Thomson-Scattering Techniques at the OMEGA Laser Facility

OMEGA Workshop 2010

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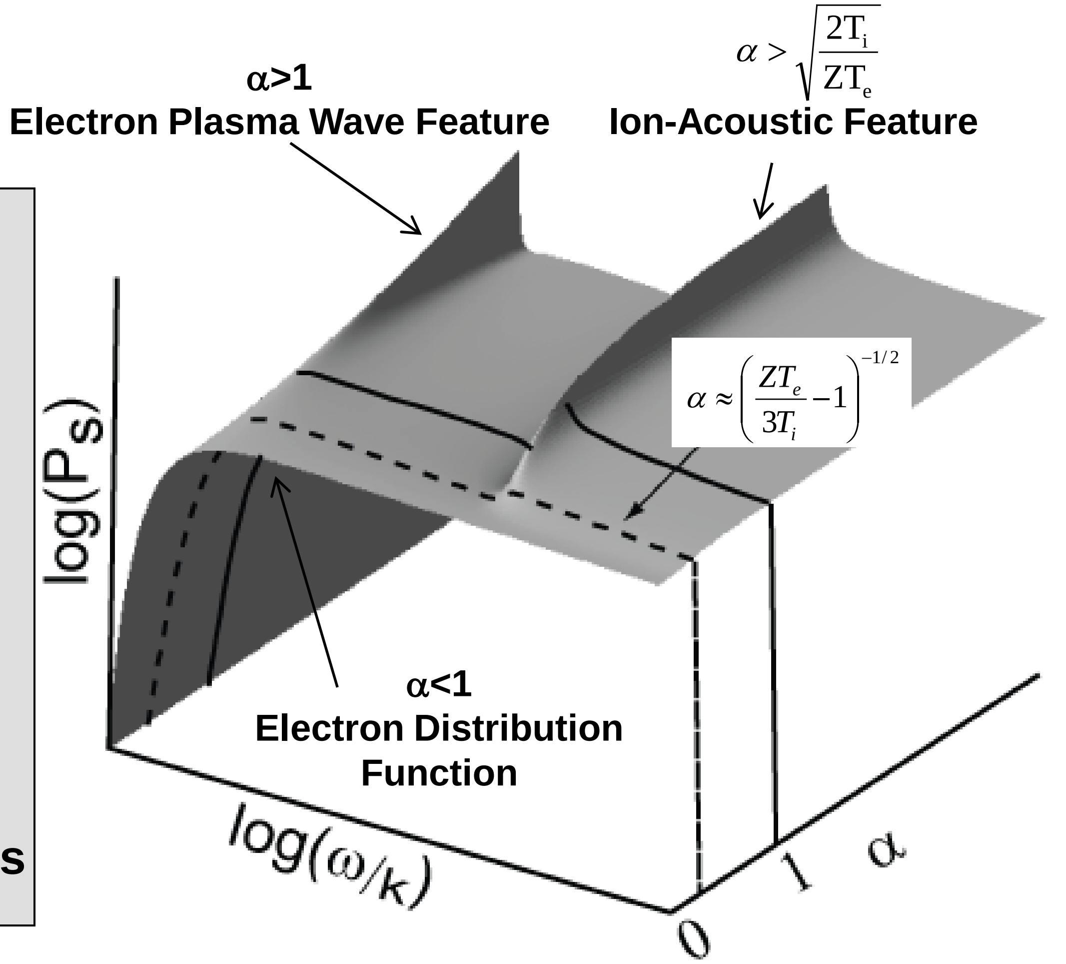
Thomson scattering is a core diagnostic in MHD facilities and should be adopted in the laser plasma community

- **Intro to Thomson scattering**
- **Electron temperature measurements**
- **Electron Density**
- **Driven plasma waves**
- **Ion temperature measurements**



α>1
Electron Plasma Wave Feature

$\alpha > \sqrt{\frac{2T_i}{ZT_e}}$

Ion-Acoustic Feature

$\alpha \approx \left(\frac{ZT_e}{3T_i} - 1\right)^{-1/2}$

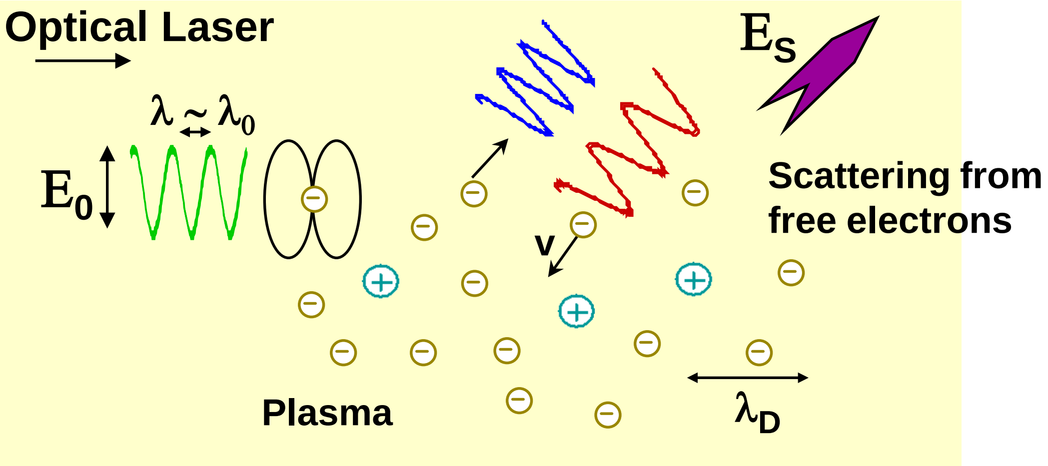
α<1
Electron Distribution Function

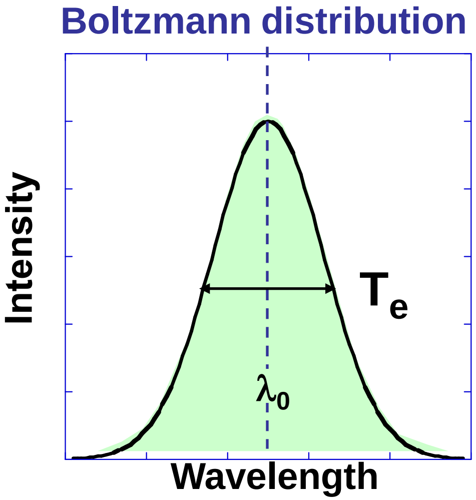
Complete Thermal Scattering Spectrum

Thomson scattering

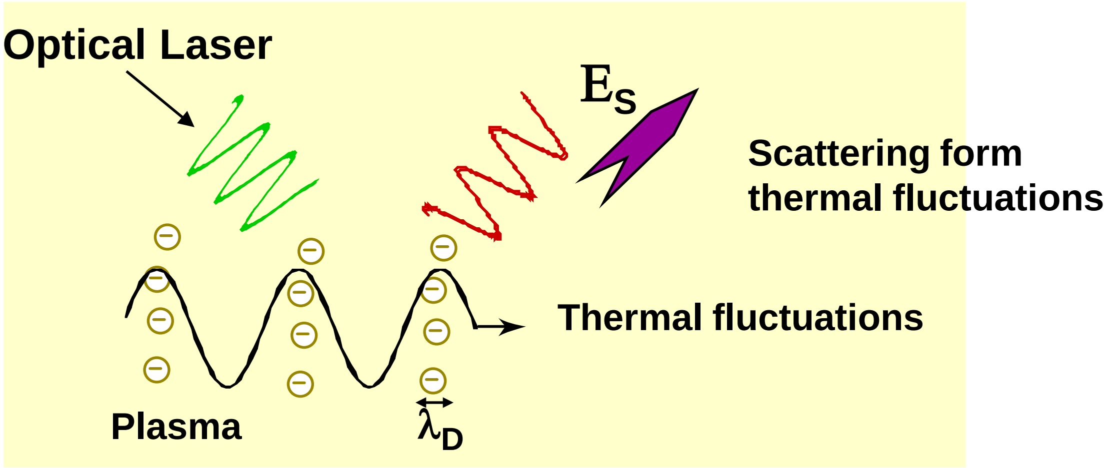
"Elastic" scattering of electromagnetic-waves from free electrons ($h\nu \ll m_e c^2$)

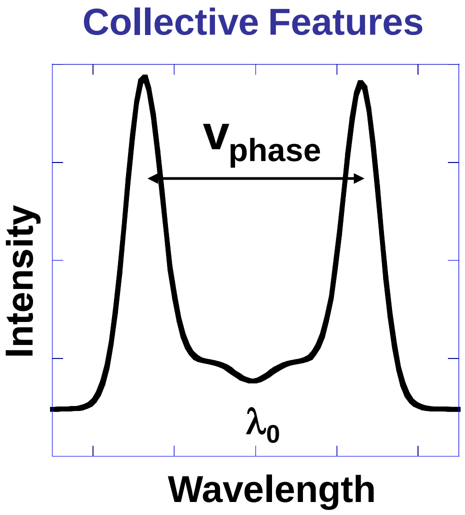
Non-collective Thomson Scattering ($\lambda < \lambda_D$)





Collective Thomson Scattering





Thomson scattering in laser produced plasmas is typically collective as a result of the relatively high densities (α~2-3)

Non-collective Regime (α < 1)

