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Interpenetration and Deflection of Ablation Streams on the Axis of Tungsten Cylindrical Wire Array

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Interpenetration and deflection of ablation streams on the axis of Tungsten cylindrical wire array

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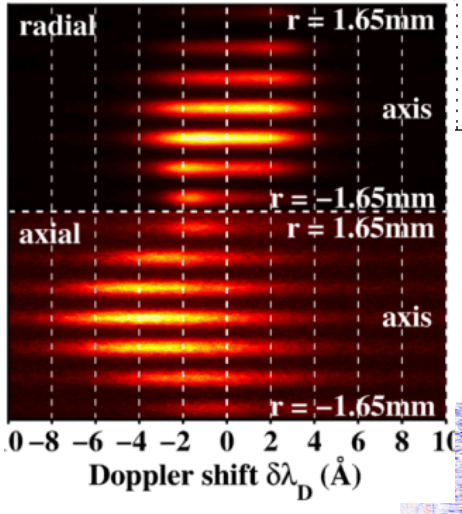
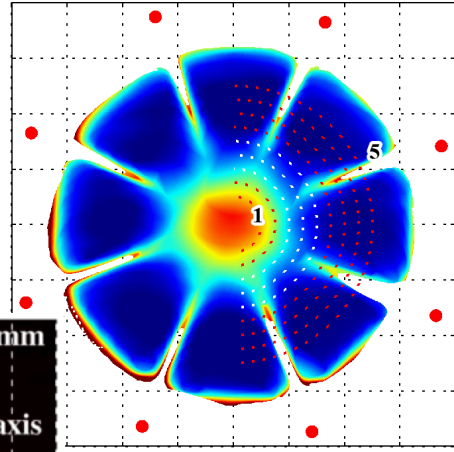
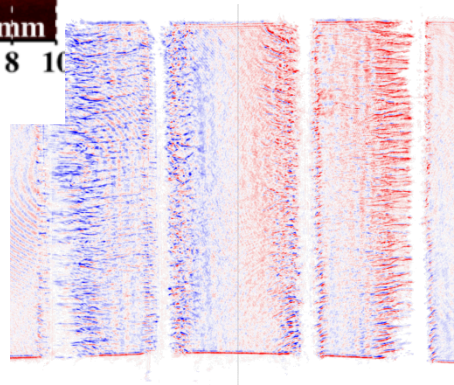
Overview

Investigation of the interactions of **Tungsten** ablation streams in wire array **z-pinches**

- Initial Interferometric Imaging:
  - Measurements of shockless – interactions between Tungsten ablation streams
- Thomson Scattering:
  - Measurements of Interpenetration and deflection
- Faraday Rotation Imaging:
  - Direct measurements of magnetic fields in Tungsten ablation streams



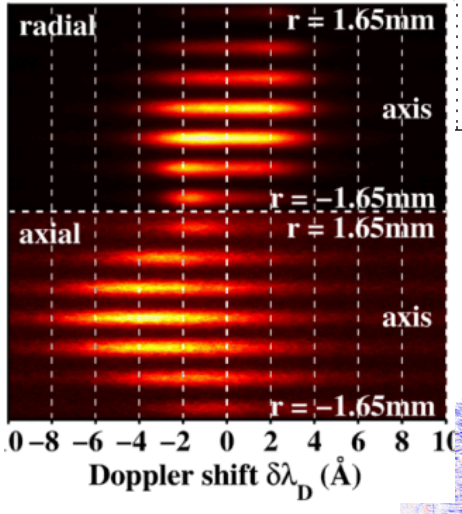


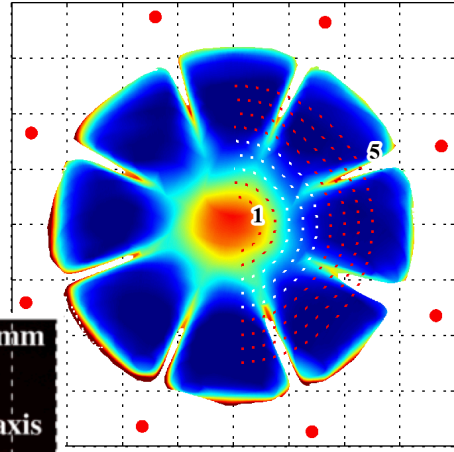


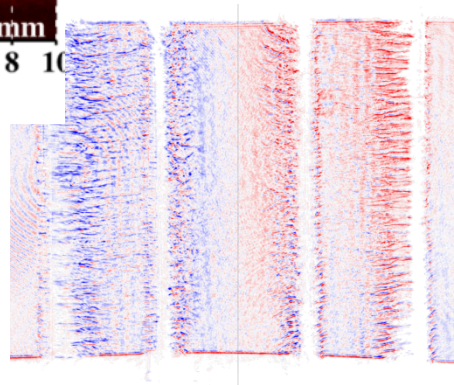
Motivation

Plasma interpenetration is an **Important** effect in **HEDP**:

- These dynamics dominate the early phases of **wire array z-pinches**
- On this axis of **ICF vacuum hohlraums**
- **Magnetic fields** are present in plasma ablated from **hohlraum walls** due to **laser interaction.**







Plasma Parameter Regime

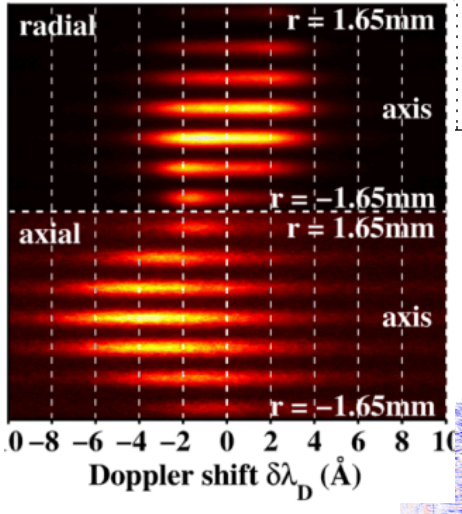
- Typical plasma parameters for experiments:

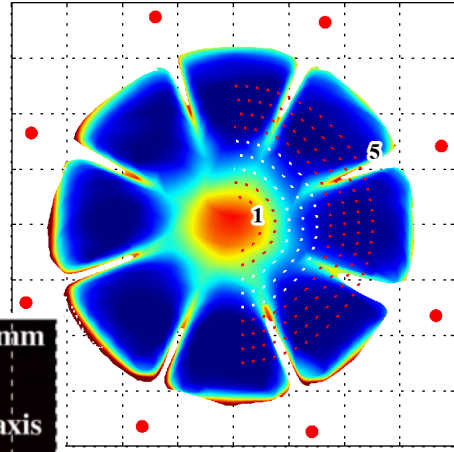
$n_e \sim 10^{18} cm^{-3}$ $T_e \sim 50$ eV $T_i \sim 10$ keV

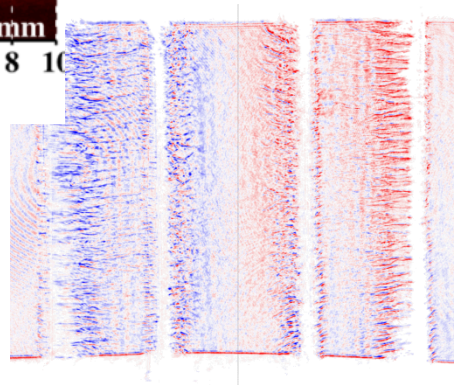
- **Plasmas** produced from **metal** wires
  - Tungsten and Aluminium

- High atomic number - radiative cooling plays an important role

- Ions are not fully stripped- ionisation effects are important





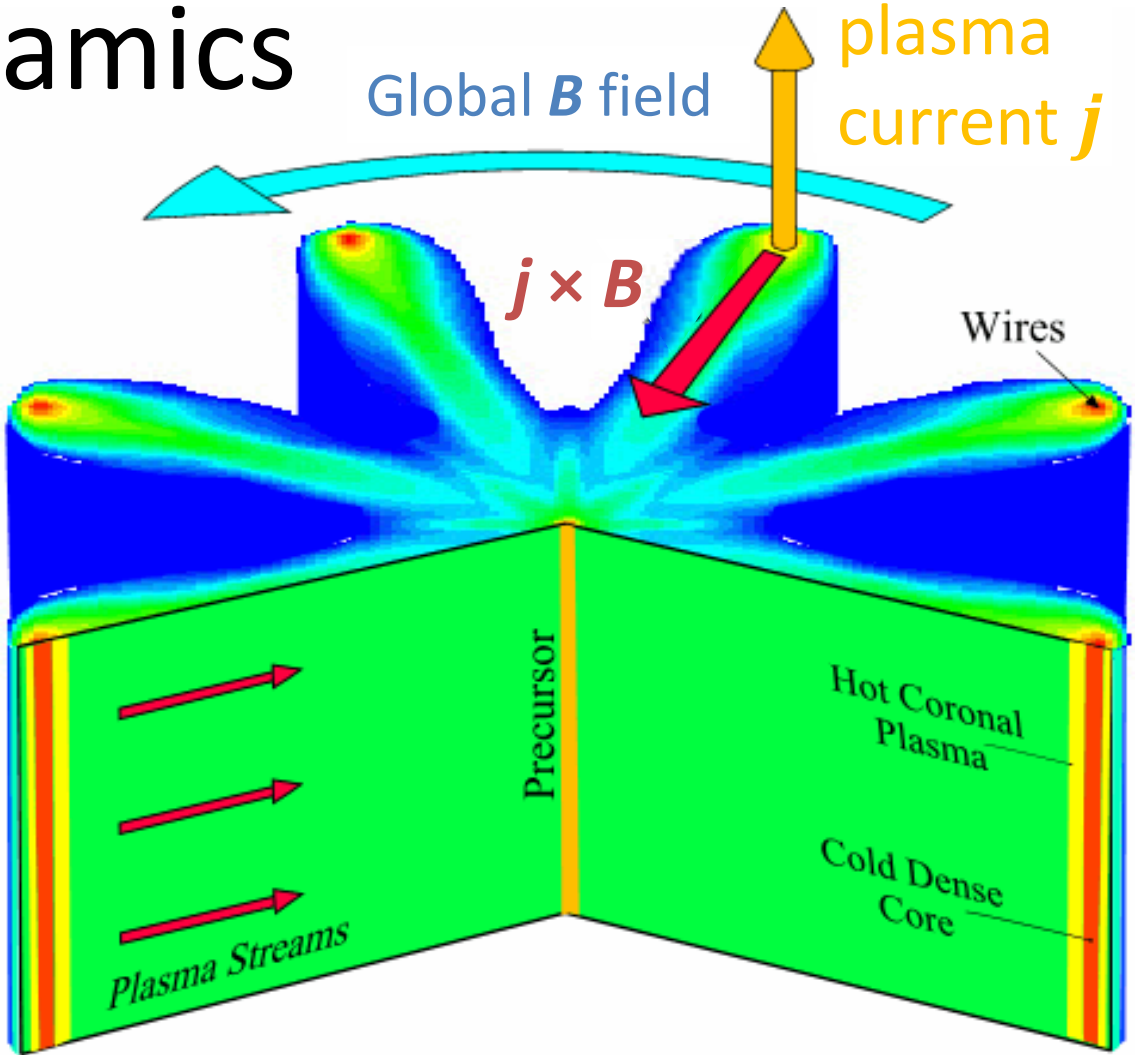


Wire array dynamics

- Plasma formed by **resistive heating** of wires

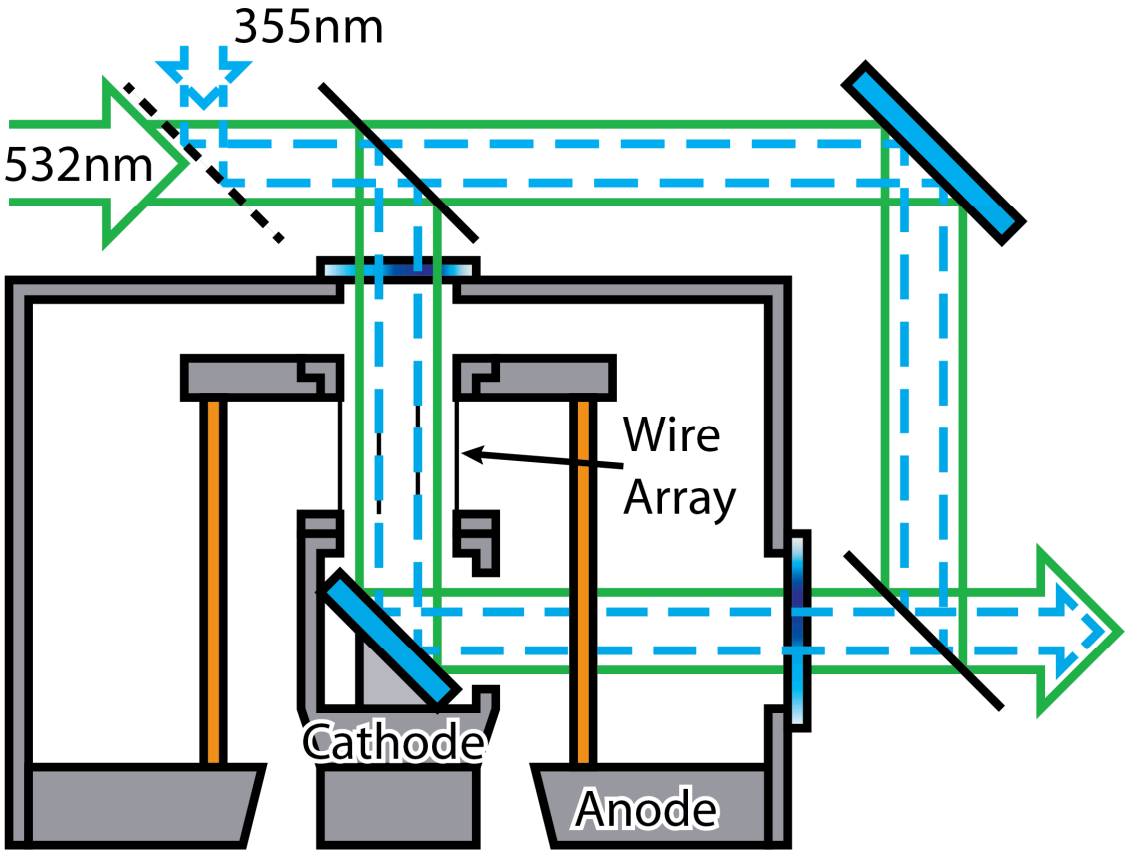
- $j \times B$ force :
  - global B field
  - plasma current j

