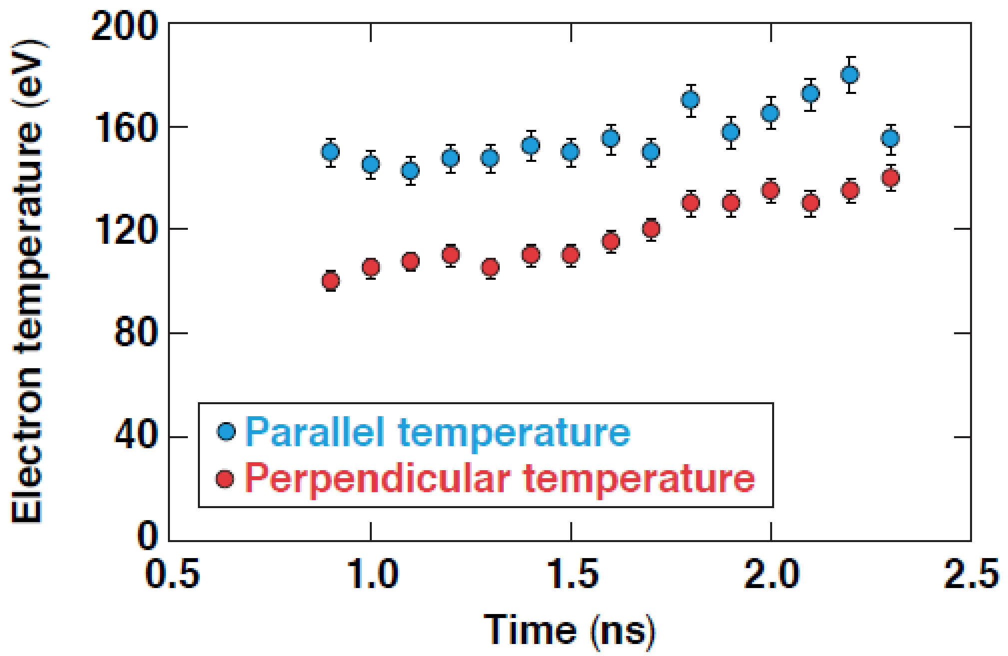
Anisotropic Electron Temperatures in Magnetized Plasmas



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Anisotropic electron temperatures were inferred from Thomson-scattering analysis of magnetized gas-jet plasmas

- **Low density Nitrogen plasmas ($\mathbf{n}_e < 10^{19}\, cm^{-3}$) were magnetized by a 15 T field produced by MIFEDS*.**

- **The plasma conditions were probed in perpendicular directions through the use of multiple Thomson-scattering beams.**

- **The electron temperatures required to fit the data with an assumed distribution function are anisotropic in velocity space.**

