# Analysis of Thomson Scattering spectra obtained in experiments on the MAGPIE pulsed-power generator

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**MIT (PSFC):** J. D. Hare

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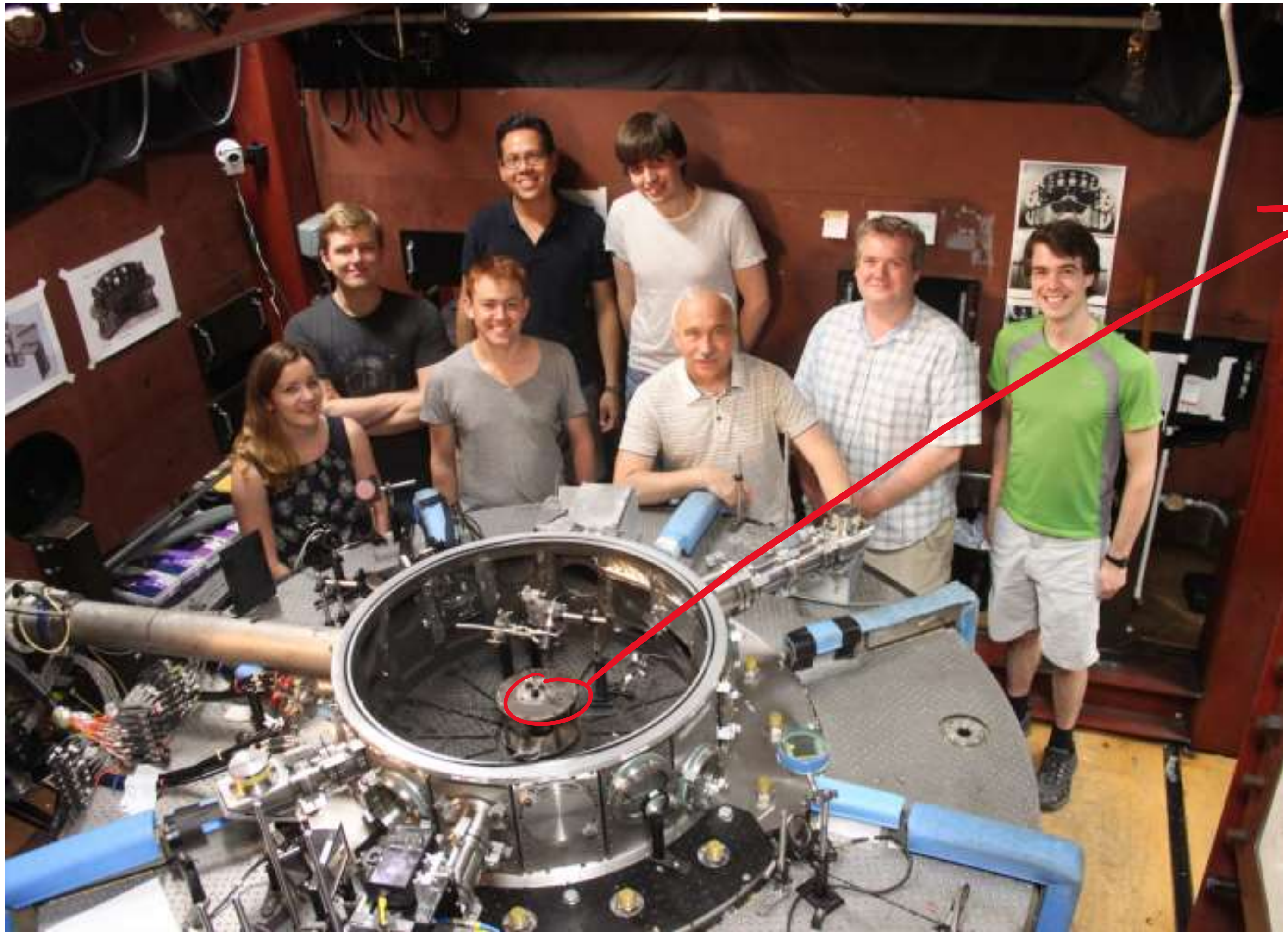
MAGPIE

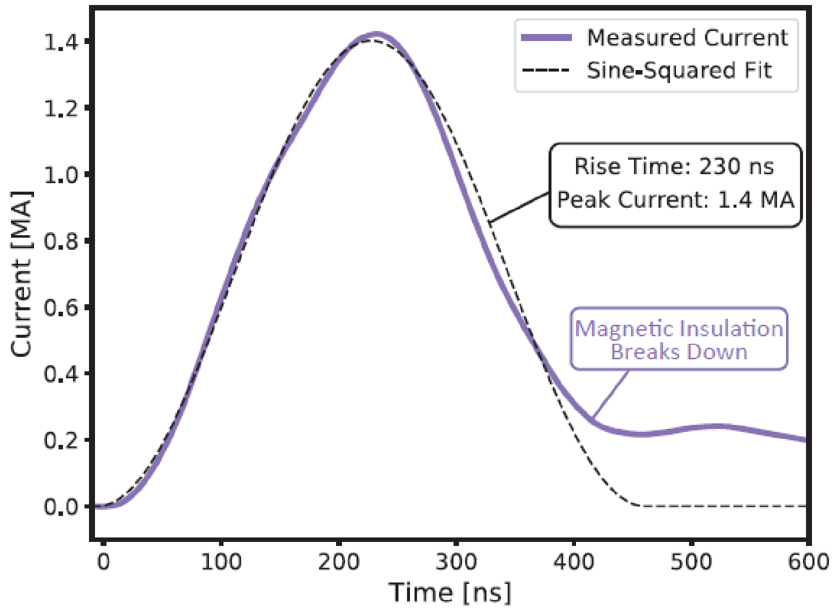
CiFS

PSFC

# The MAGPIE pulsed power generator







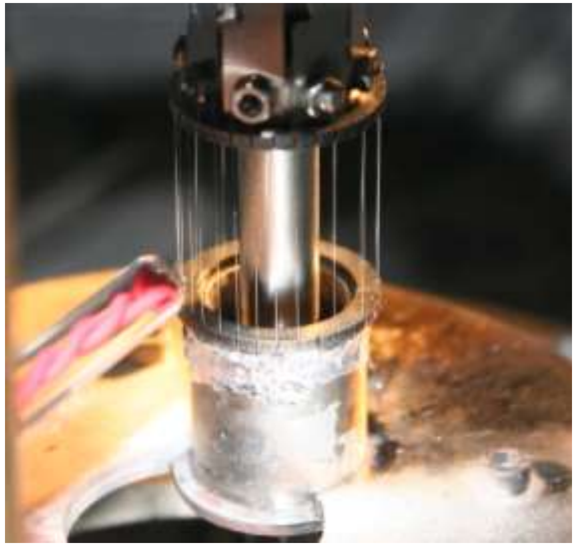

1.4 MA, 240 ns Current Pulse

X-Ray Pulse ~ 1 TW

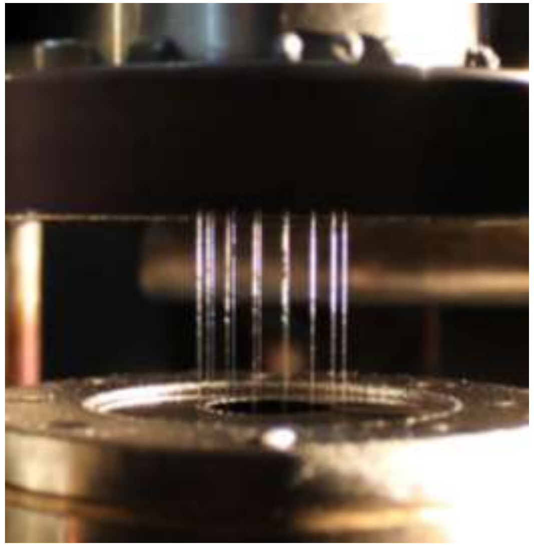
# Experimental setups fielded on MAGPIE



Exploding wire array

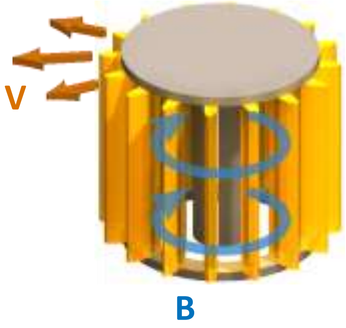


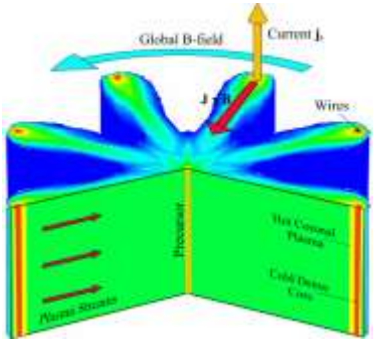
Z-pinch wire array

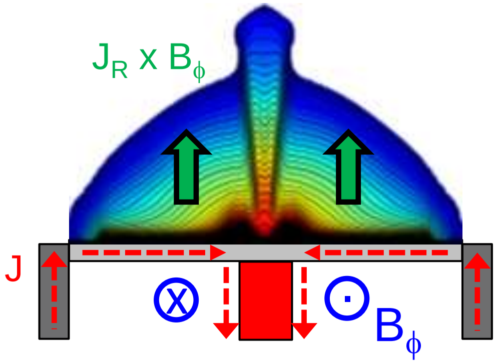


Radial foil

## Supersonic flows of plasma accelerated by $J \times B$ force



# Some recent examples of experimental work

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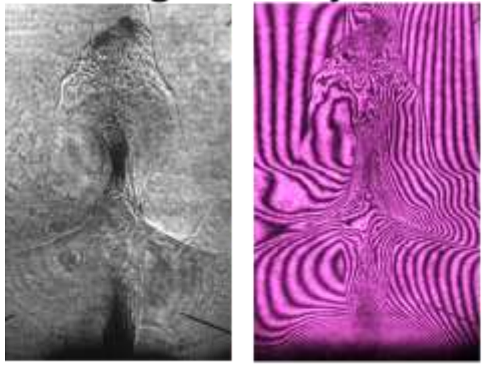
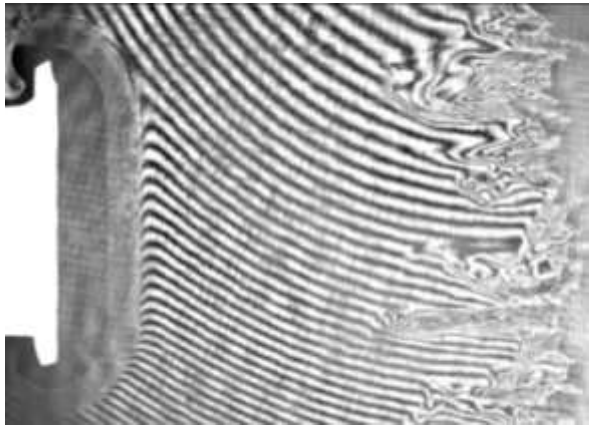
Magnetized jets



