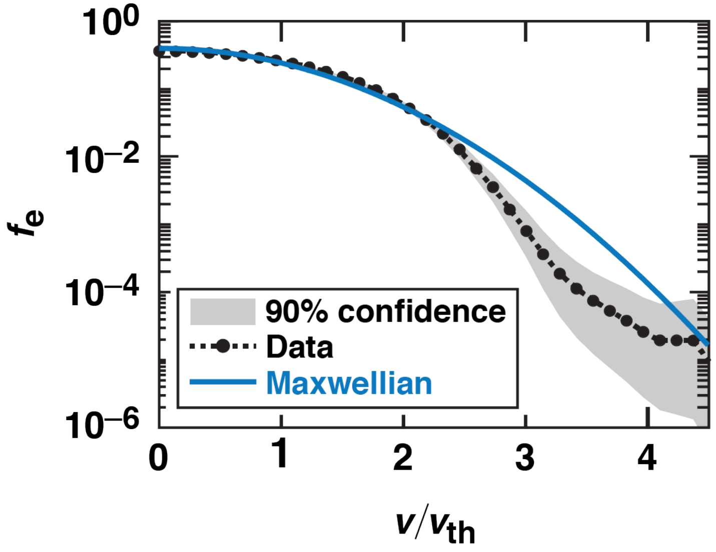
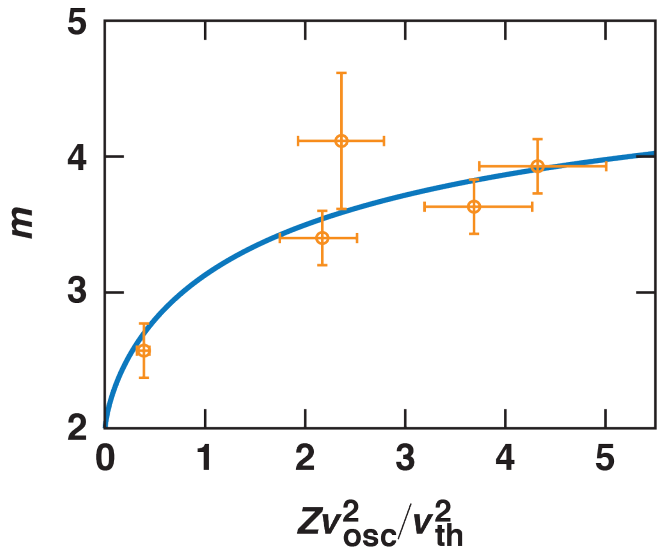
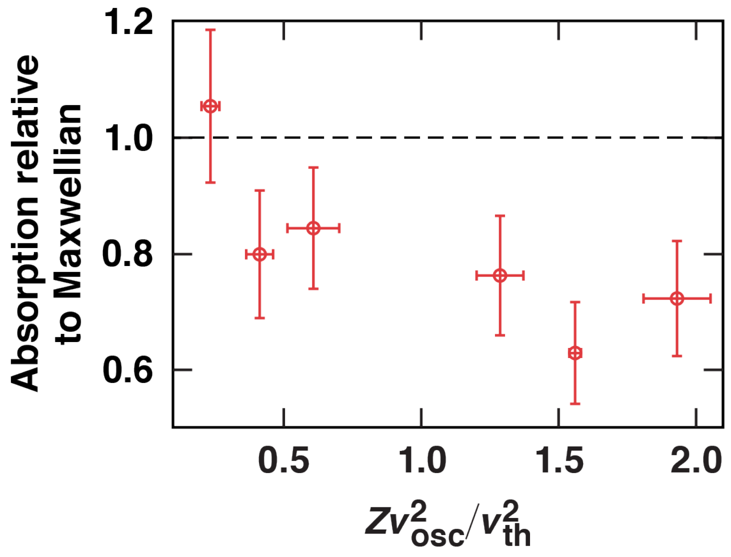
Measurements of Electron Distribution Functions in Laser-Produced Plasmas Using Angularly Resolved Thomson Scattering







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Laboratory for Laser Energetics

62nd Annual Meeting of the
American Physical Society
Division of Plasma Physics
9–13 November 2020

Summary

Angularly resolved Thomson scattering allows the first direct measurement of the electron velocity distribution over many orders of magnitude

- Electron velocity distribution function plays an important role in governing laser–plasma interactions and setting the conditions in inertial confinement fusion
- Measured distributions are super-Gaussian in the bulk due to inverse bremsstrahlung heating and Maxwellian in the tail
- Reduction in laser absorption and shift in ion-acoustic resonance due to super-Gaussian distributions were measured

Measurements of electron distribution functions can improve agreement between modeling and experiment.

Collaborators

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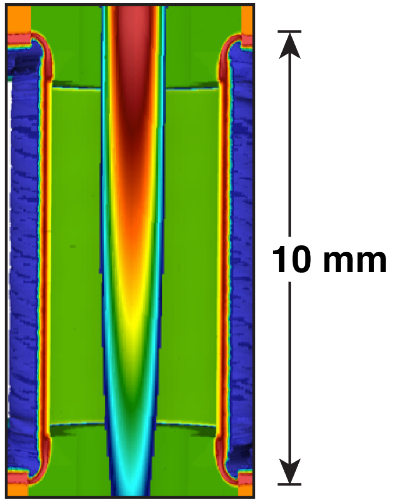
W. Rozmus

University of Alberta

Laser–plasma interactions dictate the drive and electron preheat of inertial confinement fusion experiments

MagLIF

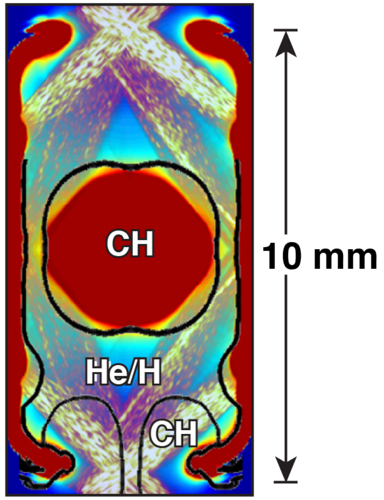
LPI limitations
Stimulated Brillouin scattering (SBS)
Stimulated Raman scattering (SRS)