***MIFEDS: Magneto-Inertial Fusion Electrical Discharge System**

Collaborators

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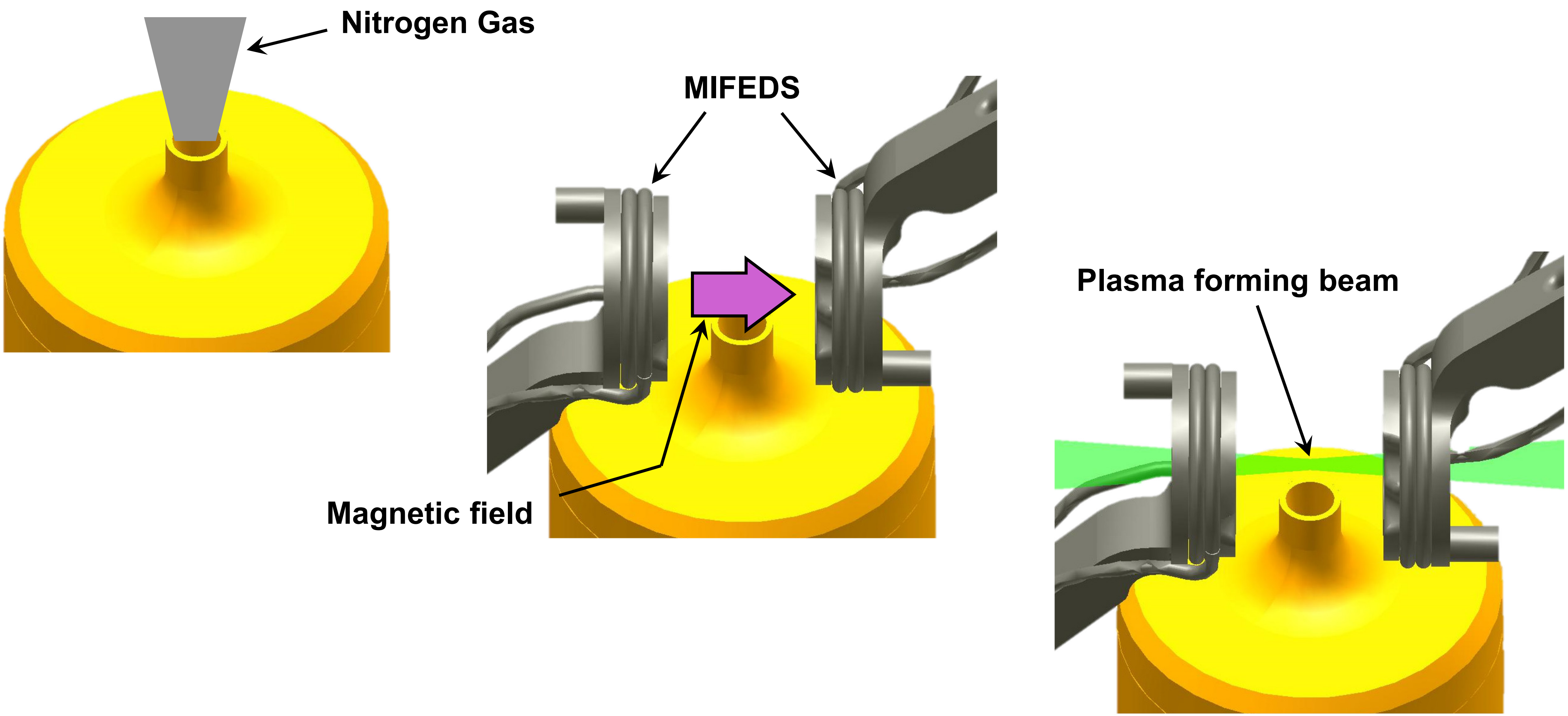
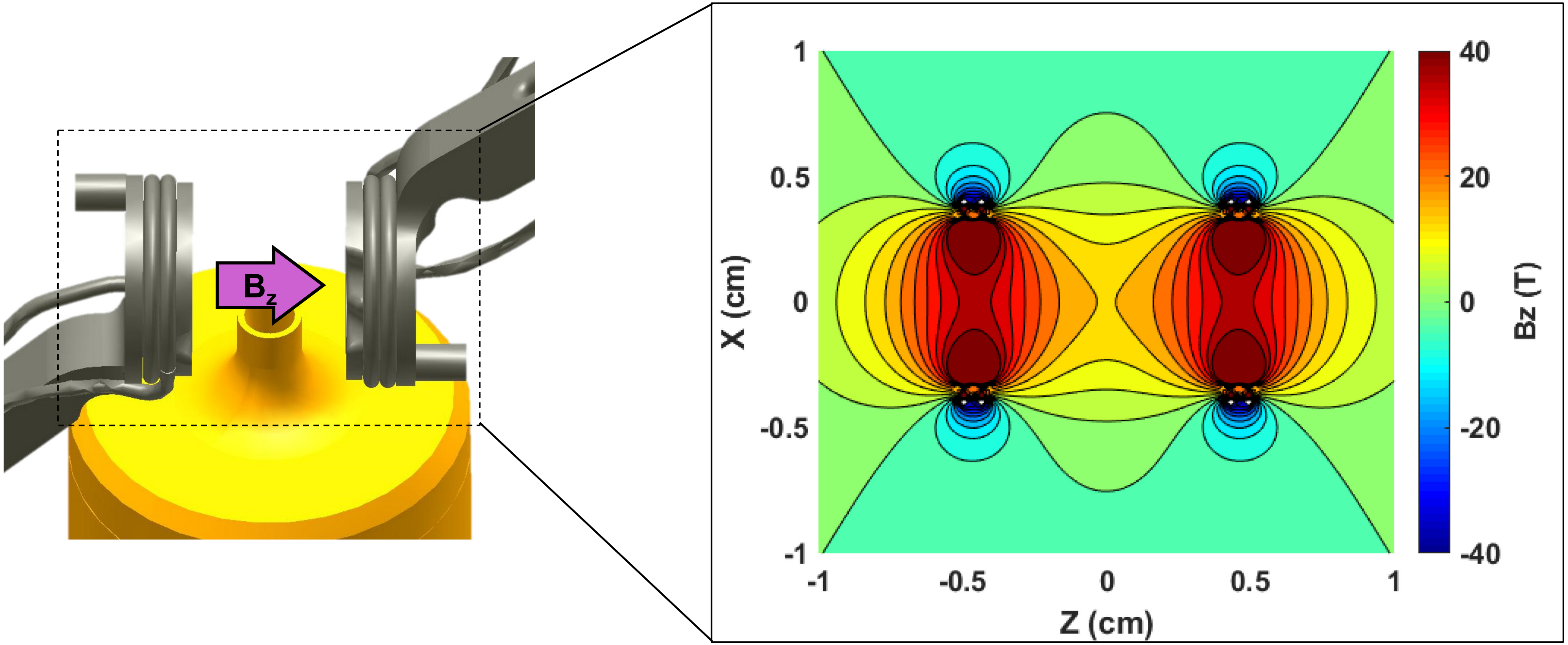
In this experiment, a 2ω beam was used to create a column of magnetized, Nitrogen plasma



2ω: Frequency doubled to 526nm
MIFEDS: Magneto-Inertial Fusion Electrical Discharge System

The magnetic field is nearly uniform over the interaction volume



Contours are 4 T steps

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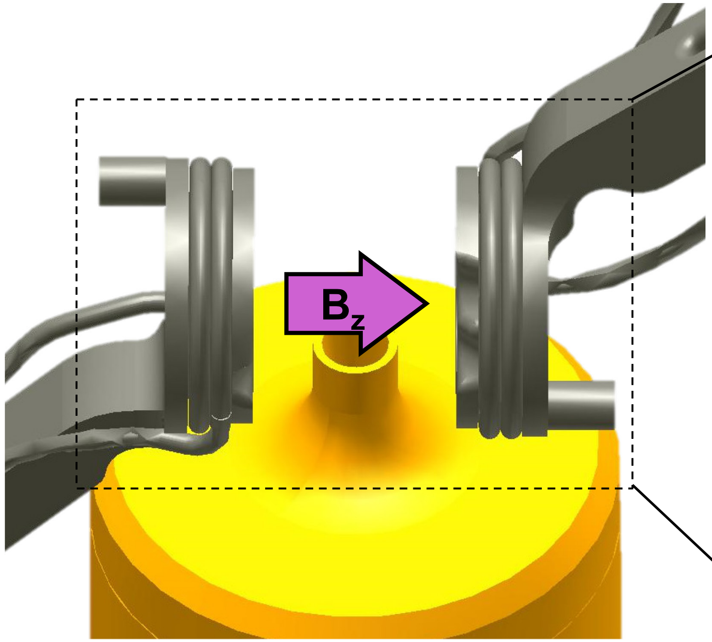