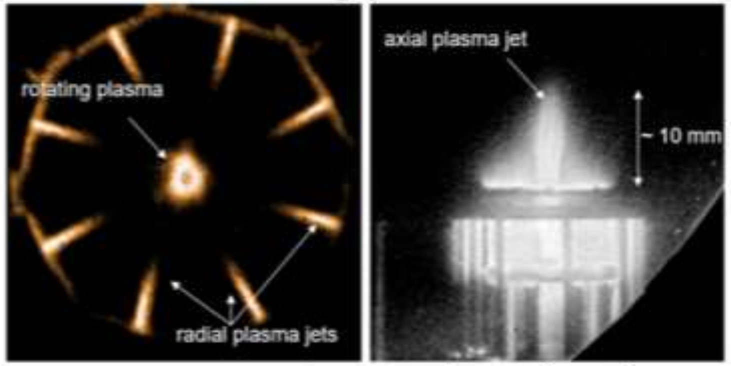
*Francisco Suzuki-Vidal*

Radiatively driven plasmas



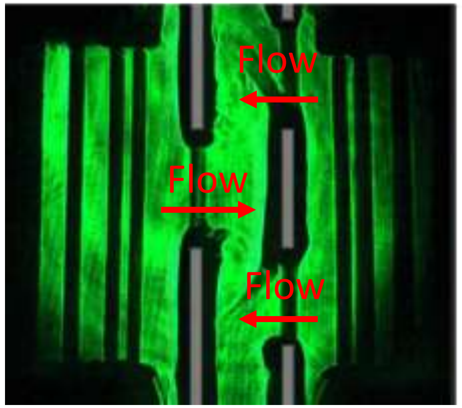
*Jack Halliday*

Rotating plasmas



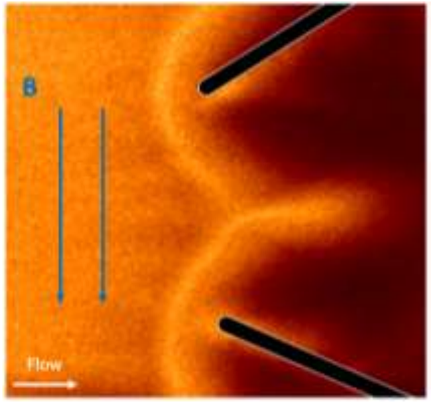

*Vicente Valenzuela-Villaseca*

Sheared flows



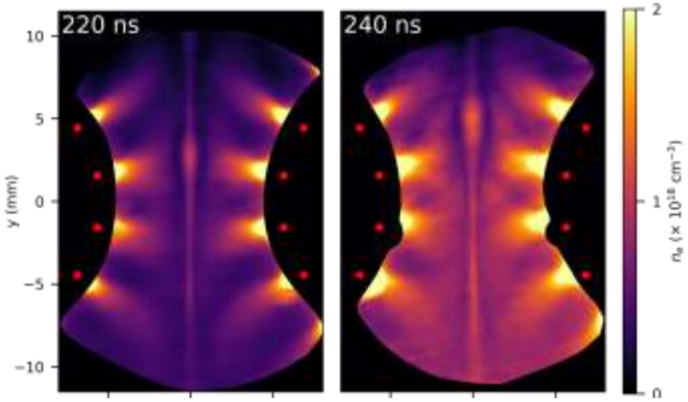

*Stefano Merlini*

Magnetized shocks




*Danny Russell*

Magnetic reconnection




*Jack Hare & Lee Suttle*

# The MAGPIE diagnostic suite

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**Interferometry**

$n_e$

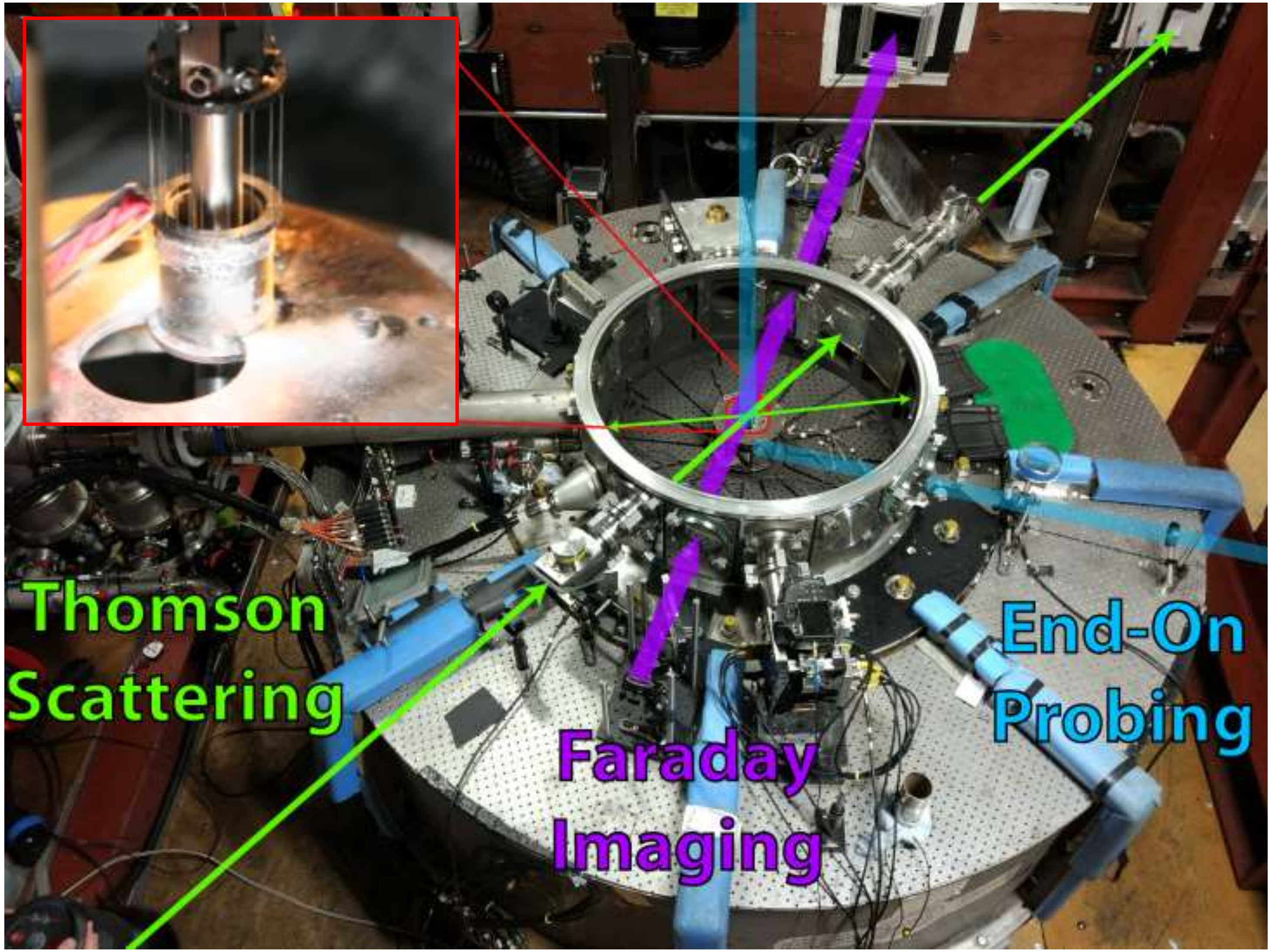
**Thomson scattering**

$V_{flow}, T_i, \bar{Z}T_e, U_d$

**Faraday polarimetry**

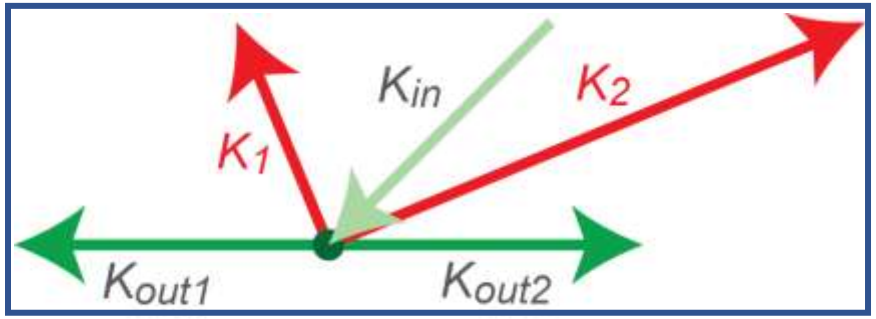
$B_{\parallel}$

*Ref*: Swadling *et al.* RSI (2014)