- **Streams** of **ablated plasma**:
  - Accelerated towards axis
  - radially converge
  - collide and interact on axis



End-on interferometric Imaging

- Pulsed Nd:YAG laser (500ps,200mJ)
- **Mach –Zehnder**
- **Two Colour**
  - **532 nm**
  - **355 nm**
- **Two time**
  - 030ns delay
- Time integrated CCD imaging

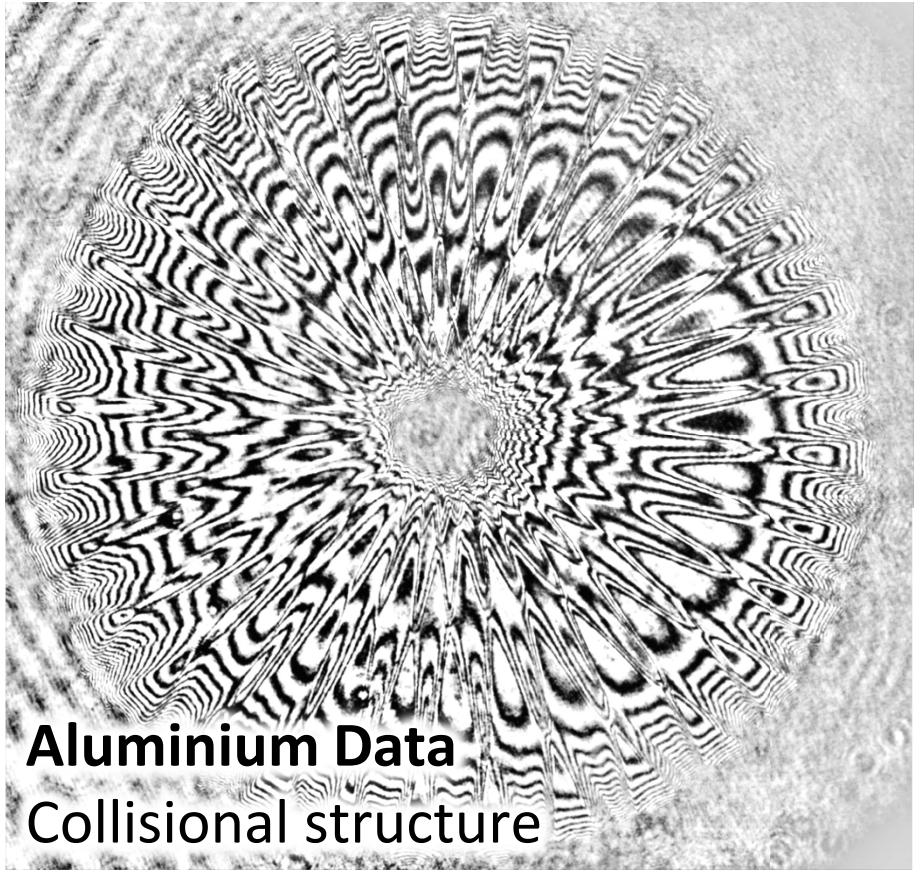


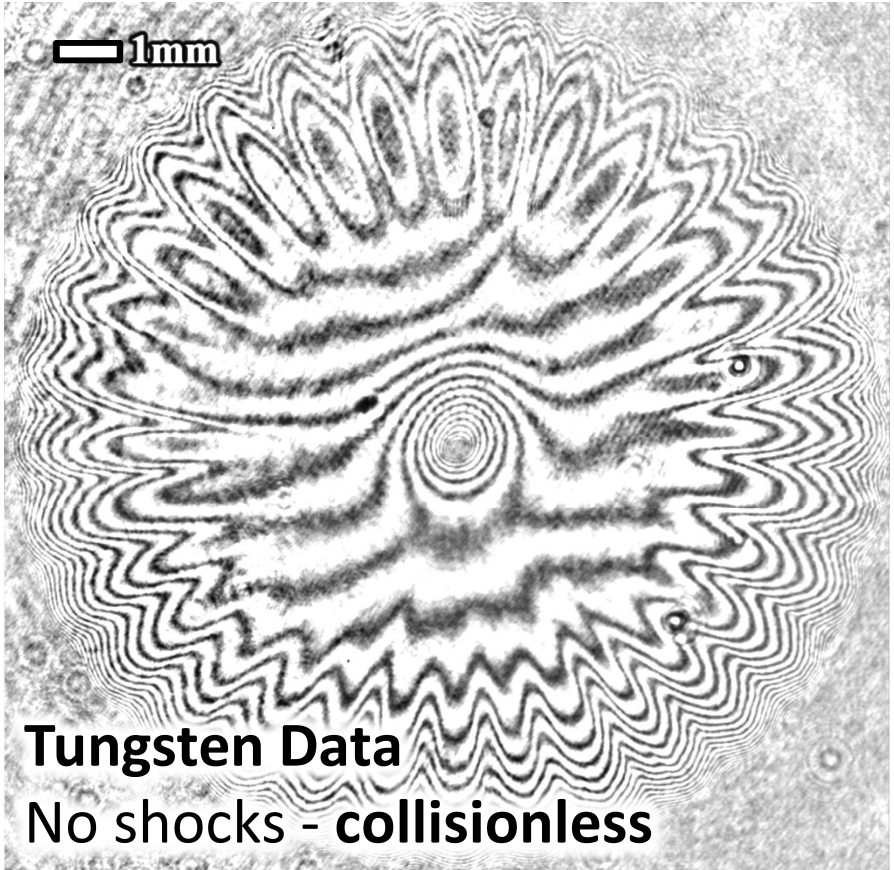
Cross-section

Interaction Dynamics for Tungsten and Aluminium

Same current, timing & wire number -120 ns

Only change between these two measurements was wire material!





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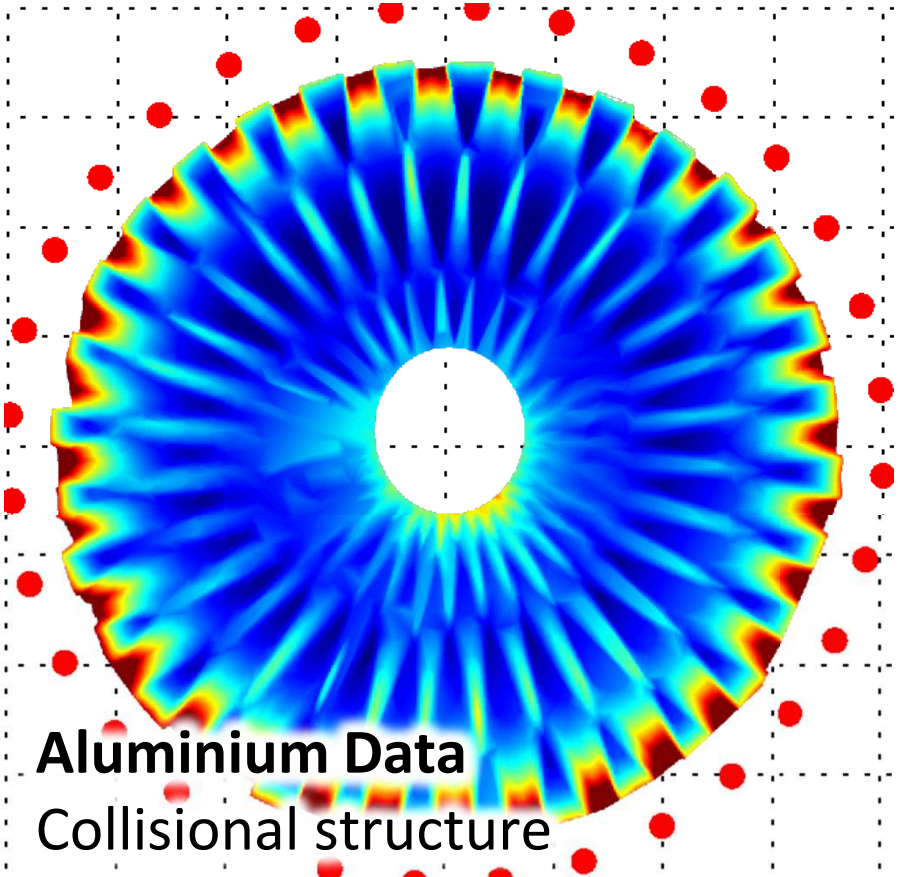
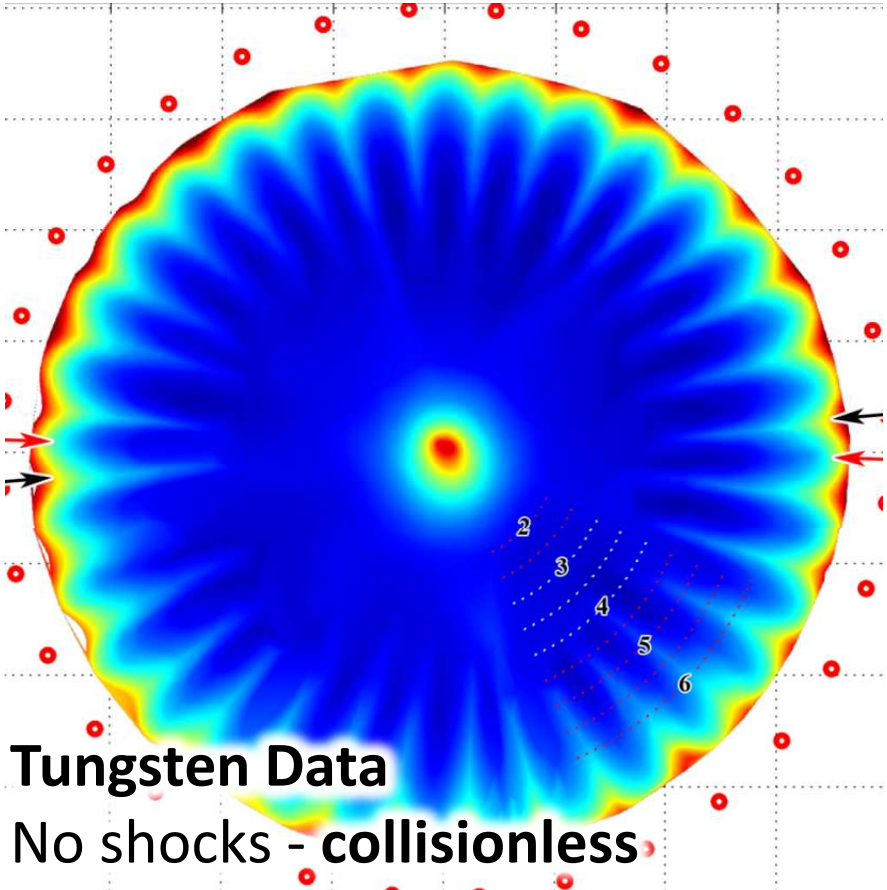