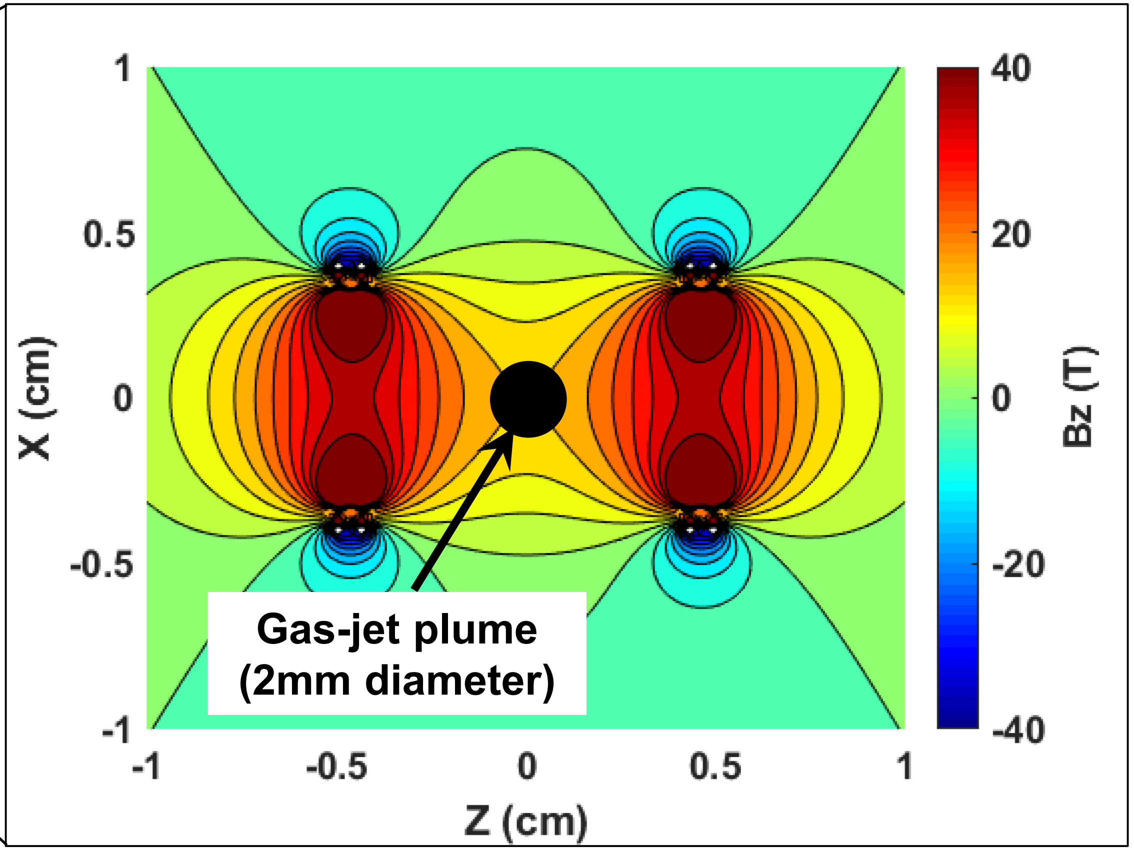

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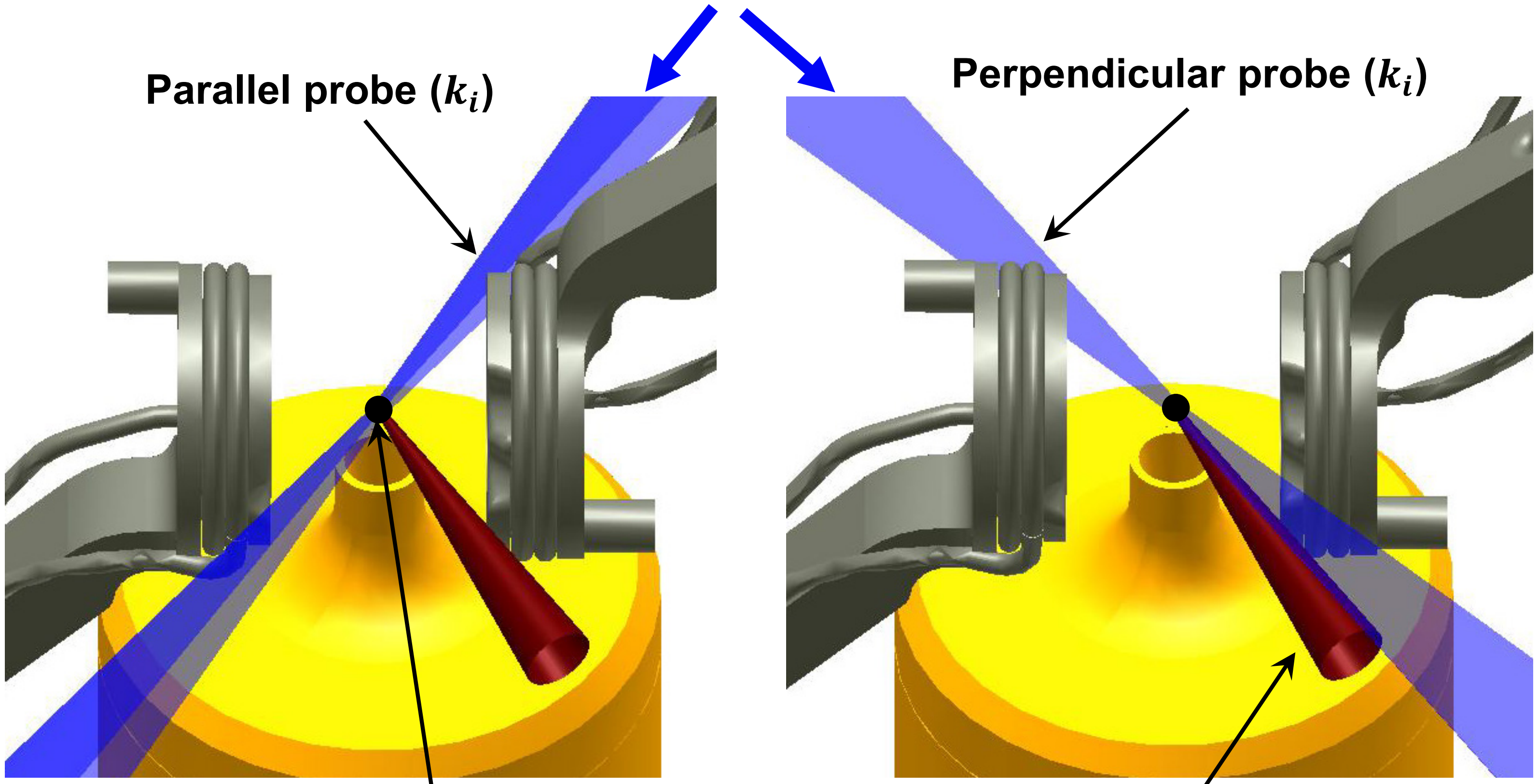
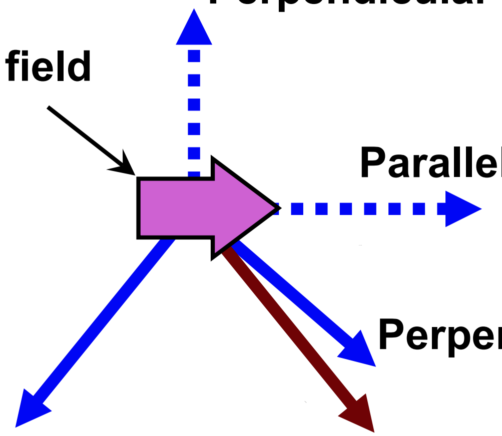
To diagnose the plasma, 3ω Thomson-scattering beams probe plasma fluctuations relative to the direction of the magnetic field