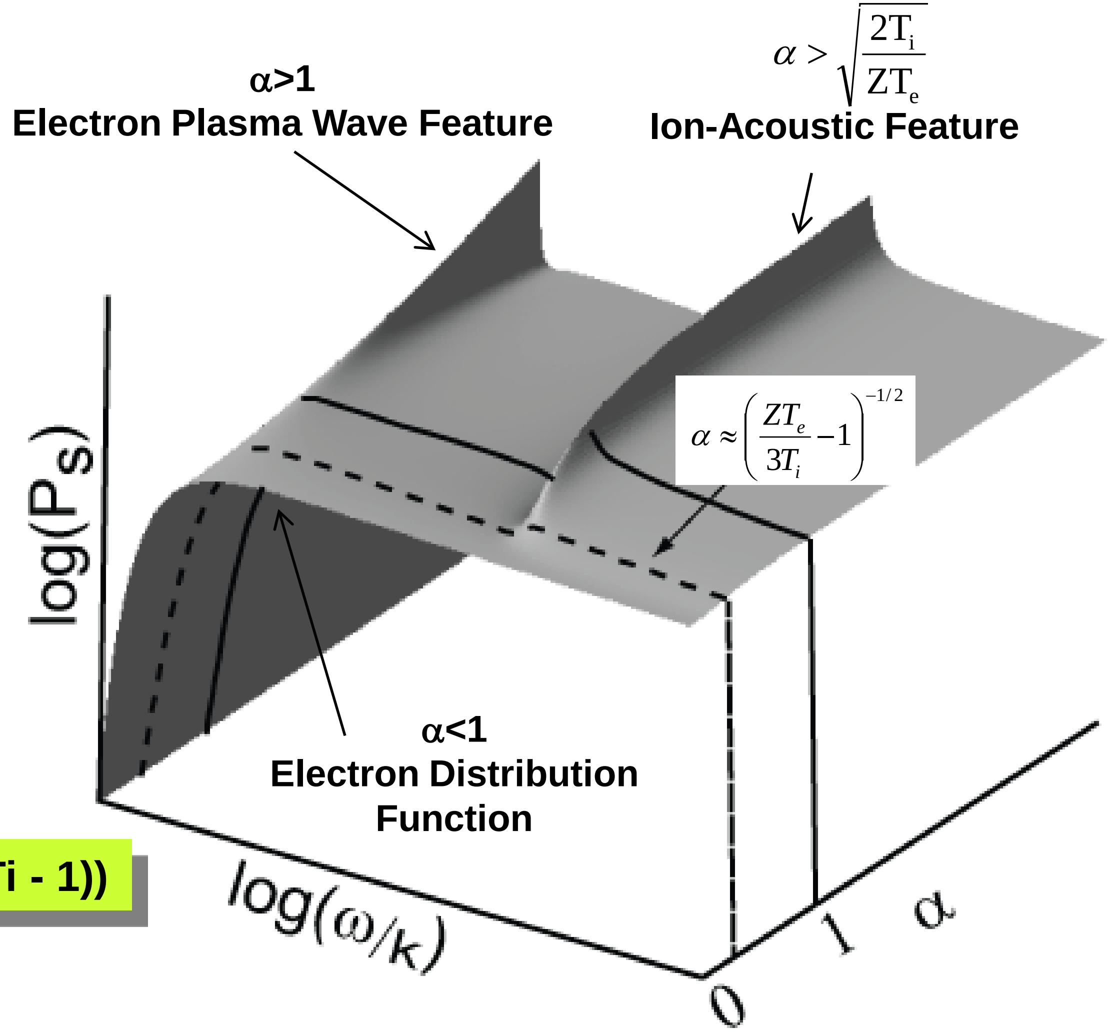
$$\Delta\lambda_{1/e} \cong \frac{2\lambda_{\mathrm{probe}}}{c}\sin(\theta/2)\sqrt{\frac{2\mathrm{T_e}}{\mathrm{M}}}$$

Collective Regime (α > 1)

$$\Delta\lambda \approx 2\lambda_{\mathrm{probe}}\left[\frac{n}{n_{cr}}+3\frac{v_{th}^2}{c^2}\right]^{1/2}$$

Collective Regime ($\alpha^2 > 1/(ZTe/3Ti - 1)$)

$$\Delta\lambda \cong 4\lambda_{\mathrm{probe}}\sin(\theta/2)\sqrt{\frac{\mathrm{ZT_e}}{\mathrm{M}}}$$



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Ion-Acoustic Feature

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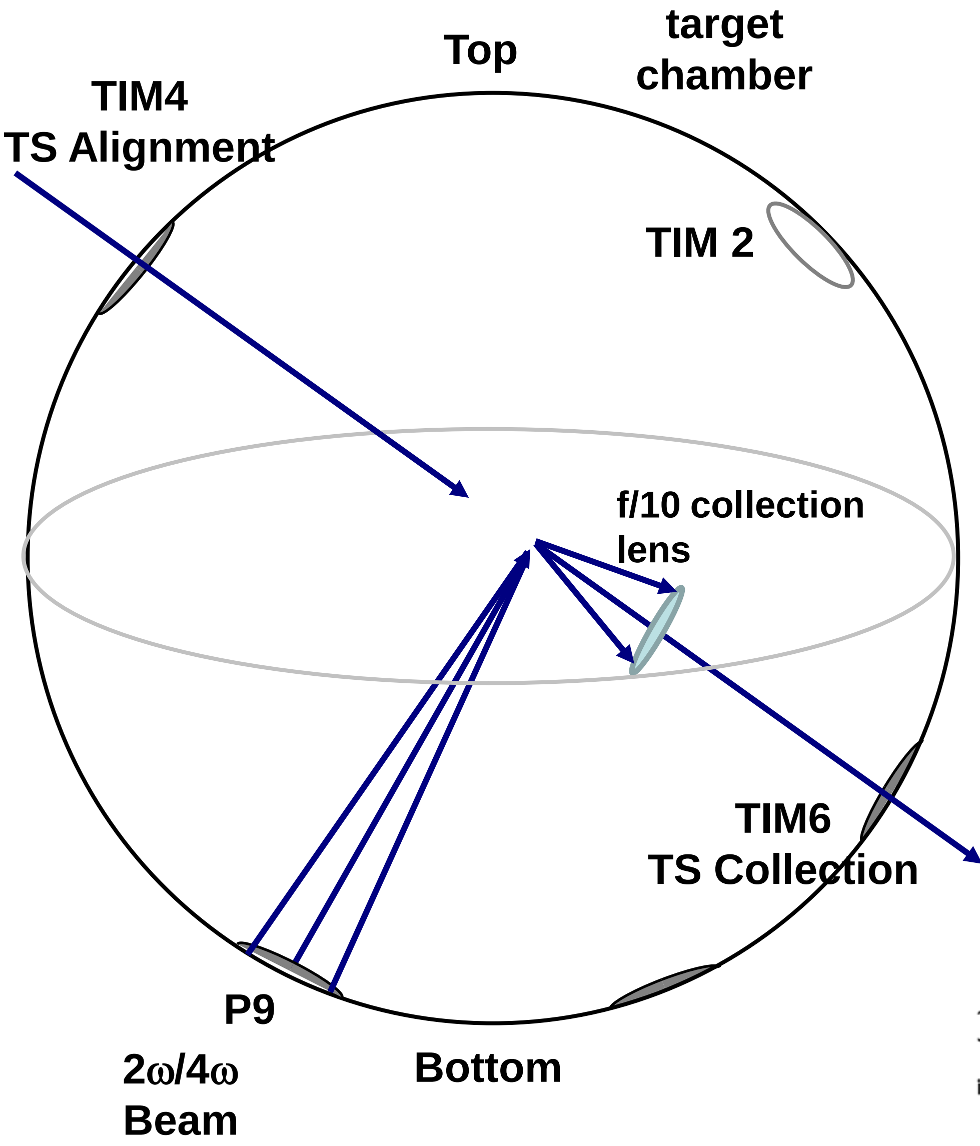
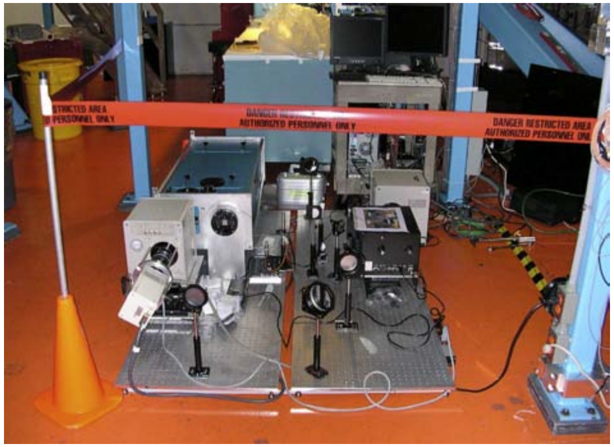
α<1
Electron Distribution Function

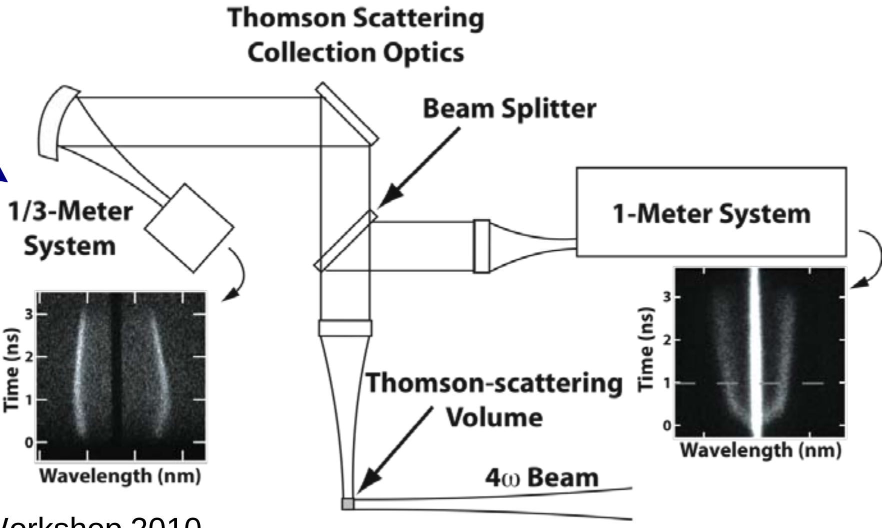
Complete Thermal Scattering Spectrum

At OMEGA, a 2ω or 4ω laser beam can be configured as the TS probe and scattered light is collected in TIM6



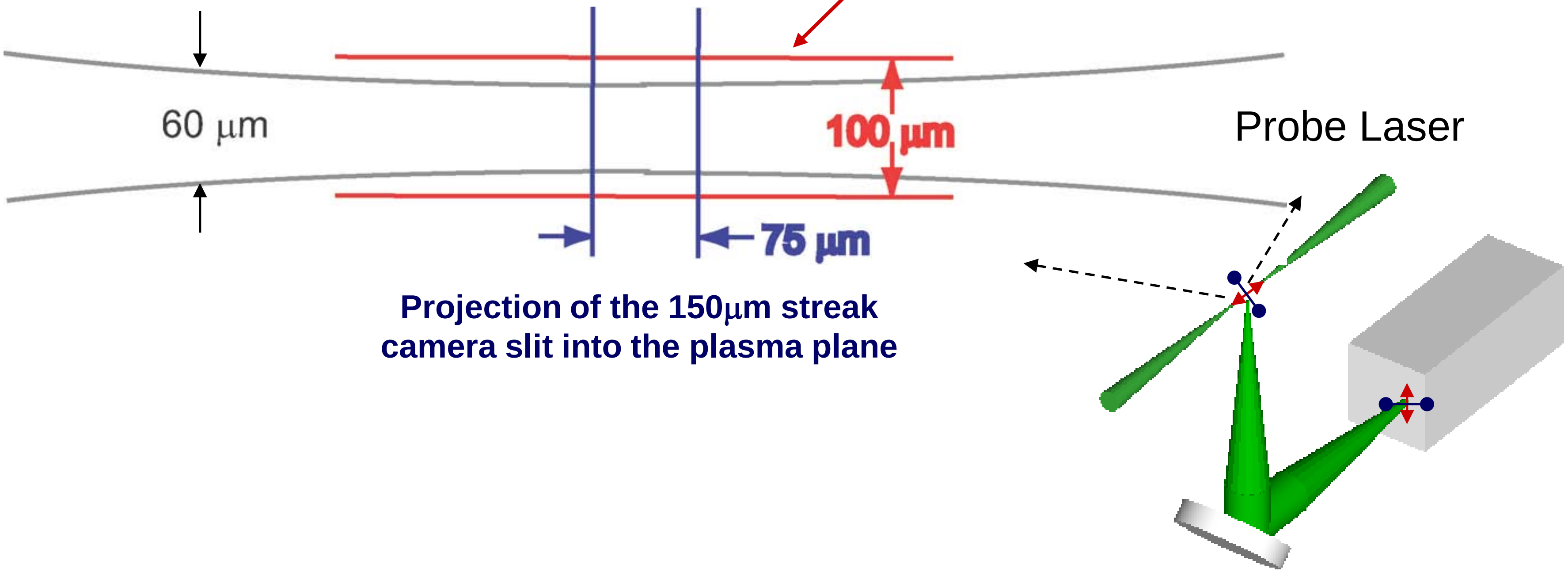
J. S. Ross *et al.* Rev. Sci. Instr., 77 10E520 (2006)