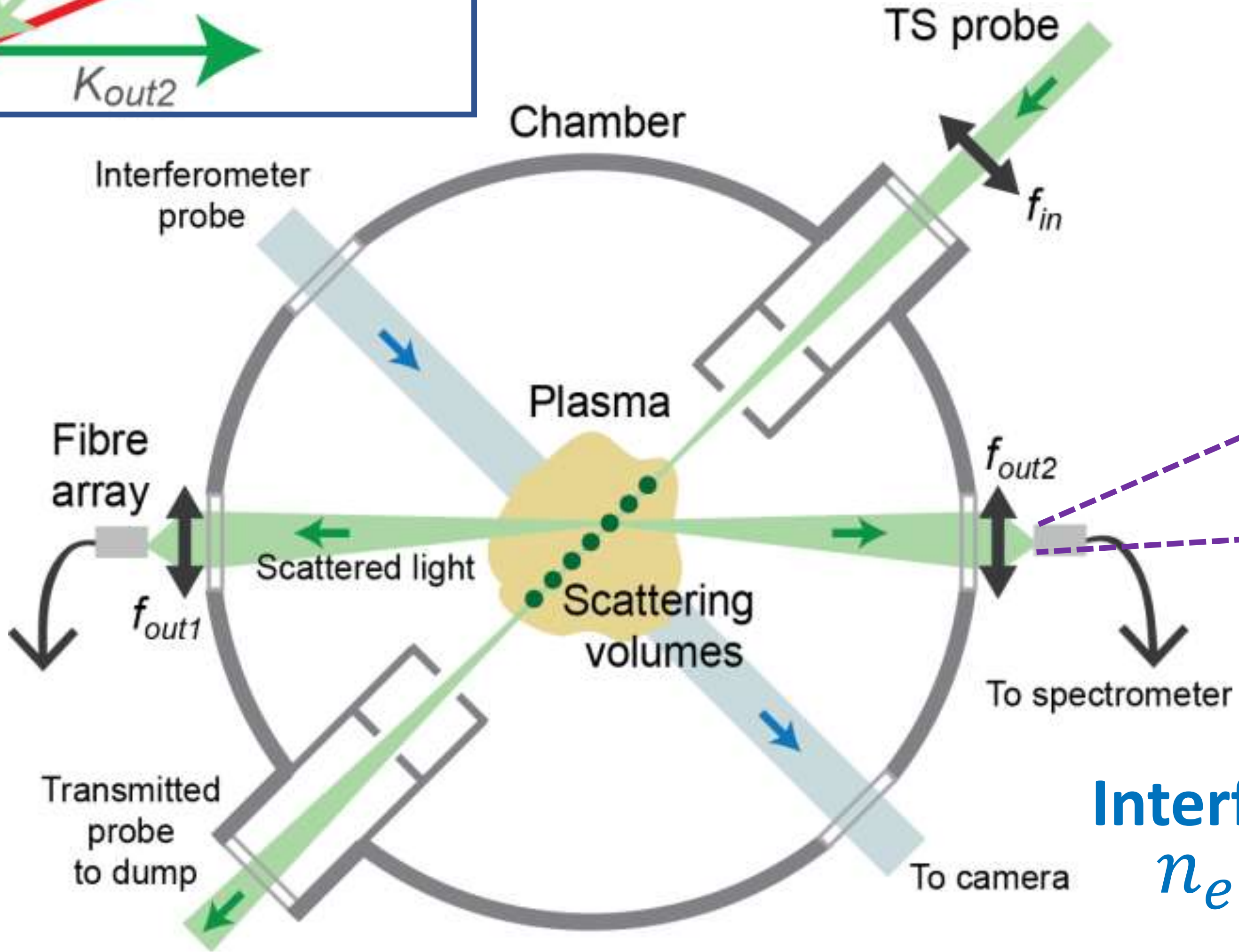


# Thomson scattering experiments on MAGPIE

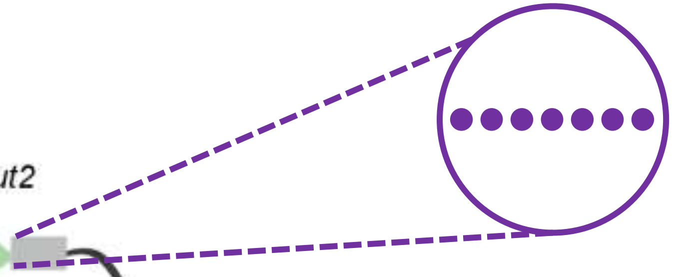





**Laser probe: 532 nm, Nd:YAG**
**3 J, 8 ns [$\sim 10^{12}$W/cm$^2$]**




## Fibre optic collection



Linear array

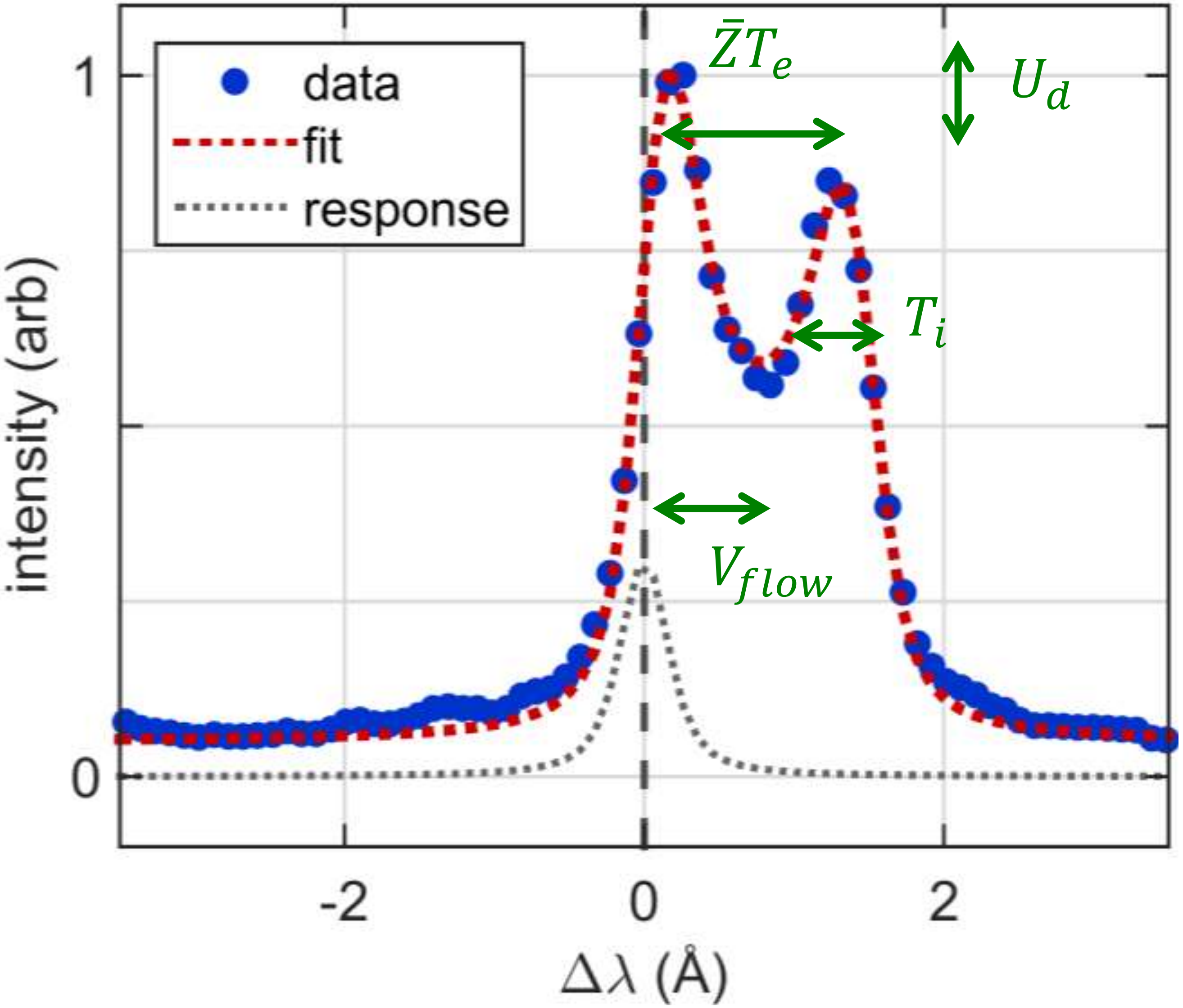
100 $\mu$m fibres

Collect spatially resolved, time gated data

## Interferometric imaging

$n_e$ , TS coordinates

# Diagnose Ion-Acoustic Wave (IAW) Feature

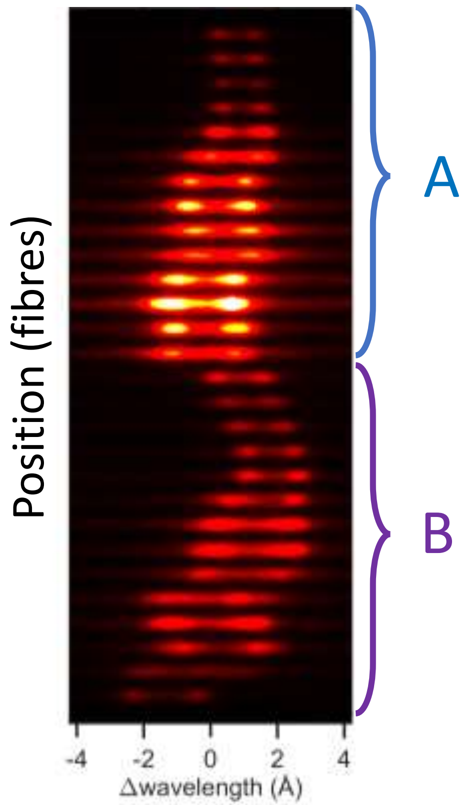



Measure:

$$V_{flow}, T_i, \bar{Z}T_e, U_d$$

Fibre 1A

Ion acoustic spectra (IAW)



# Fitting model used for Thomson scattering data (1/2)

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1. Calculate a normalised TS form factor:

$$S(\mathbf{k},\omega) = \frac{2\pi}{k}\left[\left|1 - \frac{\chi_e}{1+\chi_e+\chi_i}\right|^2 f_{e0}\left(\frac{\omega}{k}\right) + \left|\frac{\chi_e}{1+\chi_e+\chi_i}\right|^2 Z f_{i0}\left(\frac{\omega}{k}\right)\right].$$

*Assume Maxwellian distribution functions and collisionless conditions ($k\lambda_{ii},\ k\lambda_{ei} \gg 1$).*
*Normalize such that $S_{max} = 1$.*

2. Convolve $S(\boldsymbol{k},\omega)$ with the spectral response function for the spectrometer ($R[\lambda]$), obtained by fitting a Voigt profile to the spectrum of the probe laser pulse as measured by the spectrometer.

