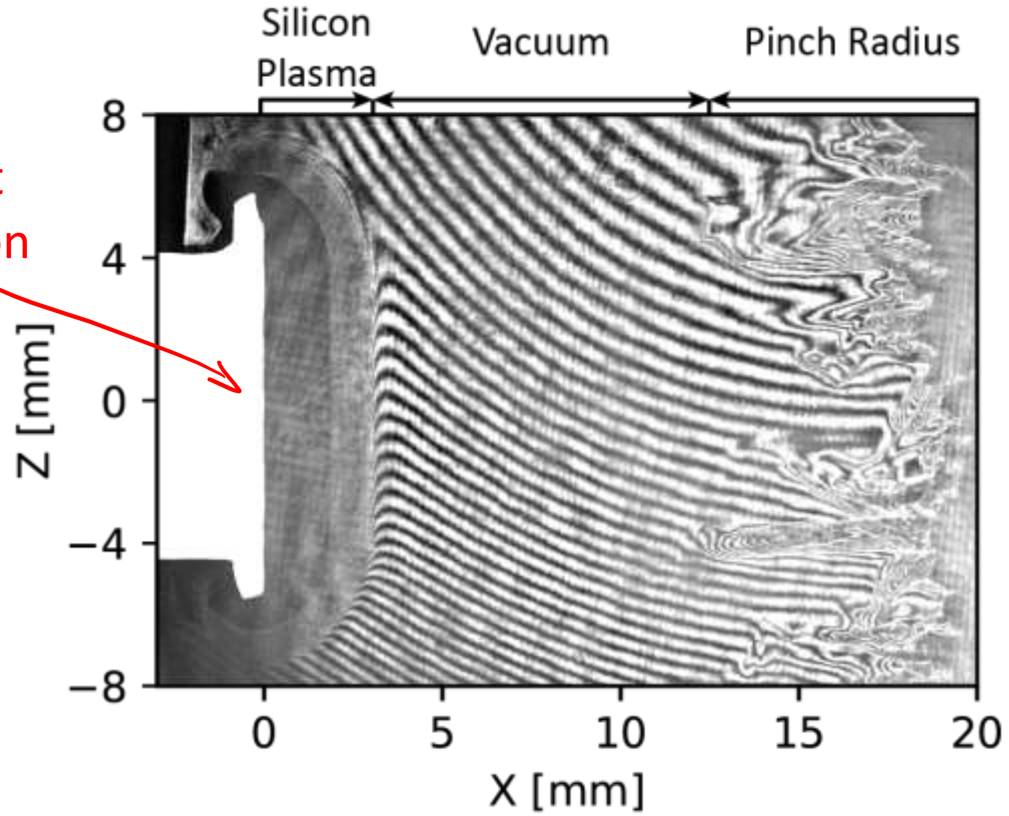
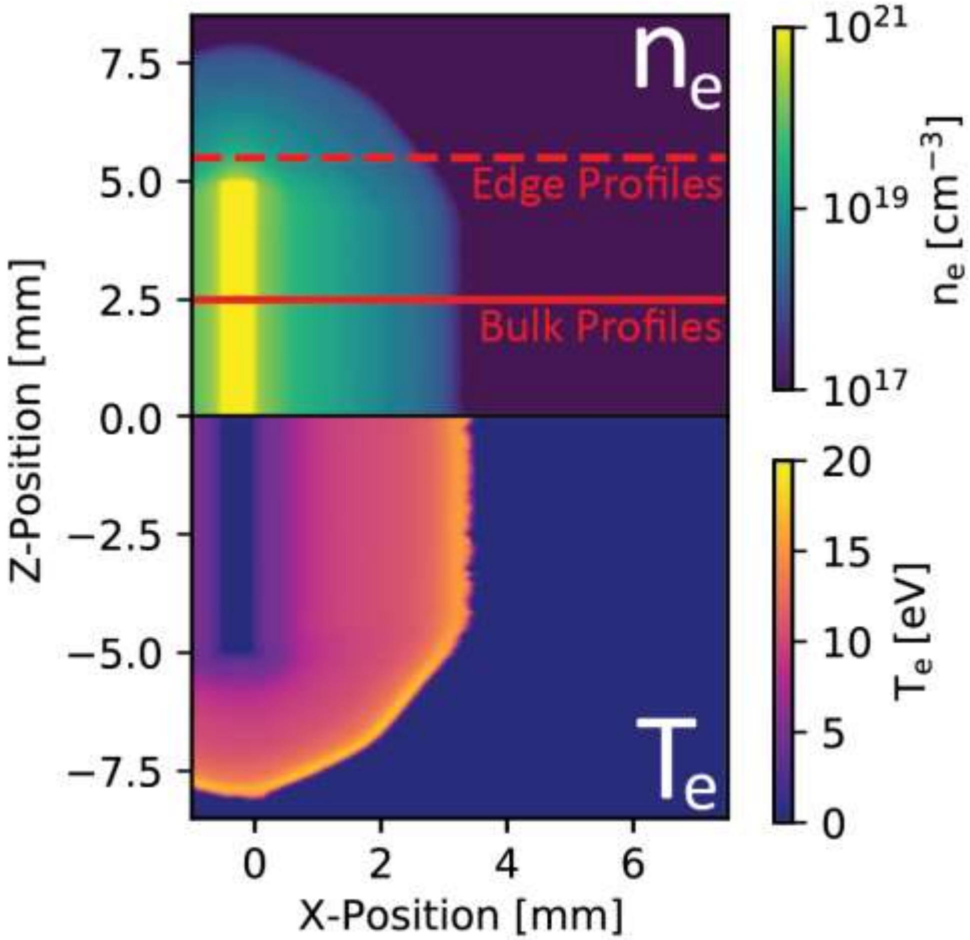


Motivation: Understand how satellites are damaged during nuclear weapon tests in the upper atmosphere.

Plasma outflow is extremely simple





- Smooth ~1D expansion profile confirmed by orthogonal laser probing
- Density profiles well reproduced by R-MHD simulations performed with Chimera

Halliday+ PoP 2022

R-MHD simulations were performed with Chimera

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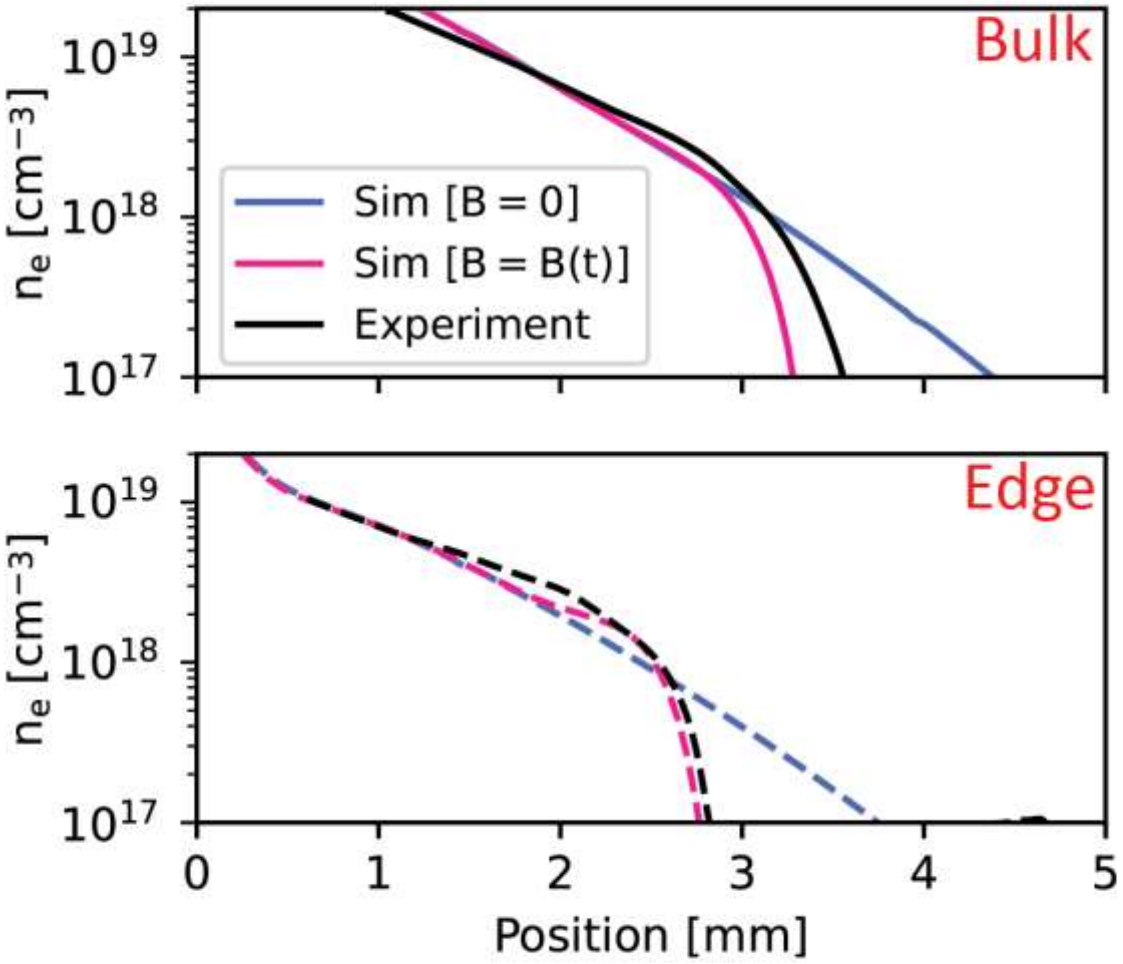
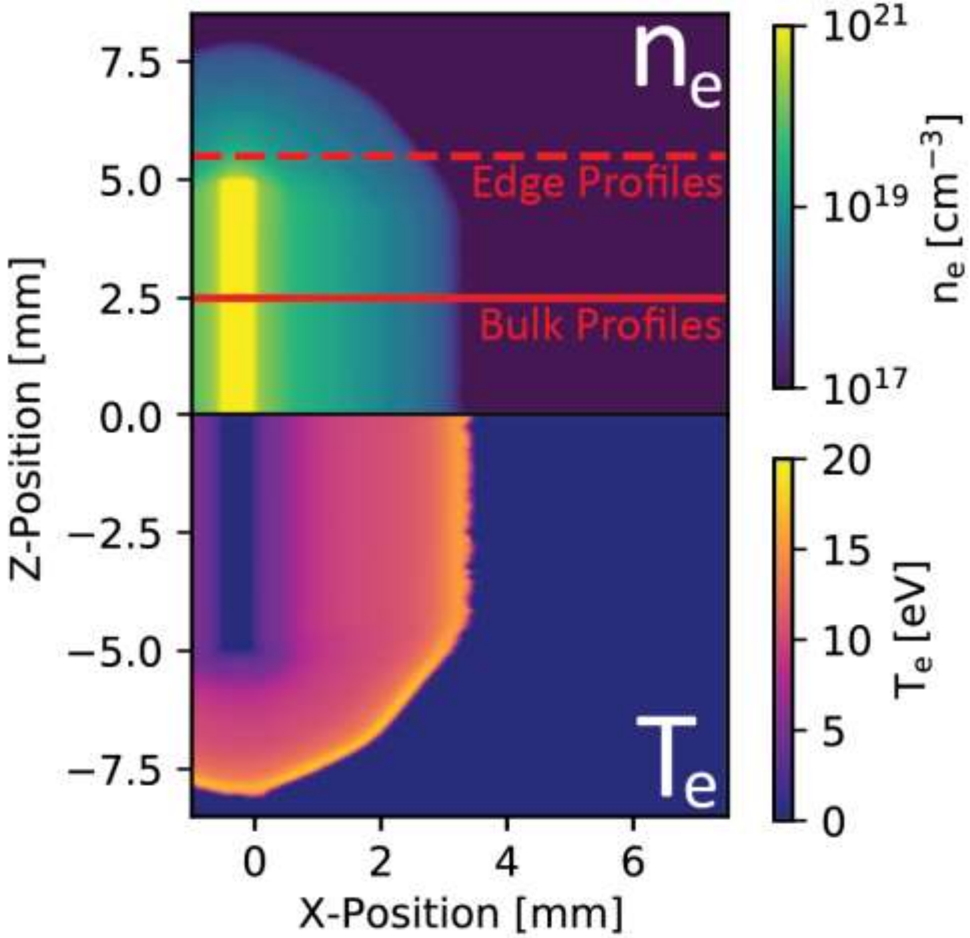
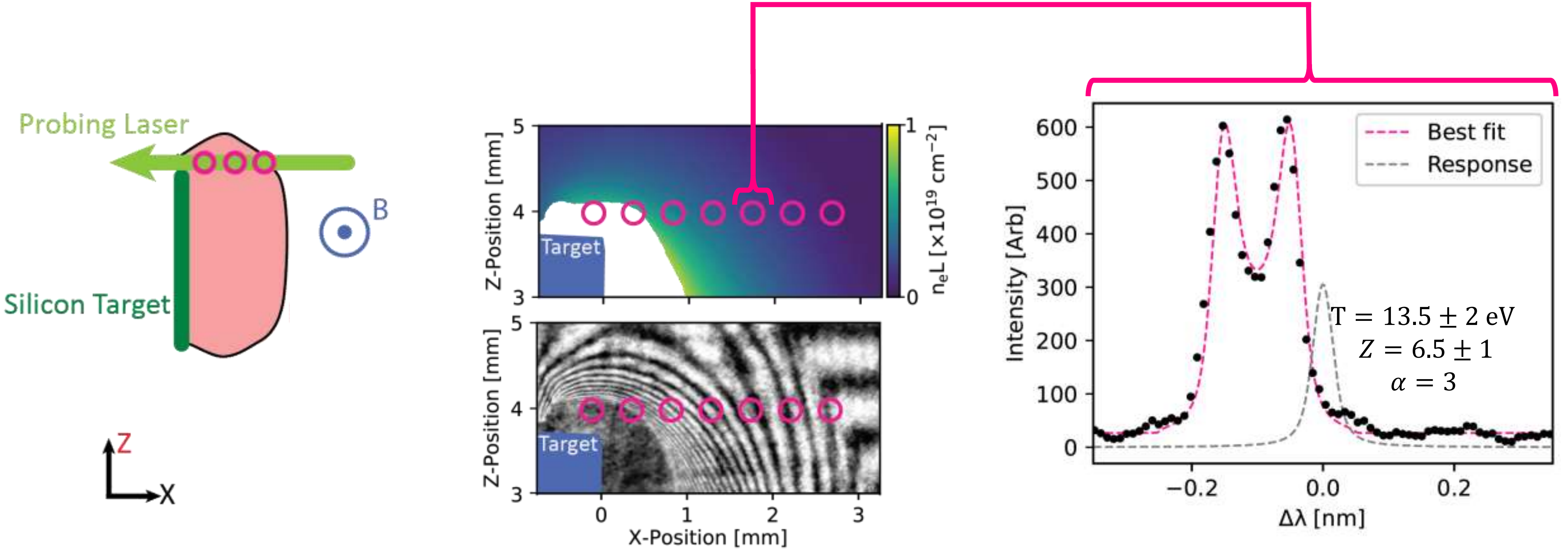