LOCAL plasma parameters are measured with Thomson scattering

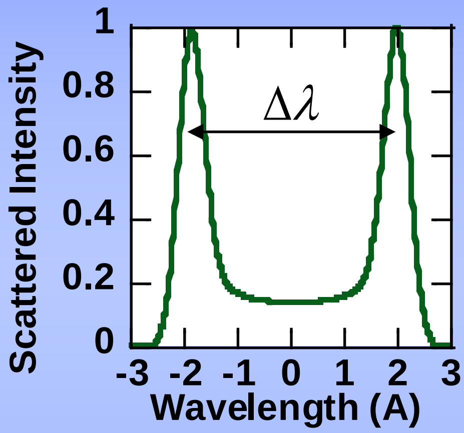
- Light is only scattered from the regions of the plasma that over lap the probe beam
- The slits on the diagnostics limit the region where light is collected



Projection of the 200µm spectrometer slit into the plasma plane

Projection of the 150µm streak camera slit into the plasma plane

Section I
Electron Temperature Measurements

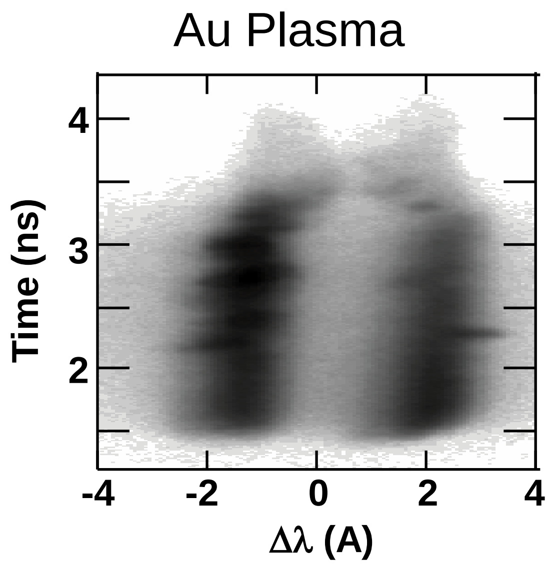


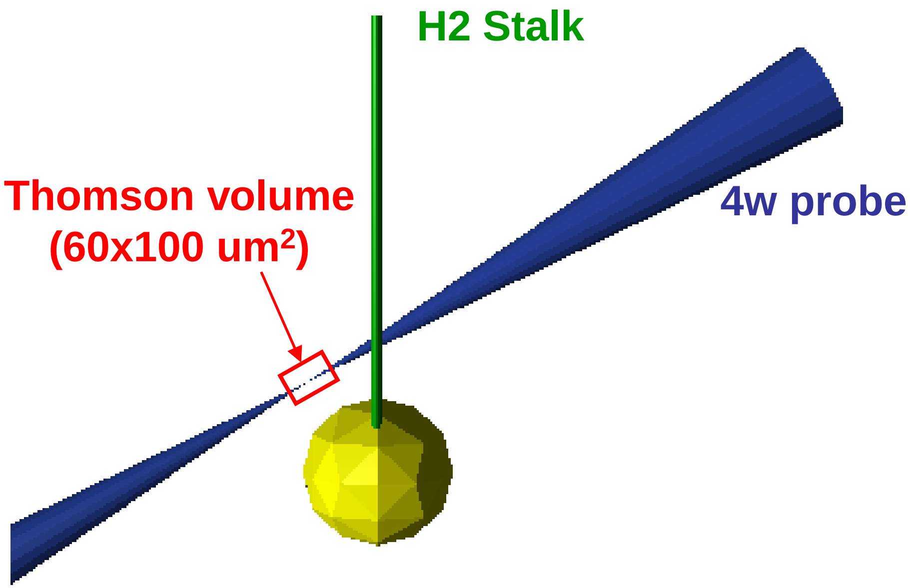
The separation between the ion-acoustic features in the scattering spectrum provides a direct measure of ZT_e

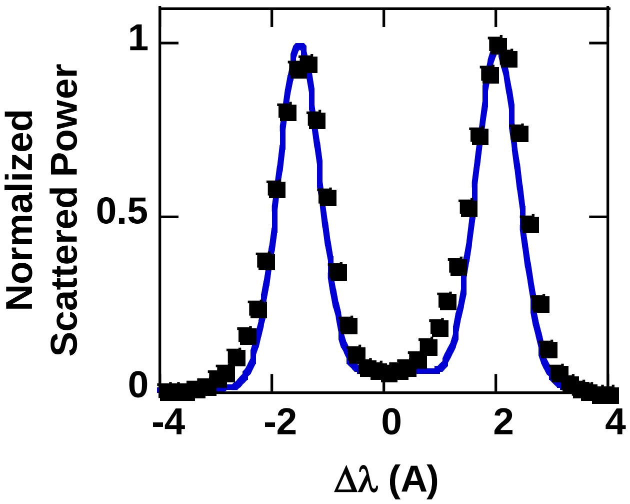
$$\Delta\lambda \cong 4\lambda_{\text{probe}} \sin(\theta/2)\sqrt{\frac{ZT_e}{M}}$$

Assuming $ZT_e >> 3T_i$

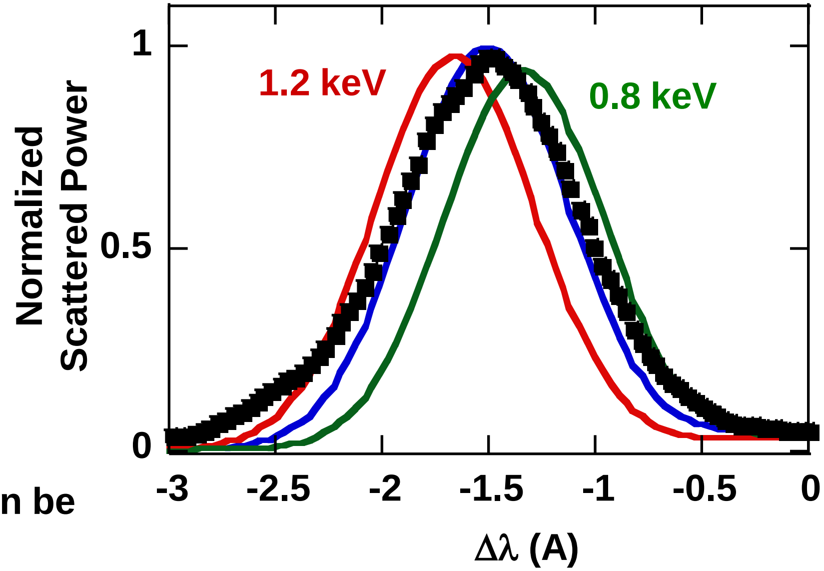
Typical Thomson scattering setups can measure the electron temperature to within 15%





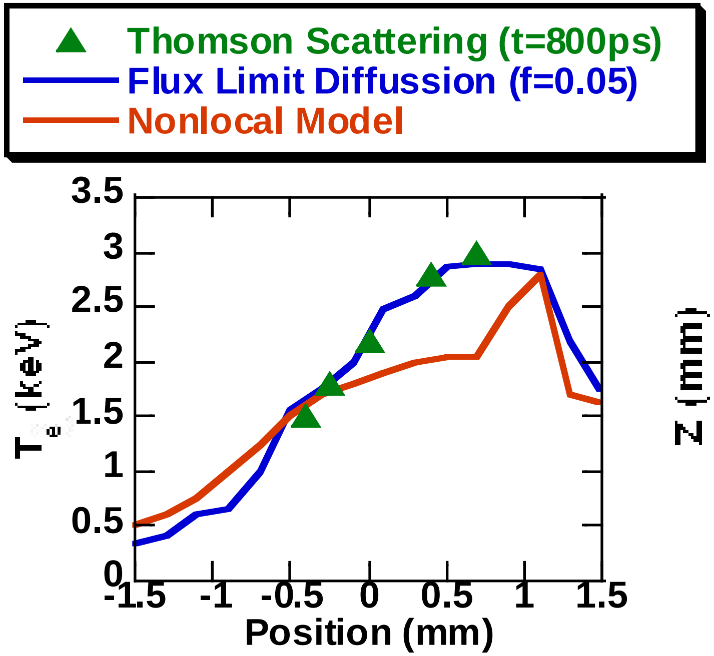


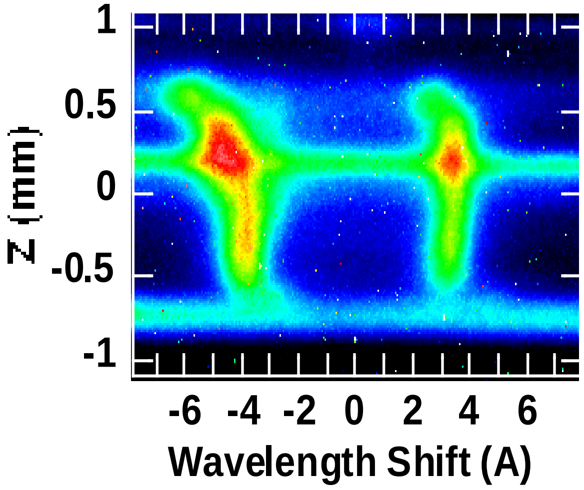
For high-Z plasmas, the ionization state can be determined using spectroscopy

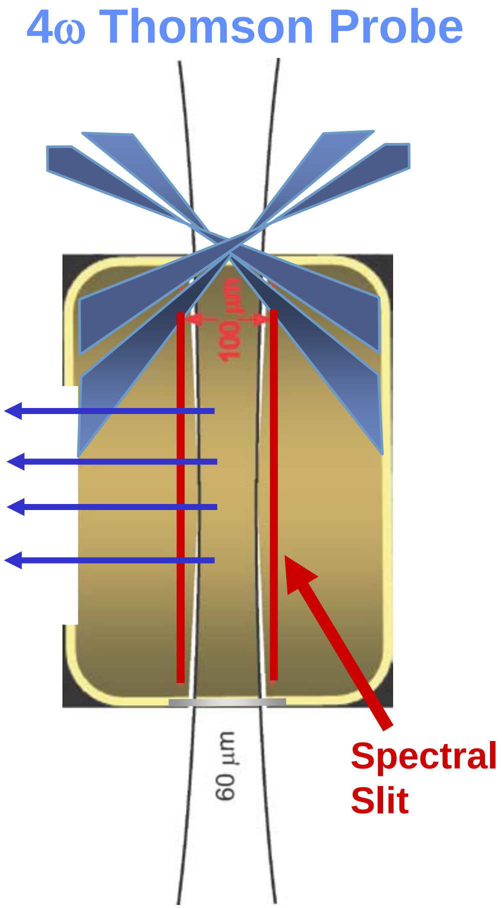


Aligning the spectral slit with the probe beam provides a scattering profile that can be used to measure temperature gradients