3. Scale $S(\lambda)$ by a normalisation constant ($A_{TS}$)

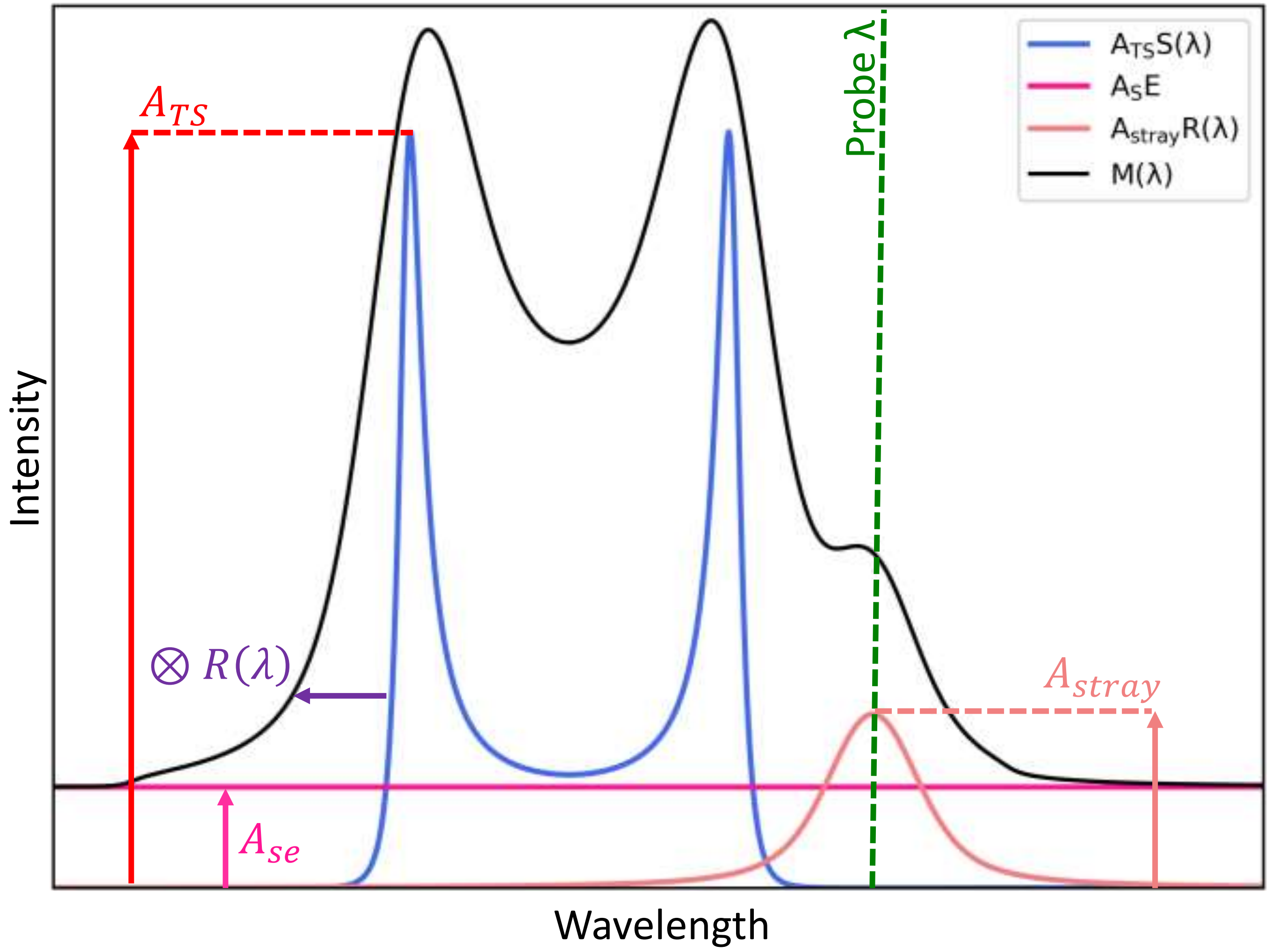
4. Add a contribution from self-emission ($A_{SE}$), assumed to be constant as a function of $\lambda$

5. Add a contribution from stray light, given by $A_{Stray} \times R(\lambda)$. Required because $\frac{r_{\mathrm{chamber}}}{c} < \tau_{MCP}$.

# Fitting model used for Thomson scattering data (2/2)



$$M(\lambda) = A_{TS} \times S(\lambda; T_e, T_i, Z, V_{flow}, V_{drift}, n_e, \boldsymbol{k}, \lambda_{probe}) \otimes R(\lambda) + A_{se} + A_{stray} \times R(\lambda)$$



# Deciding on parameters to vary in fit



**In general :**

$$M(\lambda) = M(\lambda; T_e, Z, T_i, n_e, V_{flow}, V_{drift}, \boldsymbol{k}, \lambda_{probe}, R(\lambda), A_{TS}, A_{SE}, A_{stray})$$

(Need to decide on a subset of parameters to vary in the fit!)

- Some parameters (namely $\boldsymbol{k}$, $\lambda_{probe}$, and $R(\lambda)$) can be unambiguously determined from the setup geometry or offline instrument characterisation (held constant in fit)
- Interferometry enables $n_e$ to be independently constrained (held constant in fit)
- Can use pre-tabulated data from atomic physics code (FLYCHK) to obtain $Z = Z(T_e, n_e)$ and therefore not treat as an independent fitting parameter. *Lookup is done inline with fitting process!*
- Then use least squares regression to find optimal values of $T_e, Z, T_i, n_e, V_{flow}, A_{TS}, A_{SE}, A_{stray}$
- Depending on physics context, may hold $V_{drift} = 0$ or allow this parameter to vary

# References & publicly available GitHub repo

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Python code used to perform the analysis described here available on my GitHub as part of "MagPy" data analysis module (github.com/jackHalliday/MagPy).

Fitting routines use LMFit Python package and code is designed to make it easy to play with different minimizer methods.

## References


1. **Laser probing diagnostics on MAGPIE –** G. F. Swadling *et al.* "*Diagnosing collisions of magnetized, high energy density plasma flows using a combination of collective Thomson scattering, Faraday rotation, and interferometry*" Rev. Sci. Instr. (2014)

2. **Detailed description of Thomson scattering setup –** L. G. Suttle *et al.* "*Collective optical Thomson scattering in pulsed-power driven high energy density physics experiments*" Rev. Sci. Instr. (2021)

# Some outstanding issues



- Obtaining a good quality fit tends to require manually tuning initial conditions
- Have to be  very careful about the independence of different fit parameters (e.g. $ZT_e$)
- Need to use outside physics / intuition relatively frequently (i.e. choice of ionisation model, whether to include electron drifts)
- Least squares inferred errors are too small and there is no clear way to include an $n_e$ uncertainty in analysis

Obvious way to overcome these is to manually explore how varying different fit parameters changes goodness of fit. This is time consuming and (problematically) introduces a degree of subjectivity.

# A more robust fitting technique?

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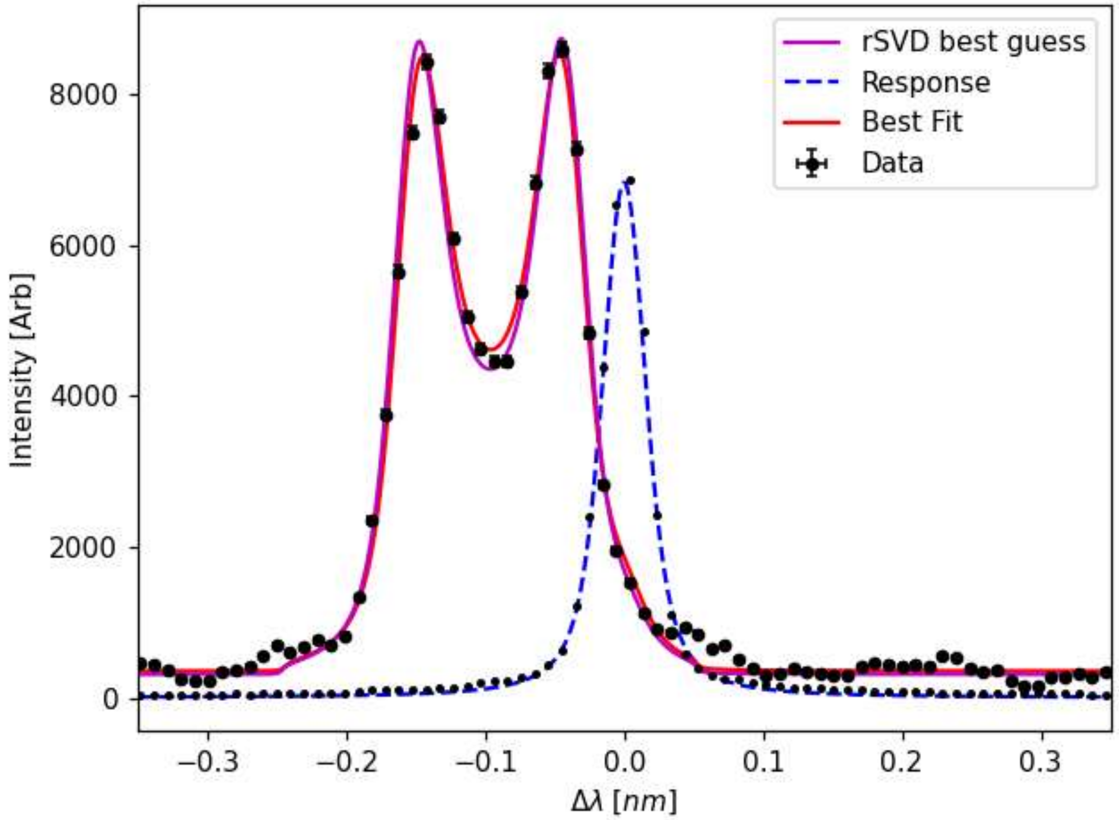
- Naively fitting $M(\lambda)$ with least squares regression requires starting point close to solution to converge