Halliday+ PoP 2022

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



Halliday+ PoP 2022

Measured $\bar{Z}$ is higher than the CR equilibrium value

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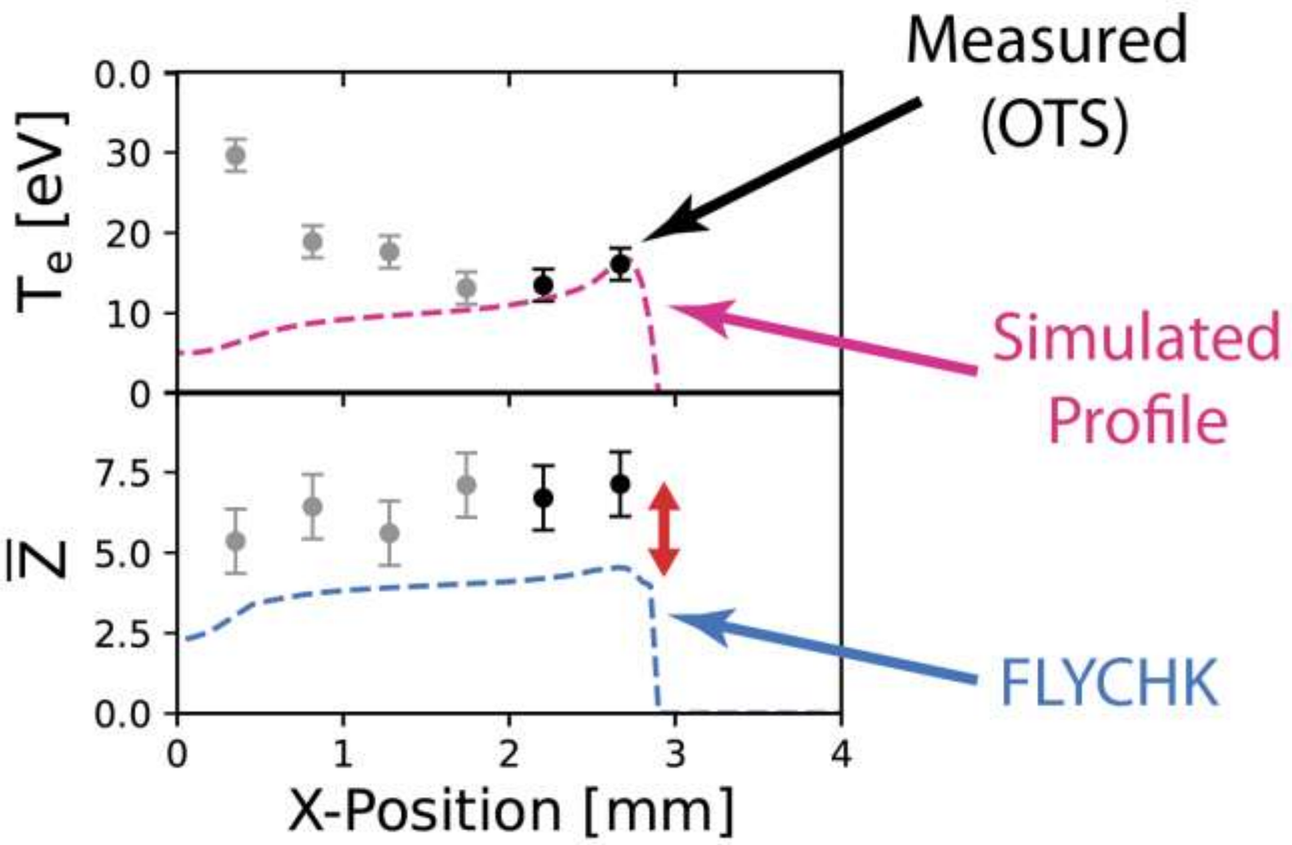
- Data points are experimental measurements from IAW Thomson scattering
- Pink curve indicates results from R-MHD simulations
- Blue curve derived by applying simulated n_e and T_e values to FLYCHK simulations (no external radiation field)
- **Significant disagreement in $\bar{Z}$ values**



Halliday+ PoP 2022

Charge state distribution altered by driving radiation?

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- PrismSPECT results with:

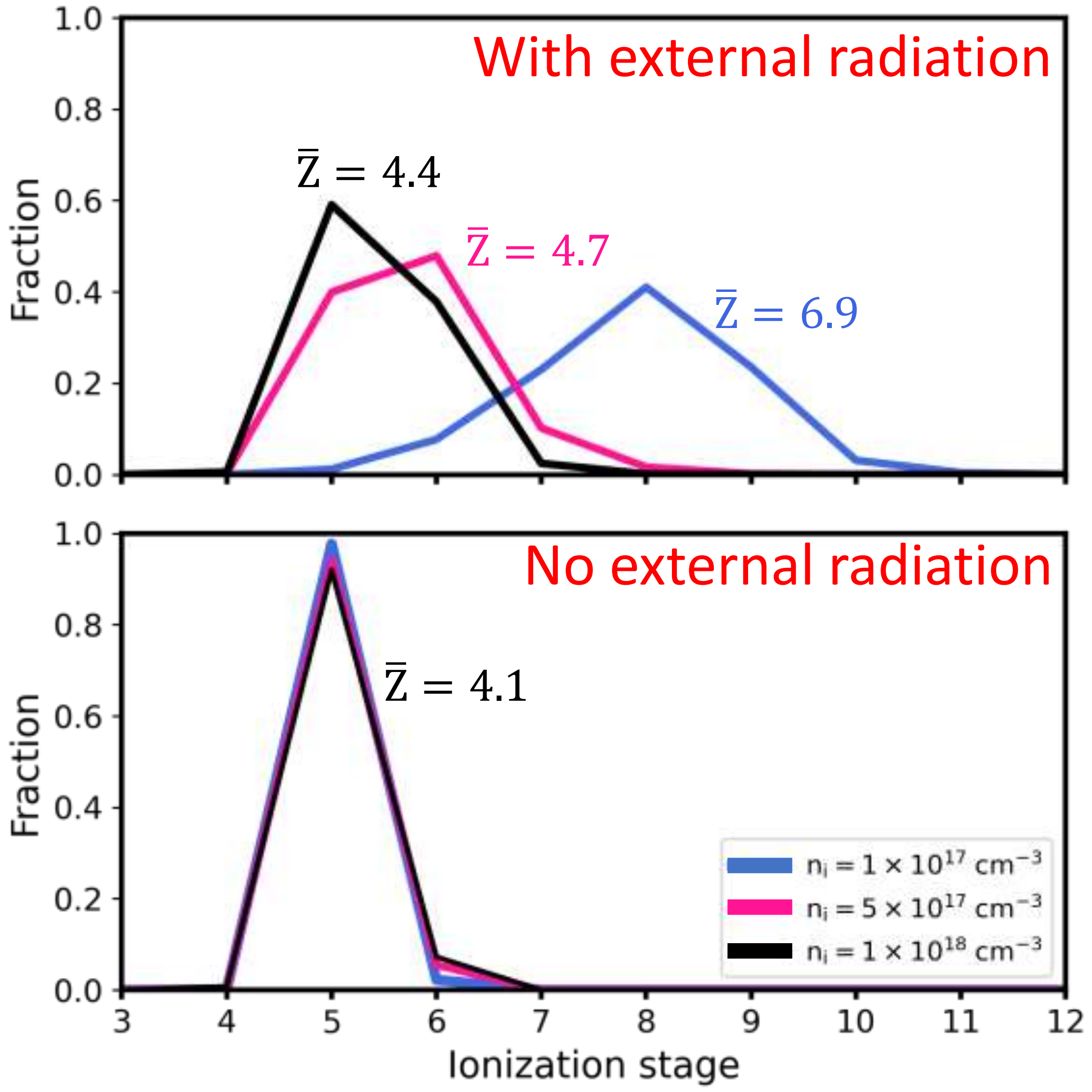
$$T_e = 10\ \text{eV}, \qquad n_i = \begin{matrix} 1\times 10^{17}\text{cm}^{-3} \\ 5\times 10^{17}\text{cm}^{-3} \\ 1\times 10^{18}\text{cm}^{-3} \end{matrix}$$

- Applied external radiation field (approximates pinch at peak emission):

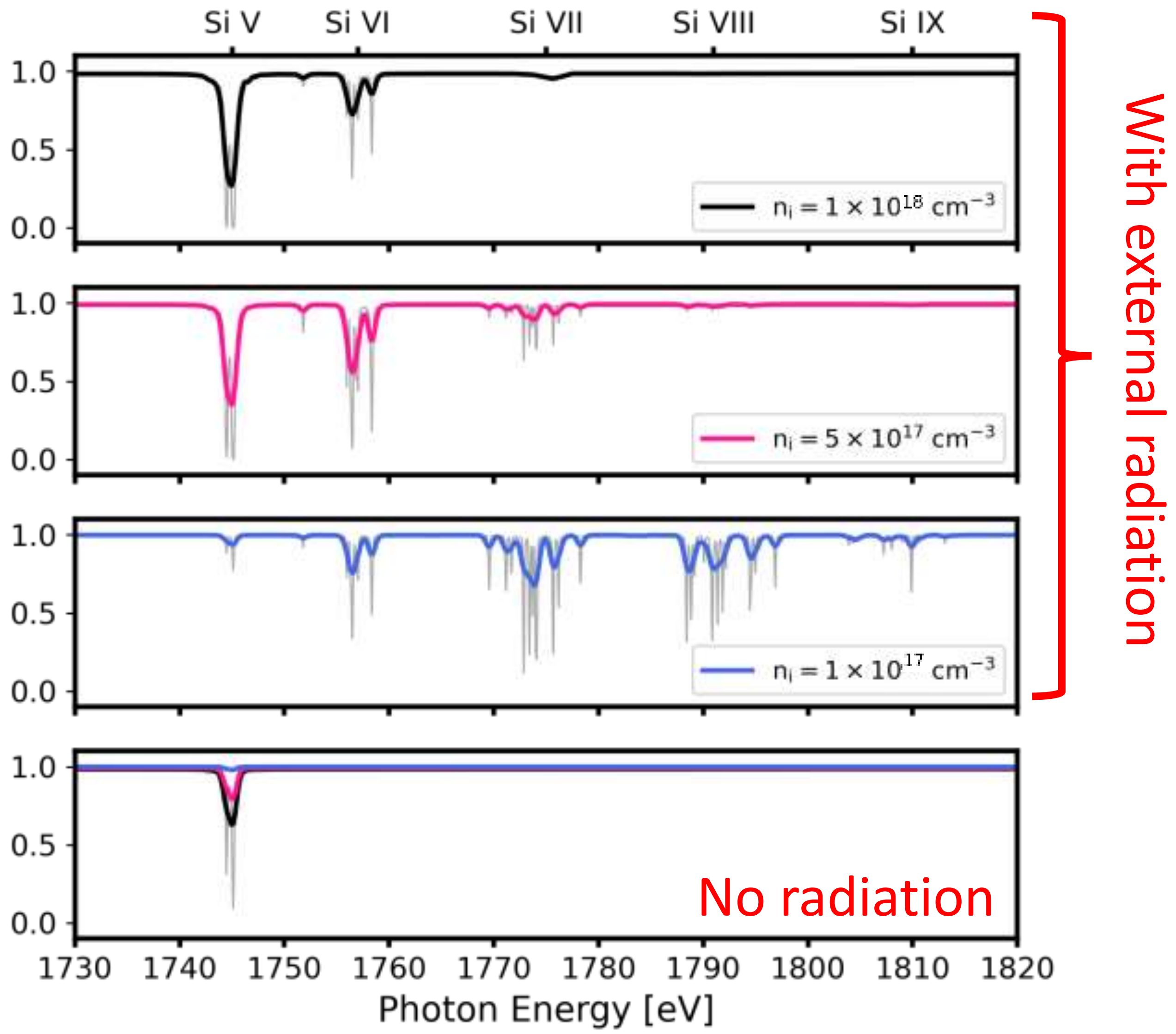
$$T_c = 150\ \text{eV}, \qquad T_B = 10\ \text{eV}$$

- Steady-state, nLTE simulation

- **Driving radiation perturbs charge state distribution**



Diagnose silicon K-Shell absorption features



- Transmission spectra are dominated by $n = 1 \rightarrow 2$ absorption features
- Absorption features for different ionisation stages spectrally separated
- Relative intensity provides diagnostic of charge state distribution
- Instrumental broadening is applied to spectra