Aluminium Data

Collisional structure

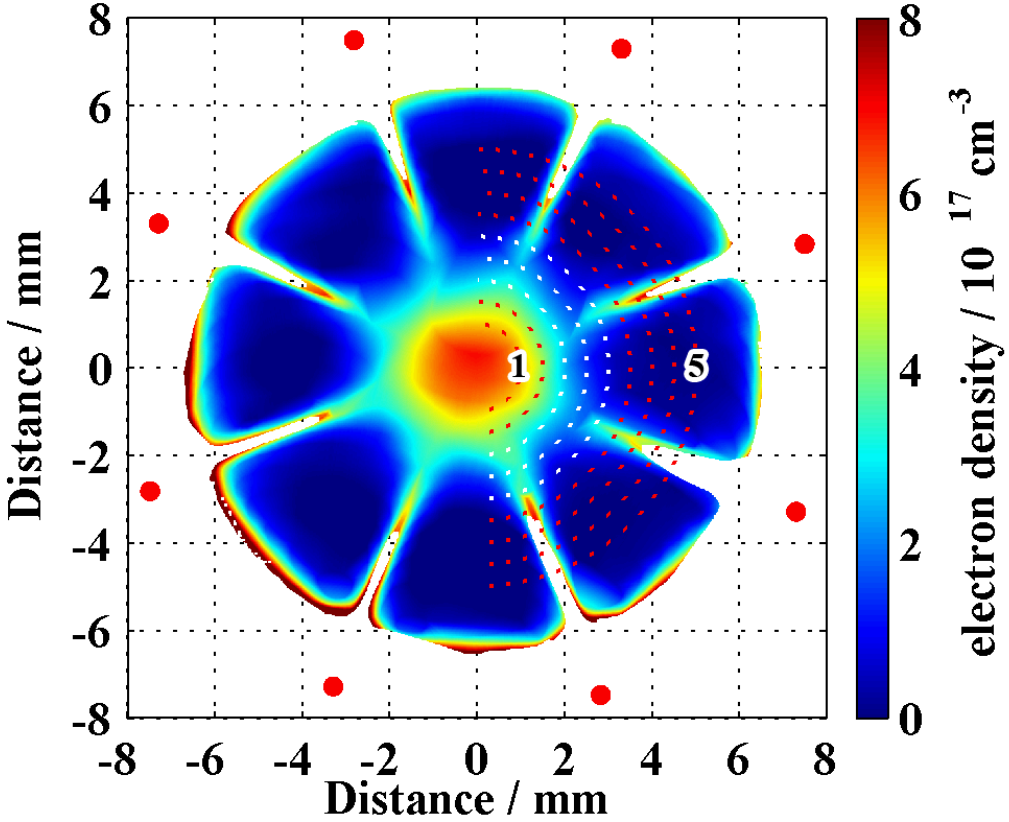


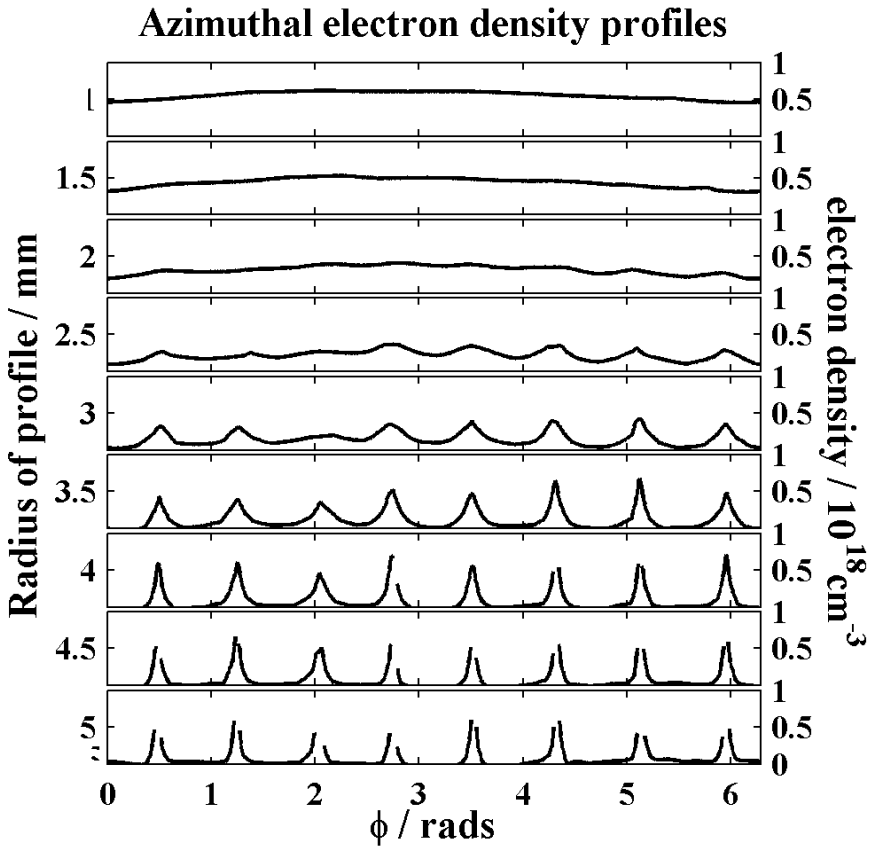
Tungsten Data

No shocks - **collisionless**

Same shock-less evolution of ablation streams seen in 8 wire arrays

why?



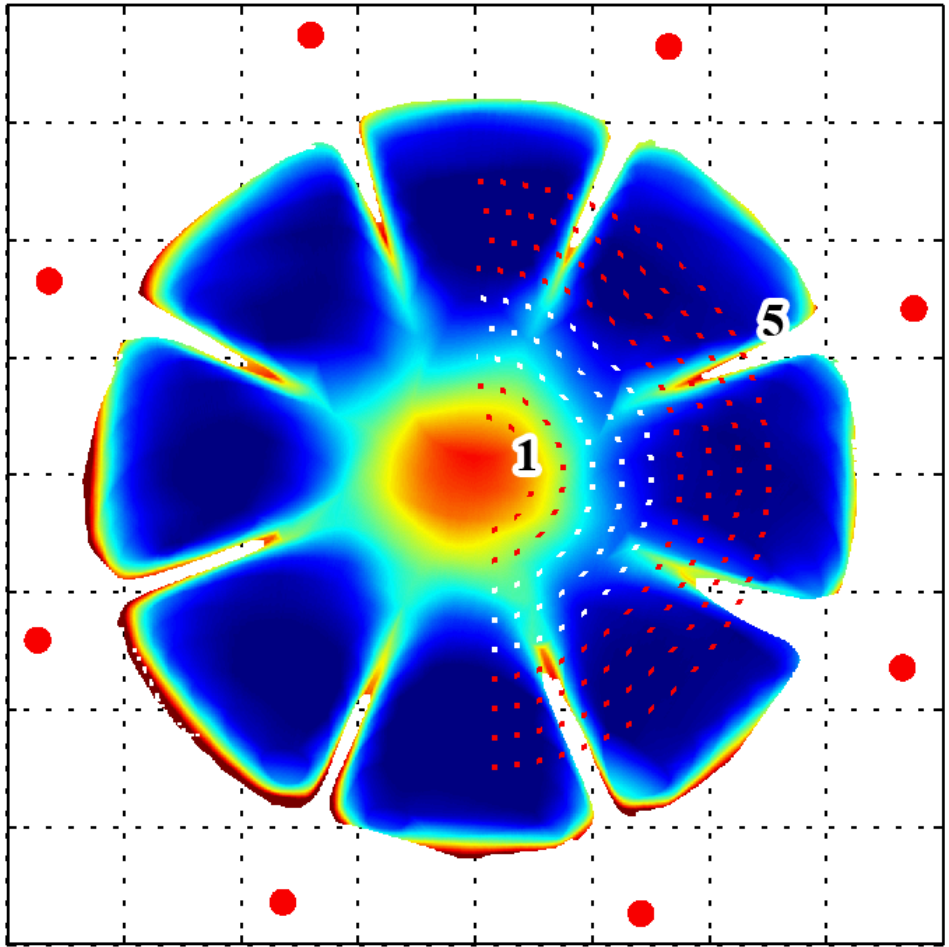


Swadling et al. - Physics of Plasmas **20**, 062706 (2013)

Thomson scattering

- Expected to see:
  - Interpenetration
  - Slowing
  - Heating

- Ion feature of Thomson scattering :
  - Ion flow velocity
  - Ion temperature
  - Simultaneous separate measurements radial and axial components



Thomson scattering diagnostic

Probe beam:

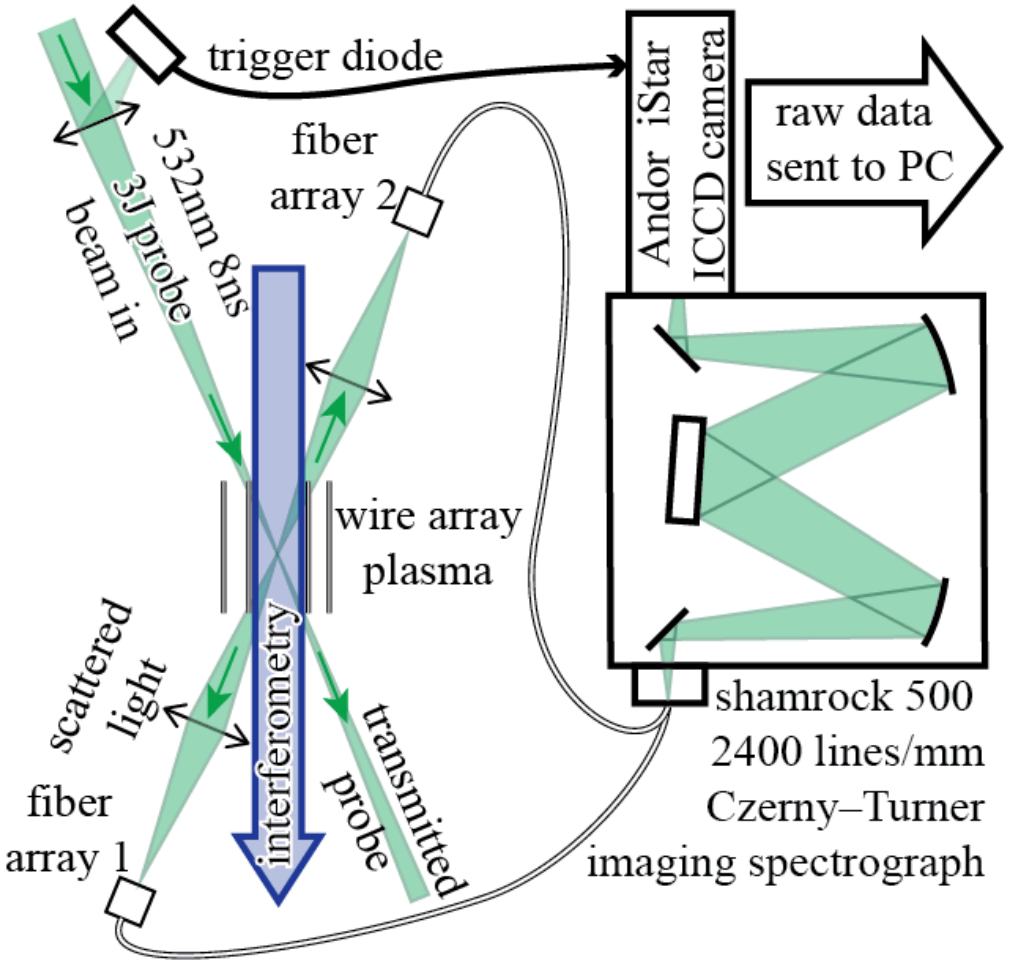
- 532 nm, 3 J, 8 ns
- 22.5° from axis

Scattered light collected at:

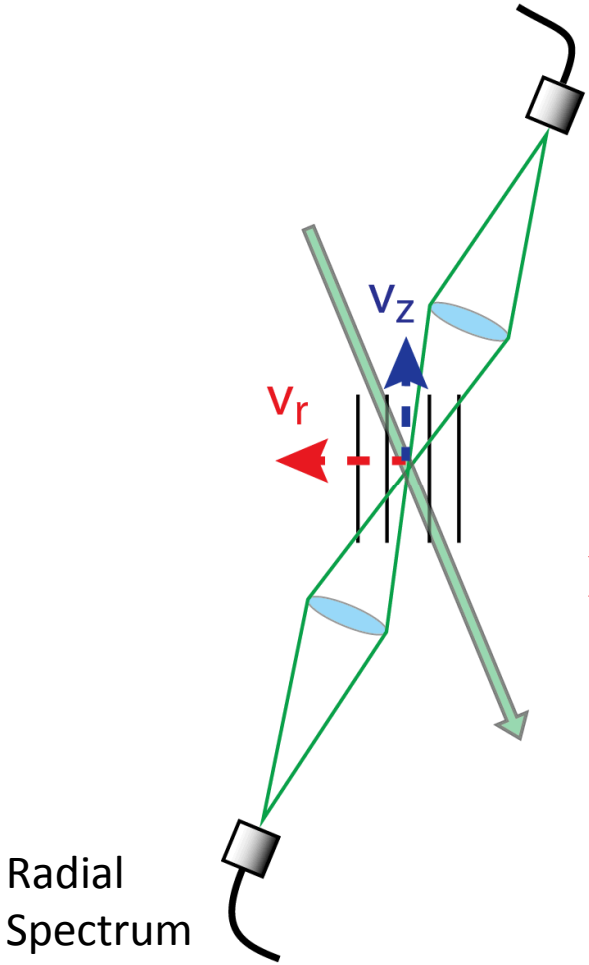
- 45° from probe
- 135° from probe

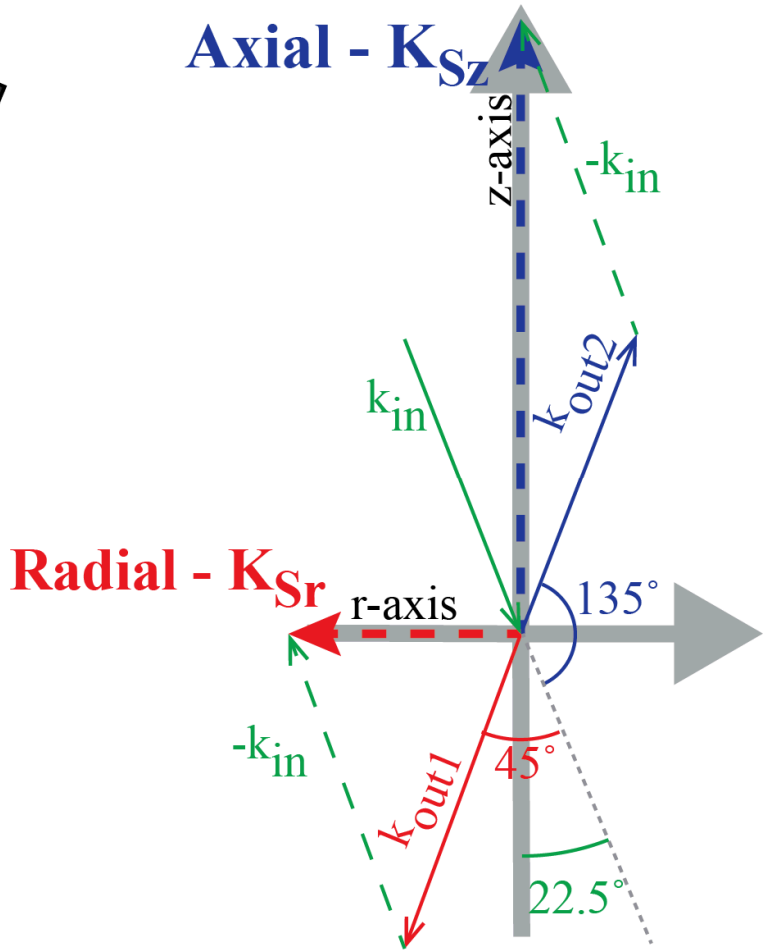
Spectrometer:

- 0.5 m 2400 lines/mm
- 4 ns gate – Andor iStar
- 0.5 Å resolution



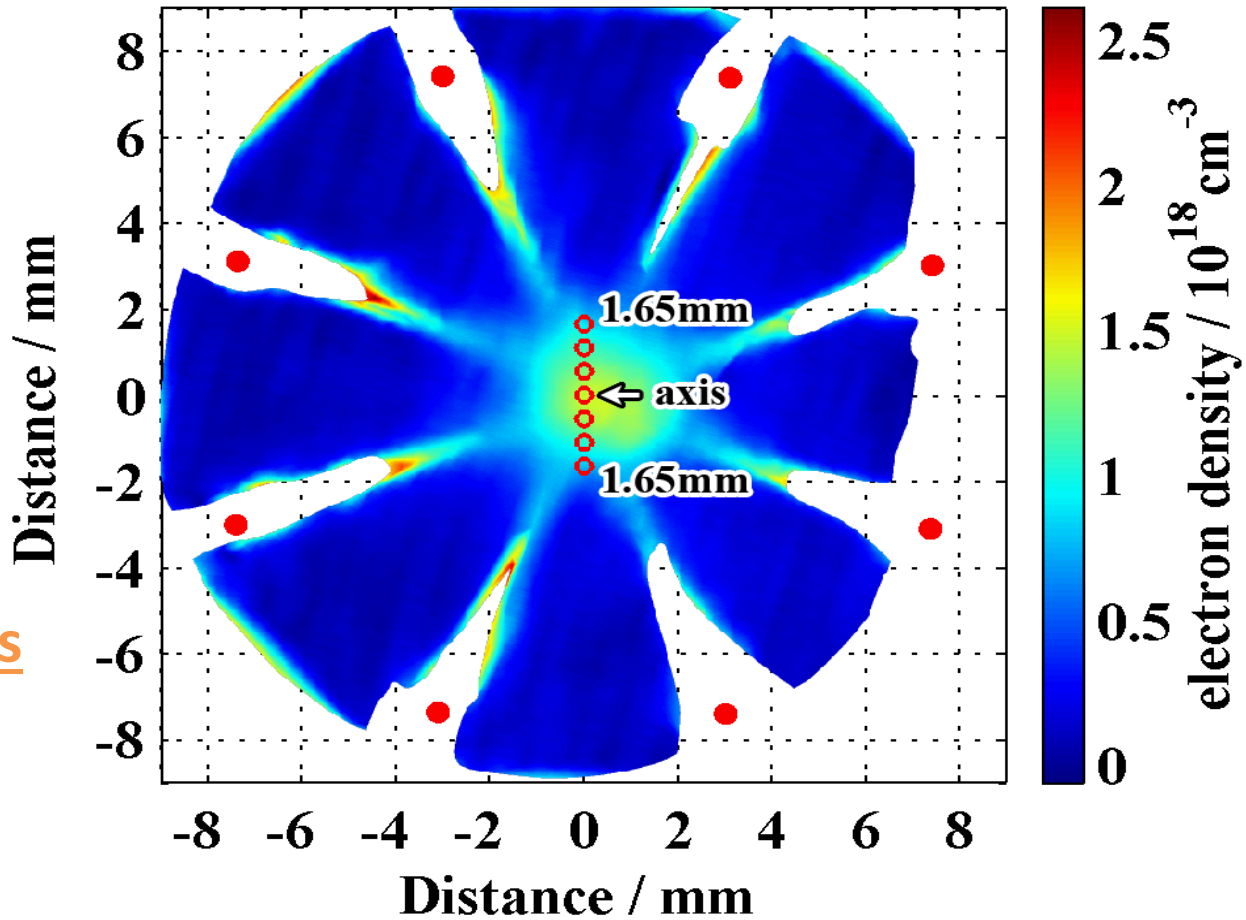
Choice of collection vectors:





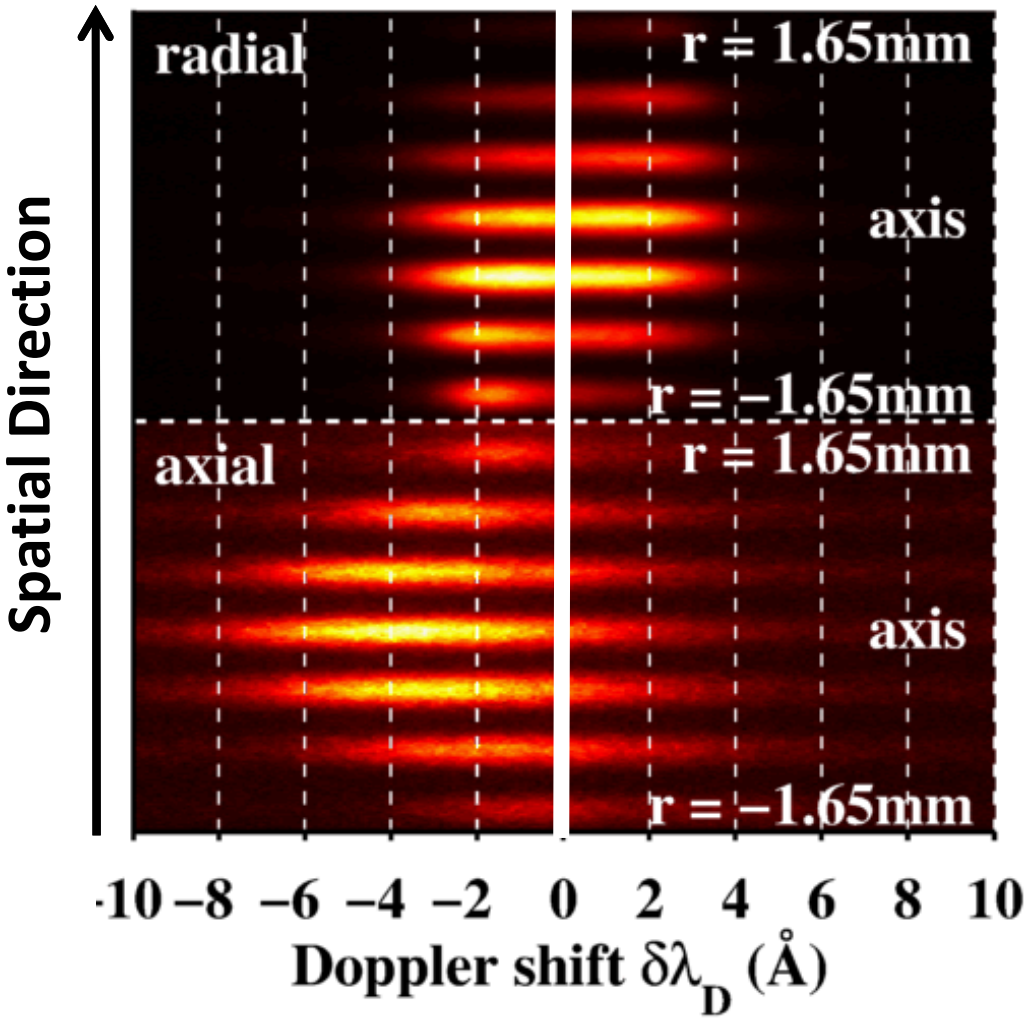
Simultaneous v_r, v_z measurements

- 7 spatial positions
- Central fibre on axis
- Others spread 1.65mm either side.
- Measurement at 120ns into 240ns pulse



Thomson data

- **Raw** spectrogram
- **Radial** spectra:
  - **interpenetration**
  - **heating**
- **Axial** spectra:
  - **Axial acceleration**



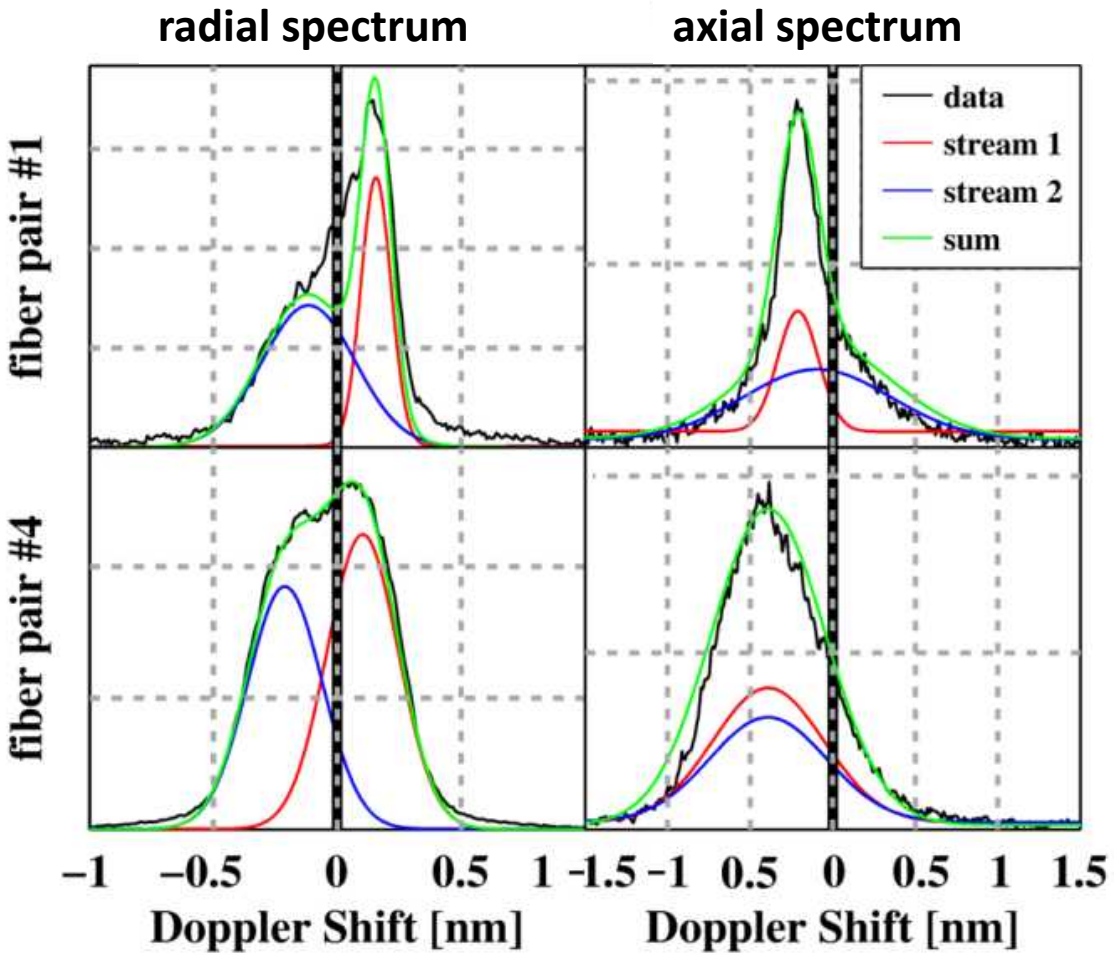
Swadling et al. – Physical Review Letters **113**, 035003(2014)