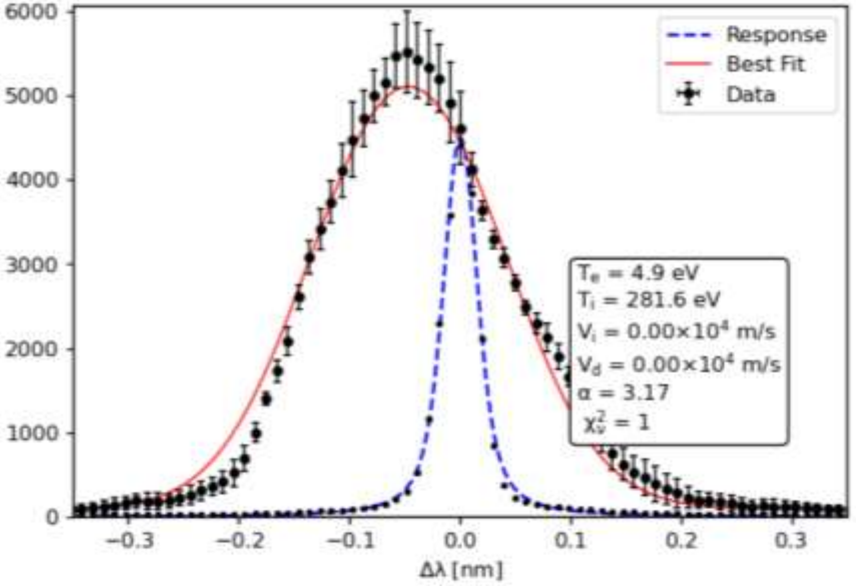
- Alternative initialisation procedure:
  1. IAW centroid found to estimate $V_{flow}$
  2. Sample $T_e, T_e$, and $Z$ stochastically whilst optimising for $A_{TS}, A_{SE}$, and $A_{Stray}$ using SVD
  3. Use the optimal solution from (2) to initialise regular least squares fit

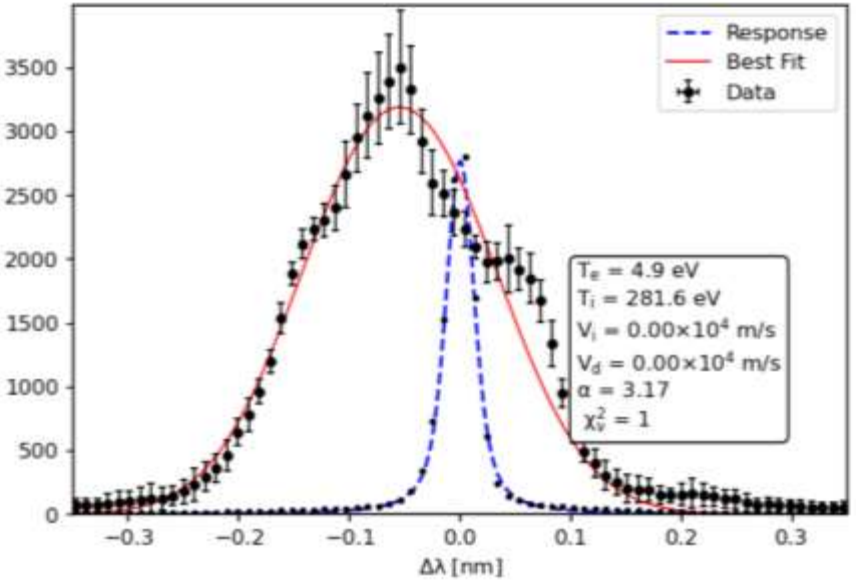
- Appears to converge more quickly & reliably, but need to explore with range of plasma conditions