E22237j

Indirect drive

LPI limitations
Cross-beam energy transfer (CBET)
SBS
SRS



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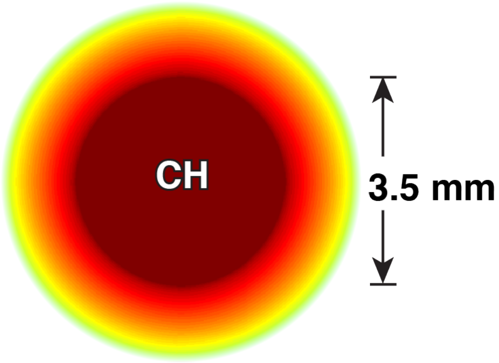
Direct drive

LPI limitations
CBET
SRS



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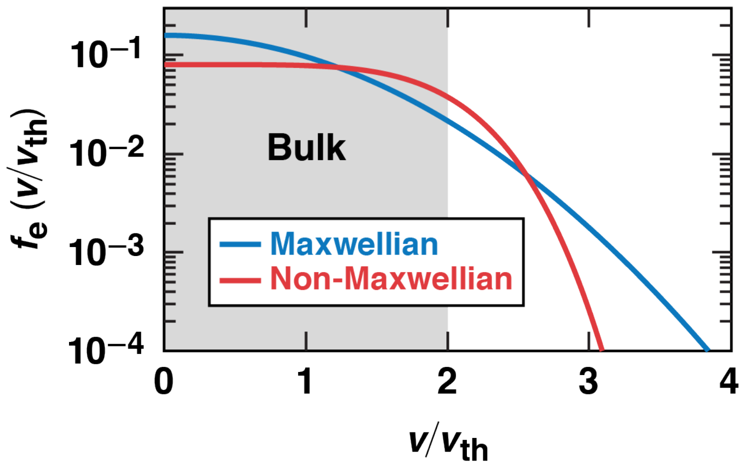
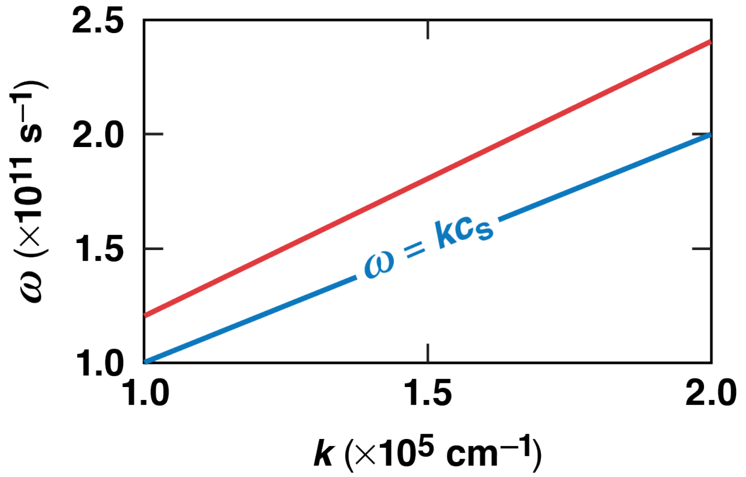
Better understanding and predictive capabilities of laser–plasma interactions can open the design space for inertial confinement fusion and other laser-based experiments.

MagLIF: magnetized liner inertial fusion
LPI: laser–plasma interaction

Modeling of laser–plasma interactions can be improved by including the electron distribution function

- The bulk of the distribution function affects
  - stimulated Brillouin scattering
  - laser absorption
  - Ion-acoustic resonance and damping





E29306

D. Turnbull *et al*., Nat. Phys. 16, 181 (2020);
B. B. Afeyan *et al*., Phys. Rev. Lett. 80, 2322 (1998).

Modeling of laser–plasma interactions can be improved by including the electron distribution function

- The bulk of the distribution function affects
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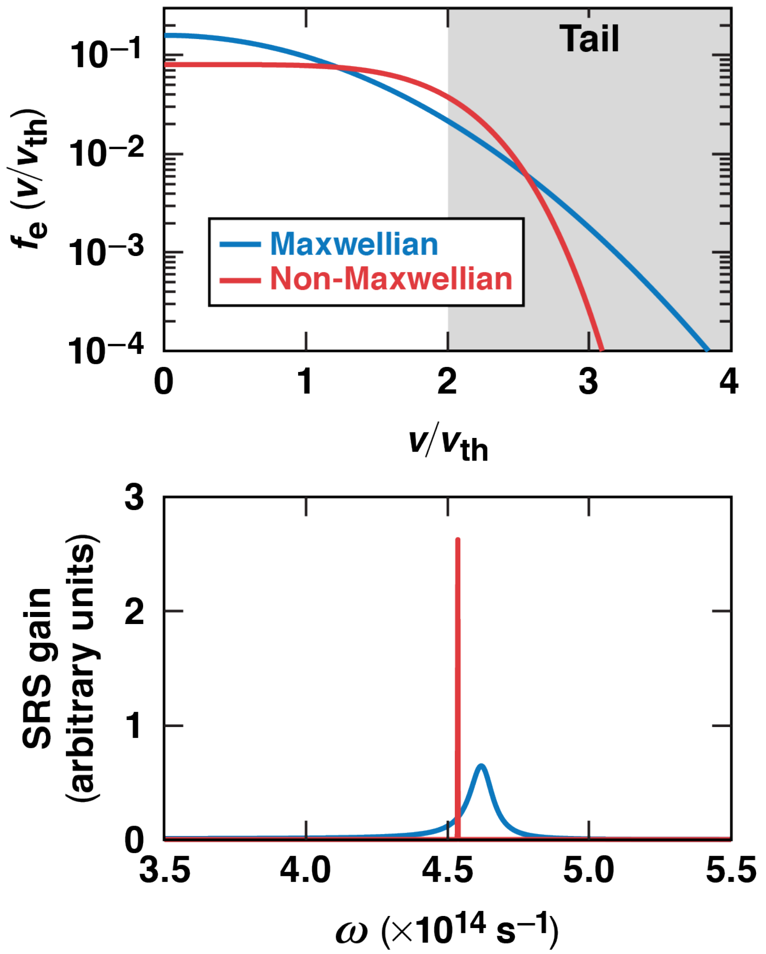
  - laser absorption
  - ion acoustic resonance and damping
- The tail of the distribution function affects:
  - SRS
  - heat flux
  - Langmuir wave resonance and damping