Diagnose silicon K-Shell absorption features

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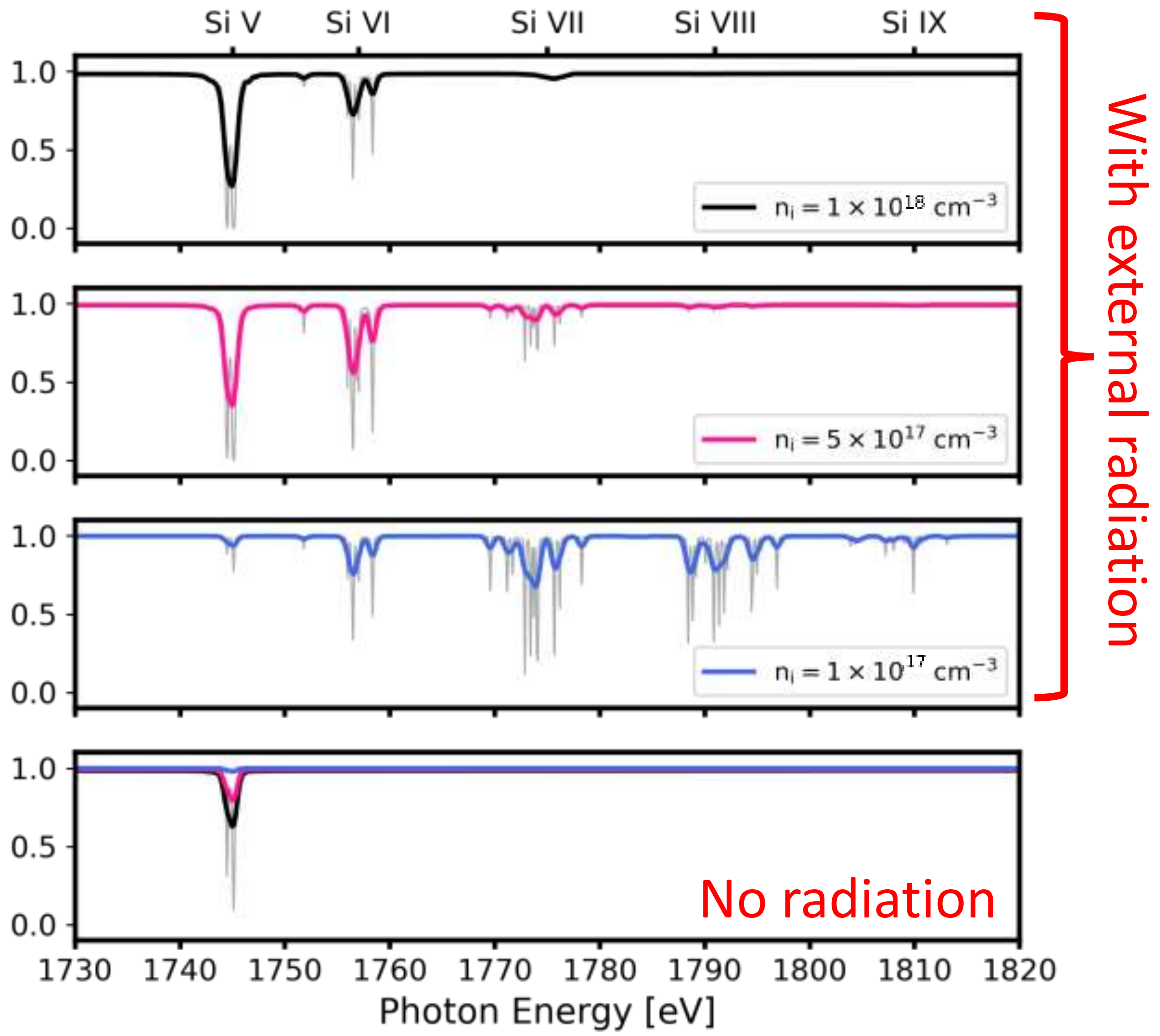
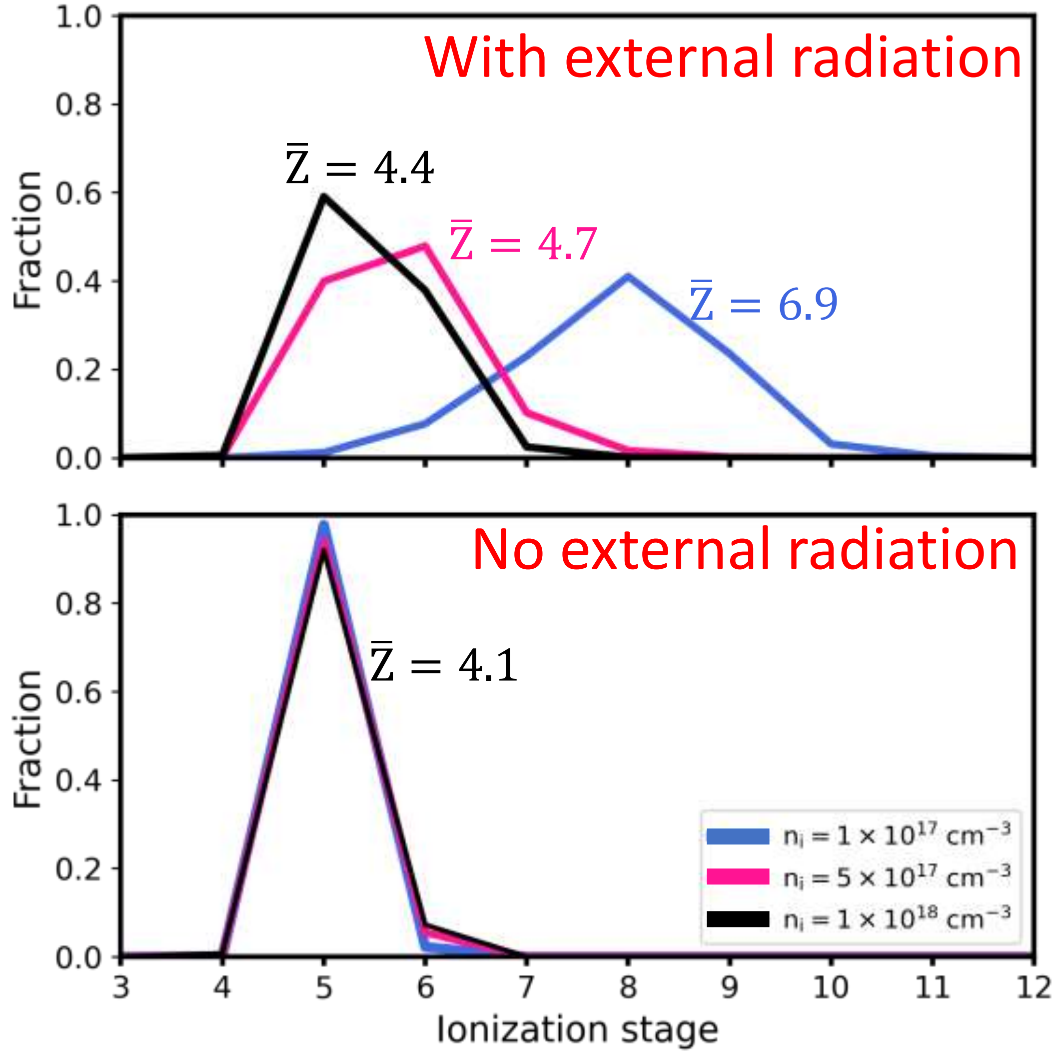
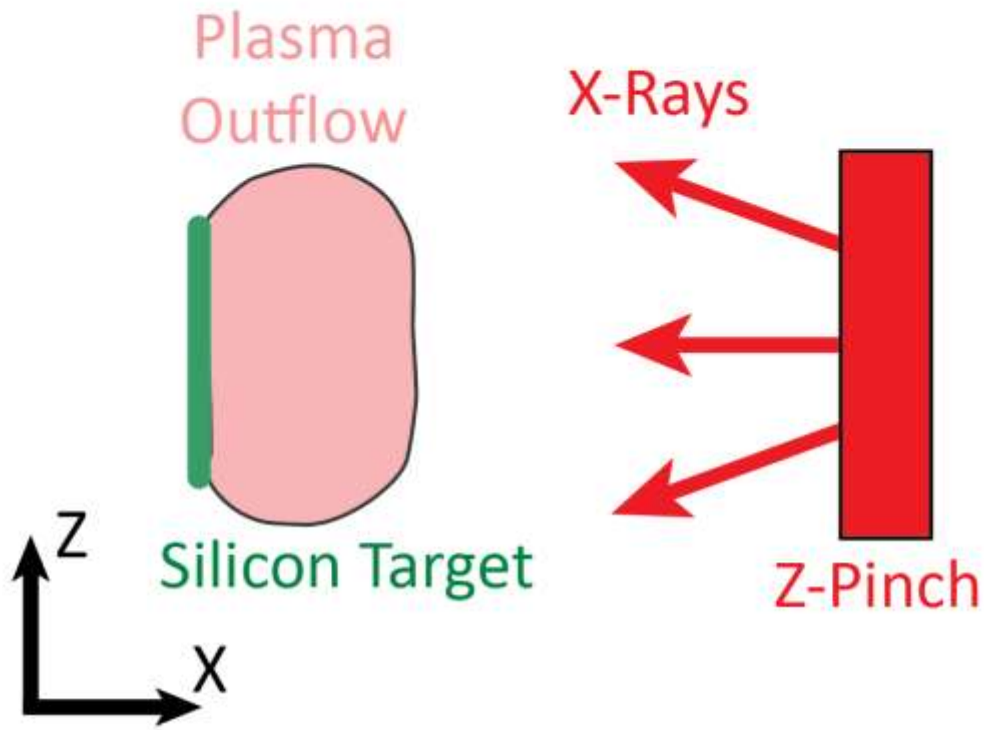
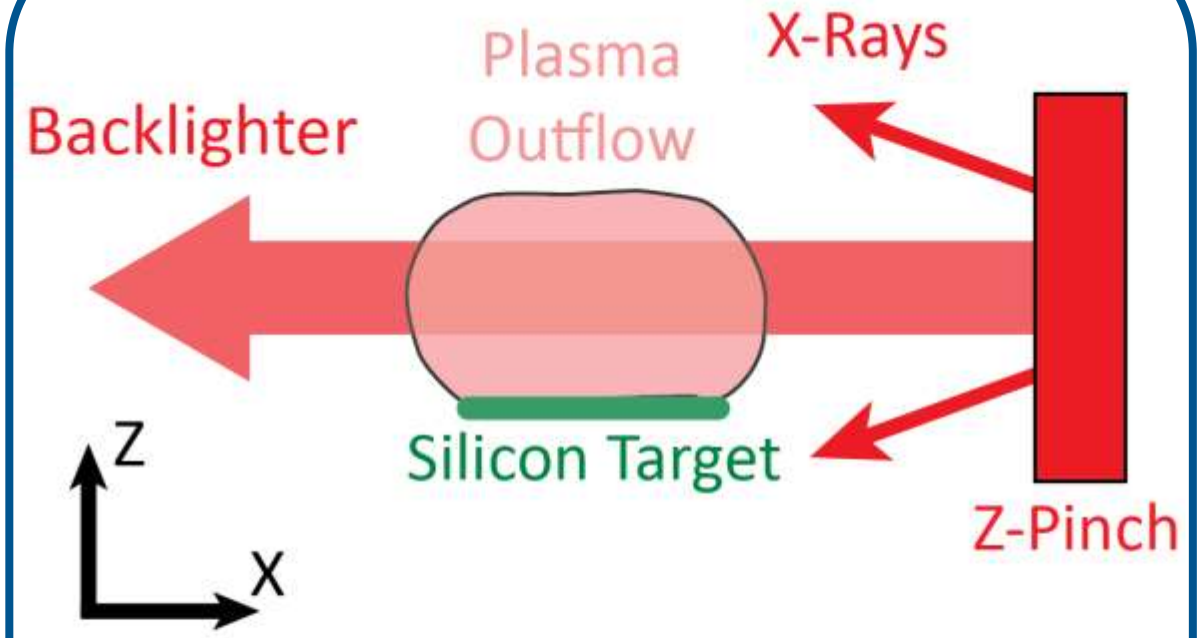




Modified setup for X-Ray absorption measurements



Existing experimental setup



Modified design for X-Ray absorption spectroscopy measurements

Spatially resolve spectra to sample range of n_e values

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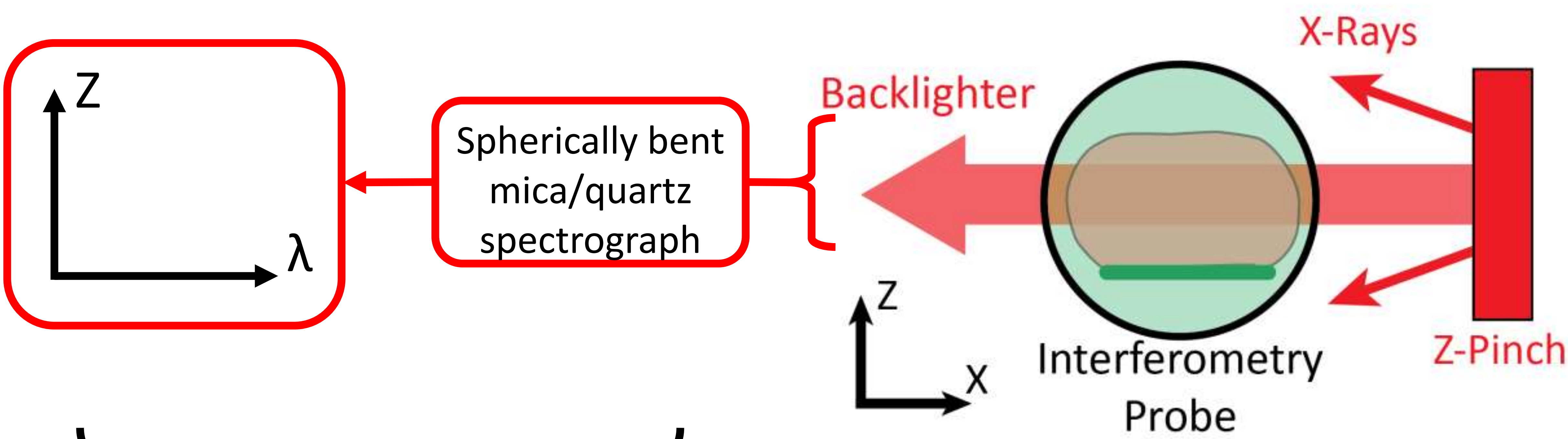

Field a curved-crystal spectrometer for spatial resolution in the direction aligned with the axis of the Z-Pinch

Probe orthogonal axis with interferometry (diagnoses $n_e[x, z]$)

Potential to access a photoionization relevant regime?