- We use an intensified CCD camera coupled to a spectrometer
- The slit of the spectrometer is aligned parallel to the probe beam
- Heating a hohlraum from one side provides a significant temperature profile that is used to test our nonlocal hydrodynamic simulations







J. S. Ross *et al.* Rev. Sci. Instr., 77 10E520 (2006)

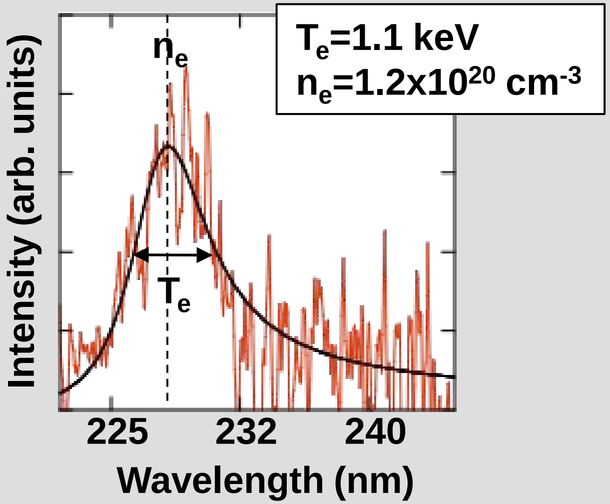
Last month S. Ross was able to measure the first high-frequency collective features from 4ω Thomson scattering

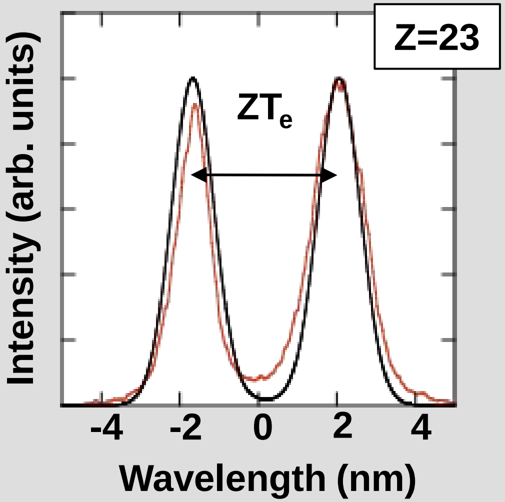
- 4ω scattering provide access to high densities
- The wavelength shift (EPW) is a measure of the density:

$$\Delta\lambda_{EPW} \approx 2\lambda_{\mathrm{probe}}\left[\frac{n}{n_{cr}} + 3\frac{v_{th}^2}{c^2}\right]^{1/2}$$

- The width (EPW) is a measure of the electron temperature
- The IAW provides a measure of Z:

$$\Delta\lambda_{IAW} \cong 4\lambda_{\mathrm{probe}}\sin(\theta/2)\sqrt{\frac{\mathrm{ZT_e}}{\mathrm{M}}}$$

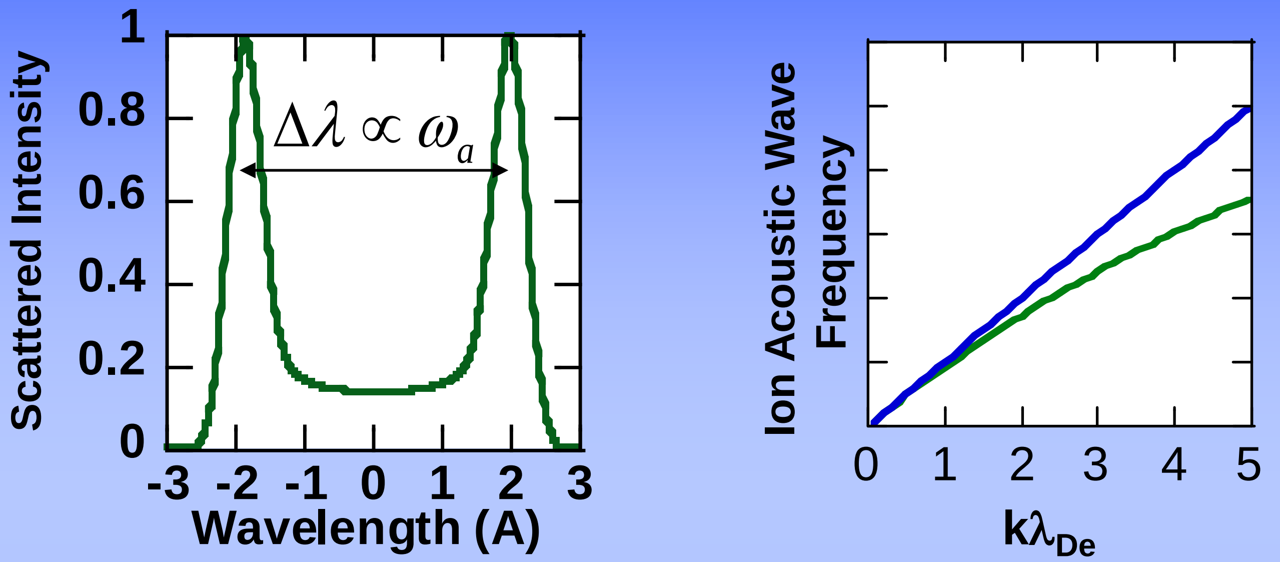




Scattering from the EPW is weak; high phase velocities → low number of particles

Section II

Local Electron Density Measurements using IAWs



- Few experiments have successfully measured the local electron density in a laser produced plasma
- A calibrated Thomson scattering system is challenging on single shot laser facilities and is unrealistic at large facilities like Omega, NIF, LILL
- Collective Thomson scattering from electron plasma waves has been demonstrated, but requires significant probe energy
- Multiple Thomson-scattering diagnostics can be used to expose the sensitivity of ion-acoustic waves to Debye shielding and provide an accurate measure of the density

Froula *et al.*, Phys. Rev. Lett. 95, 195005 (2005)

Ion-acoustic waves are dispersive; the sound speed is a function wavelength, density, and temperature

Using two TS diagnostics to probe significantly different k-vectors, we have a closed system for (Te, Ne)

$$\omega_1 = k_1 \sqrt{\frac{ZKT_e}{M} \frac{1}{1 + k_1{}^2 \lambda_D^2}} \quad \xrightarrow{k\lambda_{De} \ll 1} \quad \omega_1 \cong k_1 \sqrt{\frac{ZKT_e}{M}}$$

$$\omega_2 = k_2 \sqrt{\frac{ZKT_e}{M} \frac{1}{1 + k_2{}^2 \lambda_D^2}} \quad \xrightarrow{k\lambda_{De} > 1} \quad \omega_2 = k_2 \sqrt{\frac{ZKT_e}{M} \frac{1}{1 + k_2{}^2 \lambda_D^2}}$$

$$\mathrm{k}_a \lambda_{\mathrm{De}} \propto \sqrt{\frac{\mathrm{T_e}}{\mathrm{n_e}}}$$

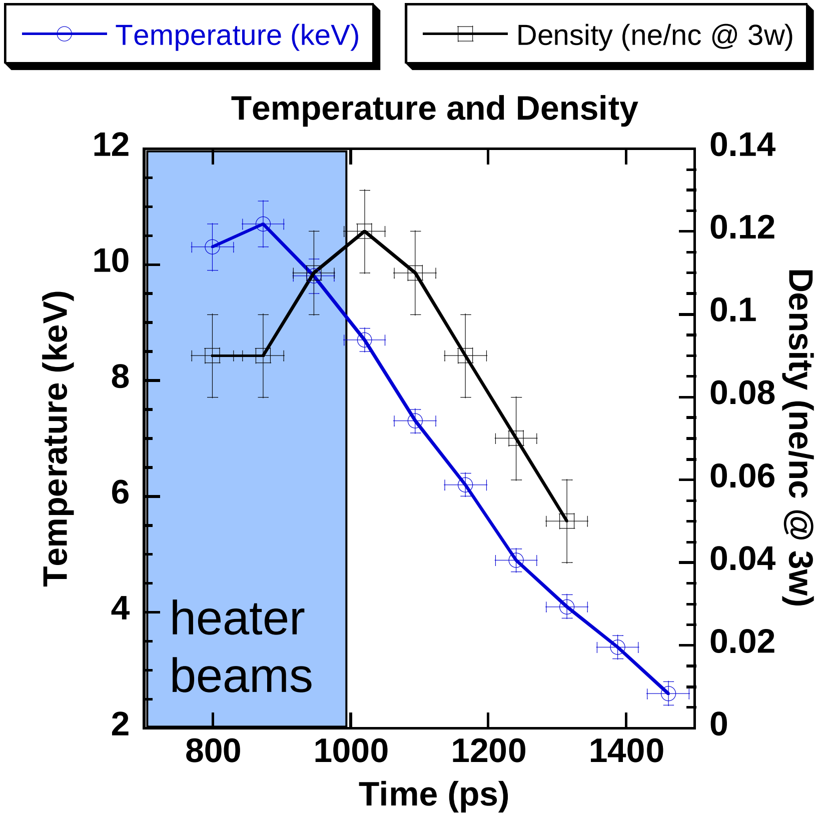
Assuming: ZTe >> Ti

- **One diagnostic is chosen to be insensitive to N_e, therefore measures T_e**
- **Second diagnostic is chosen to be sensitive to N_e**
- **The combination is a closed system for (T_e, N_e)**

Froula *et al.*, Phys. Rev. Lett., 95, 195005 (2005)

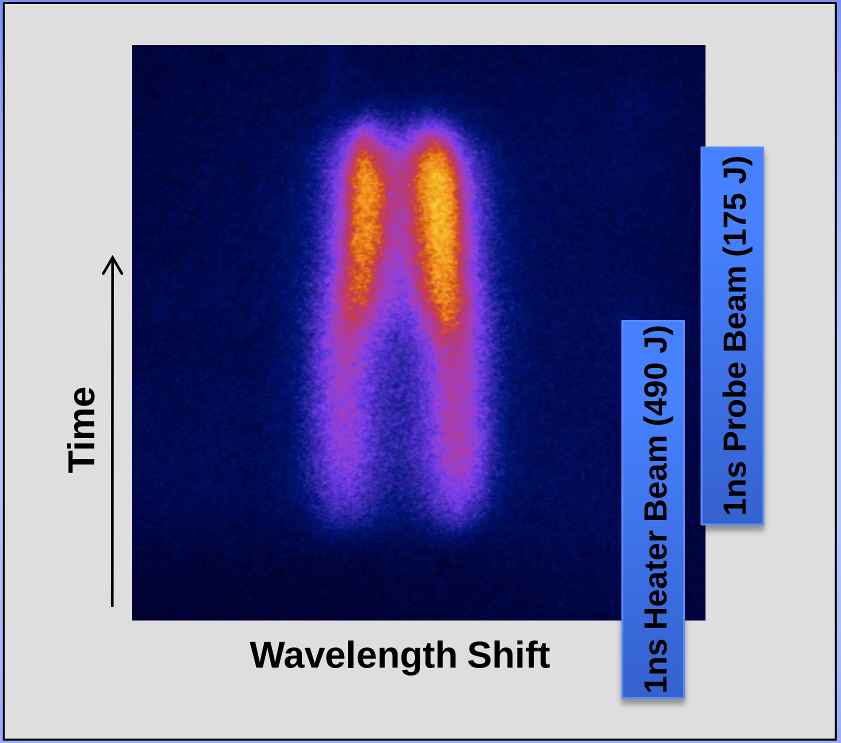
Thomson scattering measurements in half-hohlruams shot at OMEGA show a decrease in T_e from 10.7 keV to 2.6 keV over 600ps.