W. Rozmus *et al*., Phys. Plasmas 23, 012707 (2016).

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  - laser absorption
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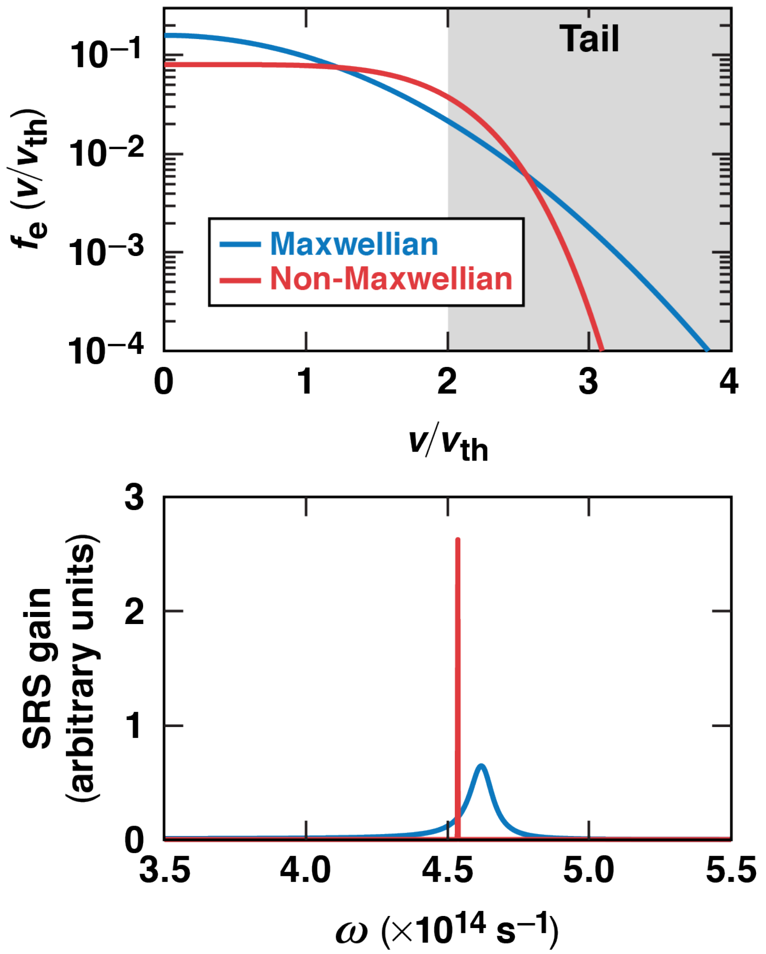
  - SRS
  - heat flux
  - Langmuir wave resonance and damping

Measurements of the electron distribution can identify distribution functions relevant for modeling.



E29307

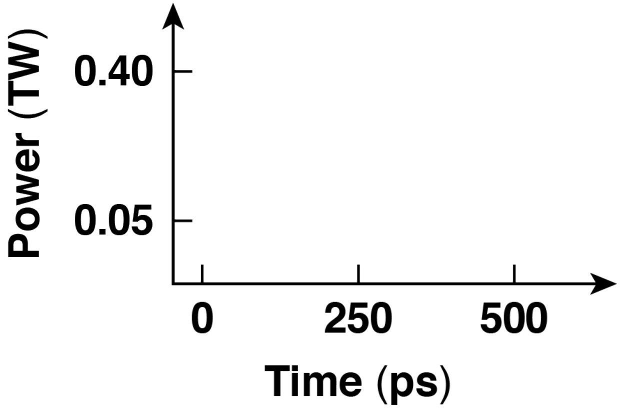
W. Rozmus *et al.*, Phys. Plasmas 23, 012707 (2016).

Outline

- Electron distribution functions impact ICF through LPI
- **Measurements of electron distribution functions with angularly resolved Thomson scattering**
- Measured distributions (bulk) and the impact on
  - absorption
  - CBET
- Measured distributions (tail)

ICF: inertial confinement fusion

Electron distribution function measurements were conducted on the OMEGA Laser System using the gas-jet platform to provide uniform well-diagnosed underdense plasmas



E29308a

A. M. Hansen *et al.*, Rev. Sci. Instrum. 89, 10C103 (2018).

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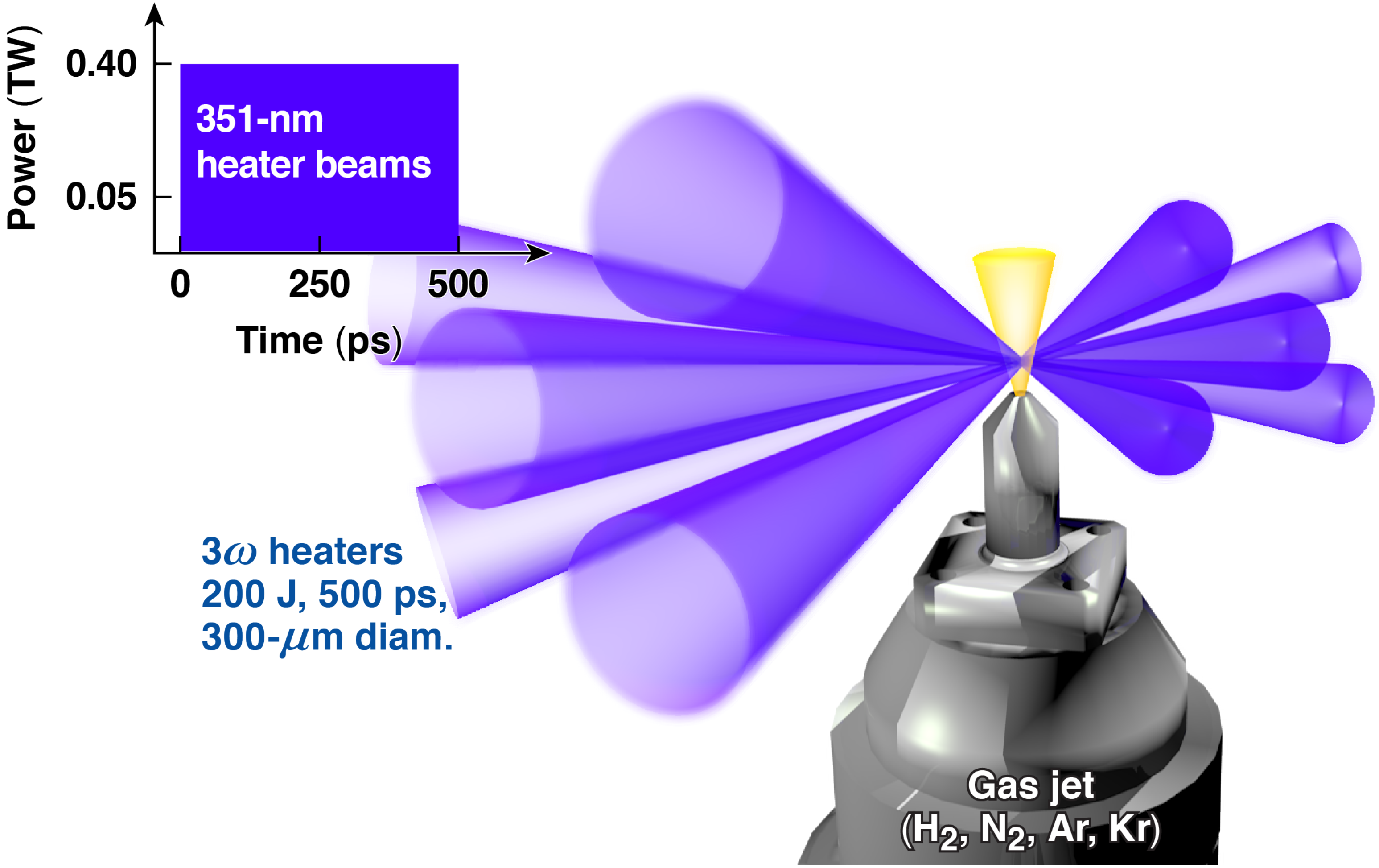