Constrained fit procedure

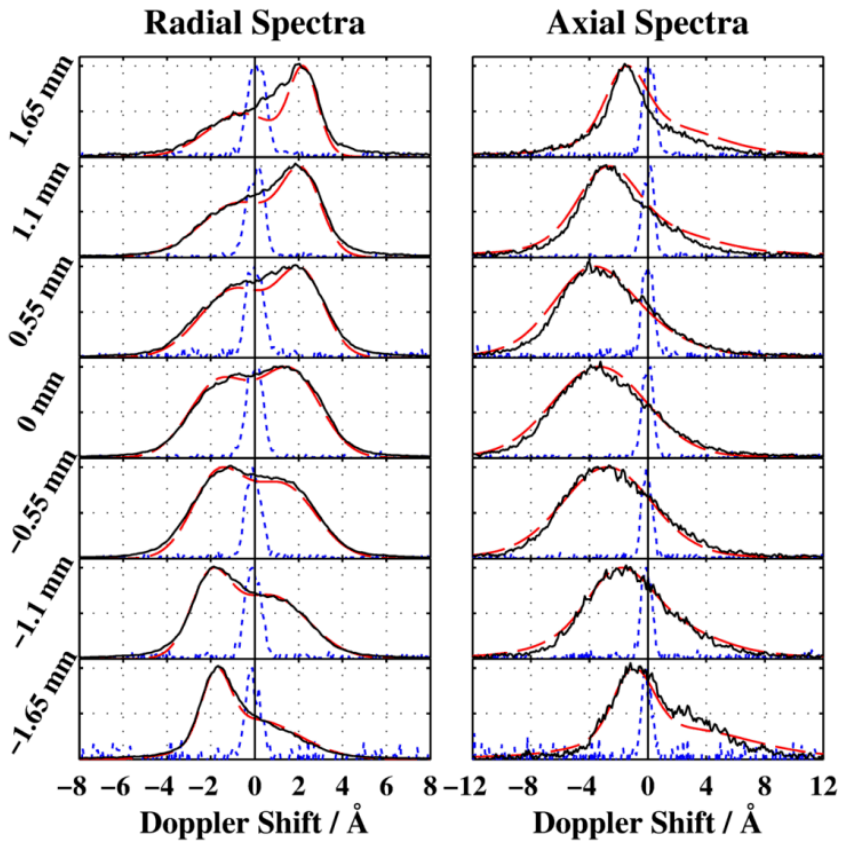
$$S(\omega,k) = \frac{2\pi}{k}\left[\left|1-\frac{\chi_e}{\epsilon}\right|^2 f_{e0}\left(\frac{\omega}{k}\right) + \sum_j \frac{\bar{Z}_j^2 n_j}{n_e}\left|\frac{\chi_e}{\epsilon}\right|^2 f_{i0}\left(\frac{\omega}{k}\right)\right]$$

$$\epsilon = 1 + \chi_e + \sum_j \chi_j, \qquad n_e = \sum_j n_j \bar{Z}_j$$

- Fits calculated using multi-component, non-relativistic, Maxwellian **spectral density function**
- Each fit constructed from **two independent ion populations**
- Radial and axial spectral are calculated **simultaneously**
- **Same ion populations**
- **Different velocity components**



Constrained fit using spectral density function S(ω,k) – Find v_r v_z T_i



- Extracted data – **black**
- Un-shifted laser – **blue**
- Constrained fits – **red**
- Each pair of fits constructed from **two independent ion populations**
- Fits match data well despite constraints

Variation in plasma parameters

radial velocity:-

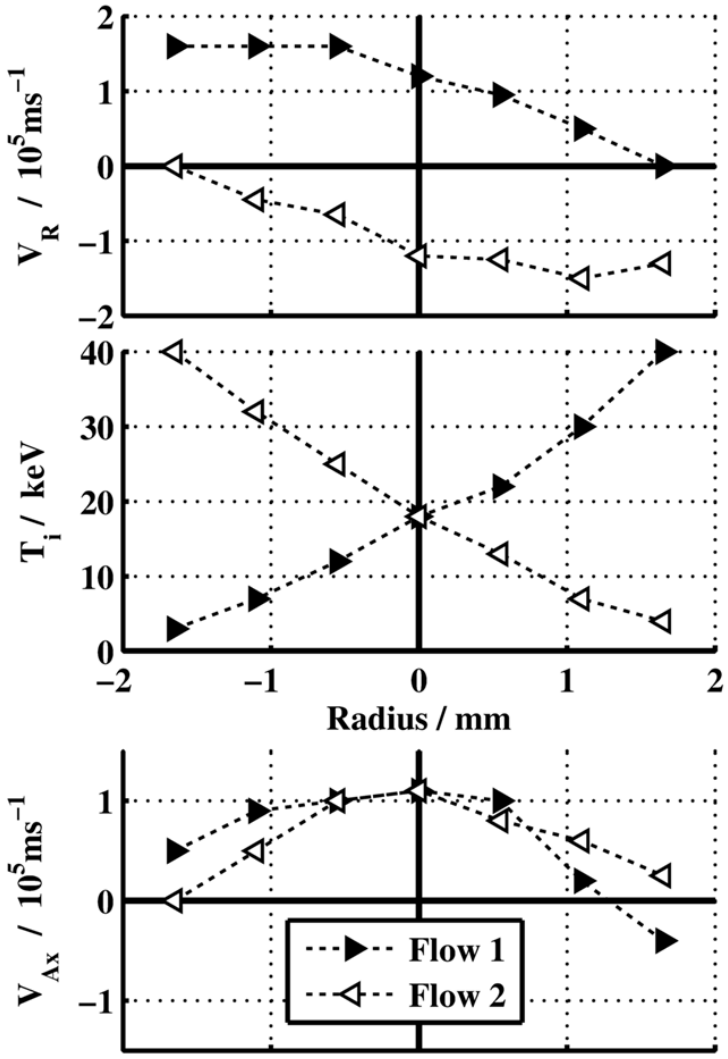
- **decreases** as flows propagate.
- **stagnated** at far side of region

ion temperature:-

- increases linearly **2 keV** to **40 keV**
- **~20keV on axis**
- measurements along **two axes** indicate **real** isotropic **ion temperature**

axial velocity:-

- **deflection** towards **anode** on **approach** to **axis**
- **deflection** back towards **cathode after axis**

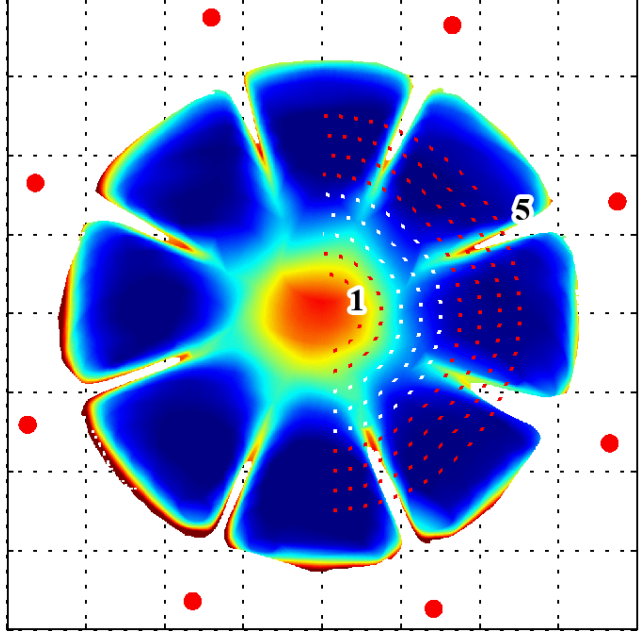


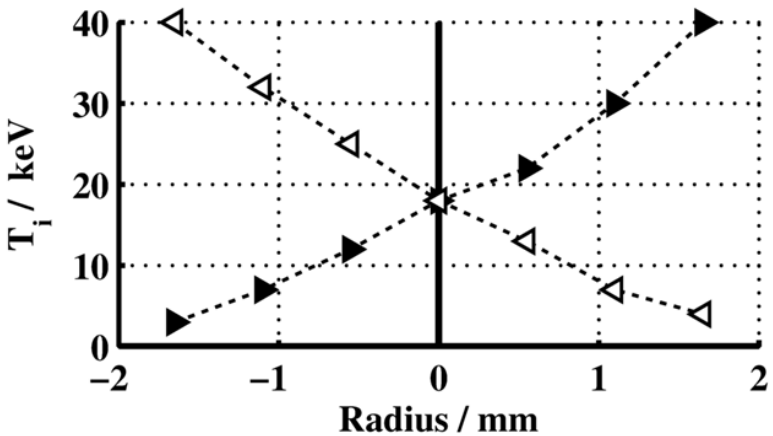
Physics of collisional interactions

Data strongly indicates that collisional effects are dominated by ion-ion collisions

- Scattering of well defined streams as they approach the array axis
  - **Cannot** be produced by ion-electron collisions

- Rapid rise of ion temperature requires majority of incoming ion KE



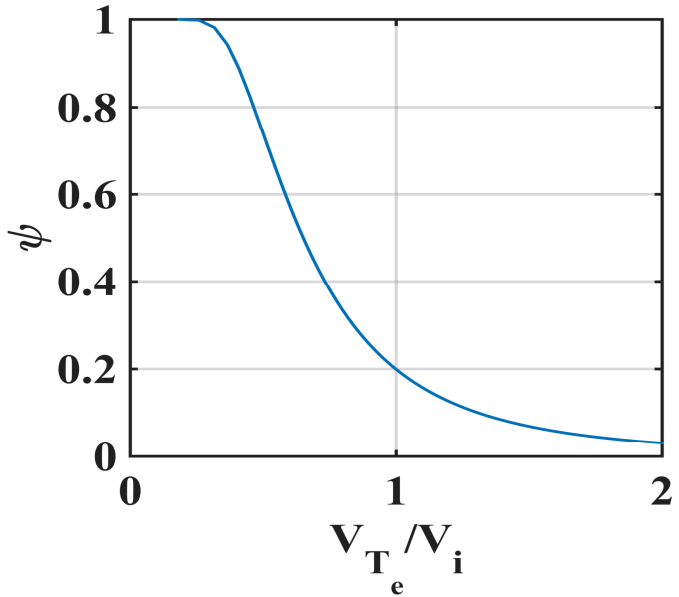


Absence of electron drag may be accounted for:

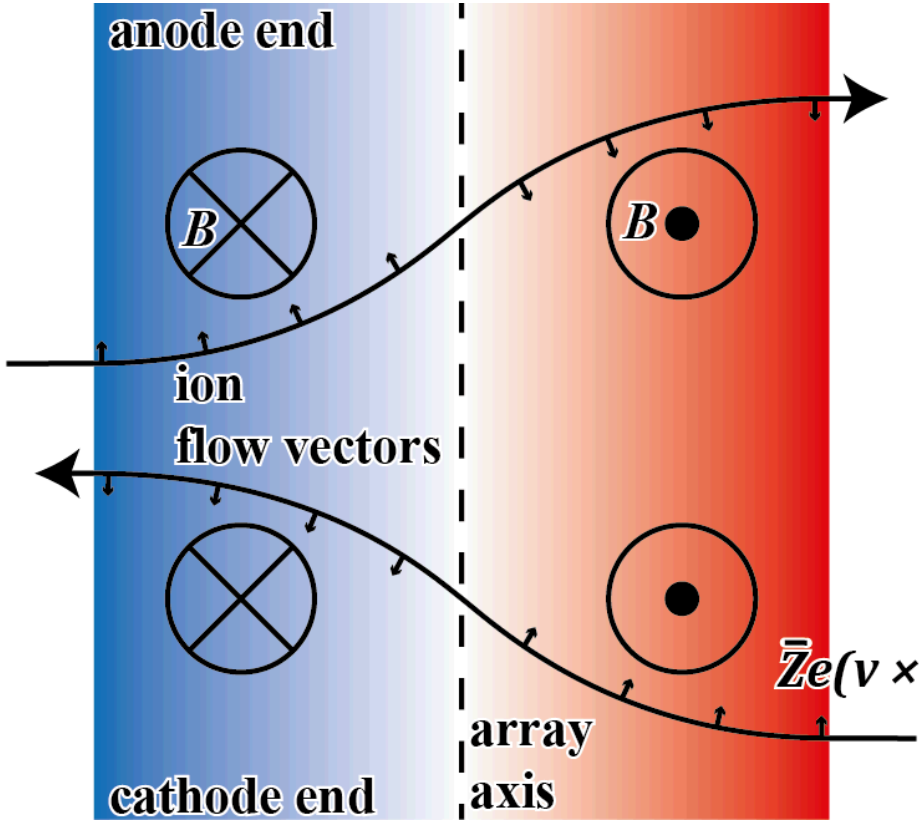
- Electrons are radiatively cooled
- Early in time the electrons are poorly coupled to the ions – τ_{ei} is long – separate temperatures
- If electrons are cold then electron-ion drag should dominate collisional interactions
- Incoming ion K.E. is ~25keV. Only a small fraction is required heat electrons to the point where $v_{Te}>v_i$ (T_e~30eV, ZT_e~450eV).
- At this T_e the velocity potential ψ falls to zero and electron drag becomes negligible