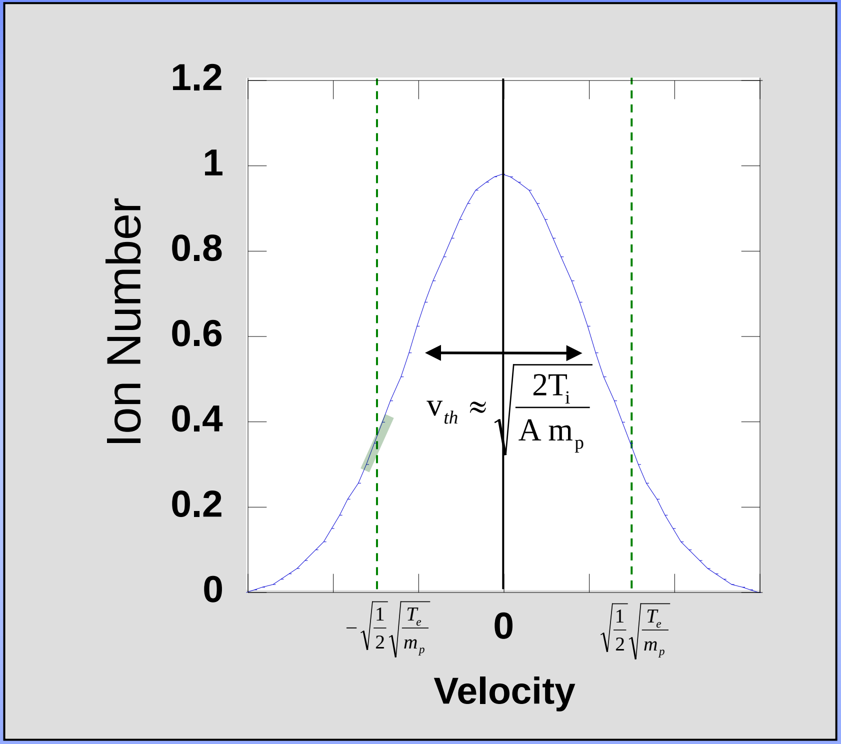
- 2ω and 4ω configurations are used to probe significantly different IAW vectors
- The uncertainty in T_e is better than 10%
- The uncertainty in n_e is better than 20%



Ross and Froula (2008)

Section III
Measuring the Amplitude Plasma Waves





- **The scattered power is a function of the Landau damping**
- **The Landau damping is a function of the ZTe/Ti through the slope and number of particles in the distribution function**

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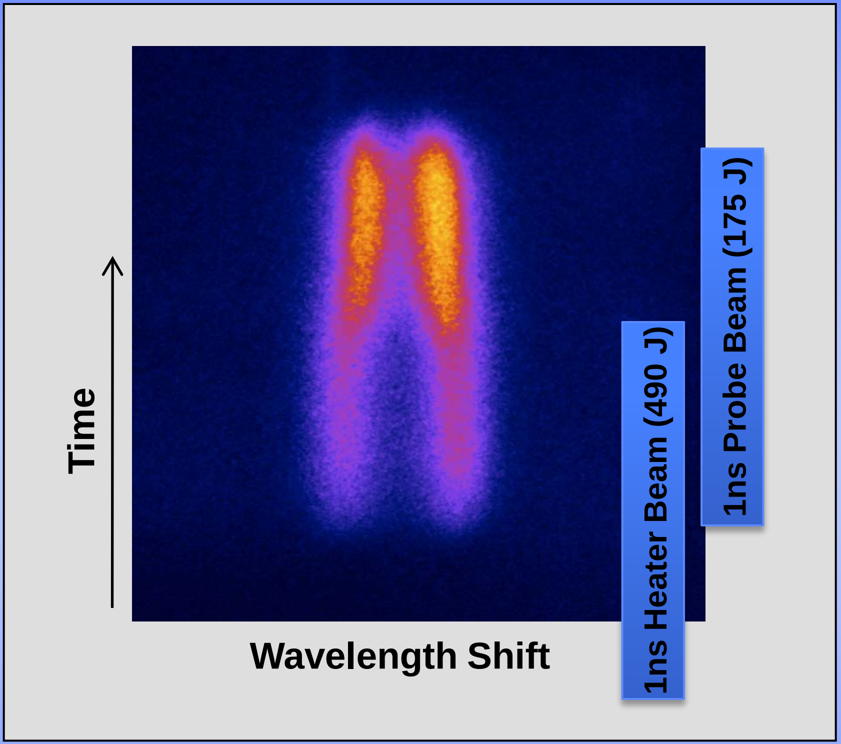
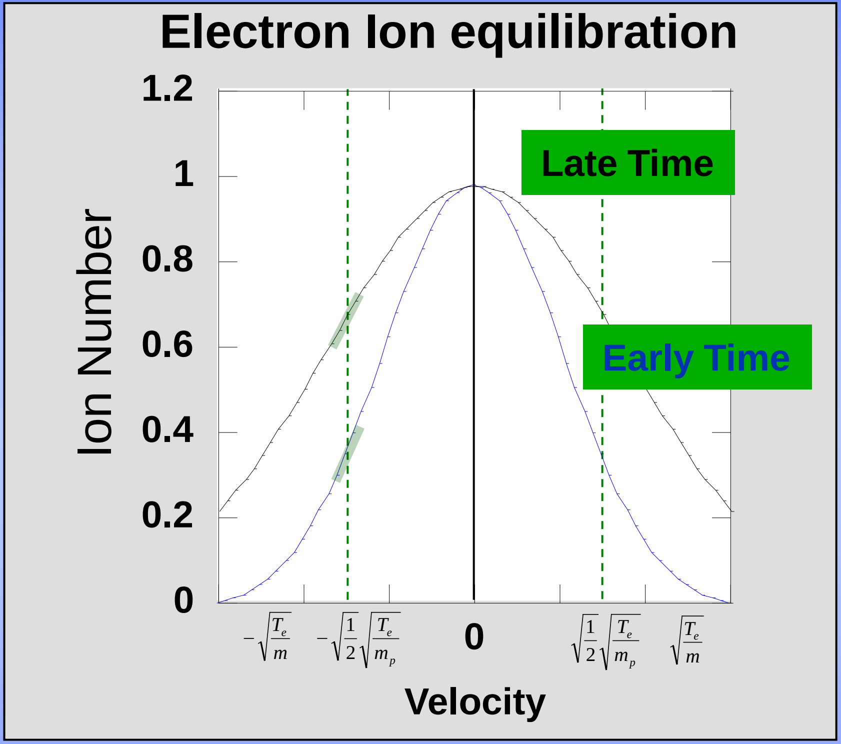
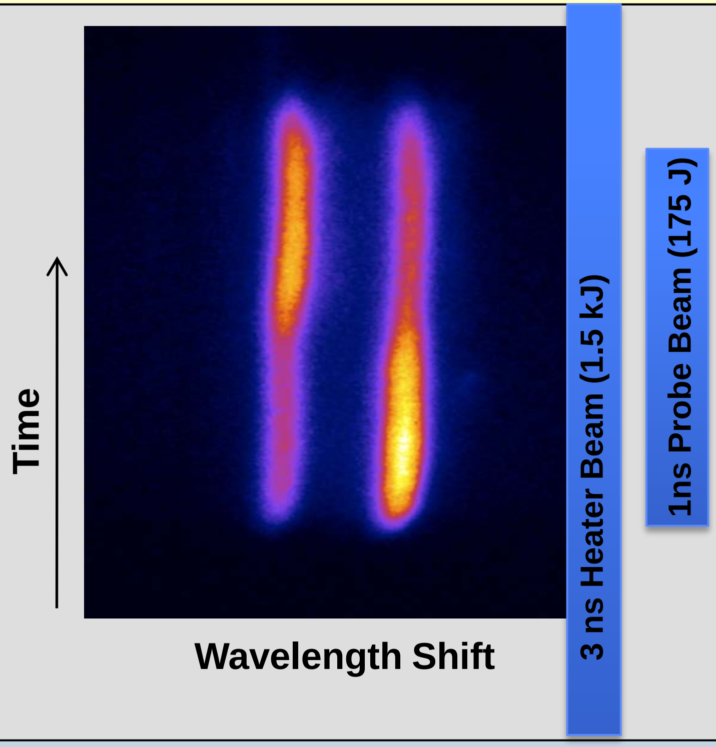




- **The scattered power is a function of the Landau damping**
- **The Landau damping is a function of the ZTe/Ti through the slope and number of particles in the distribution function**

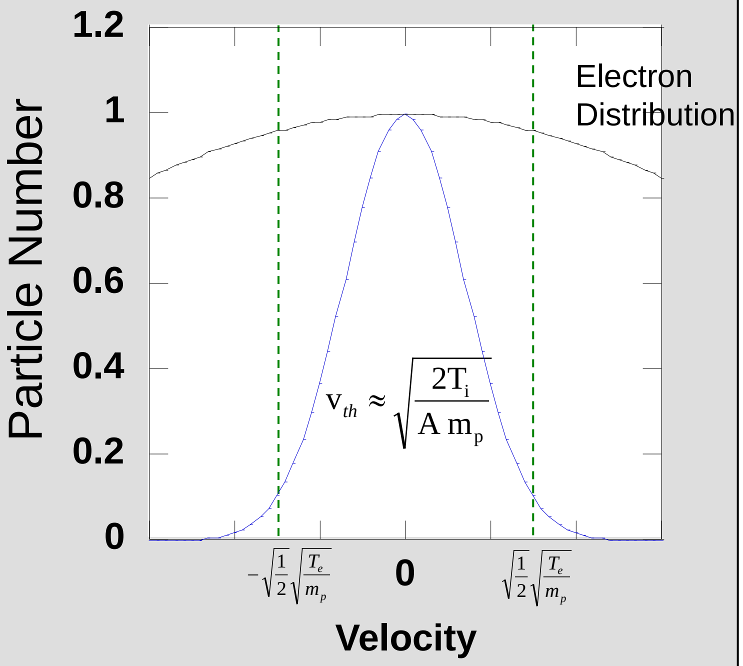
Ion vanadium, the electron and ion Landau damping have similar contributions to the total ion-wave damping

An asymmetry is measured in the ion-acoustic features for mid-Z (Z~22) vanadium targets