$$\boldsymbol{k}(\omega) = \boldsymbol{k_s}(\omega_s) - \boldsymbol{k_i}(\omega_i)$$
$$\omega = \omega_s - \omega_i$$



3ω: Frequency tripled to 351nm
subscripts denote scattered (s) and incident (i) light

The spectral shape of the Thomson-scattered light is a function of the particle distribution functions*

$$S(\mathbf{k},\omega) = \frac{2\pi}{k}\left|1 - \frac{\chi_e}{\epsilon}\right|^2 f_{eo}\left(\frac{\omega}{k}\right) + \frac{2\pi Z}{k}\left|\frac{\chi_e}{\epsilon}\right|^2 f_{io}\left(\frac{\omega}{k}\right)$$

- f_{eo} , f_{io} – One-dimensional electron and ion velocity distribution functions in the direction of the fluctuation, k
- $\epsilon = 1 + \chi_e + \chi_i$ – Longitudinal dielectric function, dependent on particle susceptibilities:

$$\chi_s = \int_{-\infty}^{\infty} d\mathbf{v} \frac{4\pi Z_s^2 e^2 n_{so}}{m_s k^2} \frac{\mathbf{k}\cdot\delta f_{so}/\delta\mathbf{v}}{\omega - \mathbf{k}\cdot\mathbf{v} - i\gamma}$$

- Z, n_{s0}, m_s – Average ionization, particle number density, particle mass

***assuming the plasma is collisionless ($k\,\lambda_{ii} \gg 1$) and unmagnetized ($\omega_{pi} \gg \omega_{ce}$)**
Froula et al., *Plasma Scattering of Electromagnetic Radiation (Second Edition)*, 2011

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Plasma modes ($\epsilon \rightarrow 0$) show up as peaks in scattered spectrum.

*assuming the plasma is collisionless ($k\,\lambda_{ii} \gg 1$) and unmagnetized ($\omega_{pi} \gg \omega_{ce}$)
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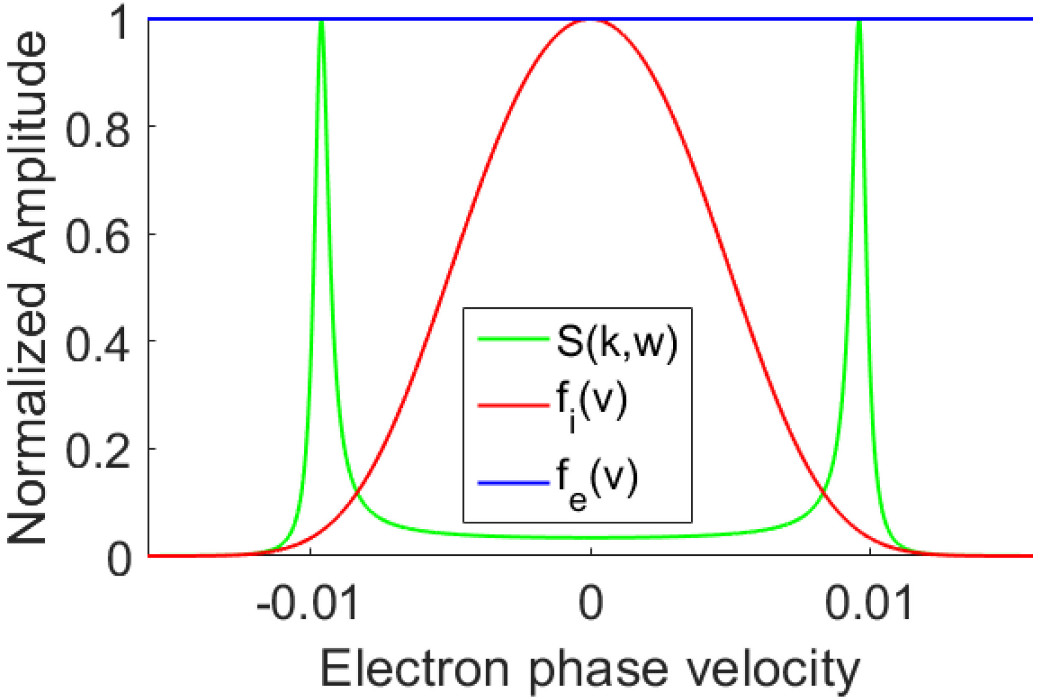
In a low frequency regime ($\omega_s \approx \omega_i$) the peaks in the scattered spectrum are produced by the Ion Acoustic mode (IAW)