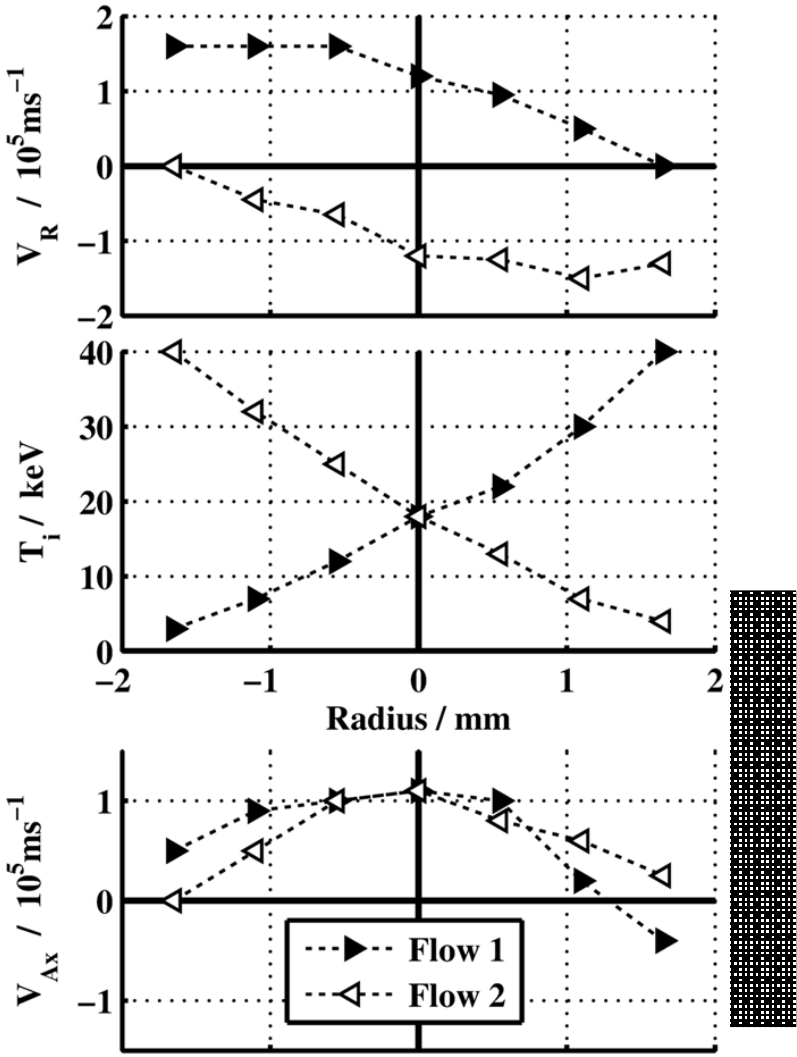
$$l_s^{i\backslash e} = \frac{1}{(1+m_i/m_e)\psi^{i\backslash e}} \frac{m_i^2 v_i^4}{4\pi \bar{Z}_e^2 \bar{Z}_i^2\, e^4 \lambda_{ie} n_e}$$

$$\psi(x^{i\backslash e}) = \frac{2}{\sqrt{\pi}} \int_0^{x^{i\backslash e}} t e^{-t} dt\ , \qquad x^{i\backslash e} = \frac{m_e v_i^2}{2k_B T_e}$$



Magnetic field on axis?



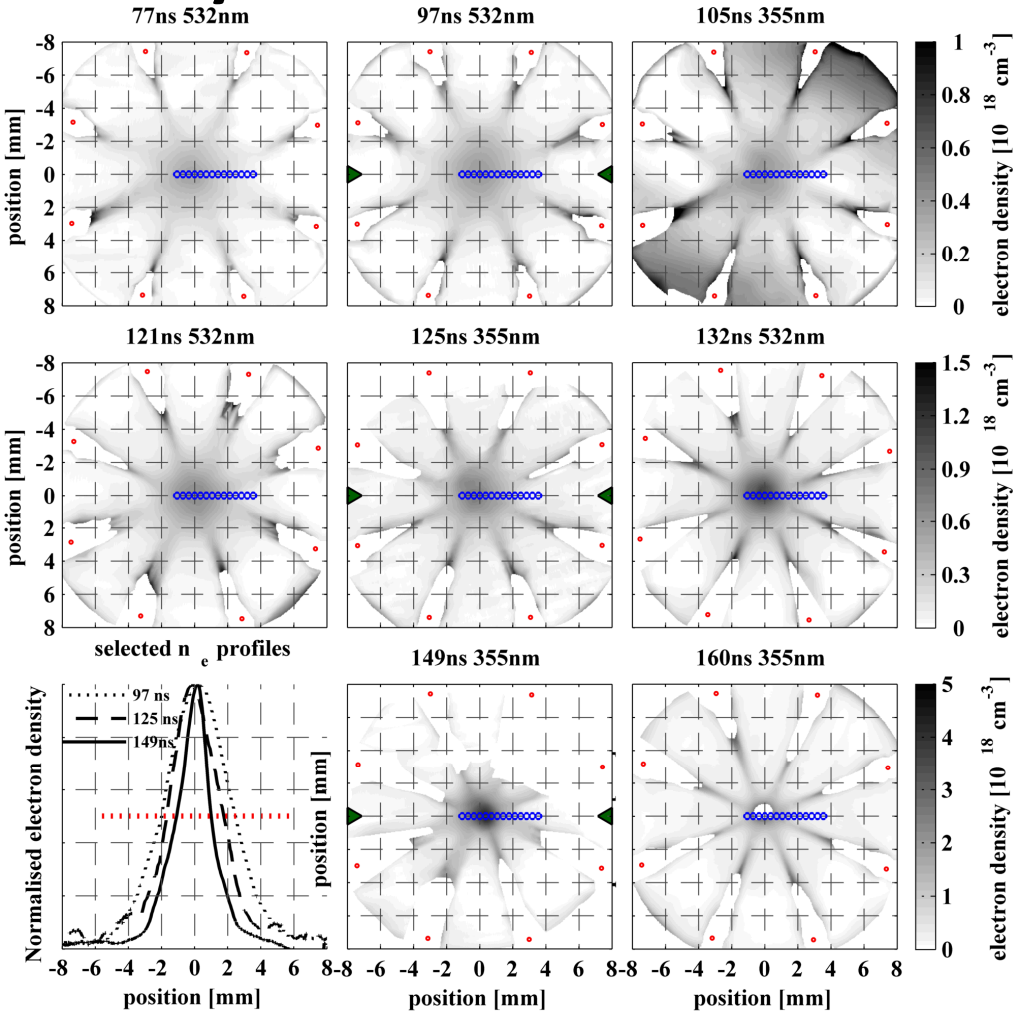


Magnetic Field required for observed 45° deflection : **20 T**

Temporal Evolution of Collisional Dynamics

- Interferometry measures temporal evolution of electron density distribution.
- FWHM of distribution gives a measure of the interpenetration length
- Images captured from 77 – 160 ns
- Shows transition from collisionless to collisional dynamics

Swadling et al. – Physics of Plasmas **22**, 072706 (2015)



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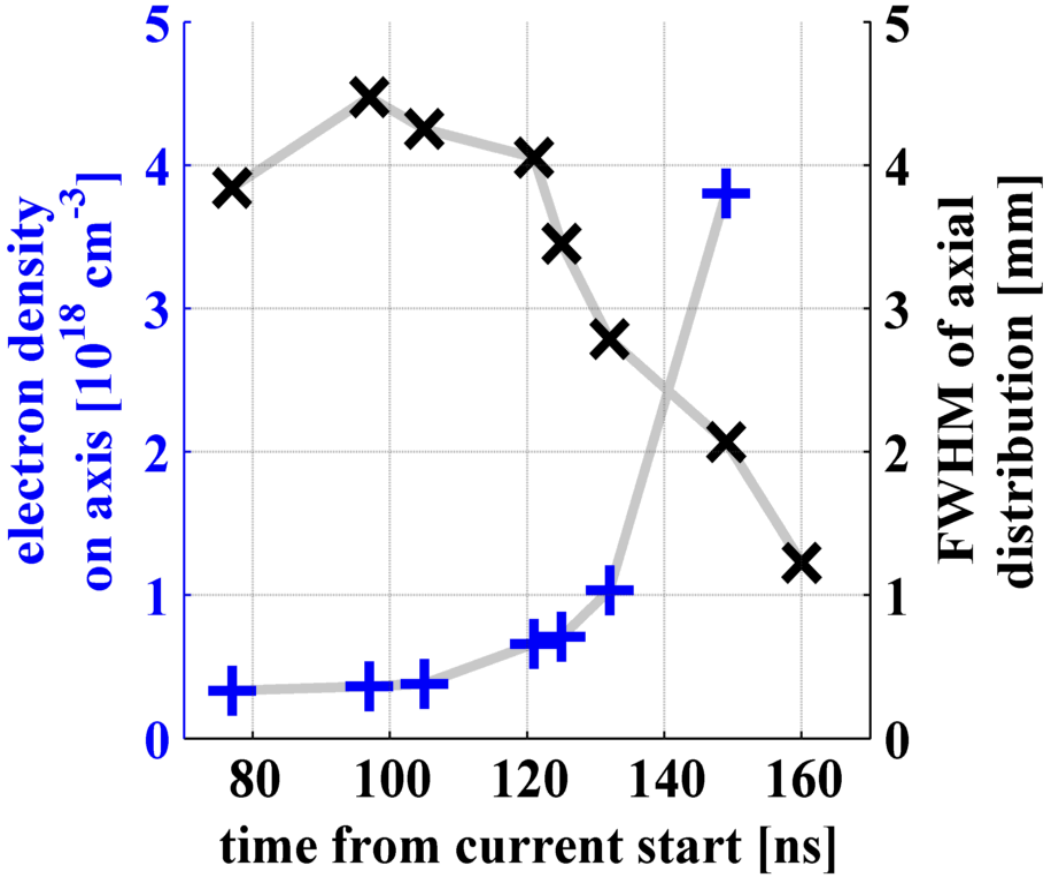
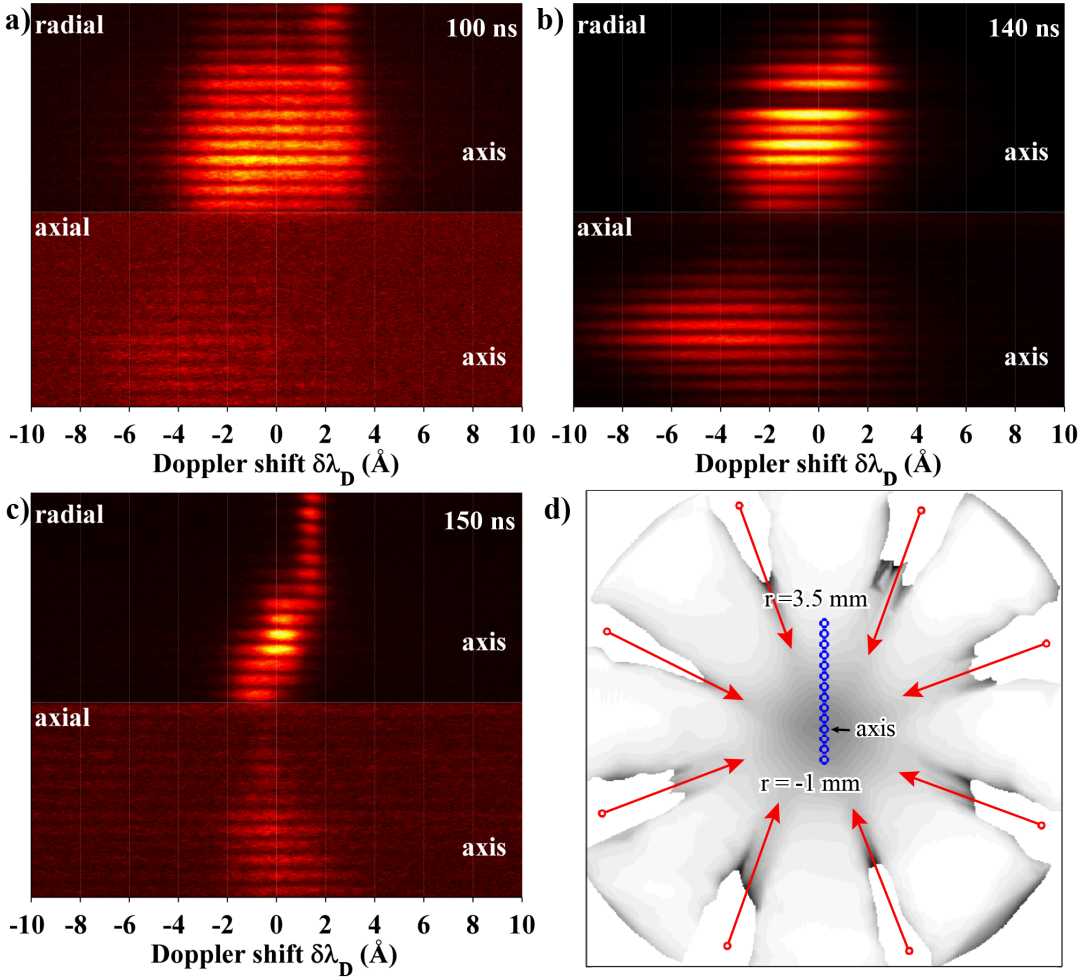