The asymmetry changes directions mid-way through the probe beam; the heater beams are on throughout the probe beam

The ion damping in vanadium is on the order of the electron damping



$$v_\phi \approx \sqrt{\frac{Z}{A}}\sqrt{\frac{T_e}{m_p}}$$

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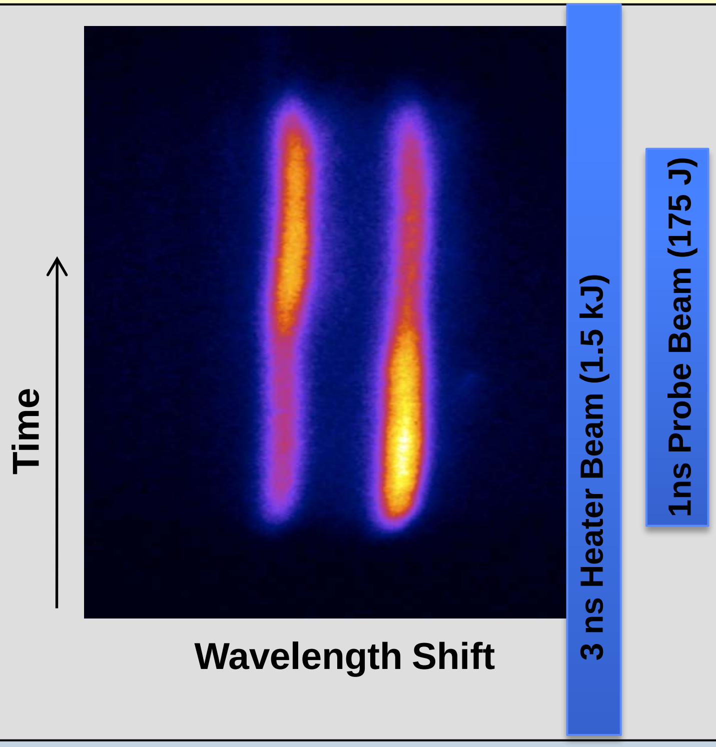

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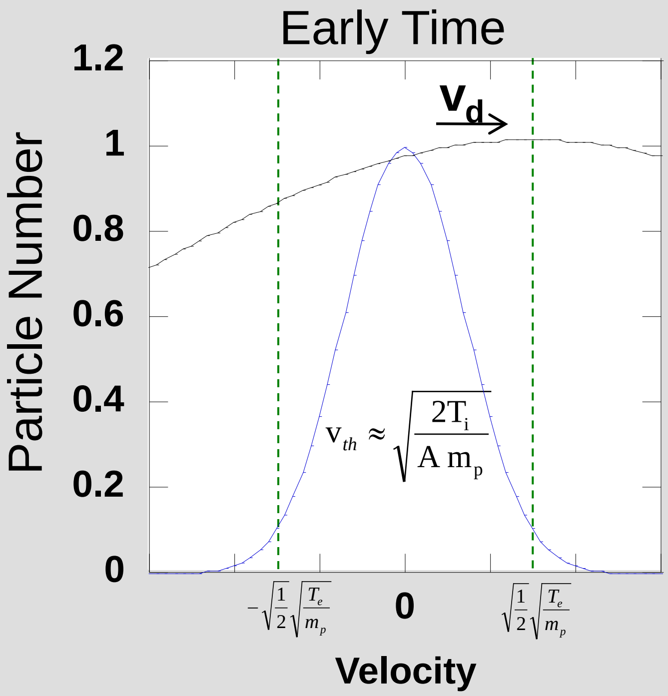
Introducing a drift between the electrons and ions (via return current) changes the LD



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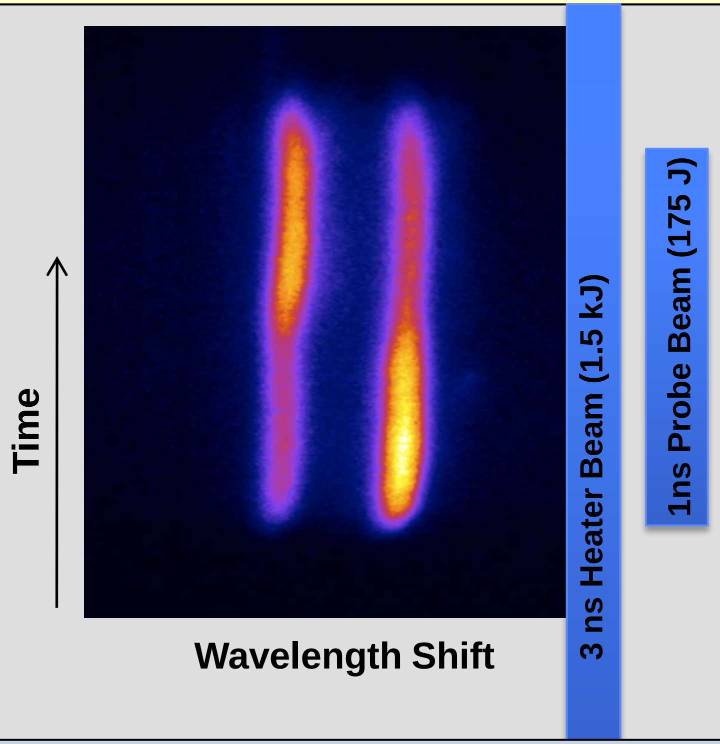

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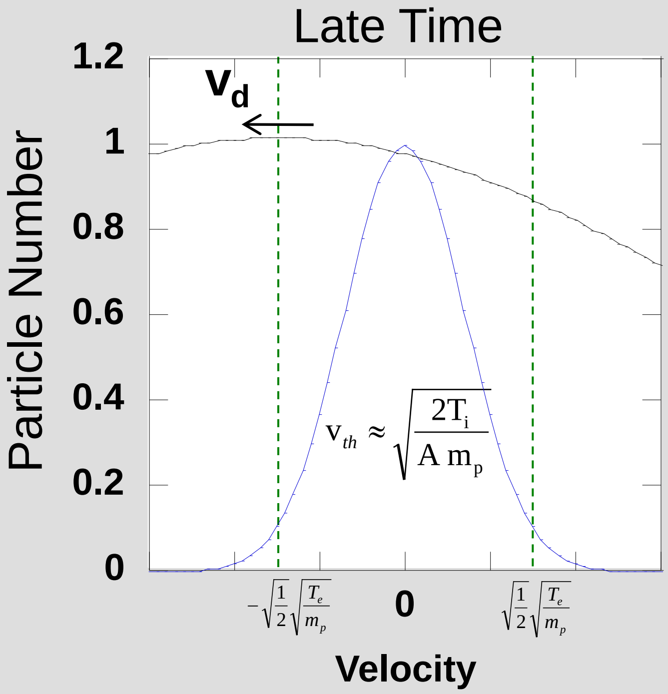
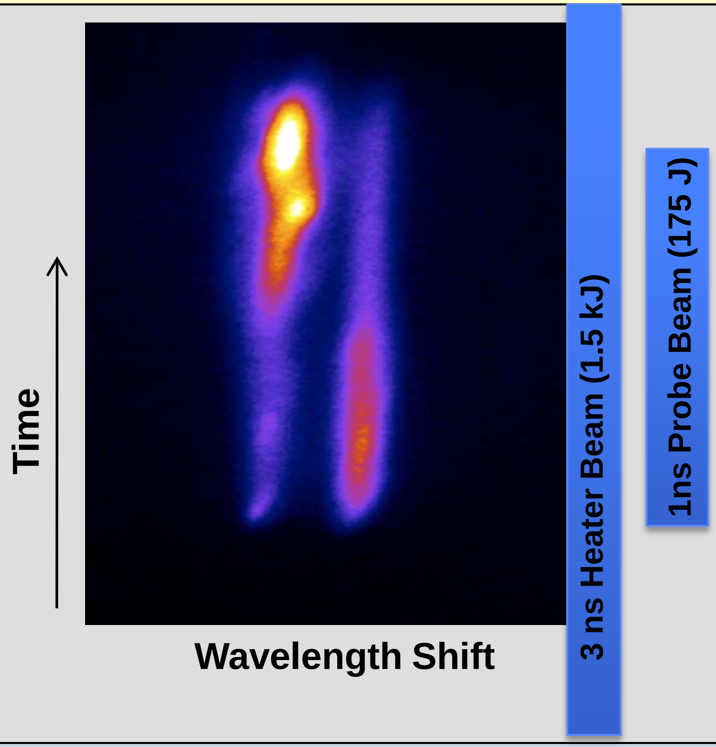


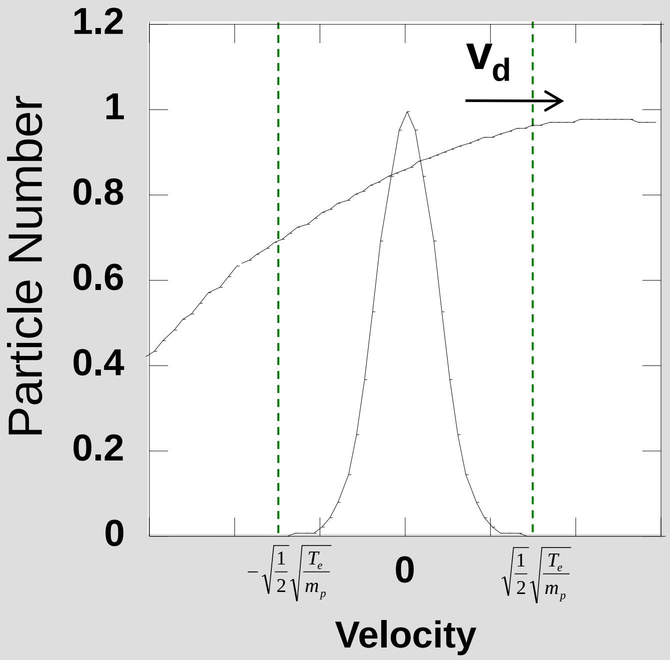
The electron Landau damping is reduced/increase leading to an asymmetric scattering spectrum

Increasing the charge state (Z) eliminates the ion Landau damping and the ion wave becomes unstable

When the return current changes directions, the ion-acoustic wave becomes unstable



In Au, there are no ions at the phase velocity; the ion-damping is zero



When the drift velocity exceeds the ion-acoustic phase velocity, the mode becomes unstable