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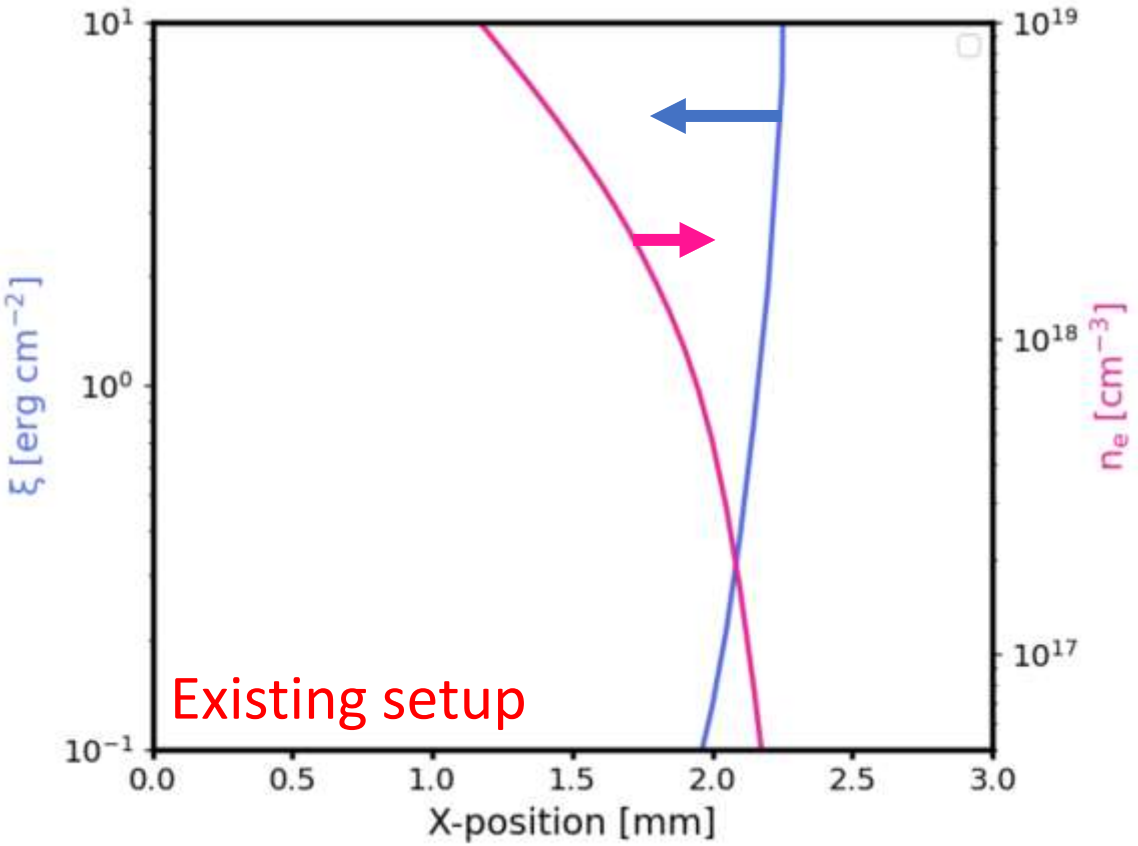
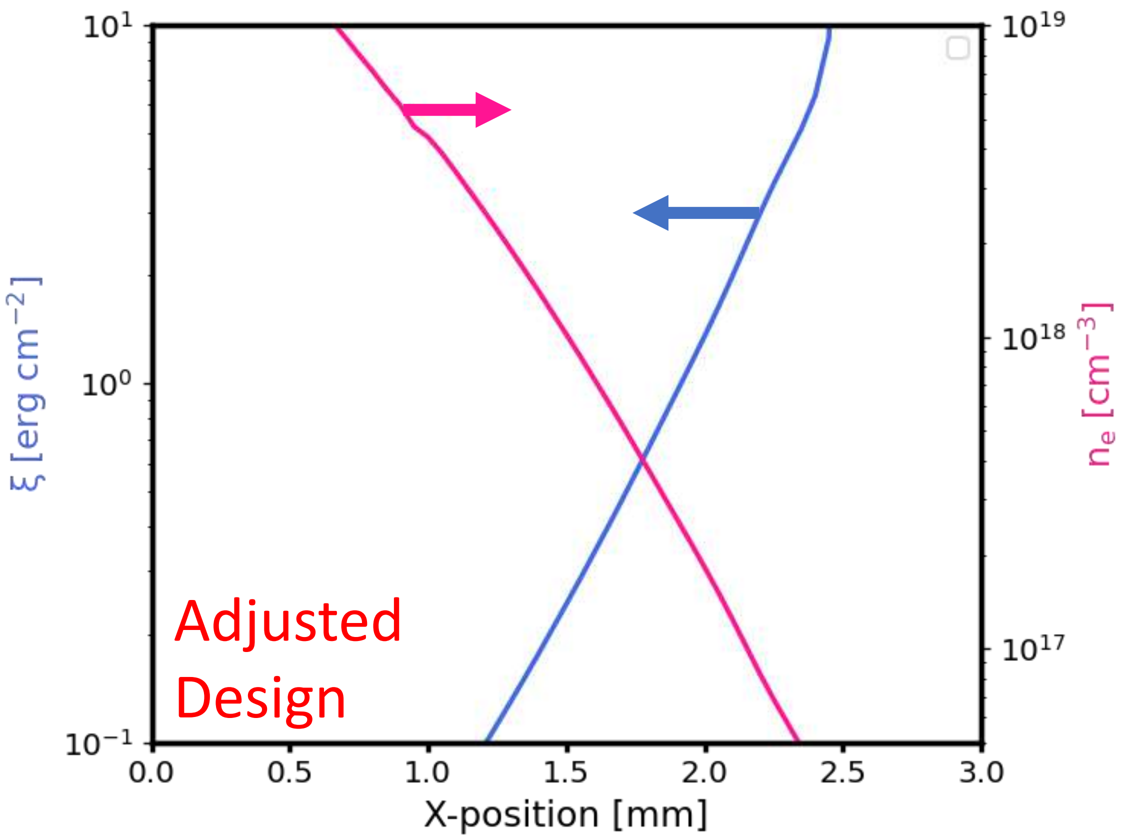
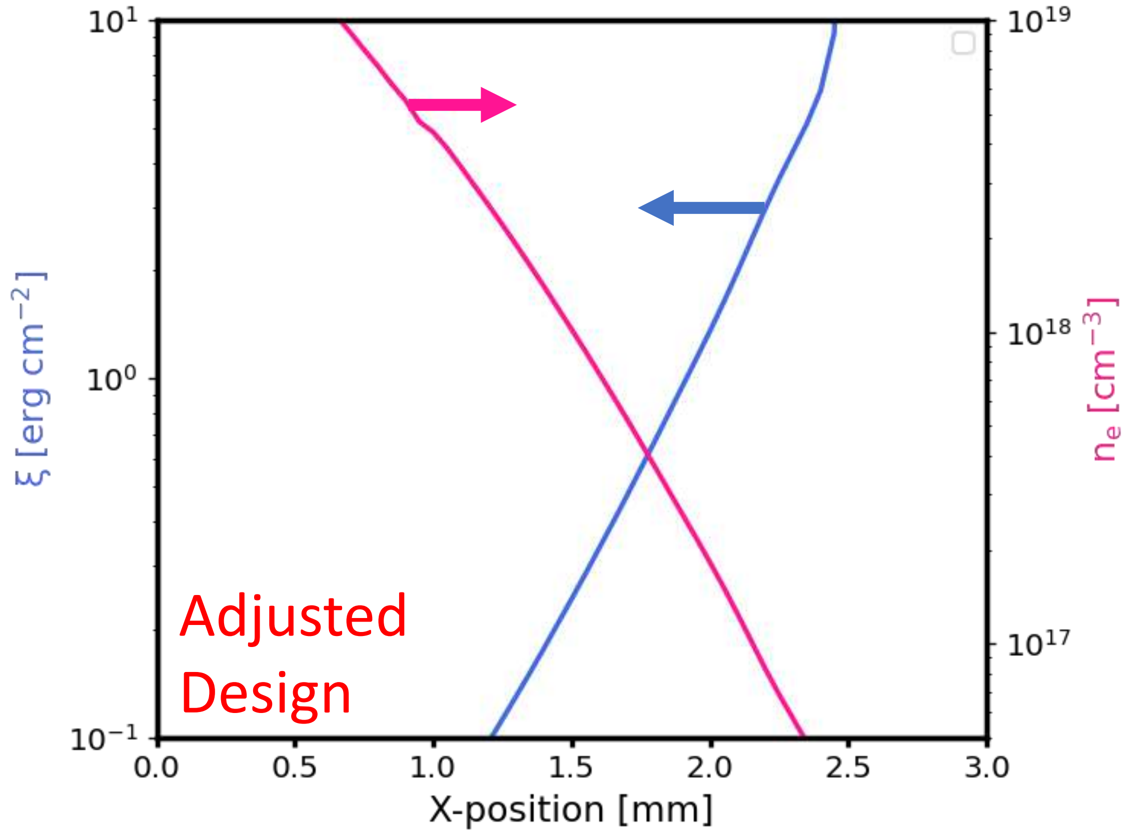




Photoionization parameter, $\xi = \int d\nu F_\nu / n_e$

Potential to access a photoionization relevant regime?

Relevance – accretion disk physics



Photoionization parameter, $\xi = \int d\nu F_\nu / n_e$

Applications in EUV Photolithography

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- Minimum feature size scales with λ
- Current state-of-the-art is EUV lithography ($\lambda \sim 13$ nm $\implies \varepsilon \sim 900$ eV)
- Source uses laser to heat $\sim$mm scale tin droplets (50 kHz rep-rate!)
- Similar density and temperature conditions to 1 MA Z-Pinch driven experiments
- Experimental data would be helpful to validate atomic kinetics modelling [J. Sheil+ EUVXRAY 2022]

Photo credit: ASML Holdings 2023

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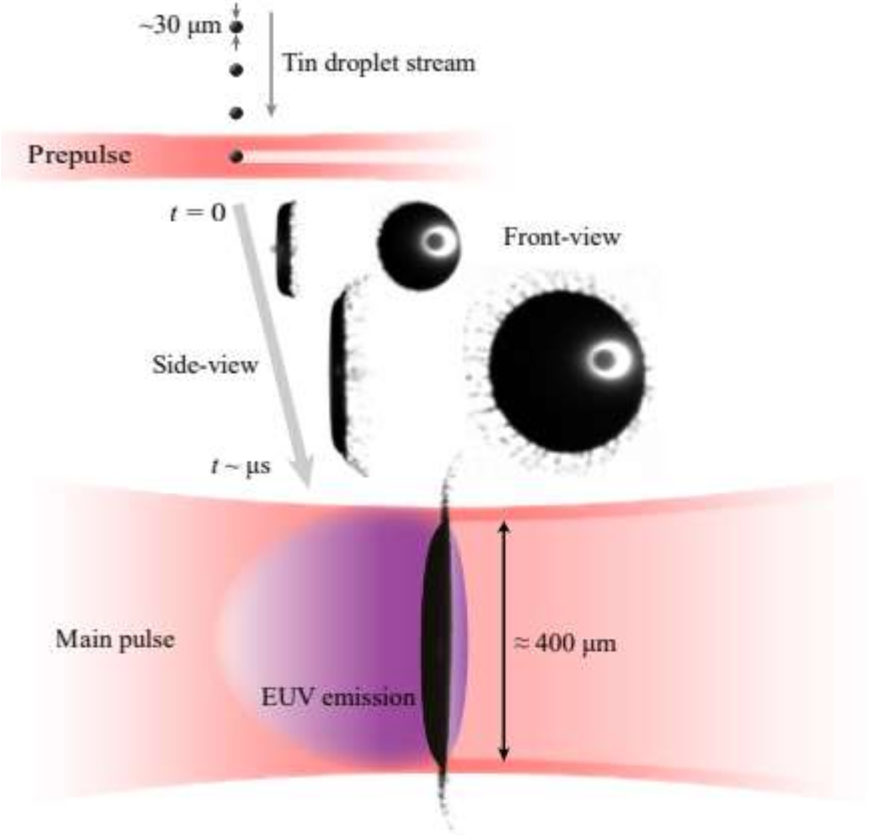

Photo credit: B. Liu PhD Thesis 2022

Overview & Motivation

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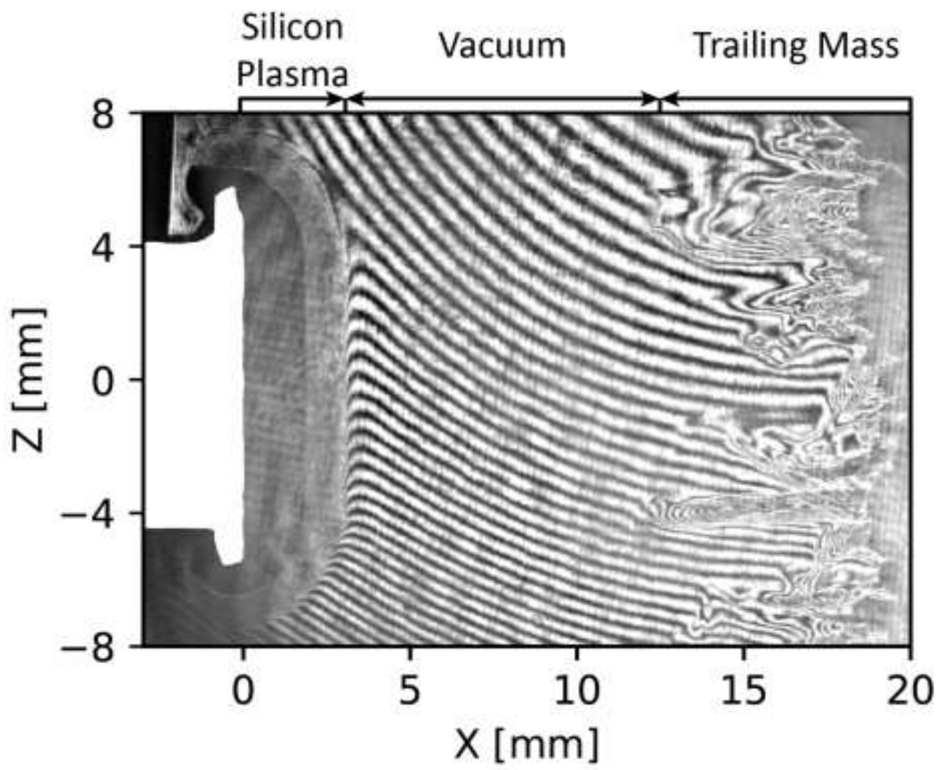
Wire arrays at 1 MA