For a Maxwellian electron distribution, the IAW ($\omega^2 = k^2\, C_s^2$) resonance is at a phase velocity, $\frac{\omega}{k}$, near the ion sound speed, $C_s \approx \sqrt{(ZT_e + 3T_i)/m_i}$, **in the direction of the fluctuation.**



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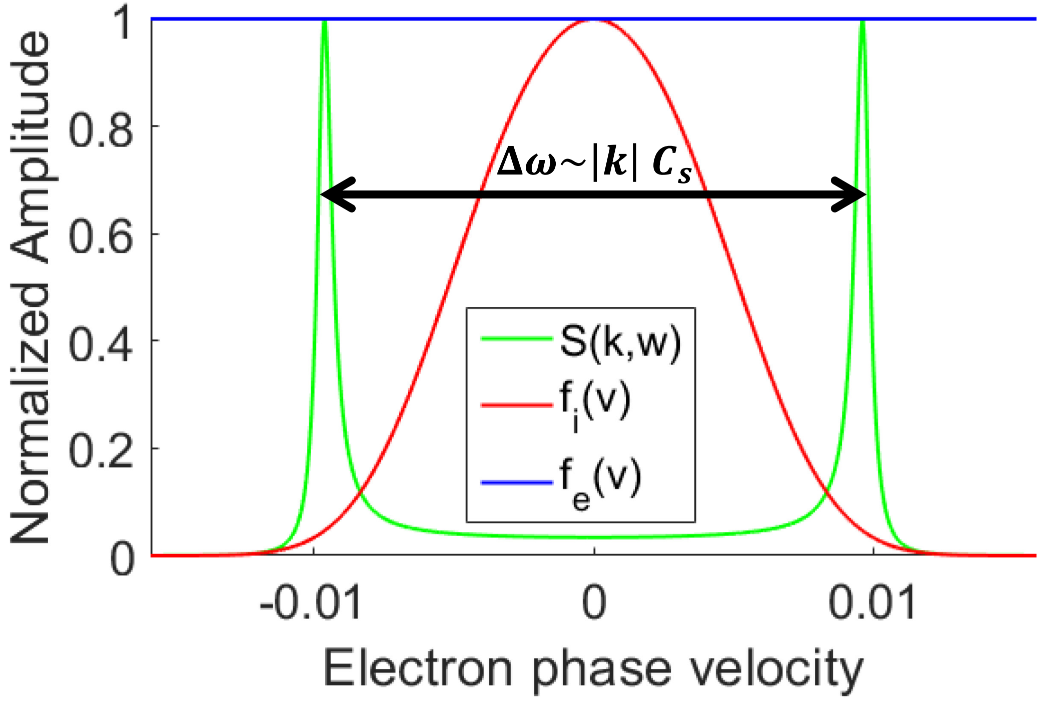
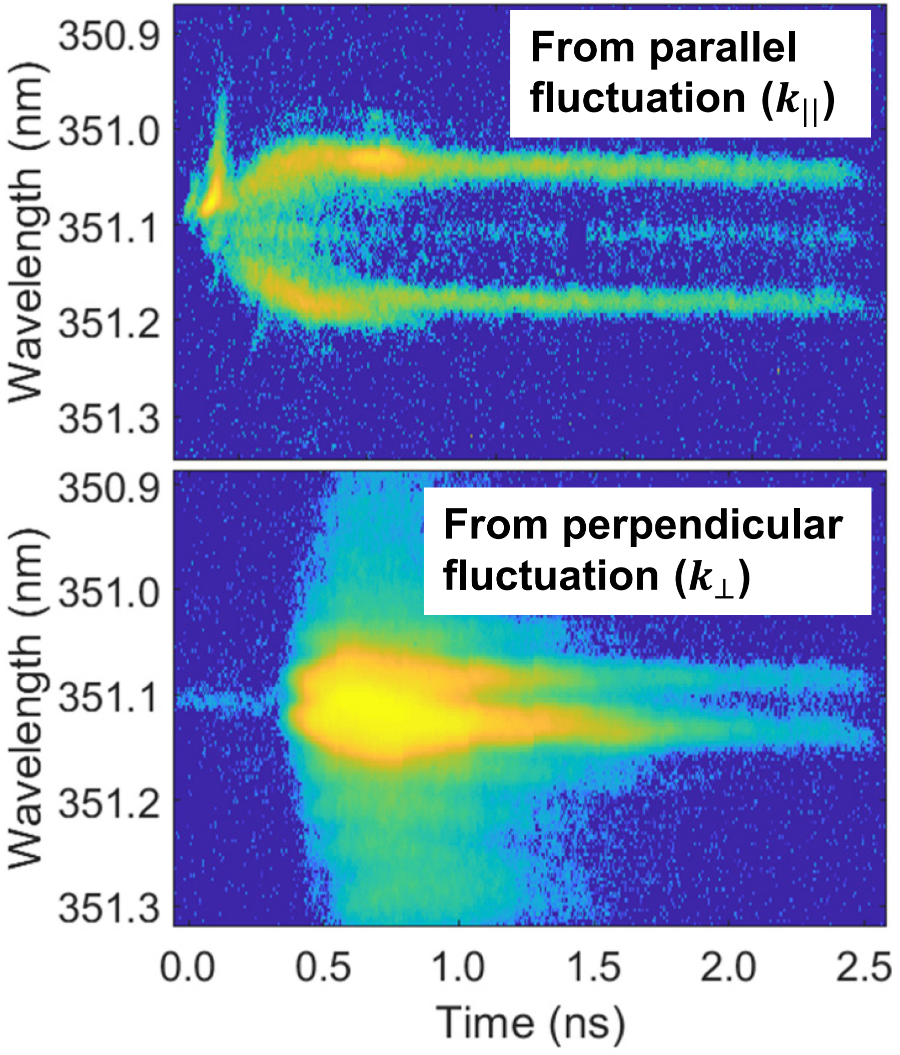