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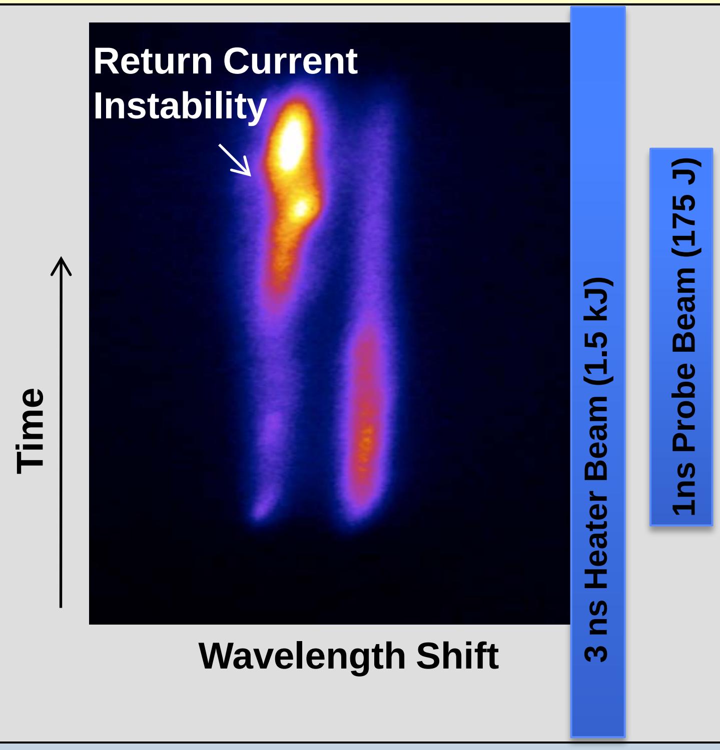

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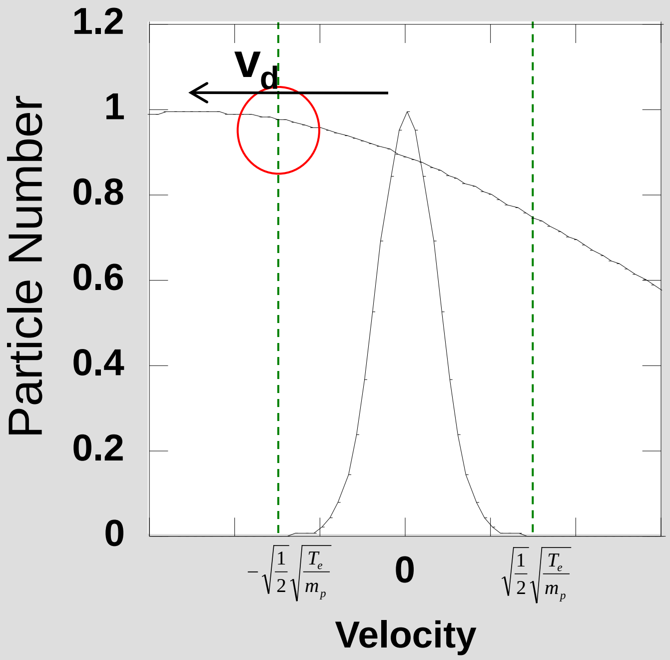

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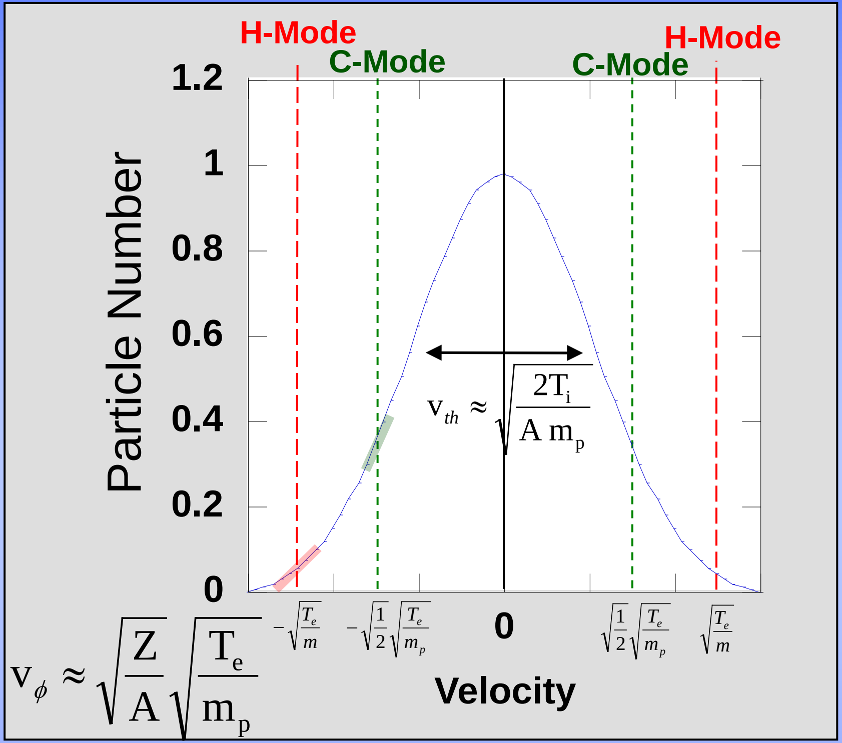
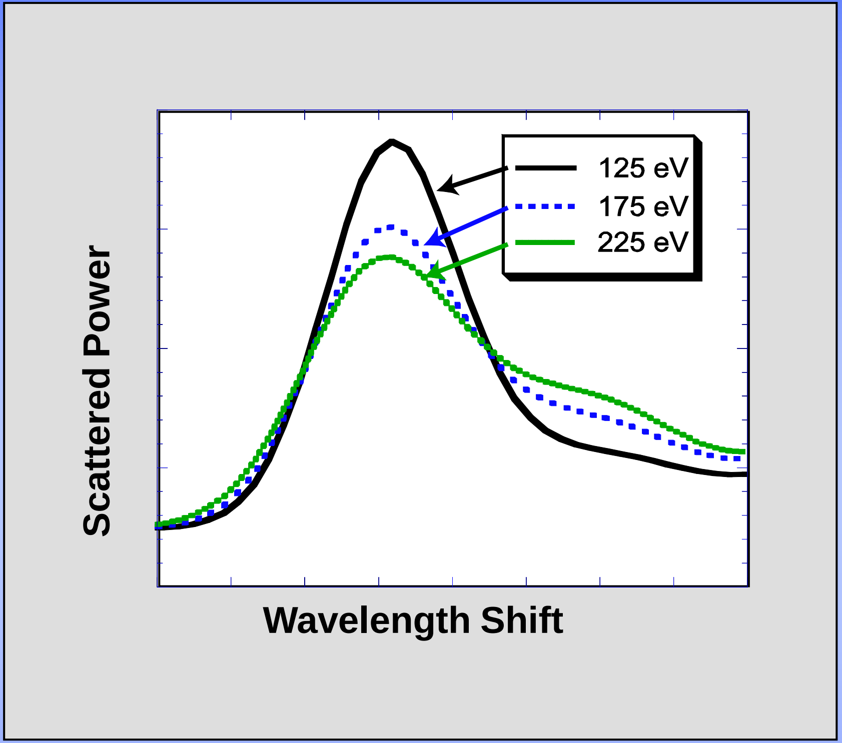
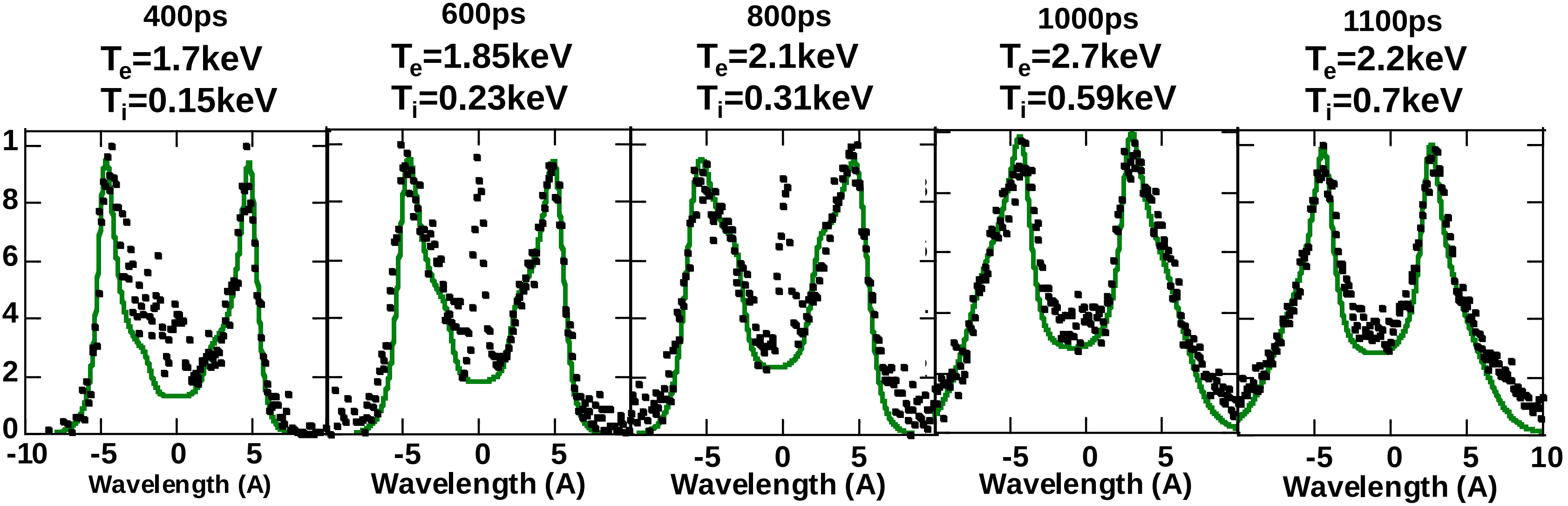
Section VI
Ion Temperature Measurements





- Theoretically the ion temperature can be determined from the width of the ion-acoustic features
  - — due to gradients within the TS volume make this measurement uncertain and therefore, unreliable in laser produced plasmas
- Multi-ion species plasmas allow the accurate measurement of ion temperature from the relative amplitude of the ion-acoustic modes

Multi-ion CH plasmas allow an accurate measure of both the electron and ion temperature