Laser probing measurements [Halliday+ PoP 2022] characterize hydrodynamics

My work: Cold plasma, large system size – platform is a great testbed for problems in atomic kinetics (also radiation hydrodynamics)

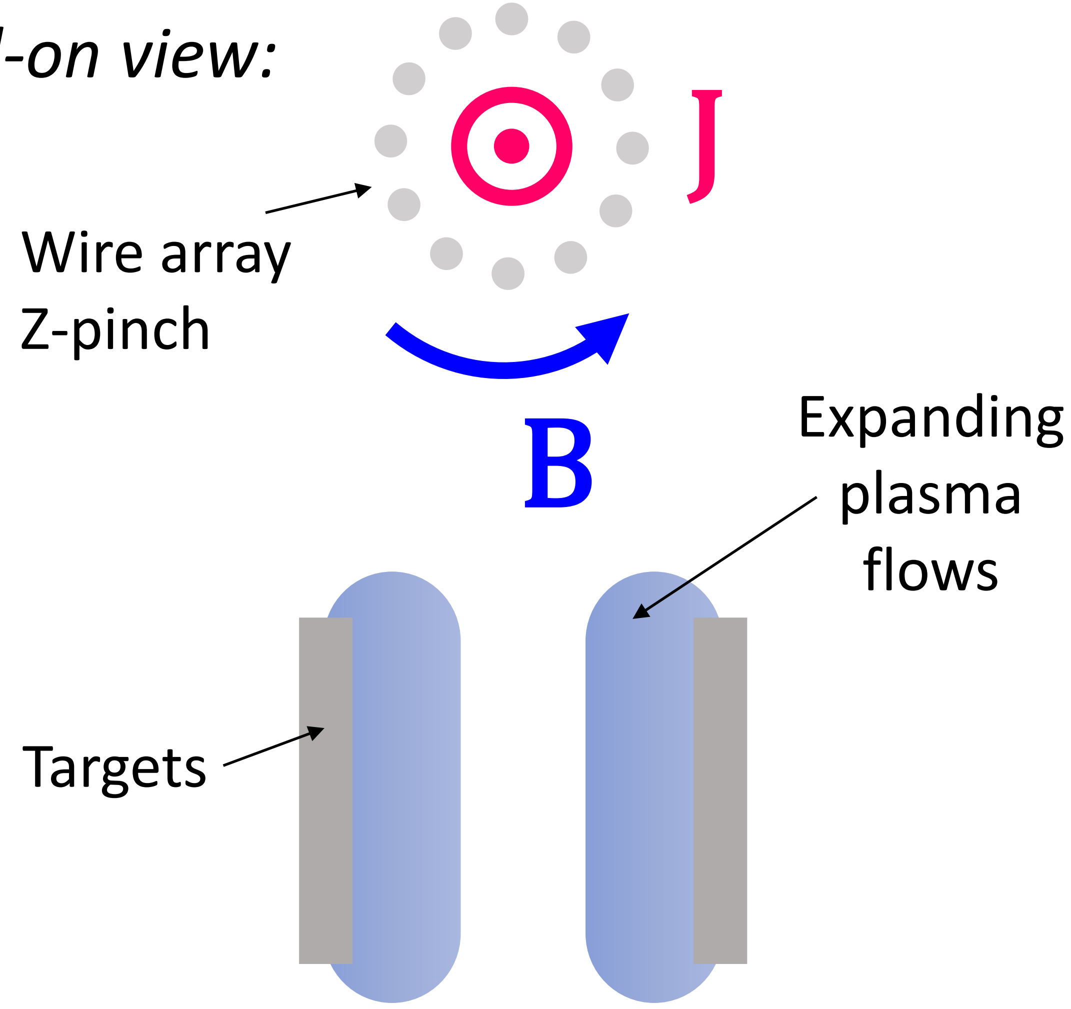
Work from MAGPIE: Potential to study radiative instabilities using colliding flows



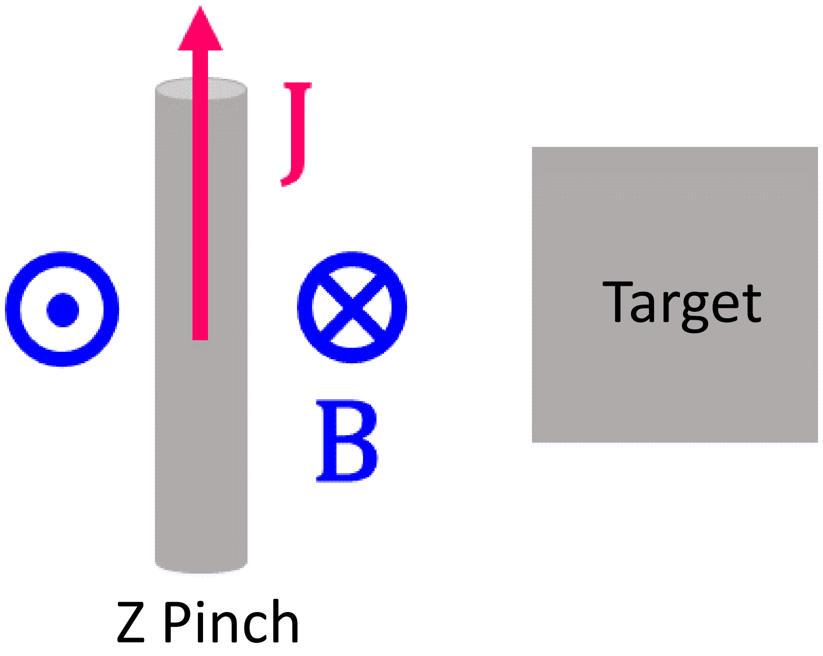
Motivation: Understand how satellites are damaged during nuclear weapon tests in the upper atmosphere.

Dynamical laboratory astrophysics experiments

End-on view:



Side-on view:



Slide credit: K. Marrow

A collimated, dense stagnation layer is formed

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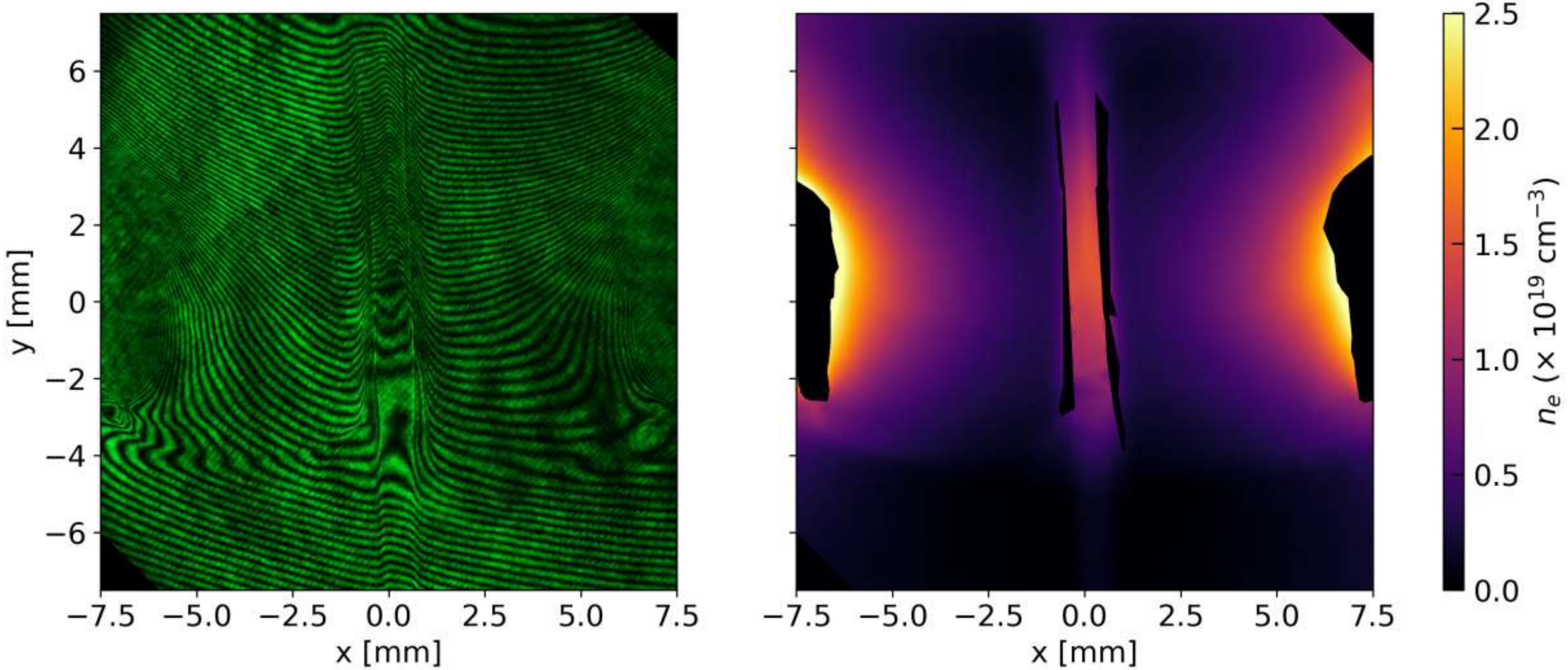
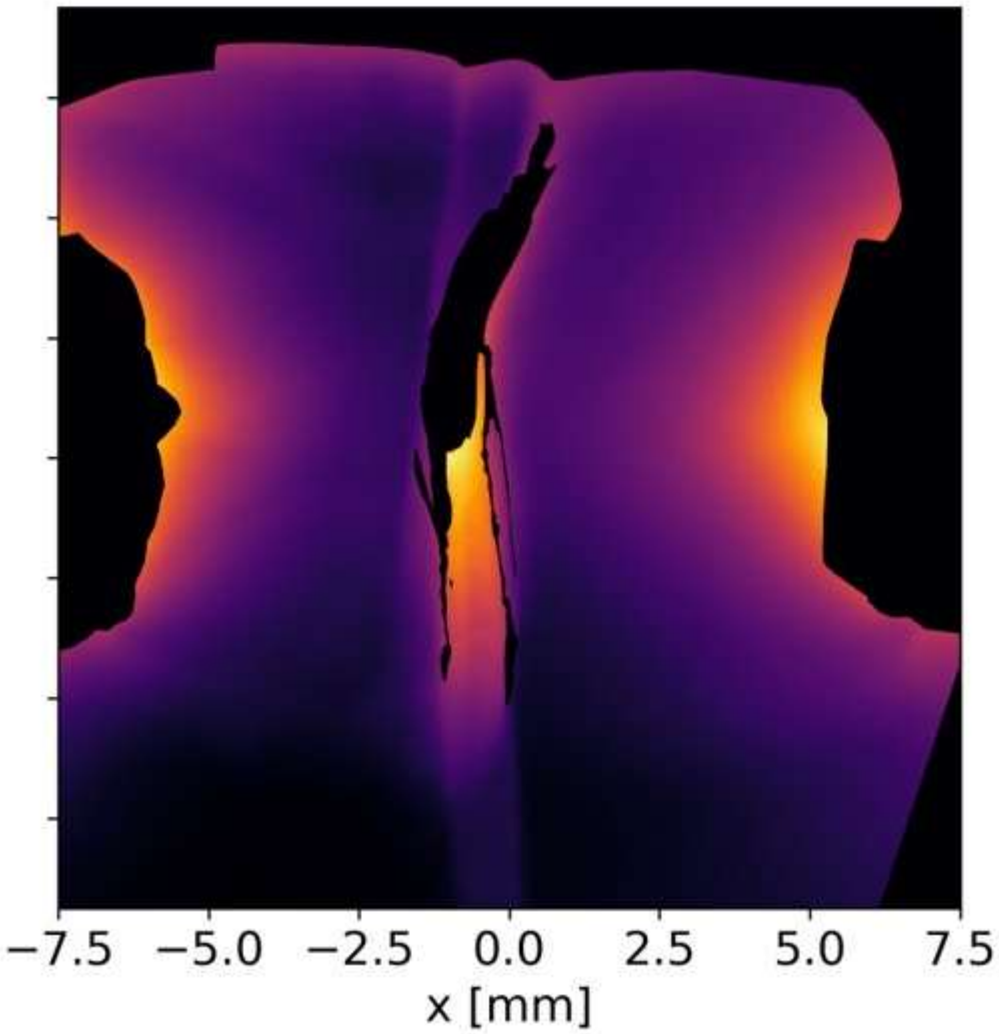