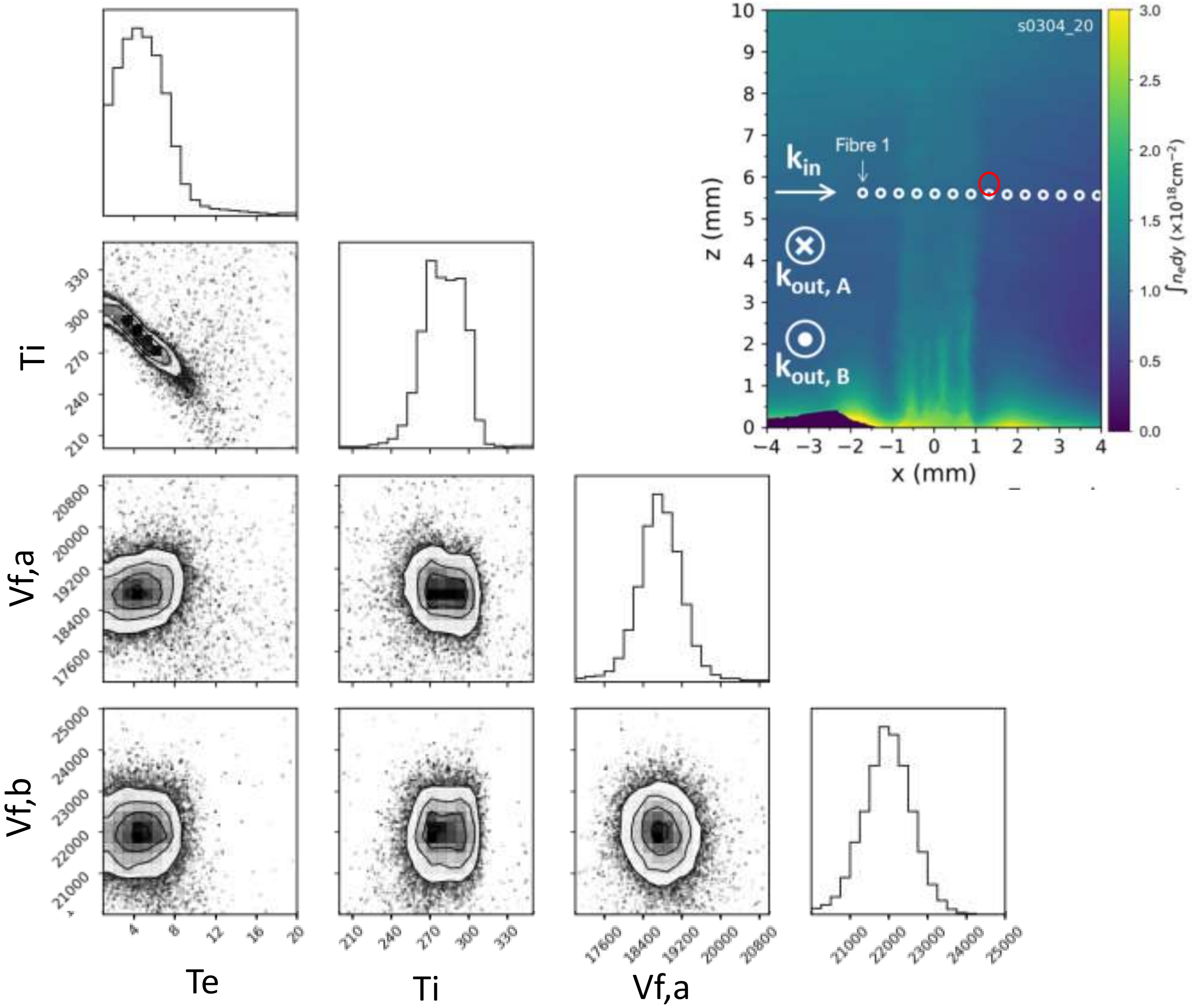


# Posterior distribution estimation with emcee



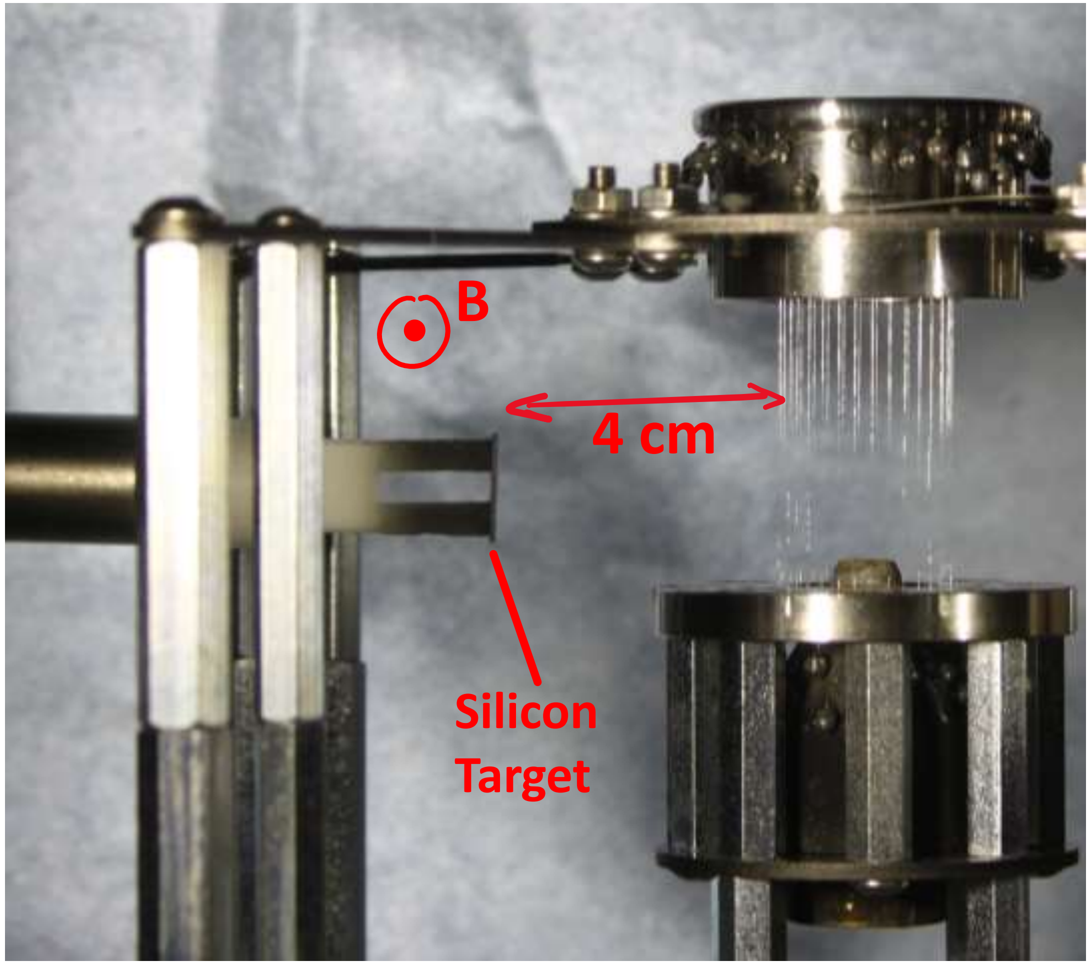


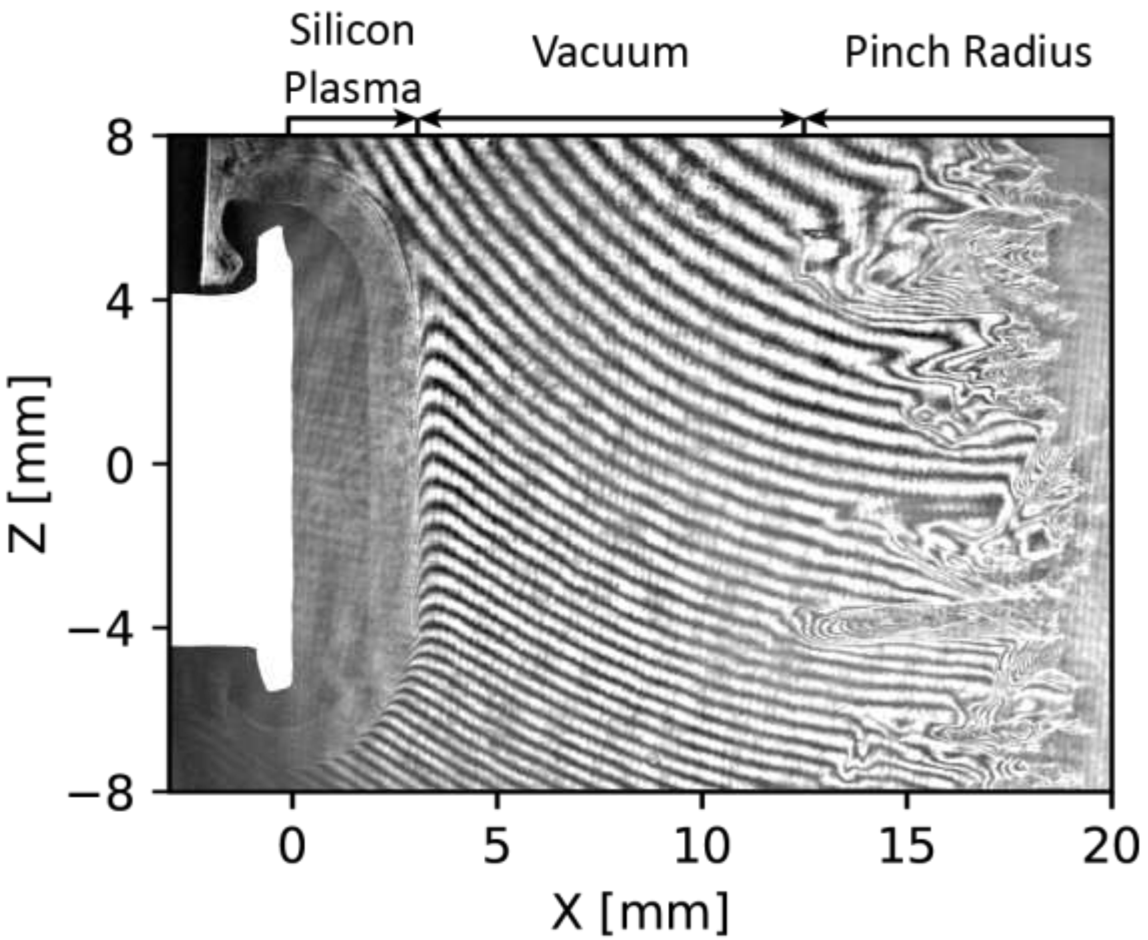



# Thomson scattering data – X-Ray driven ablation






Reference: J. W. D. Halliday et al. "*Investigating radiatively driven, magnetized plasmas with a university scale pulsed-power generator*" Physics of Plasmas (2022)

# Thomson scattering data – X-Ray driven ablation

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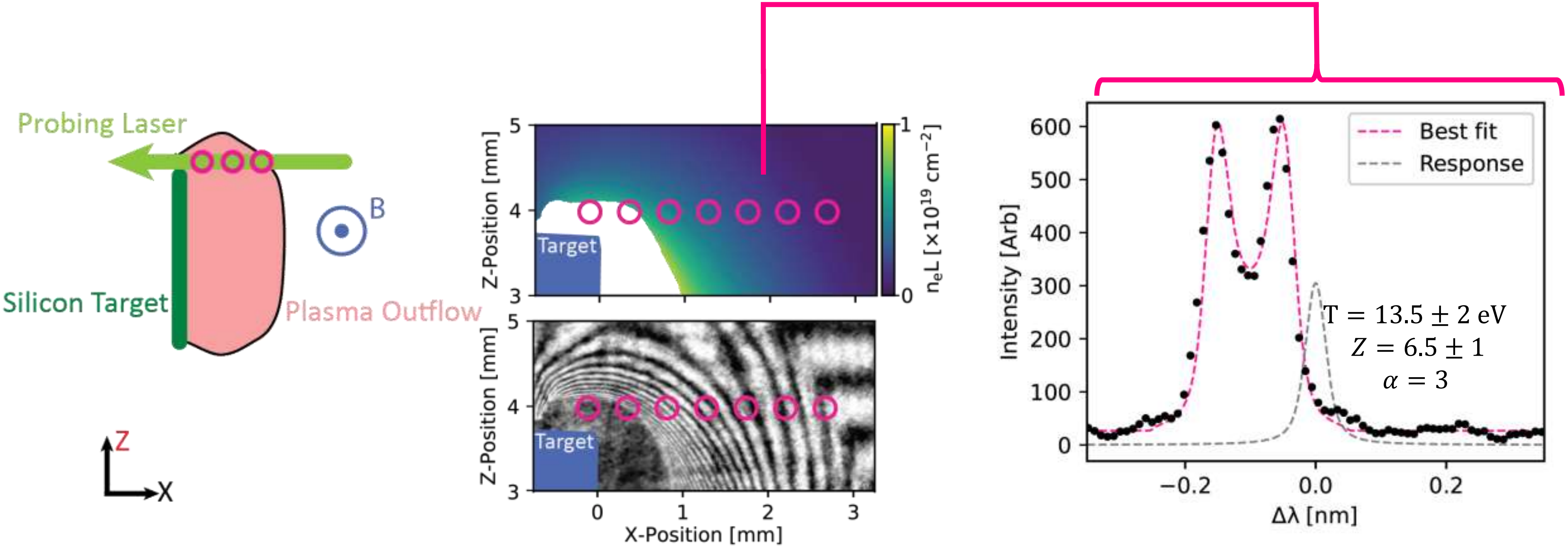