A measurement of the frequency shift between these peaks is a measurement of the plasma mode frequency in the direction of the momentum-conserved fluctuation.

In our experiment, the spectrum of scattered light from the orthogonal fluctuations have an inconsistent frequency shift



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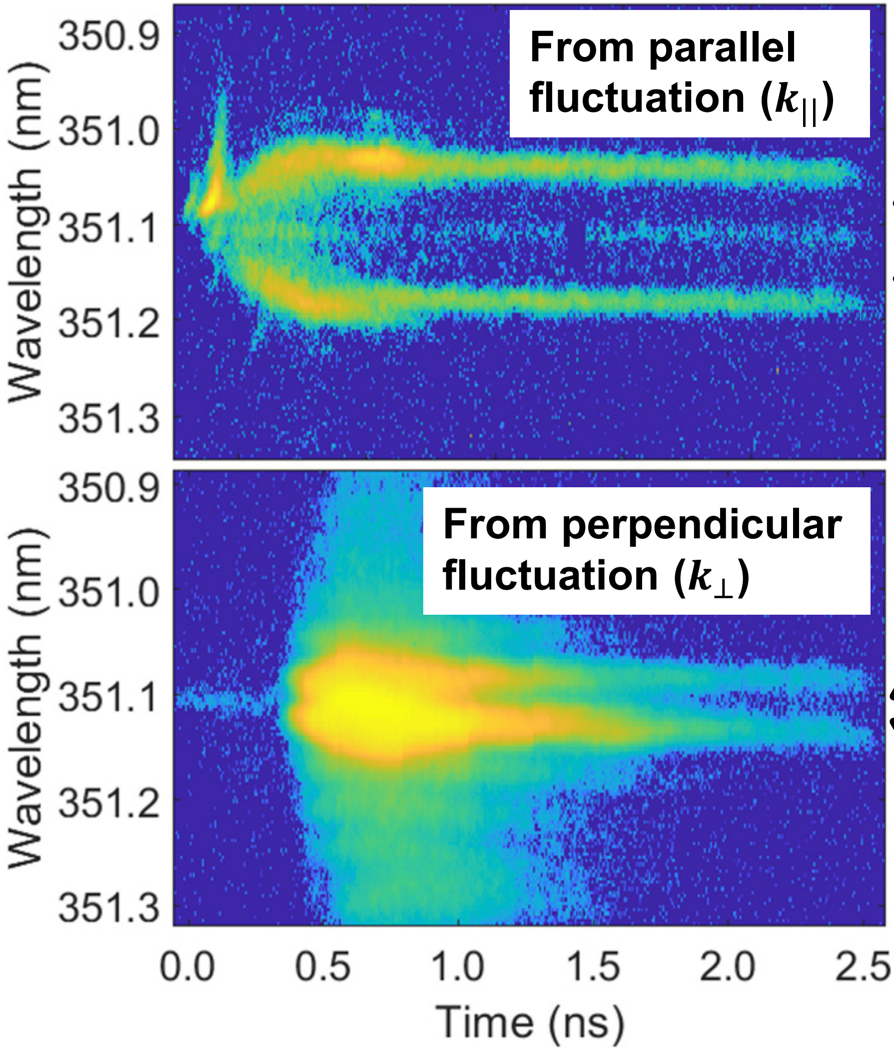
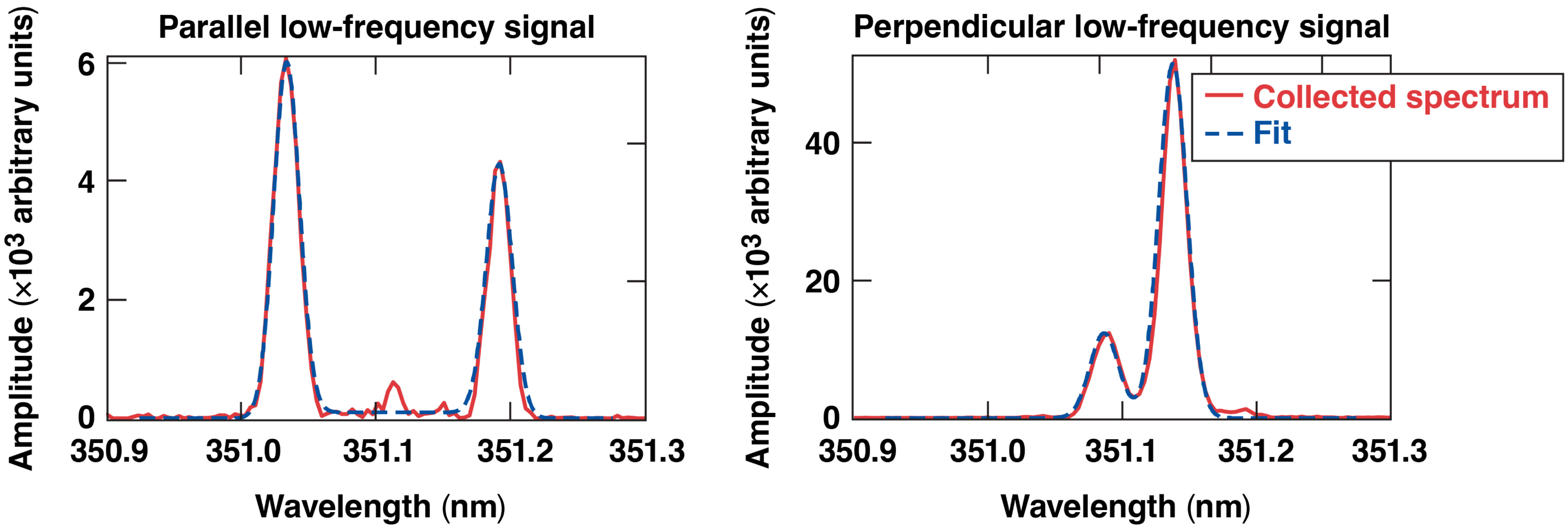