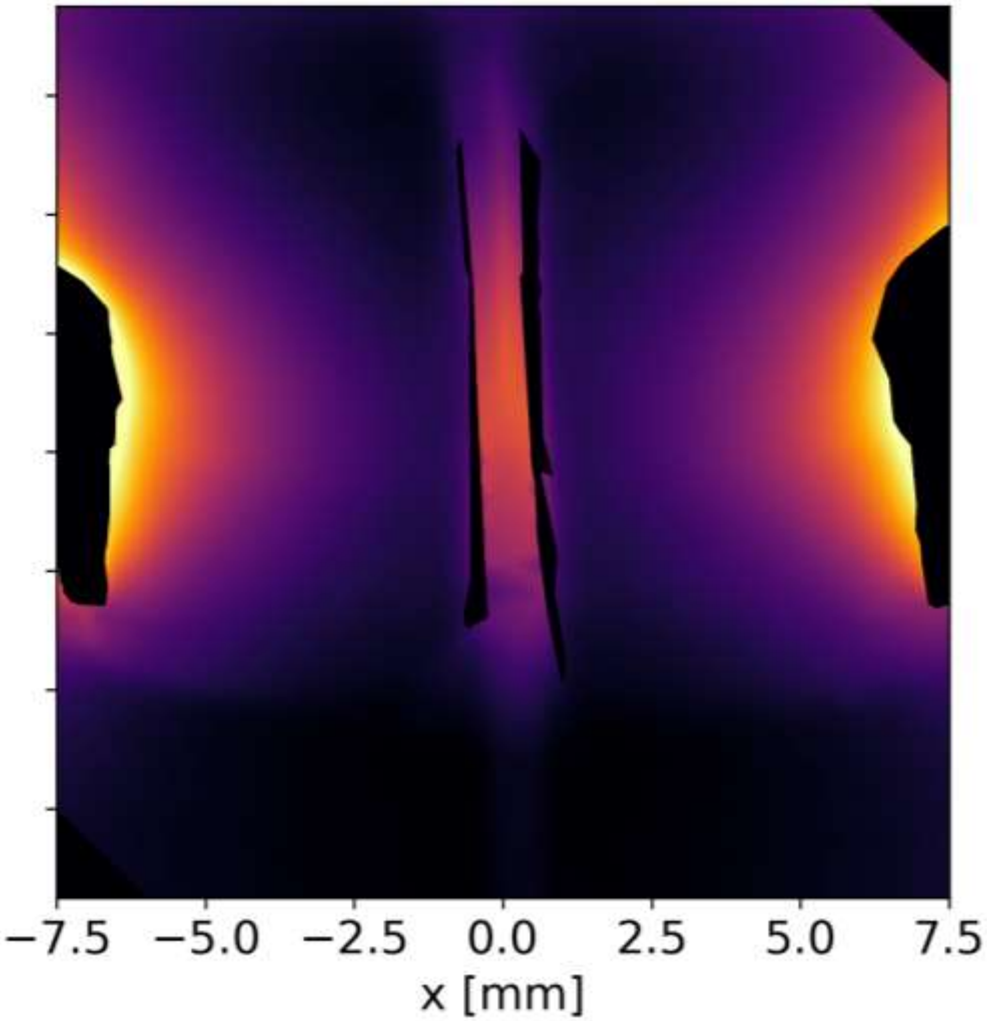
Slide credit: K. Marrow

The morphology is sensitive to plasma composition

Silicon

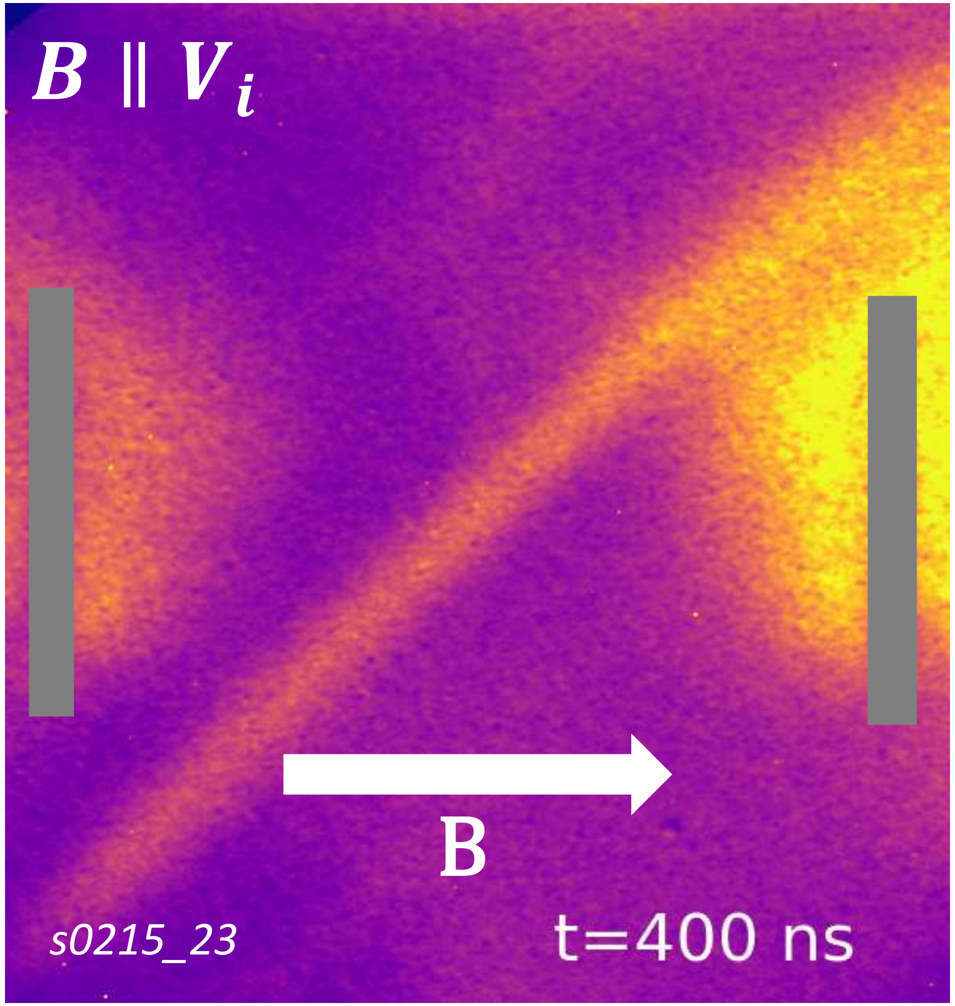


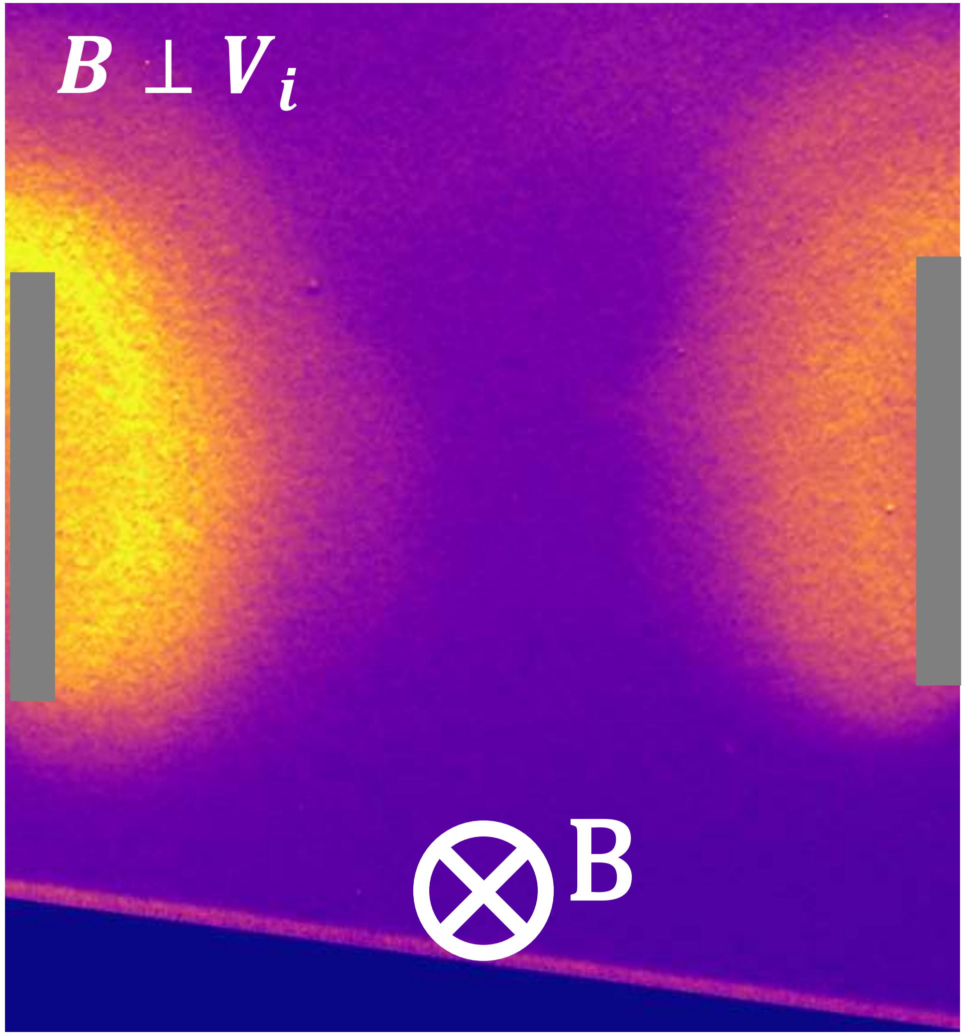
Carbon



Slide credit: K. Marrow

Layer formation is supressed by an orthogonal B field





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Raditive instabilities in protostellar jets

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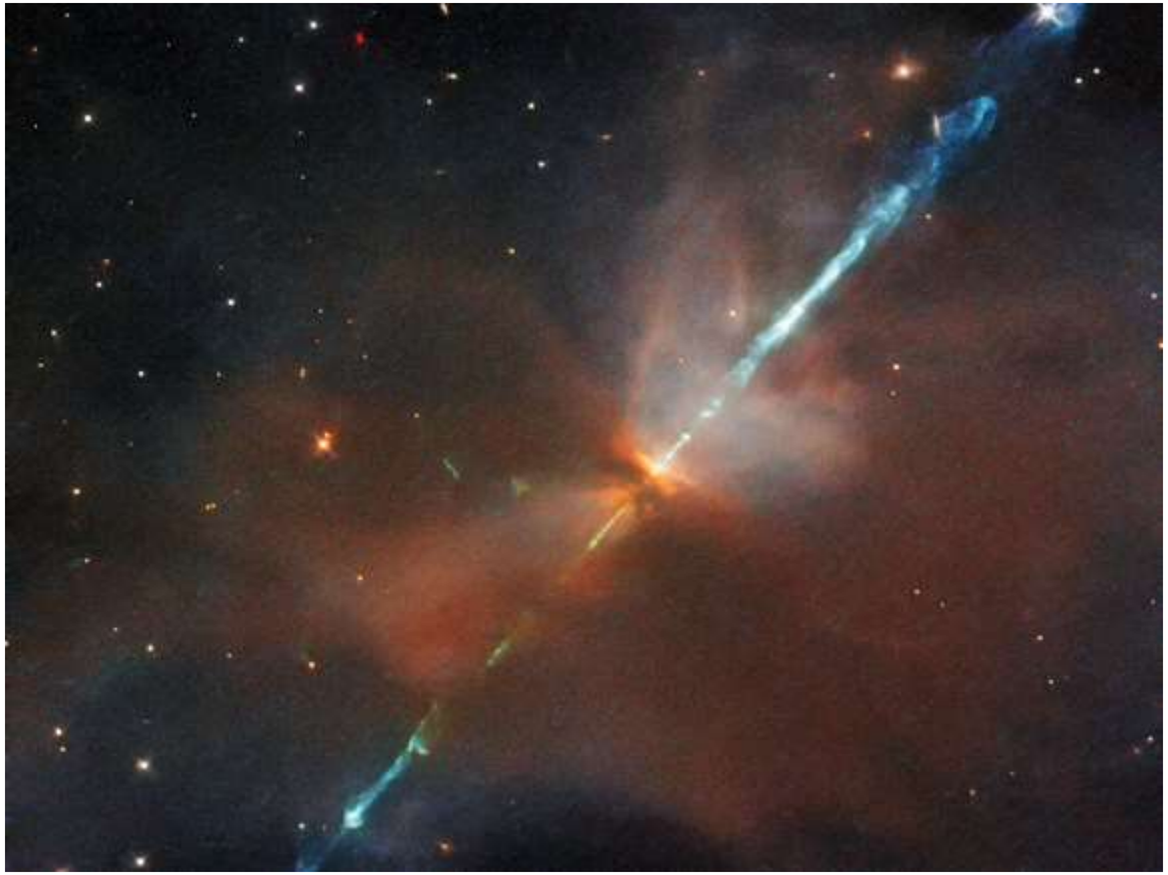
Structure in proto-stellar jets are believed to be driven by radiative instabilities.



Credit ESA/NASA

Slide credit: K. Marrow

Conclusions

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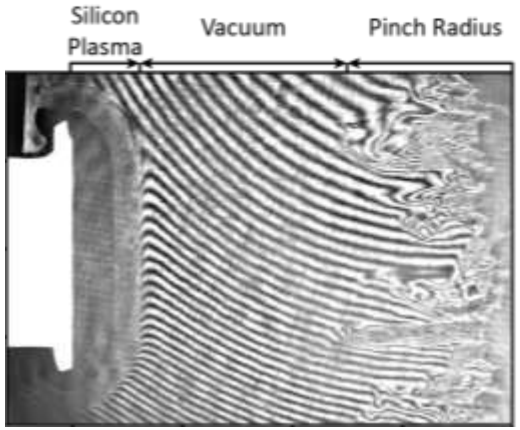

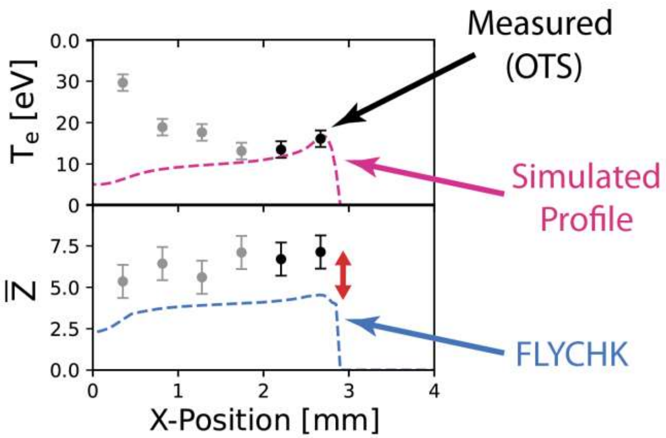

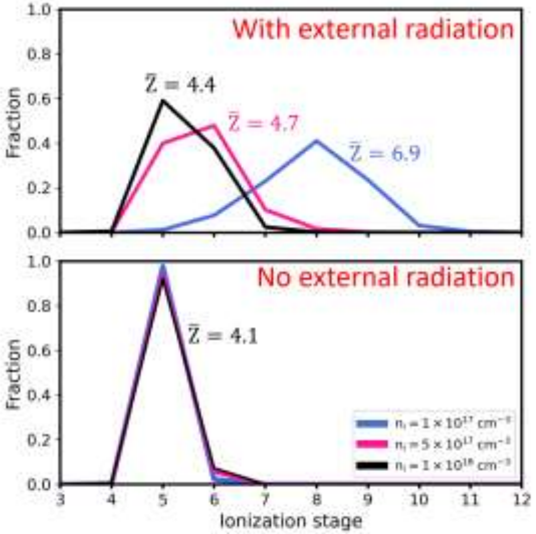

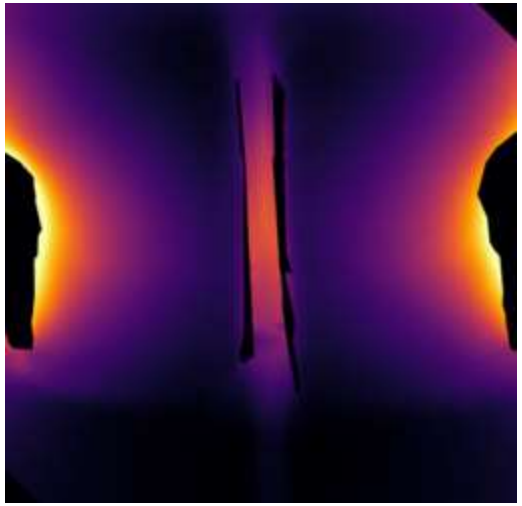

- Hydrodynamic features are simple & well- characterized [Halliday+ PoP 2022]
- Thomson measurements hint that driving radiation changes $\bar{Z}$
- Novel testbed for atomic-kinetics models – relevant to accretion disk physics
- Potential to study radiative instabilities relevant to stellar jets

This work was supported by the US Department of Energy under Award Nos. DE-SC0020434 and DE-NA0003764, and by the US Defence Threat Reduction Agency under Award No. HDTRA1-20-1-0001. Some additional computing support was provided by the UK Central Laser Facility (CLF). My current position is supported by the UK Engineering and Physical Sciences Research Council under Award Nos. EP/X01133X/1 and EP/X010791/1.