E29308b

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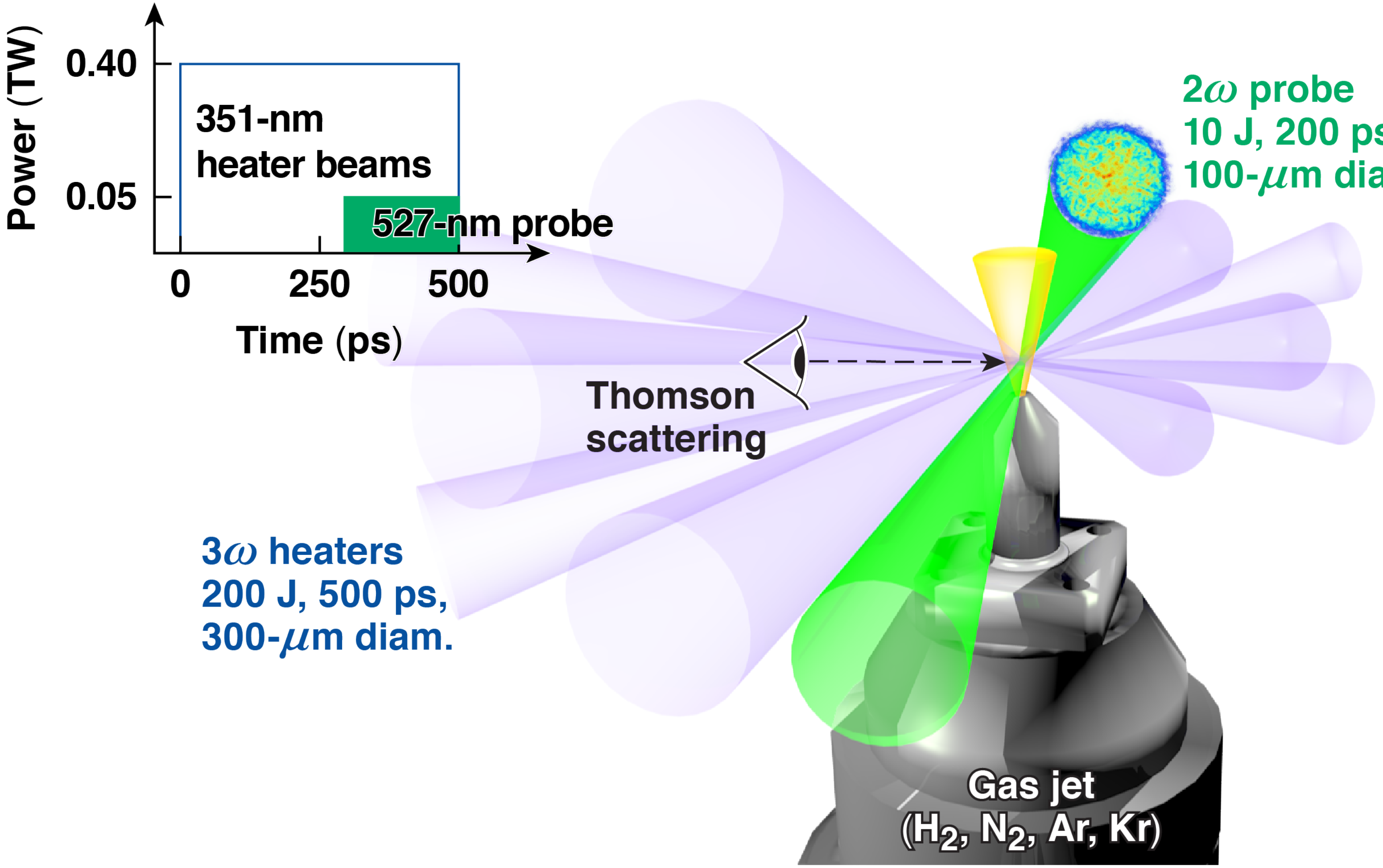


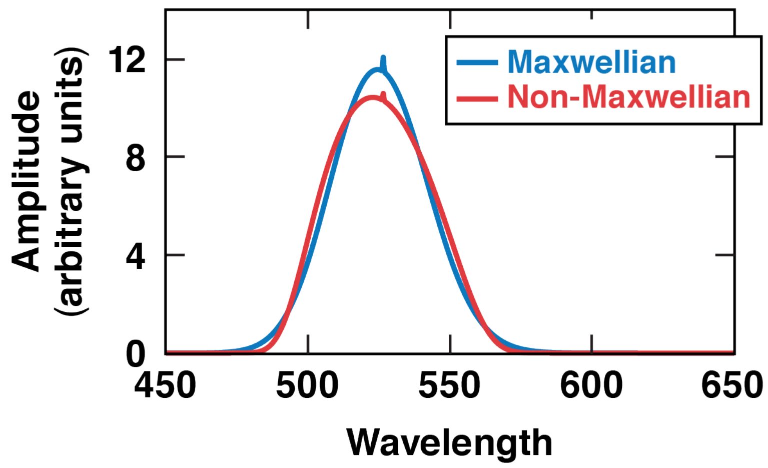
E29308c

A. M. Hansen *et al.*, Rev. Sci. Instrum. 89, 10C103 (2018).

Noncollective Thomson scattering directly measures the electron distribution function, but dynamic range limits measurements to the bulk