$$\Delta\lambda \sim \omega \approx k_\parallel C_s \sim k_\parallel \sqrt{T_e}$$

$$\Delta\lambda \sim \omega \approx k_\perp C_s \sim k_\perp \sqrt{T_e}$$

Inspection of the two scattering features shows the frequency shift is due to a difference in the electron temperature*



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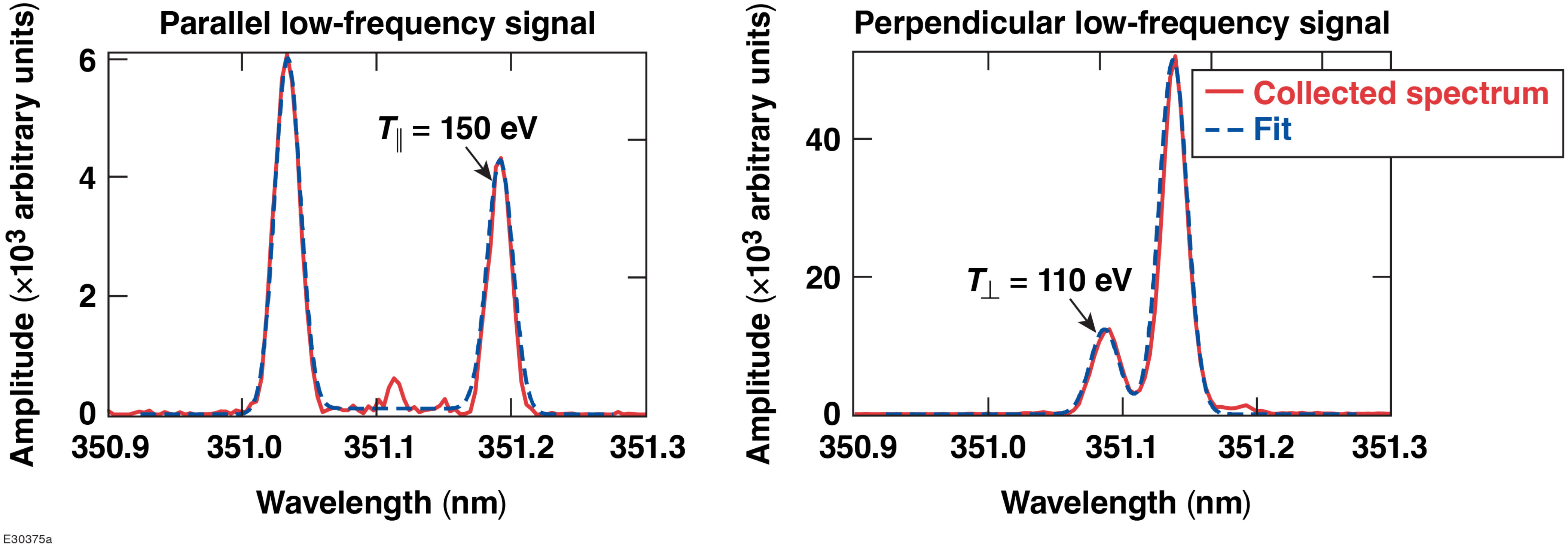