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

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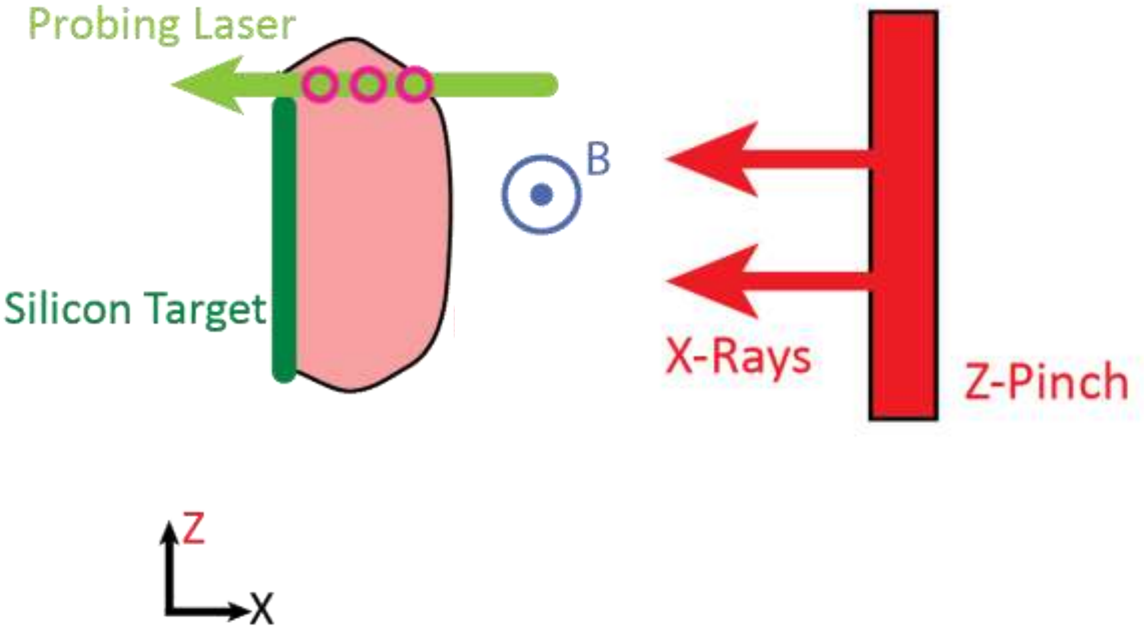
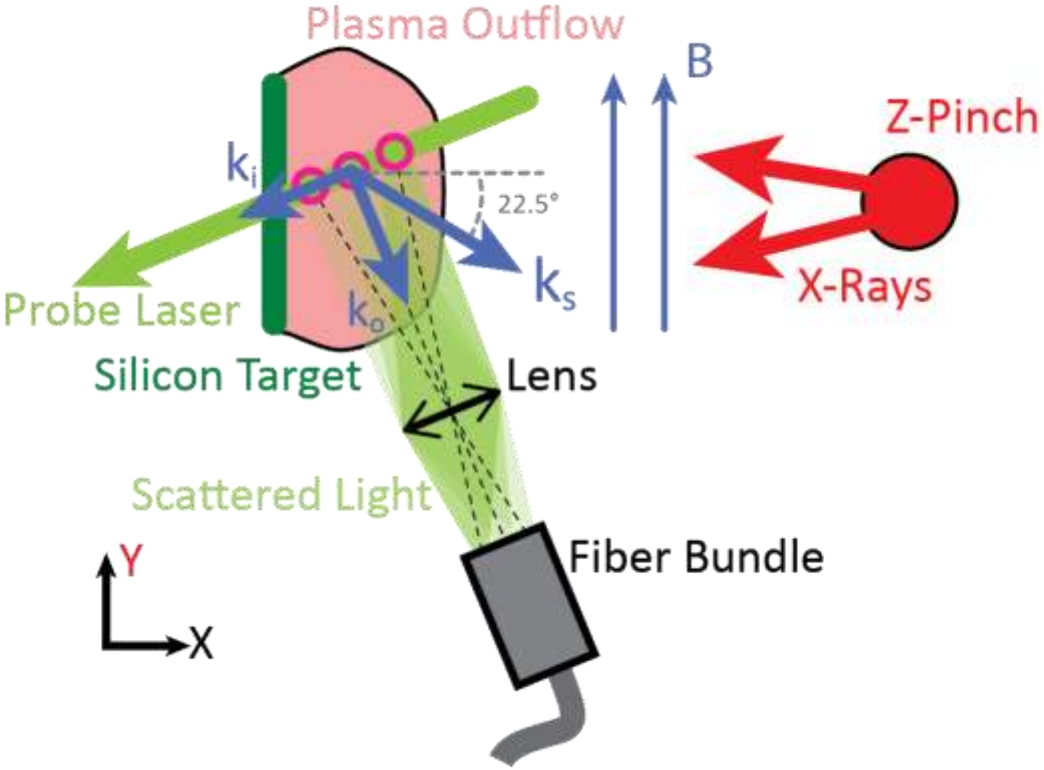


Side-On (X-Z plane) view of the experiment



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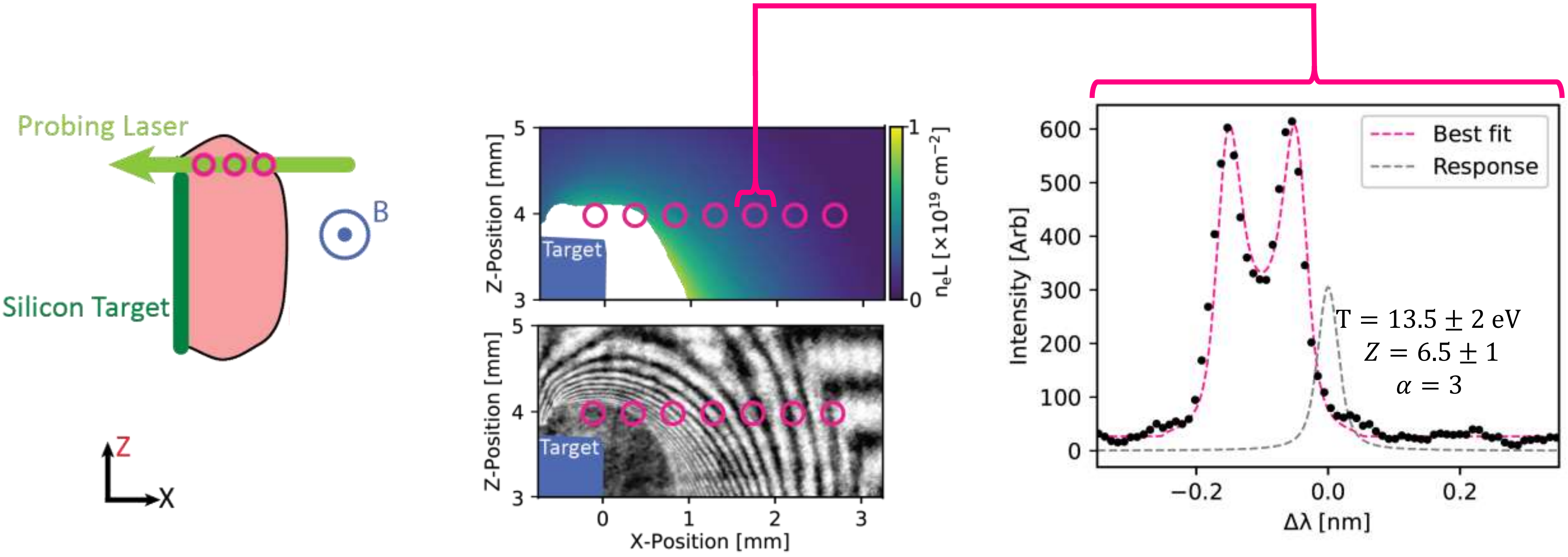
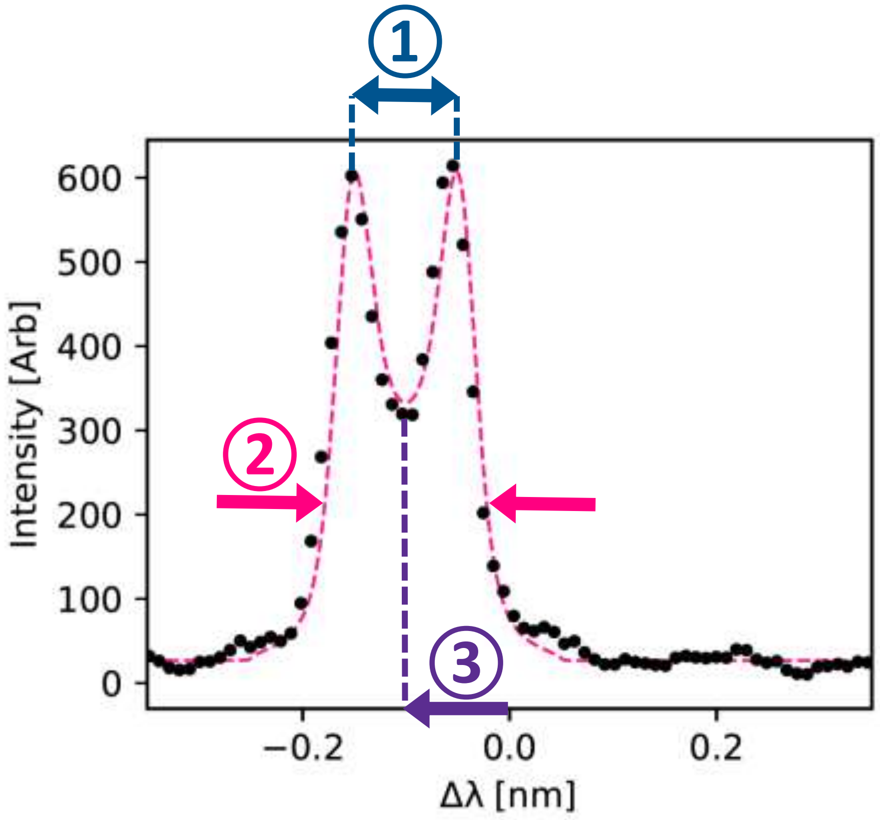