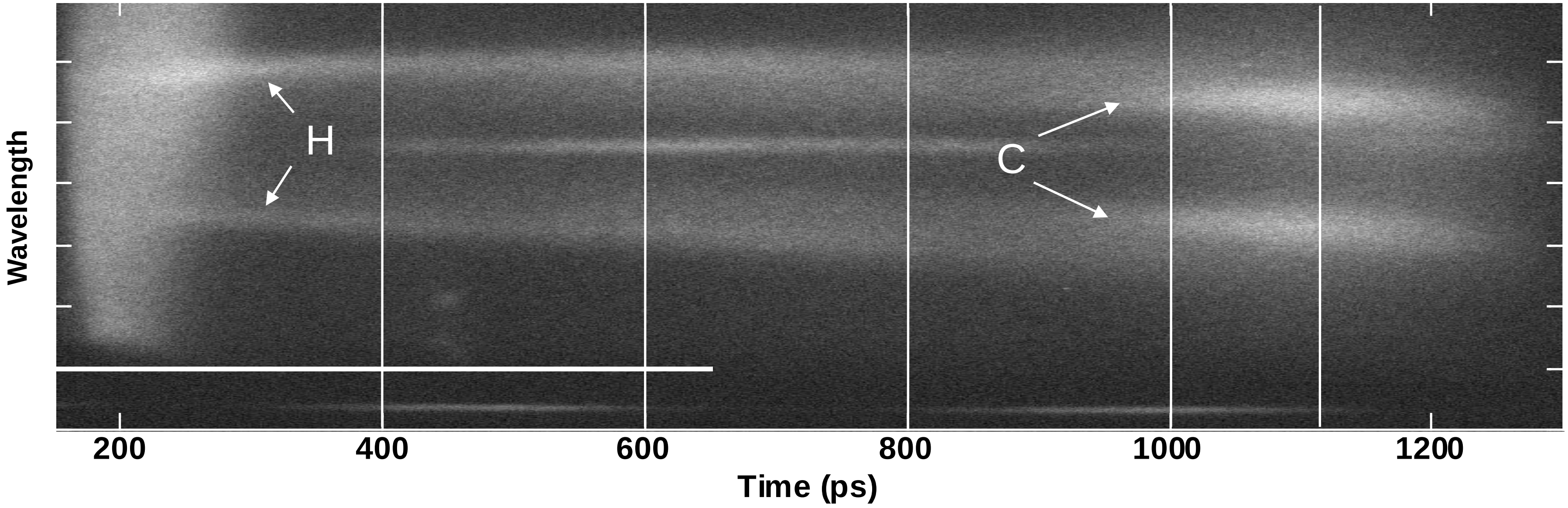
400ps T_e=1.7keV T_i=0.15keV

600ps T_e=1.85keV T_i=0.23keV

800ps T_e=2.1keV T_i=0.31keV

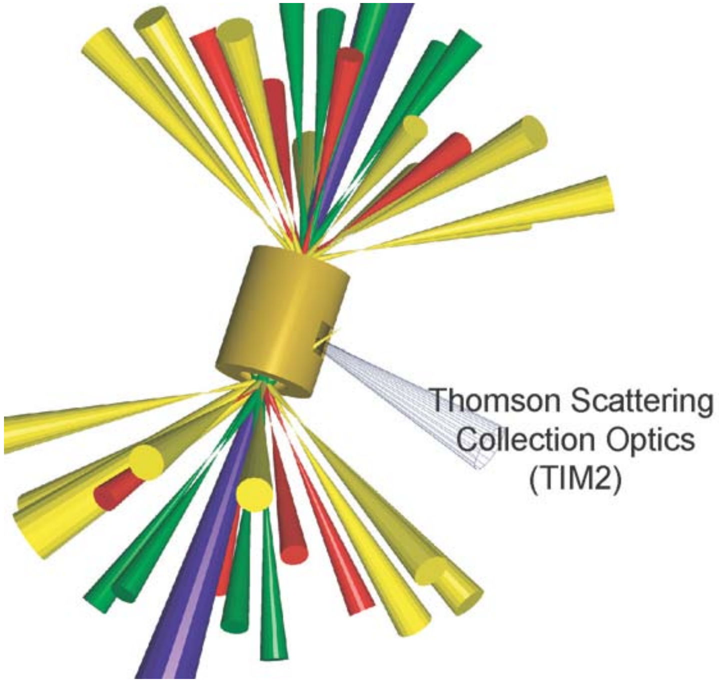
1000ps T_e=2.7keV T_i=0.59keV

1100ps T_e=2.2keV T_i=0.7keV



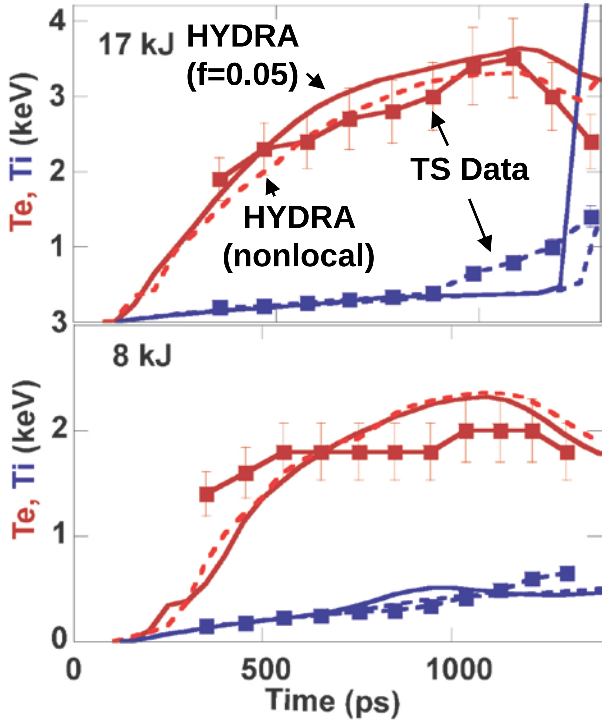
These results were used to validate hydrodynamic simulations which provides a foundation for our Laser-plasma interaction studies

33 frequency tripled (355nm) laser beams are used to heat the target



Along the axis of the hohlraum a uniform hot plasma is produced

Varying the energy in the 33 Heater beams scales the temperature in the gas fill

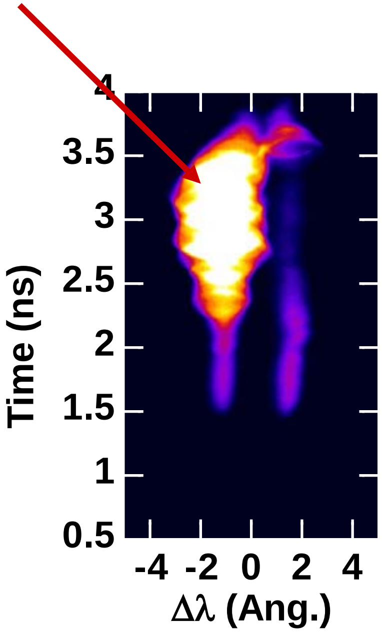


A peak temperature of 3.5 keV is measured for a n_e/n_{cr}=6%

D. H. Froula *et al.* Phys. Plasmas, 13 052704 (2006)

Conclusions

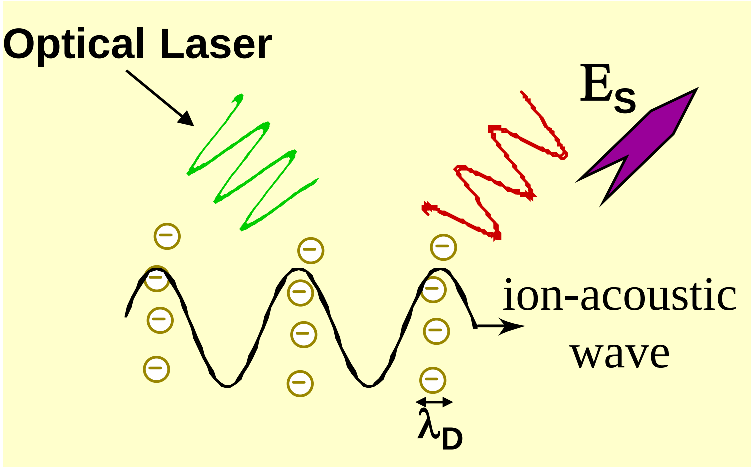
- Thomson scattering is a proven diagnostic to measure local plasma parameters in laser produced plasma experiments
- We have shown a new technique for measuring the LOCAL electron density using the ion-acoustic features
- Currently we are investigating the effects of heat flow in high-Z plasmas where we have recently observed a large asymmetry (100:1) in the ion-acoustic spectrum



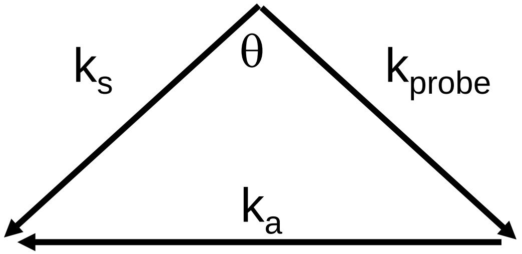
- We have been successful in measuring TS spectra using laser energies between 0.5J and 200J.
  - **Energy requirement is determined by background generated by heater beams:**
    - **Small single beam facilities require ~1J**
    - **Large multi-beam facilities (>10 beams) require 10-100J**

Thomson scattering in laser produced plasmas is typically collective as a result of the relatively high densities (α~2-3)

Collective Thomson Scattering



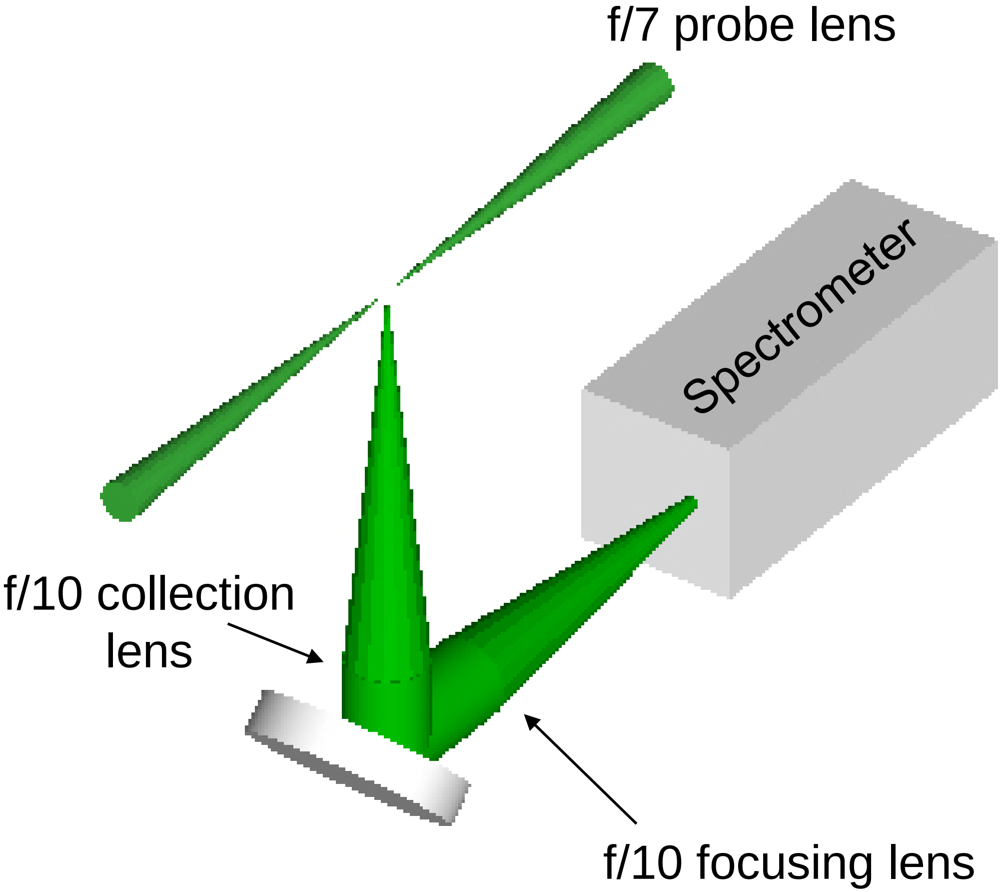
$$k_a = k_{probe} - k_s$$



$$k_a = 2k_{\mathrm{probe}} \sin\left(\theta/2\right)$$

Scattering from defined wave vector

Typical Setup



θ=102° at OMEGA

D. H. Froula *et al.* Rev. Sci. Instr,, 77 10E522 (2006)