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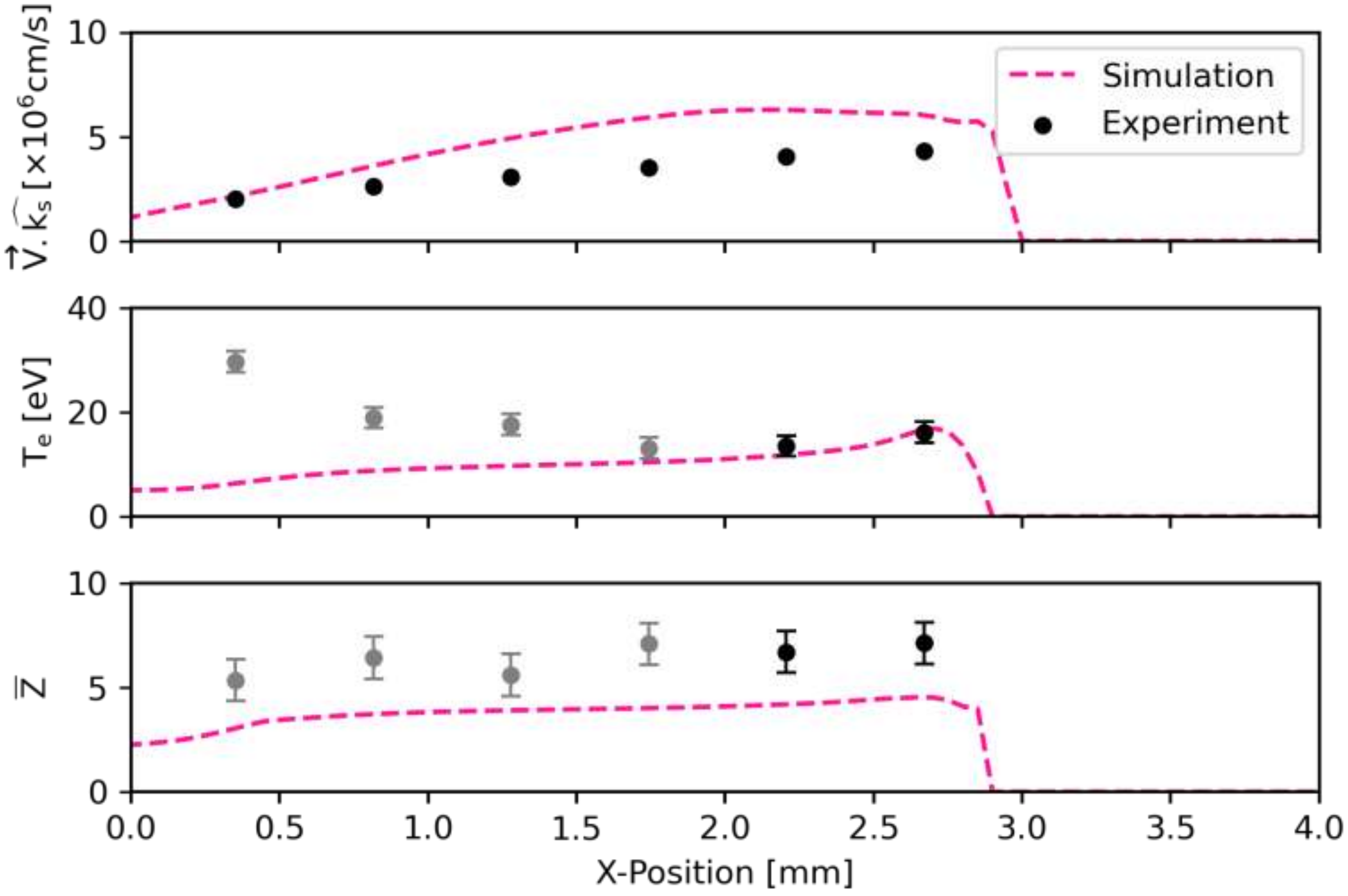
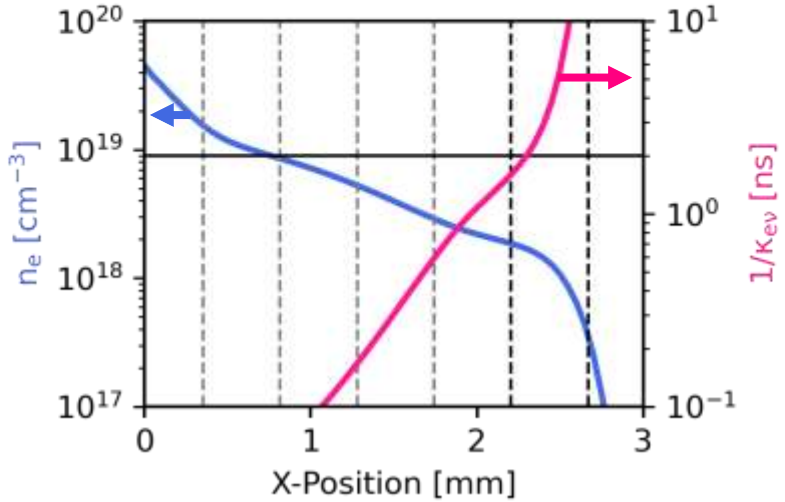



Calculated from sims!

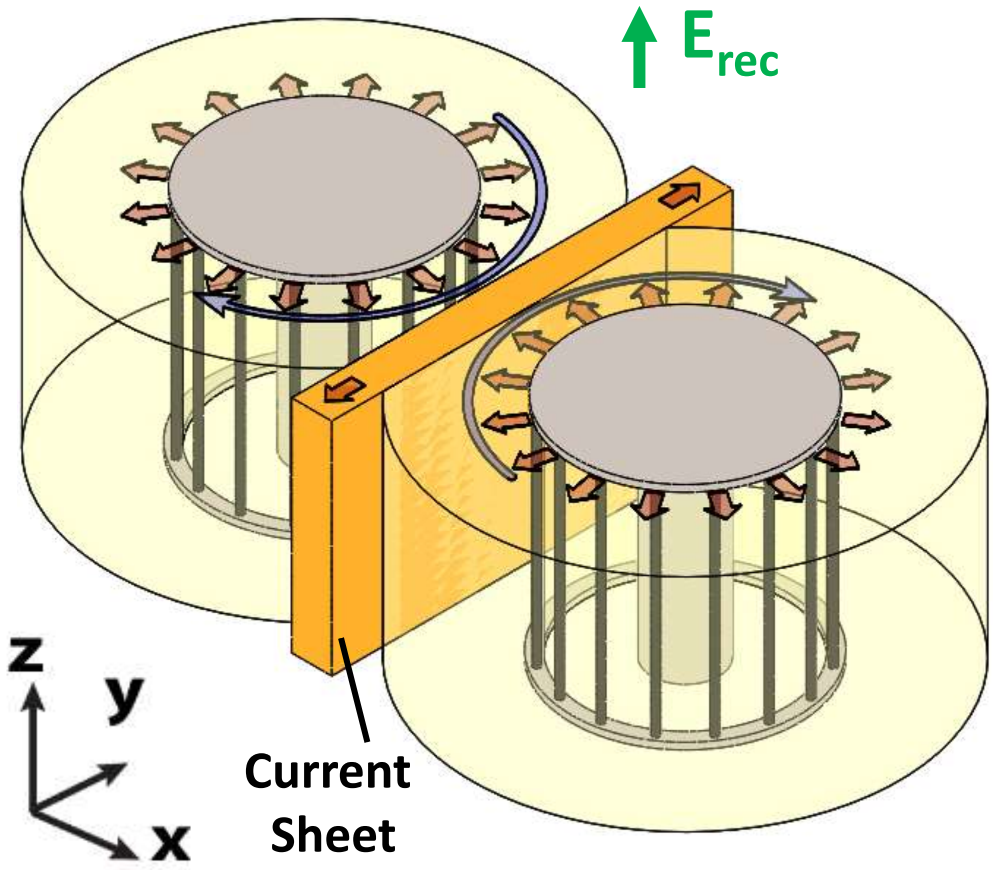


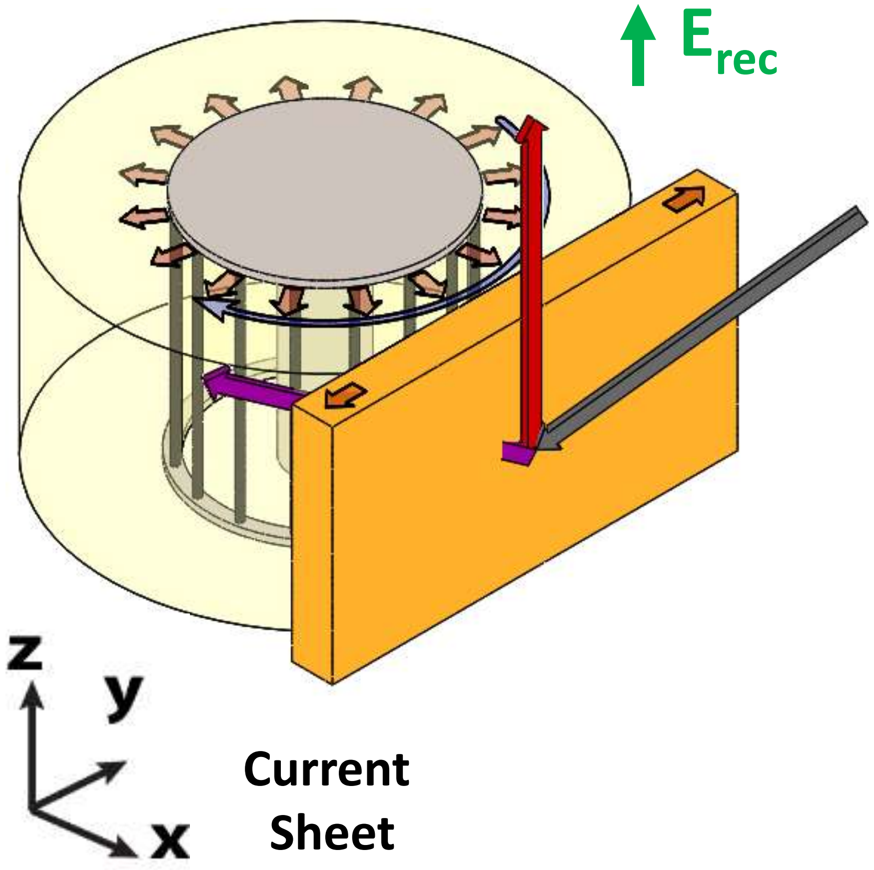

$$\kappa_{\nu e} \propto \frac{Z n_e^2 \ln(\Lambda) T_e^{-\frac{3}{2}}}{\sqrt{\omega^2\left(1-\omega_p^2/\omega^2\right)}}$$