Analysis of Ion-Acoustic Thomson Scattering Data

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 $\vec{V}.\widehat{k_s}$

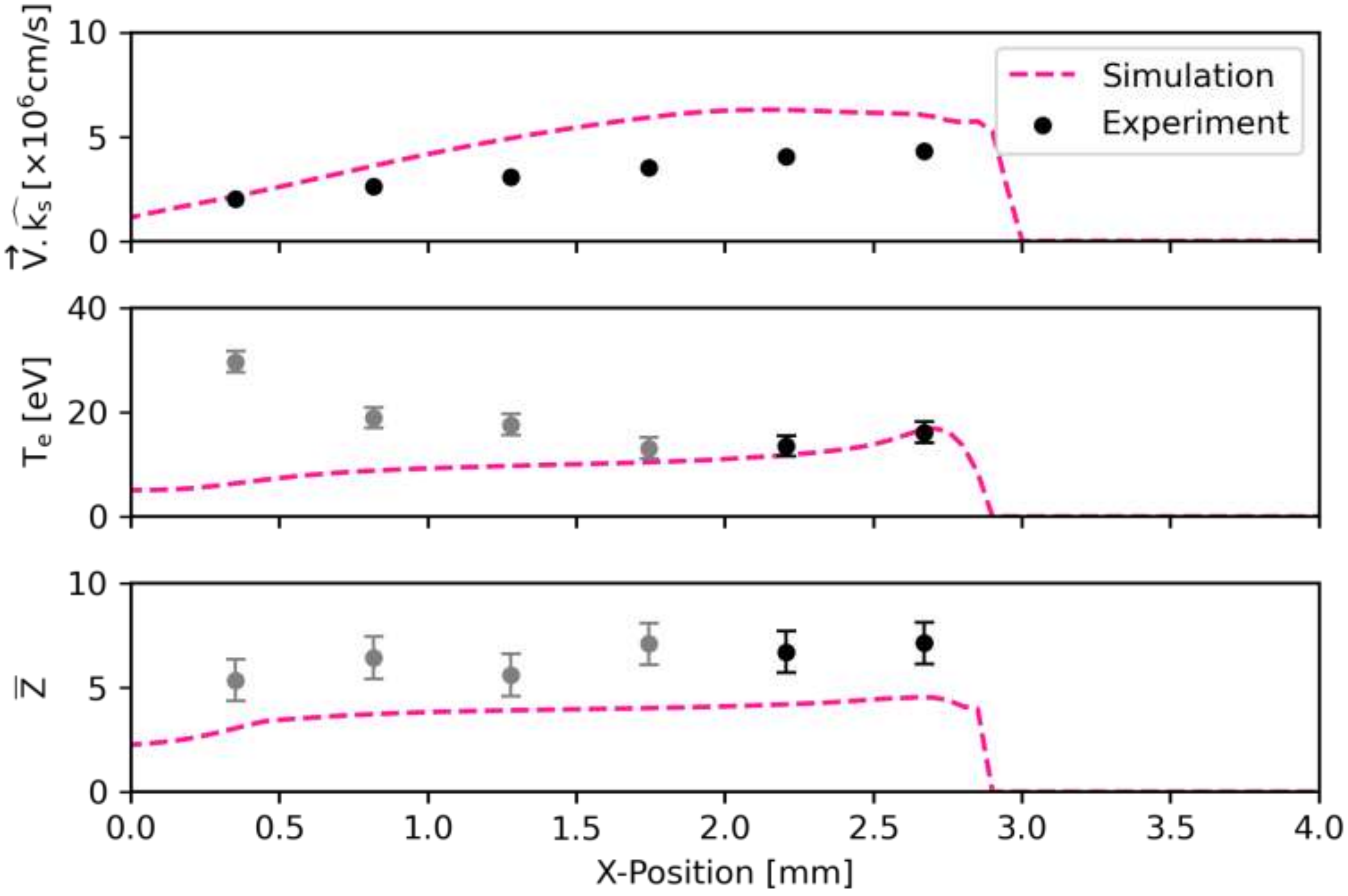


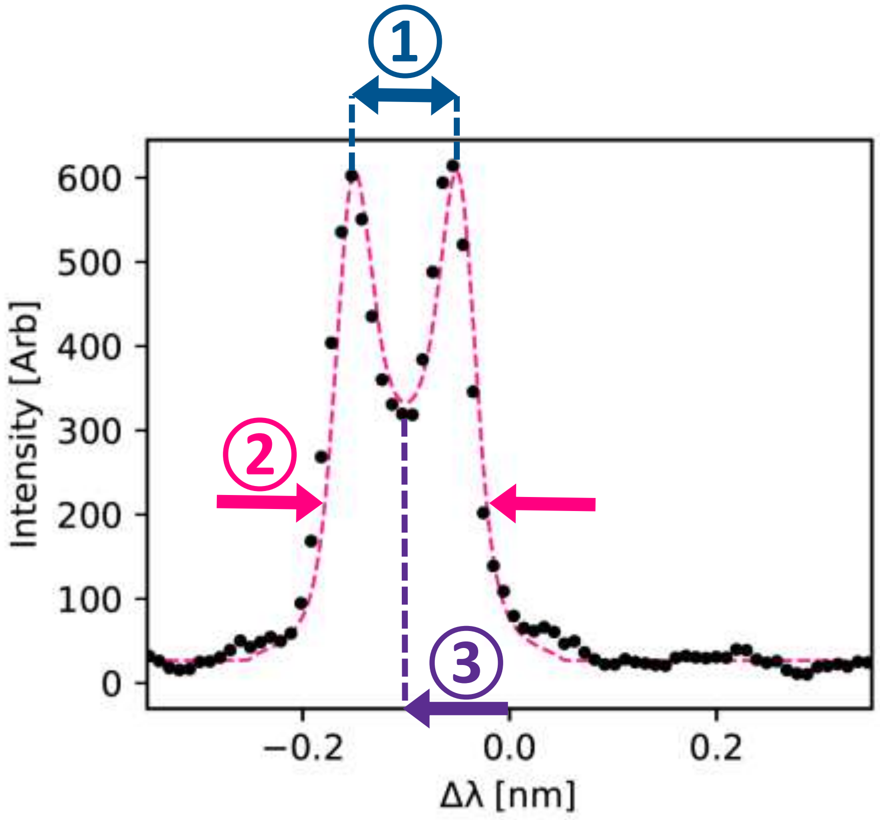
Enforced $T_e = T_i$, and allowed $\bar{Z}$ to vary ($\tau_{ei} \lesssim 1$ ns).

Convolved calculated spectra with measured spectral response.

Constrained value of n_e from (near simultaneous) interferometry.

Analysis of Ion-Acoustic Thomson Scattering Data





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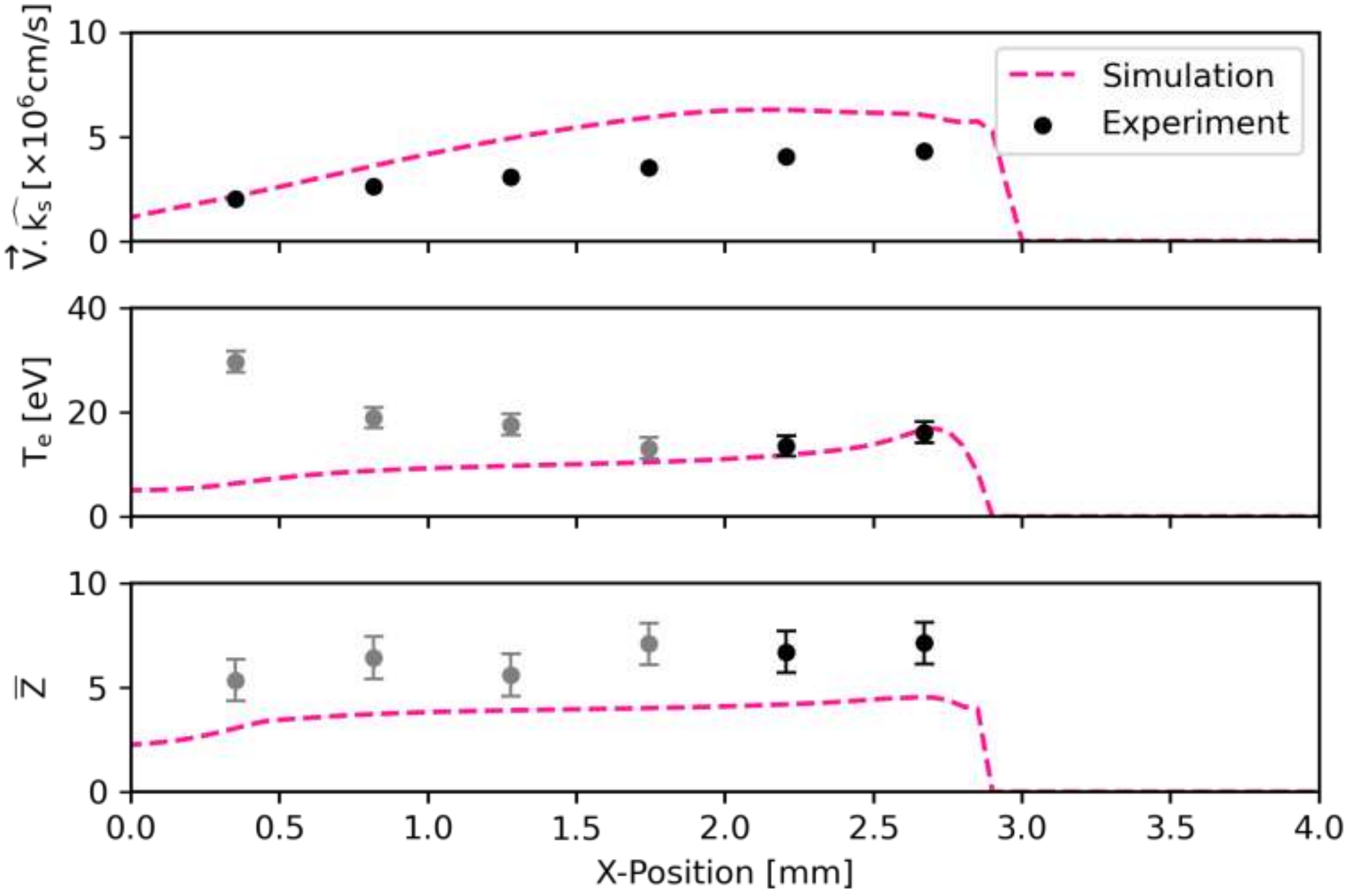
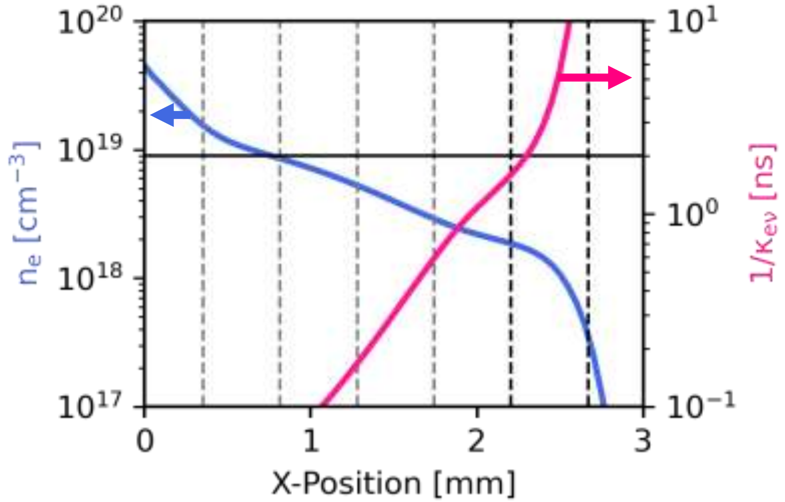


Calculated from sims!



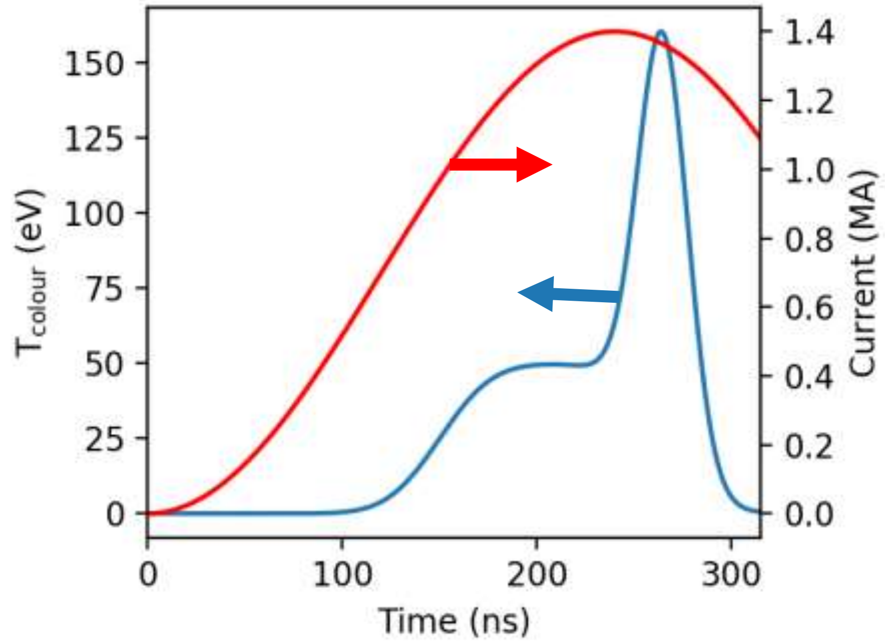
$$\kappa_{ve} \propto \frac{Z n_e^2 \ln(\Lambda) T_e^{-\frac{3}{2}}}{\sqrt{\omega^2\left(1-\omega_p^2/\omega^2\right)}}$$

N. R. L. plasma physics formulary

Spectral Character of Radiation at ~1 MA Level

Imperial College London

- **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



Visible Emission Features of High Z Elements

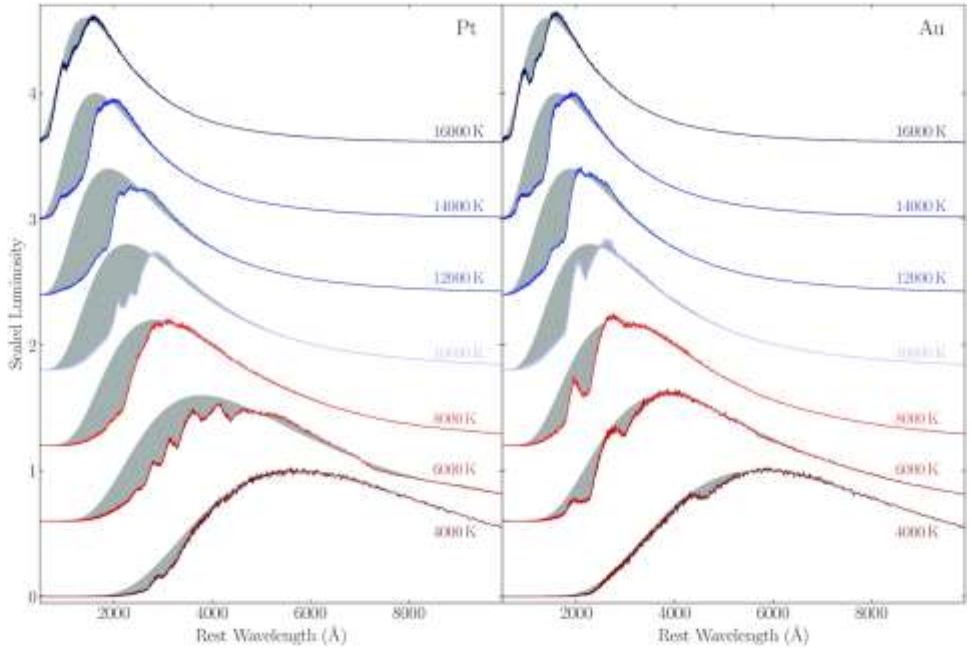
Imperial College London

- Binary neutron star mergers primary candidate for nucleosynthesis of high Z elements (i.e. Gold, Platinum)

- Constrain composition of outflowing material using observed spectra

- Potential to verify atomic modelling efforts [Gillanders+, MNRAS 2022] via experimental measurements

- Temperature range of interest in the range $1 - 10\ \mathrm{eV}$. There are relevant spectral features in the visible.



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

Imperial College London

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