- **Noncollective Thomson scattering is directly dictated by the distribution function**

$$P_{s,\,NC} \propto f(v/v_{th})/v_{th}$$



E29309a

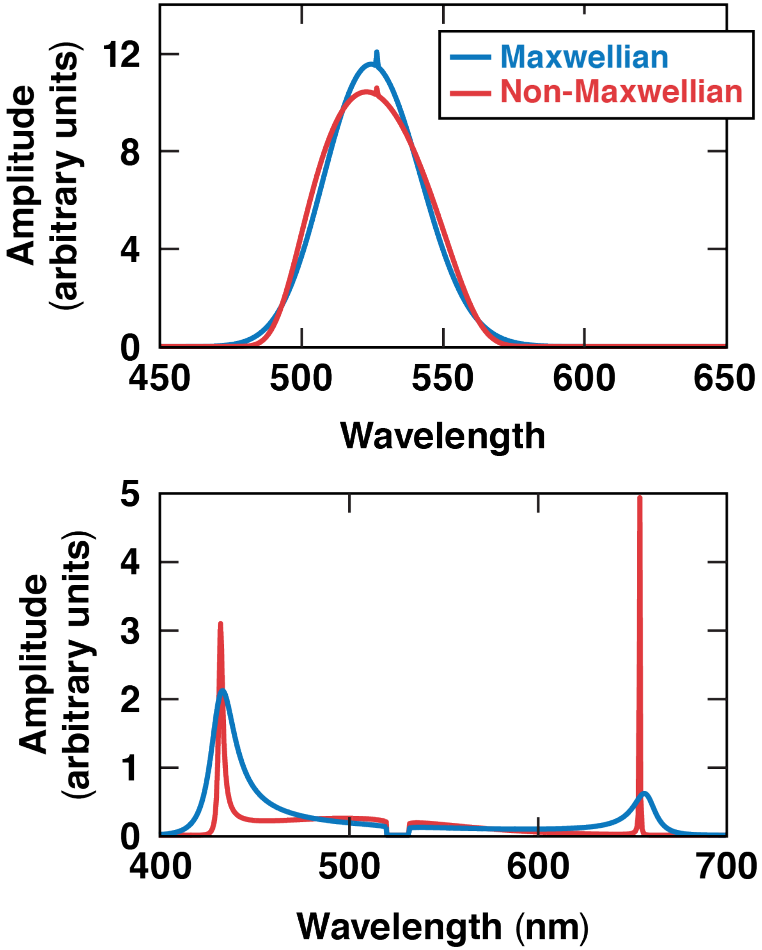
Noncollective Thomson scattering directly measures the electron distribution function, but dynamic range limits measurements to the bulk

- Noncollective Thomson scattering directly dictated by the distribution function

$$P_{\mathrm{s,\,NC}} \propto f(v/v_{\mathrm{th}})/v_{\mathrm{th}}$$

- Collective Thomson scattering is related to the distribution function and the susceptibility
- The susceptibility (χ) is dependent on the distribution function

$$P_{\mathrm{s,\,peak}} \propto \frac{f_{\mathrm{e}}\left(\frac{v}{v_{\mathrm{th}}}\right)}{df_{\mathrm{e}}/dv}$$



E29309

Noncollective Thomson scattering directly measures the electron distribution function, but dynamic range limits measurements to the bulk

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$$P_{s,\,NC} \propto f(v/v_{th})/v_{th}$$

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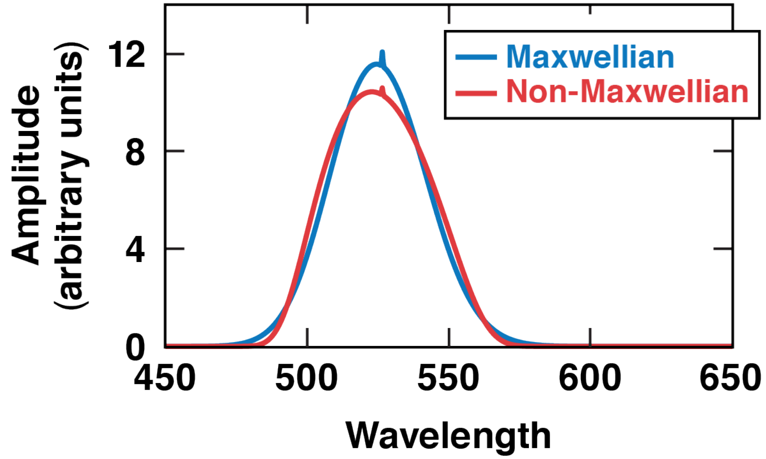
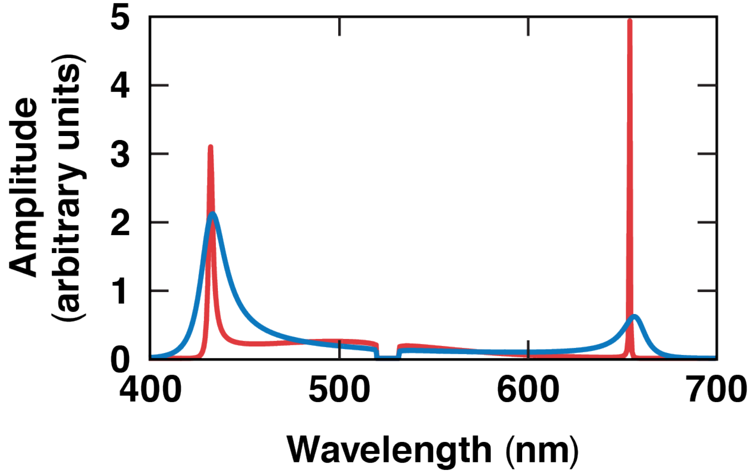
- **The susceptibility (χ) is dependent on the distribution function**