Further TS measurements illustrate flow property evolution

- Measurements over a range of experimental times **100 – 150 ns**
- More fibers:
  - **14** per channel instead of 7
- Improved **spatial resolution**



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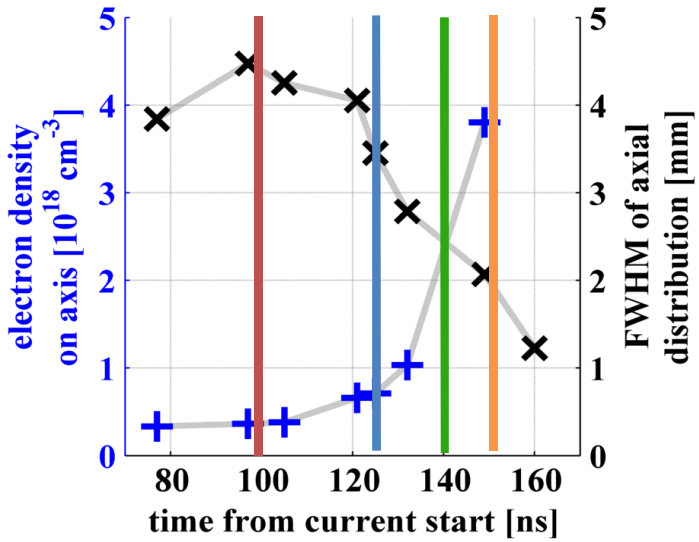
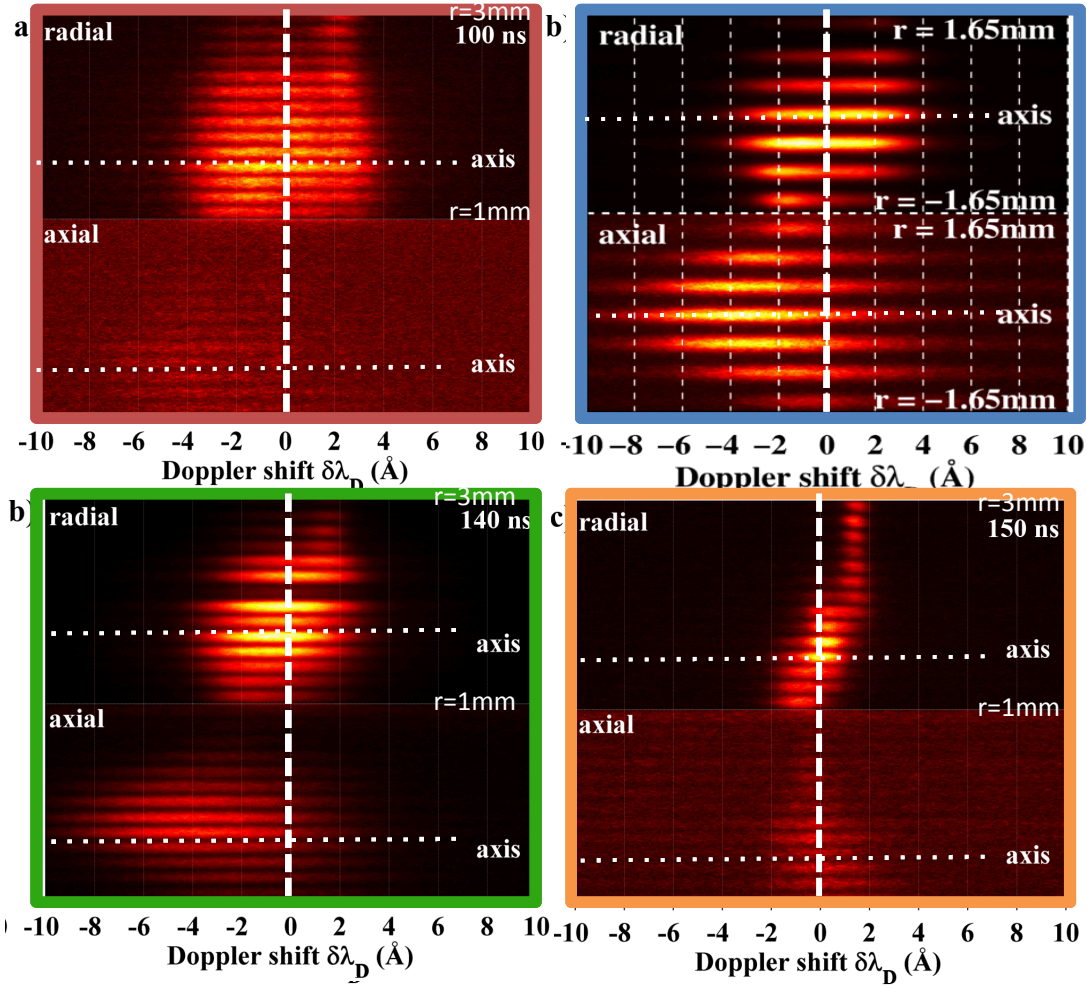
Further TS measurements illustrate flow property evolution

Structure of measured TS spectra reflect changing interaction dynamics

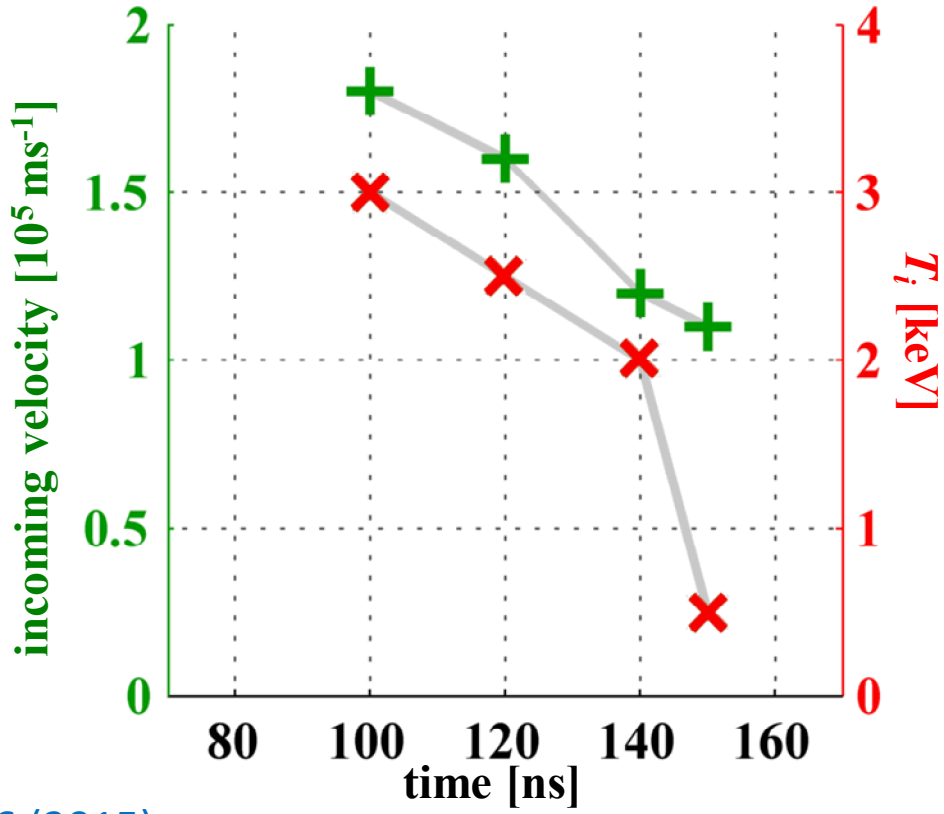




Swadling et al. – Physics of Plasmas 22, 072706 (2015)

Temporal evolution of incoming streams

- Analysis and Fitting of TS data reveals trends in plasma parameters
- From 100 to 150 ns:
  - The velocity of incoming ions falls from 1.8×10^5 ms^{-1} to 1.1×10^5 ms^{-1} (×2.5 reduction in K.E. per ion)
  - The Ion temperature of the incoming ions falls from 3keV to 500eV – onset of radiative cooling



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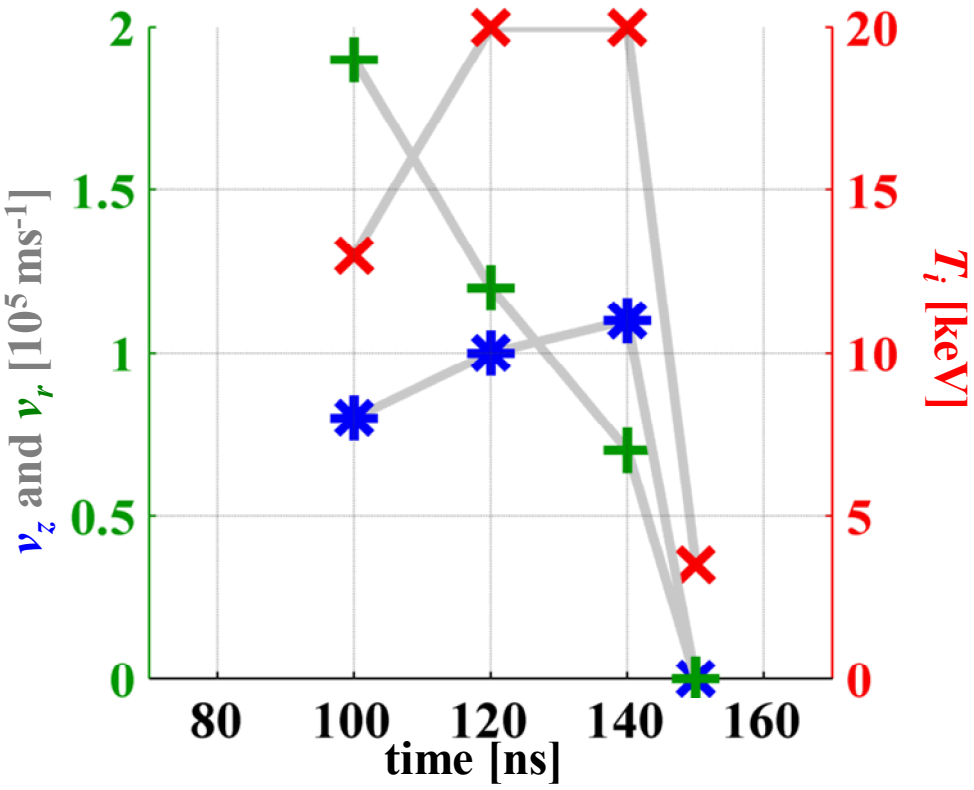
Plasma properties at the axis of the array

- Radial velocity falls:
  - incoming velocity is decreasing
  - ion-ion collision frequency is increasing
- Axial velocity on axis:
  - Initial increase:
    - Perhaps increasing magnetic field on axis as drive current rises
    - Reduced radial velocity will lead to larger deflections
  - Decreases at 150ns:
    - Collapse of magnetized precursor column
- Ion temperature on axis
  - Initial rise due to increased ion-ion collisional heating
  - Levels off and then falls due to onset of radiative cooling



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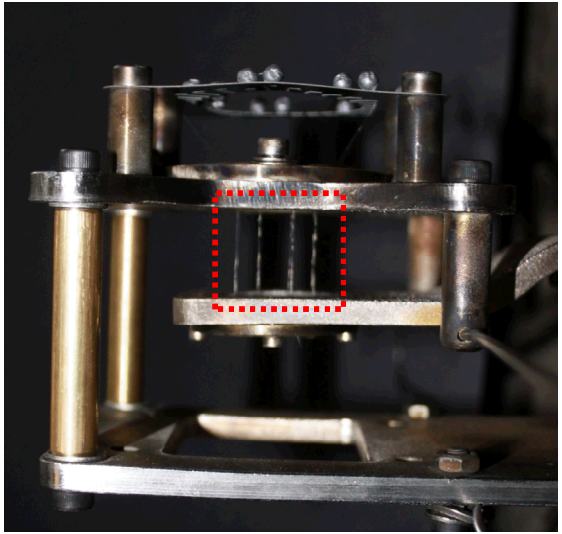
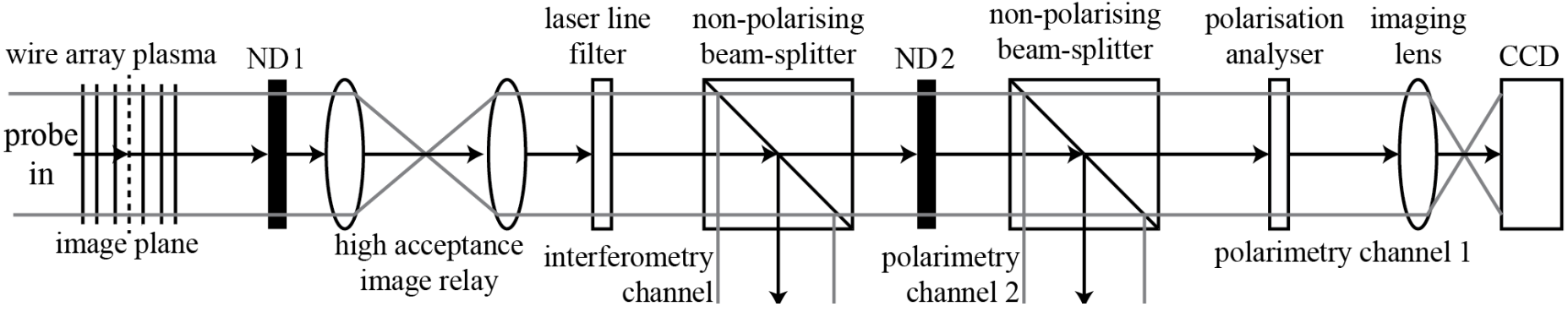
Faraday Rotation – Measurement of B