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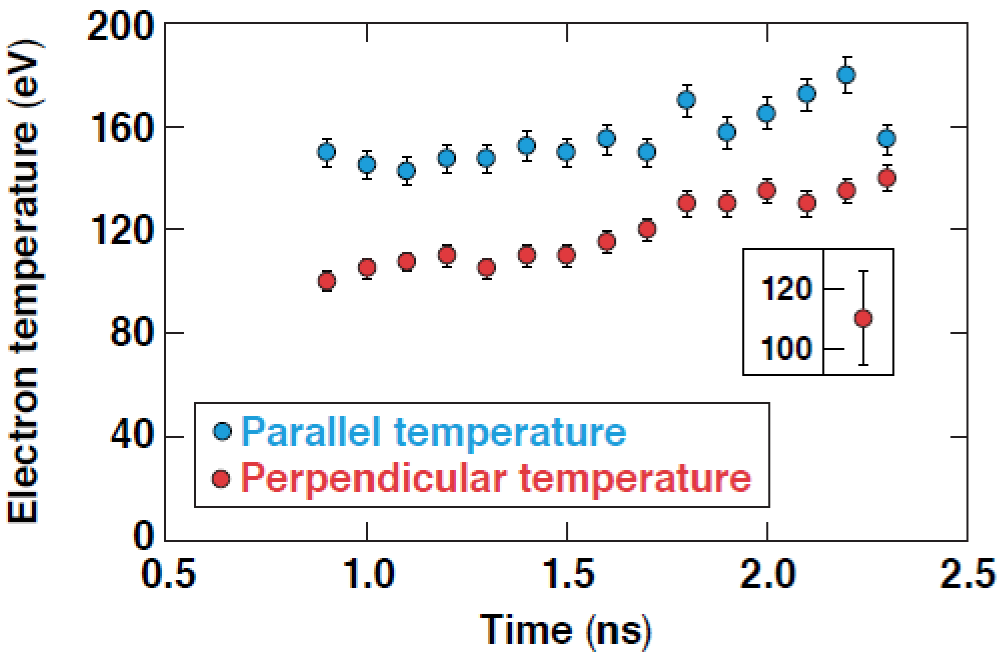
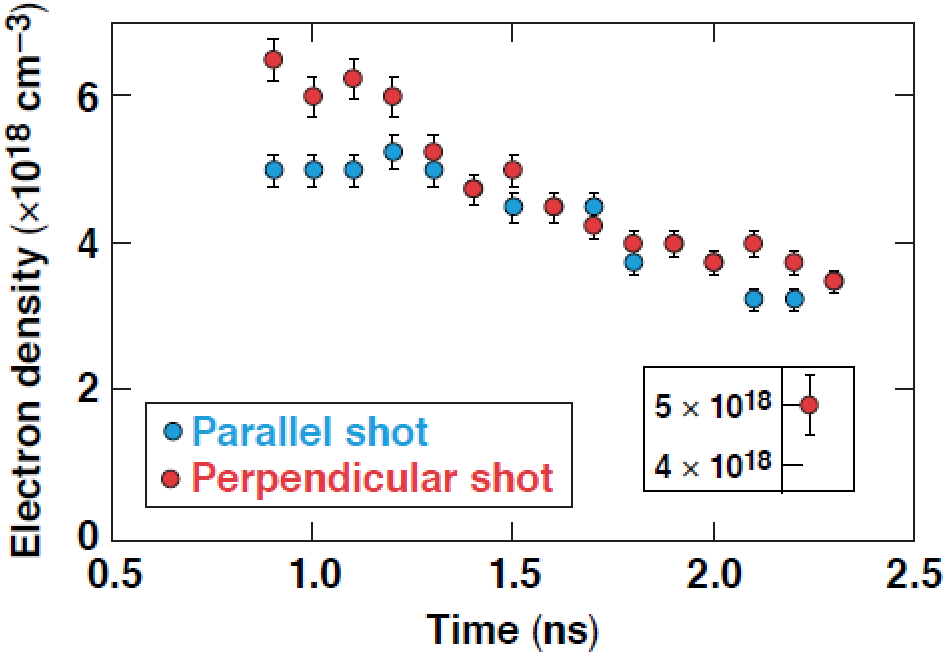
Consistently lower perpendicular temperatures are required to fit the data for the duration of the 2 ns experiment





These data are characterized by a plasma beta $\beta = \frac{P_{thermal}}{P_{magnetic}} \sim 2$ and a Hall parameter $\omega_{ce}\tau_{ei} \sim 10$

- What have we considered in modeling these results?
  - PIC, CGL cooling, VFP, 2nd order perturbation modeling
  - List what we have tried:
  - 1D pic sims (Han) – What did this tell us?
  - Calculation of magnetic modes – Ideal Magnetosonic Wave moves in wrong direction
  - Magnetic field skin effect near nozzle (Tony) – Does not create any significant gradients in magnetic field
  - Look at local EDF (toy model, 'ud') effect on IAW frequency – Changes amplitude/damping of the modes, not the frequency
    - Same as 1st order vector correction to distribution function
  - Collisionless CGL cooling / magnetic mirror – Are the electrons collisionless enough for this?
- What are we working on currently?
  - 2^{nd} order, anisotropic tensor corrections
  - Collisional ion effects in the IAW

The frequency shift of the plasma mode is inconsistent with the expected MHD wave

A magnetoacoustic wave would be driven by the compression of the magnetic field in addition to the plasma:

$$\omega^2 = \frac{1}{2} k^2 \left(c_s^2 + v_A^2\right)\left[1 \pm (1-\delta)^{1/2}\right]$$

$$\delta = \frac{4k_\parallel^2}{k^2}\left(\frac{c_s^2\, v_A^2}{\left(c_s^2 + v_A^2\right)^2}\right)$$

– This would result in a frequency *upshift* (relative to the IAW frequency) and would be interpreted as a *greater* perpendicular temperature

Boyd & Sanderson

An alternate explanation of the results is a non-isotropic electron velocity distribution

- From simple adiabatic theory*
  - Expanding plasma maintains magnetic invariants in the parallel/perpendicular direction:

$$\frac{d}{dt}\left(\frac{P_{||}B^2}{\rho_0^3}\right) = 0$$

$$\frac{d}{dt}\left(\frac{P_{\perp}}{\rho_0 B}\right) = 0$$

- With constant density:
  - $P_{\perp} \propto B,$ $\quad P_{\|} \propto B^{-2}$
- With a "frozen-in" magnetic field
  - $P_{\perp} \propto n^2 \propto B^2,$ $\quad P_{\|} \propto n \propto B$

*no pressure transport along field lines

Chew, G. F., M. L. Goldberger, and F. E. Low. "The Boltzmann equation an d the one-fluid hydromagnetic equations in the absence of particle collisions." Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 236.1204 (1956): 112-118.

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A dynamic balance between inverse-bremsstrahlung heating, collisional relaxation, and adiabatic cooling could explain these results.

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Thanks!