$$P_{s,\,peak} \propto \frac{f_e\left(\frac{v}{v_{th}}\right)}{df_e/dv}$$

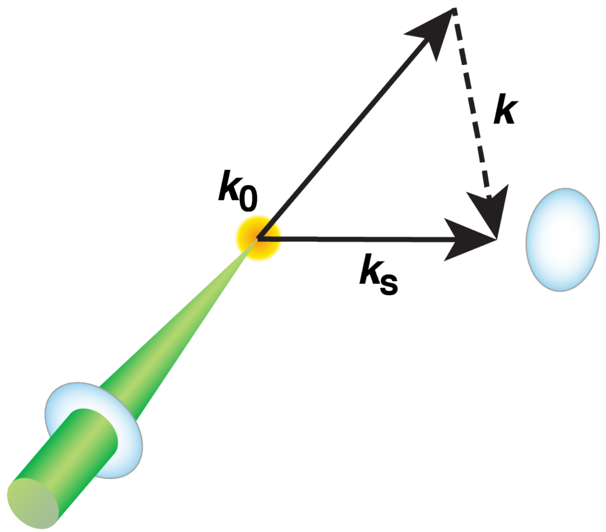
A small-scattering cross section and limited dynamic range have limited electron distribution function measurements to the bulk or a predetermined functional form.





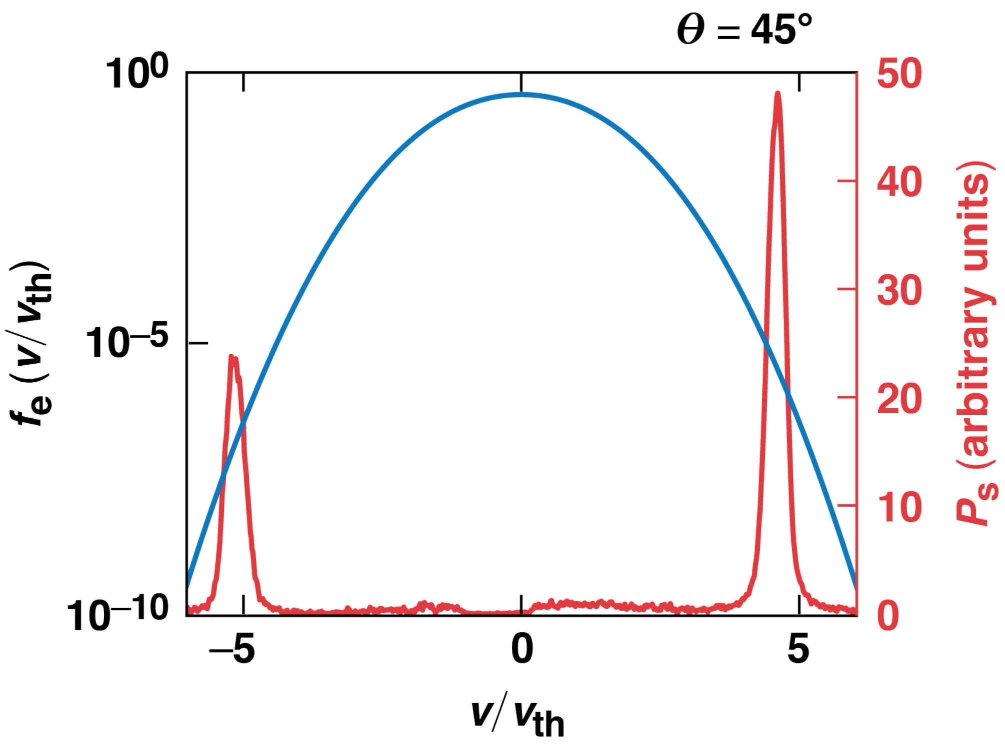
E29309

Angularly resolved Thomson scattering allows direct measurement of the distribution function over many orders of magnitude with limited dynamic range