- **Rotation angle** α is **small**
  - Maximize via **λ^2 scaling** – probe at **λ = 1053 nm**

- This **increases deflections** of the probe by plasma gradients.
  - Require **high acceptance** angle θ_a (**low F-number**)

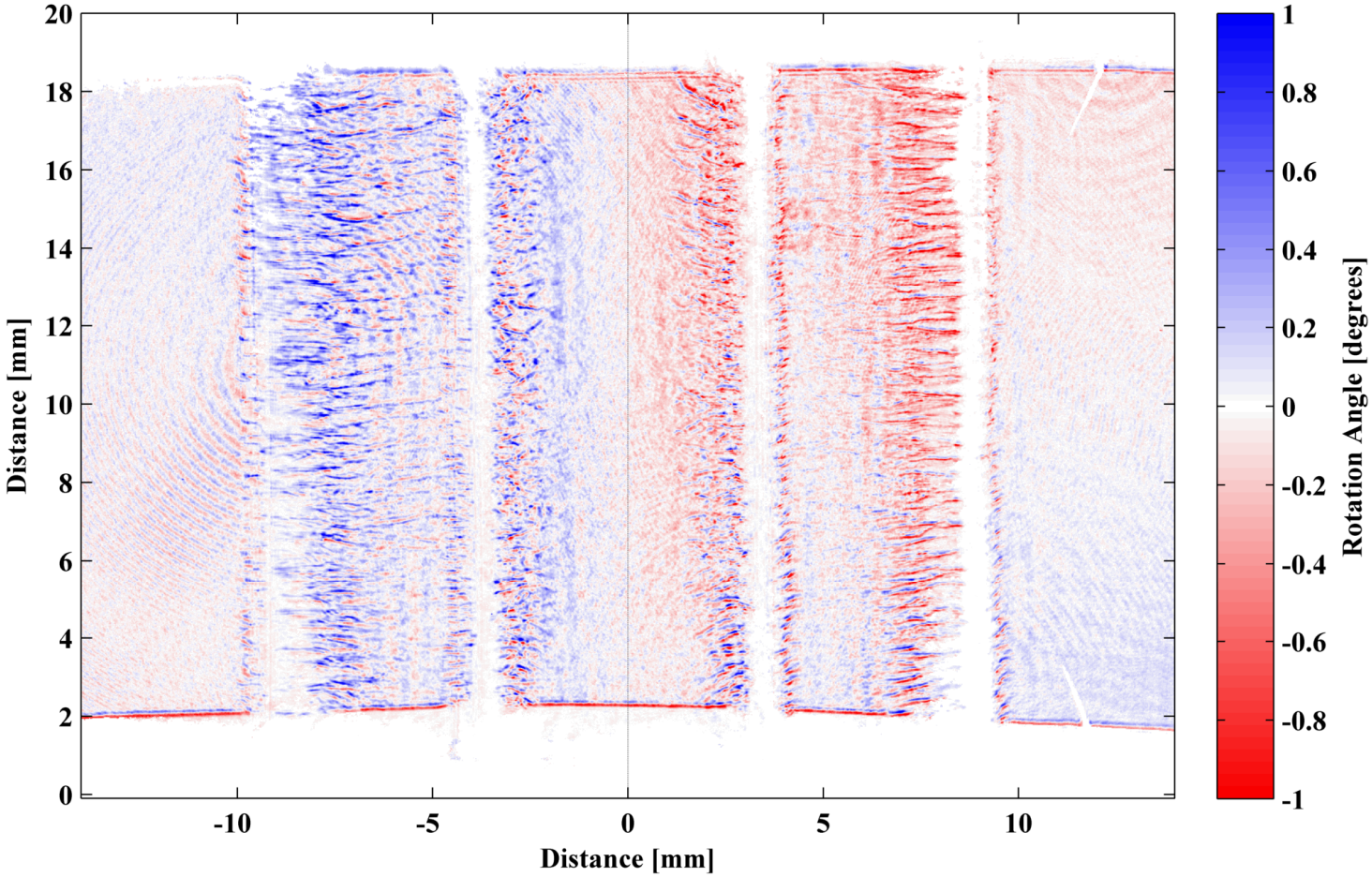
- Collection of plasma **self-emission** scales with θ_a^2.
  - Need more energetic probe to overcome self-emission **5J** compared to **100mJ**





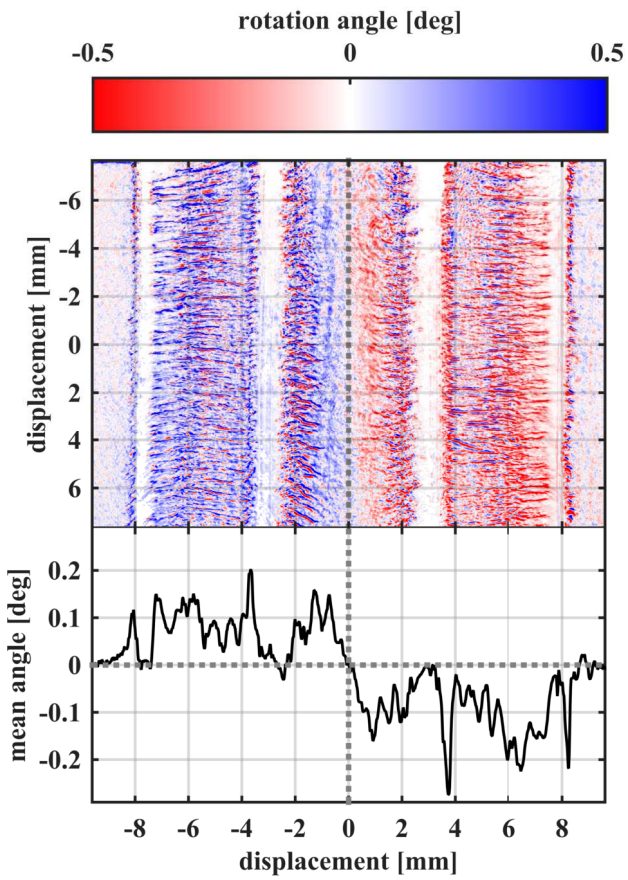
Evidence of Magnetic field advection in wire array ablation streams

At **125 ns** we see evidence of **magnetic field advection** in ablation streams and possibly some **field on axis**

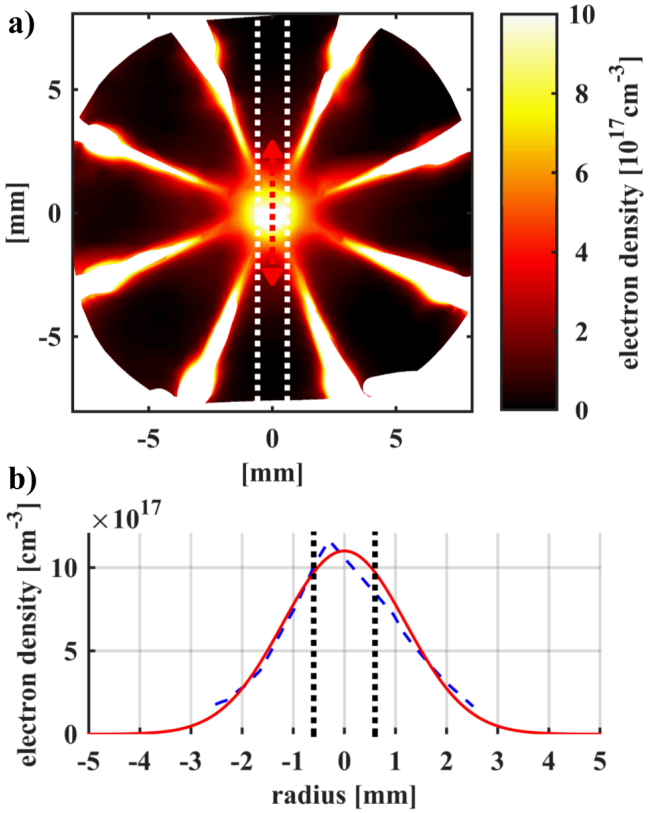


Estimate Magnetic field strength

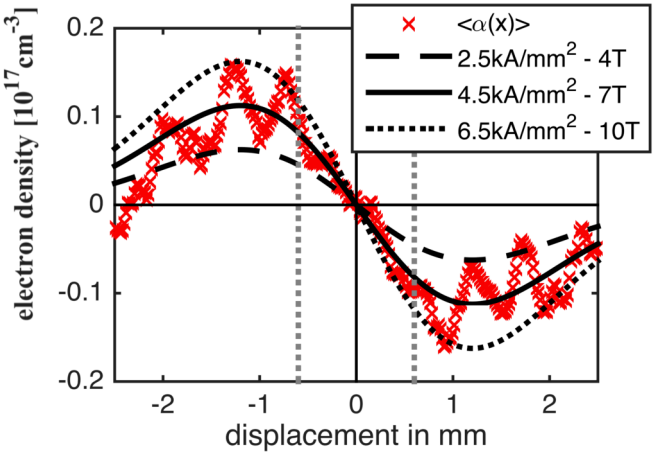
1. Take **axial average**



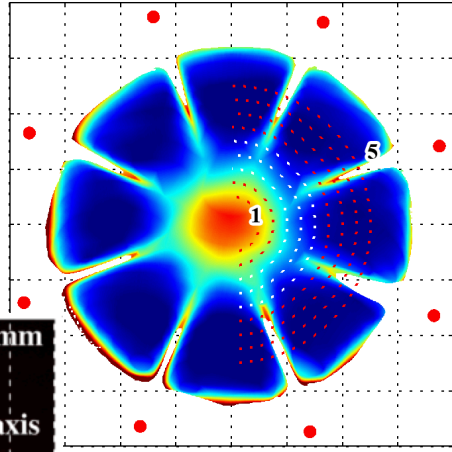
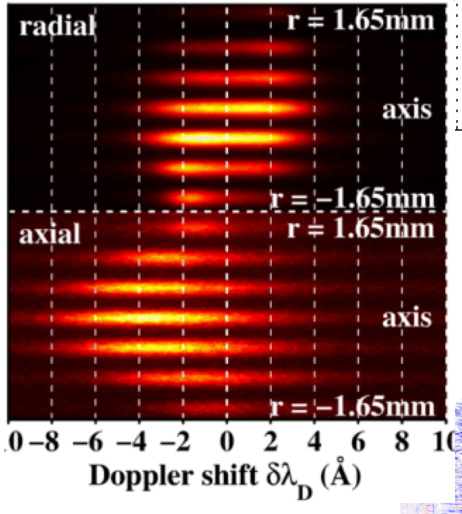
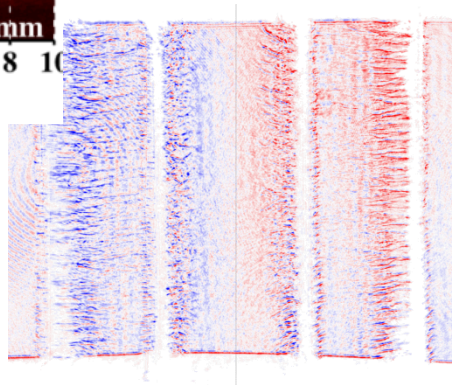
2. **Fit radial electron density** using Gaussian



3. Calculate **Abel transform** assuming **uniform current density**



This calculation suggests we should expect **B = 4 -> 10 T 2.5mm from axis**

Summary

- **Interferometry**, **Thomson Scattering** and **Faraday rotation** use to study **Tungsten Ablation Streams**
- We observe **Interpenetration**, and **deflection** of these flows as they **interact** at the array axis
- The nature of these interactions evolve over time, moving **towards** a **collisional interaction** regime
- Accurate modelling will require multi-fluid models with detailed accounting of various rates in order to accurately reproduce collisional dynamics and changes in electron-ion equilibration
- Quantitative nature of this data should be helpful for benchmarking codes designed to operate in this regime