**N. R. L.** plasma physics formulary

# Enhanced IAW fluctuations in Magnetic Reconnection

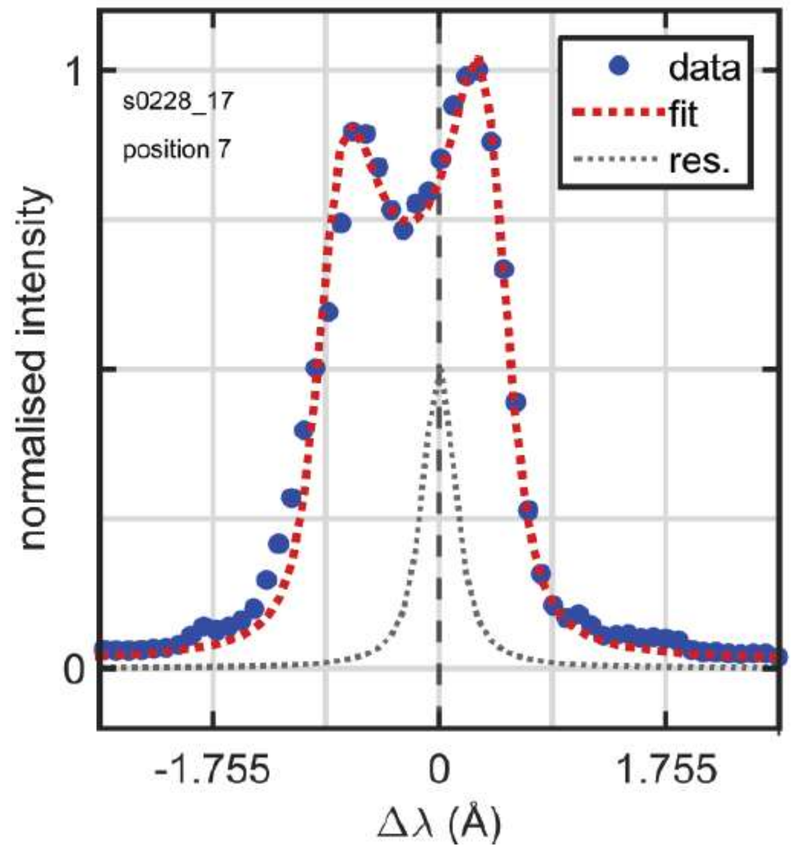




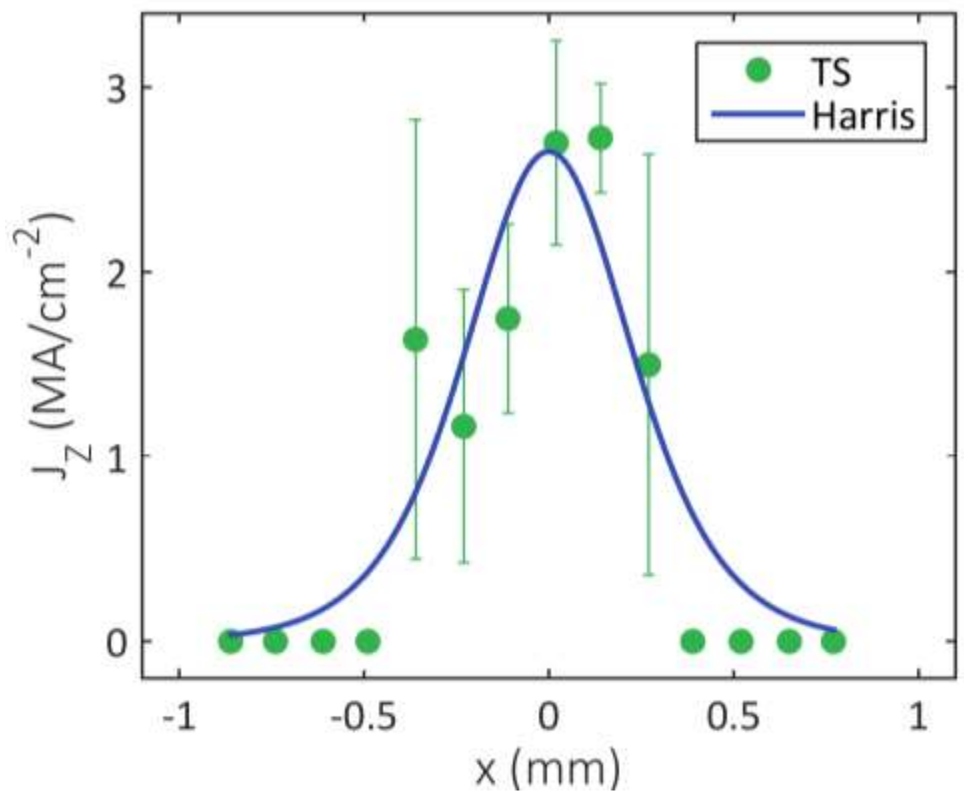
# Enhanced IAW fluctuations in Magnetic Reconnection






$U_{drift}, n_e$

Current density $J_Z$ profile




**Consistent with Harris sheet profile, using measured upstream $B_0$ from Faraday rotation polarimetry**

L Suttle – PRL (2016), PoP (2018), RSI (2021)

# Enhanced IAW fluctuations in Magnetic Reconnection

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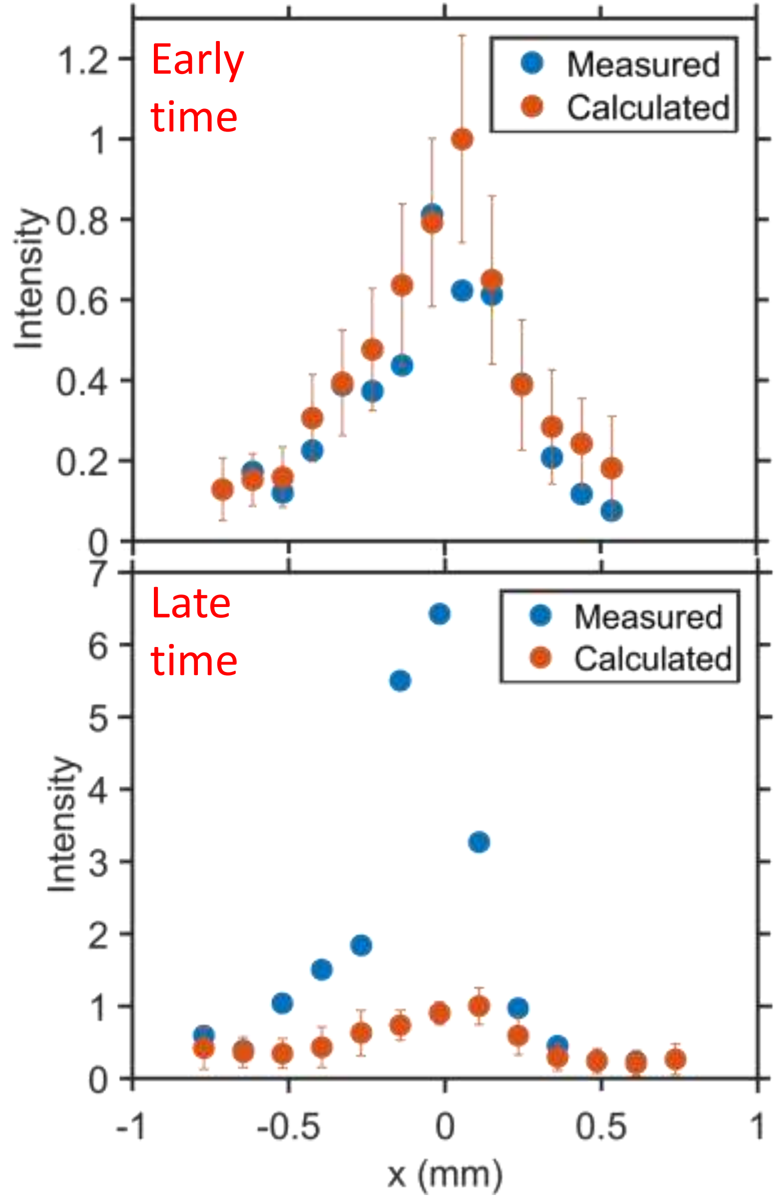


**Predicted (calculated) intensity**

$$I_{TS} \propto n_e \int S(\omega, K) d\lambda$$

- Total intensity of ion-acoustic fluctuations observed to be in excess of the thermal level
- Enhancement usually attributed to ion-acoustic instability – not the reason here as IAW peak asymmetry reliably measures electron drift
- Theoretical analysis suggests plasma ought to be marginally stable to ion acoustic instability

# Enhanced IAW fluctuations in Magnetic Reconnection

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**Criteria for ion-acoustic turbulence in multiply ionized plasma ($\bar{Z} \gg 1$):**

Ryutov, Derzon, and Matzen: The physics of fast Z pinches
Rev. Mod. Phys., Vol. 72, No. 1, January 2000

Another current-driven microinstability is the ion acoustic instability, which typically has a higher threshold in terms of the relative velocity of electrons and ions. Extensive studies of this instability are summarized in the surveys by Vedenov and Ryutov (1975) and Galeev and Sagdeev (1979). In a singly charged plasma this instability can be present only if the electron temperature is much higher than the ion temperature, $T_e \gg T_i$; at $T_e \sim T_i$ the ion sound speed is comparable to the thermal velocity of the ions, and acoustic waves experience a strong ion Landau damping. However, in a plasma with $Z_{eff} \gg 1$, this instability can be excited even at $T_i > T_e$. Indeed, the sound speed in a plasma with high-$Z$ ions is equal to

$$\sqrt{\frac{Z_{eff}T_e + T_i}{m_i}}, \qquad (7.3)$$

while the ion thermal speed is $\sqrt{2T_i/m_i}$. Imposing a constraint that the sound speed exceed the ion thermal speed by a factor of 2, one finds the condition of weakly damped ion acoustic waves in a high-$Z$ plasma:

$$T_e > 7T_i/Z_{eff}. \qquad (7.4)$$

One sees that, at $Z_{eff} \gg 1$, weakly damped ion acoustic modes can exist even at $T_i > T_e$. The critical current velocity for the onset of ion acoustic instability under such conditions is several ion thermal velocities.

↔

$$U_{drift} > c_S \qquad (1)$$

$$c_S > 2V_{i,Th}$$

$$\sqrt{\frac{\gamma(\bar{Z}T_e + T_i)}{m_i}} > 2\sqrt{\frac{2T_i}{m_i}} \qquad (2)$$

$$\bar{Z}T_e > 3.8T_i$$

(weak Landau damping)

(1) satisfied at all times.

(1) & (2) satisfied only at late time.

| Layer parameters | Early time | Late time |
|---|---|---|
| $c_S$ (km/s) | 63 | 39 |
| $U_{drift}$ (km/s) | 72 | 70 |
| $V_{i,Th}$ (km/s) | 55 | 17 |
| $ZT_e$ | 260 | 225 |
| $3.8\ T_i$ | 1596 | 152 |

(Estimated at early time from Faraday rotation)