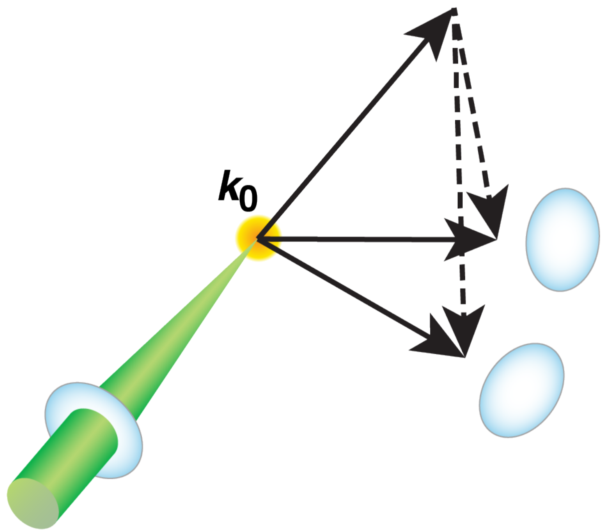
E29310b

$$k^2 = k_0^2 + k_s^2 - 2k_0k_s\cos\theta$$

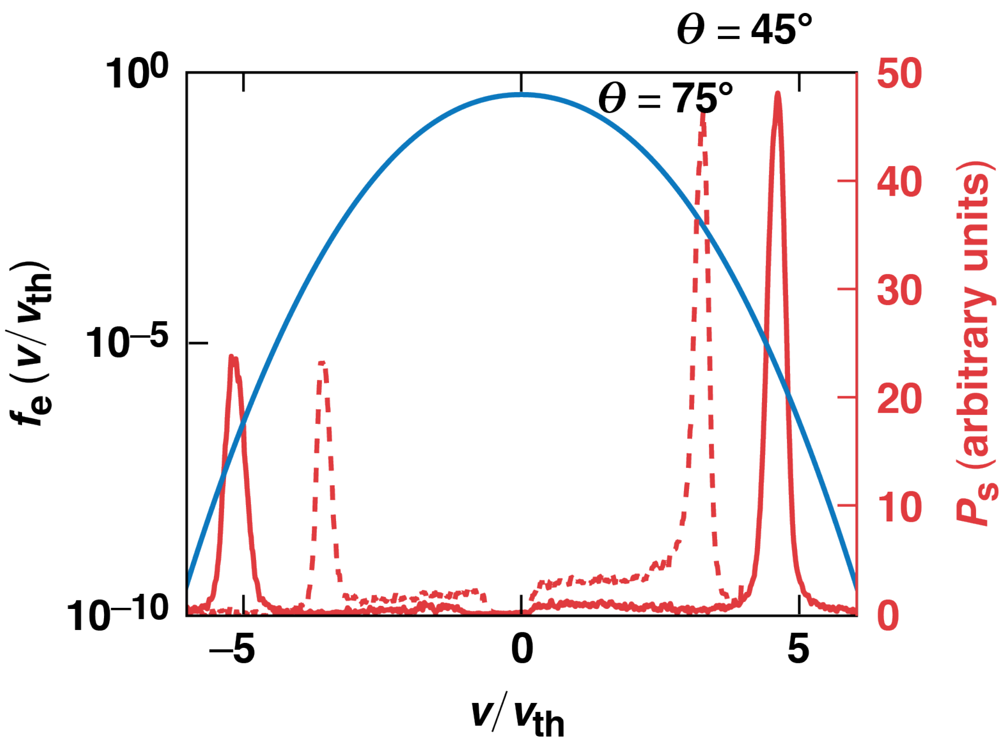


$$\frac{v}{v_{th}} = \frac{\omega}{kv_{th}}$$

Angularly resolved Thomson scattering allows direct measurement of the distribution function over many orders of magnitude with limited dynamic range



E29310a



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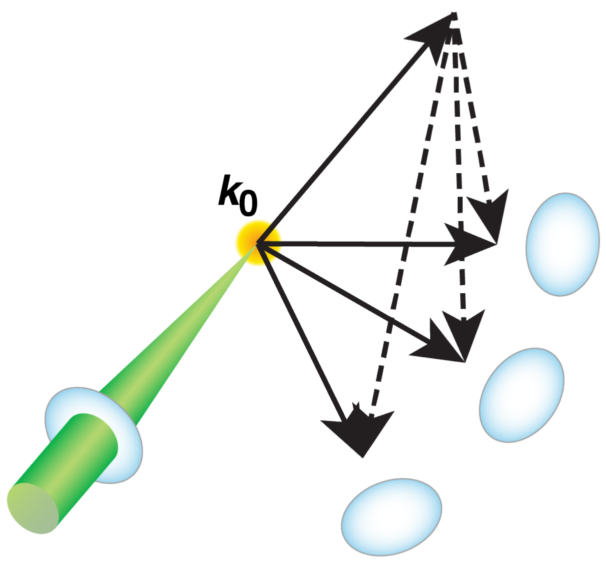

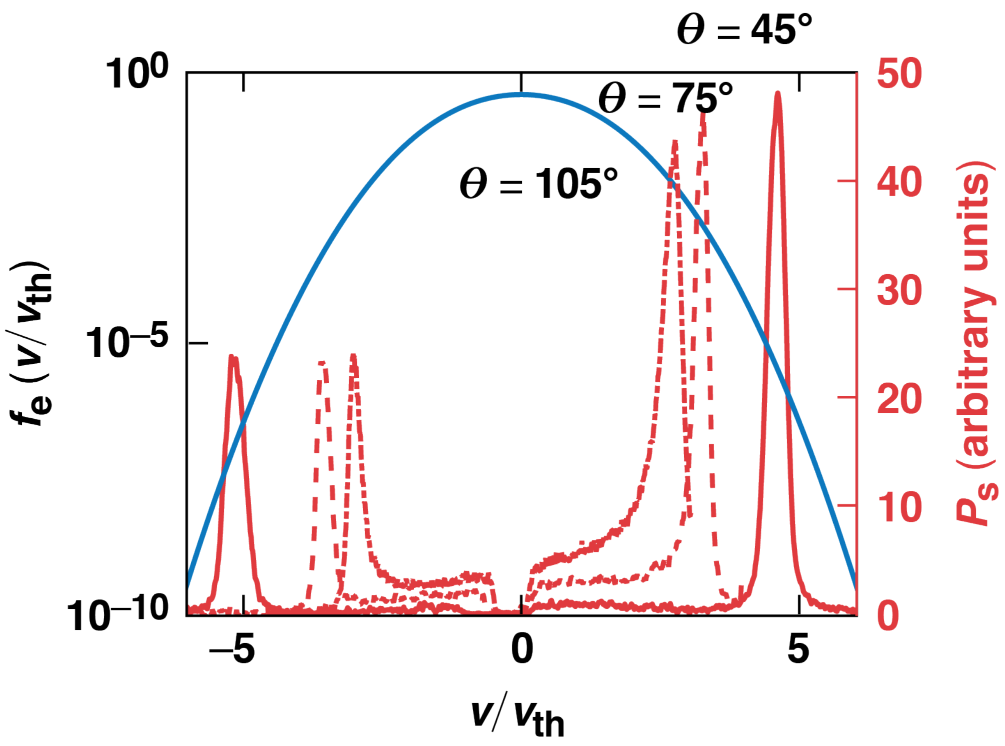

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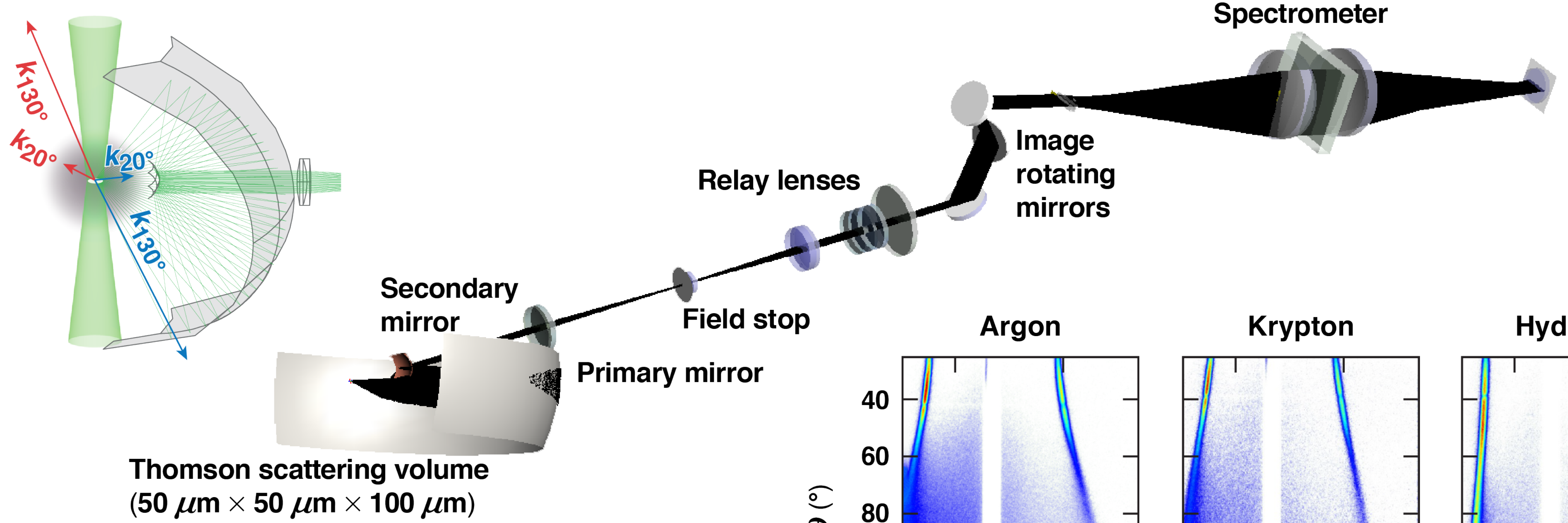
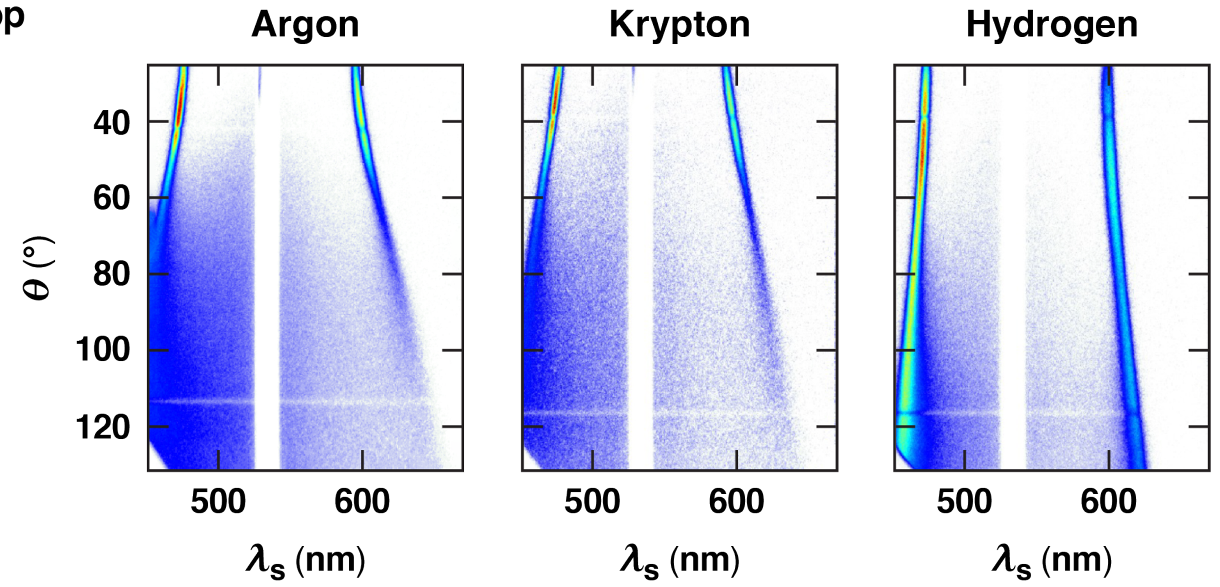
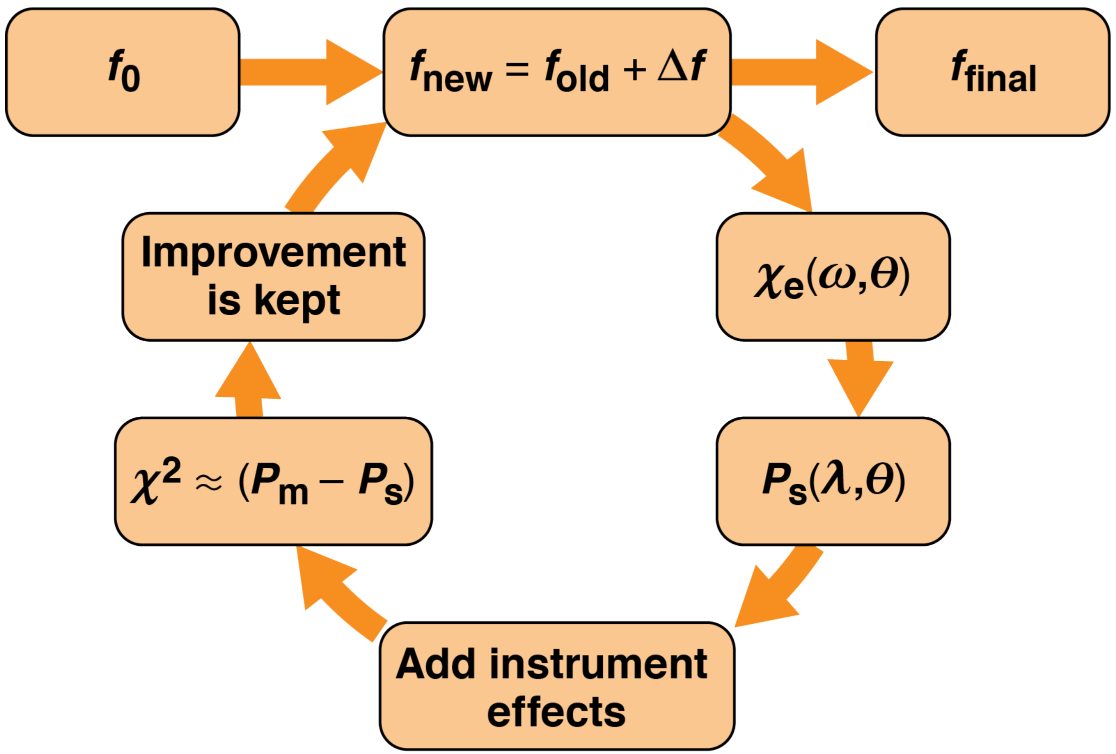
A diagnostic was invented to measure the electron distribution function by angularly resolving the Thomson-scattering spectrum





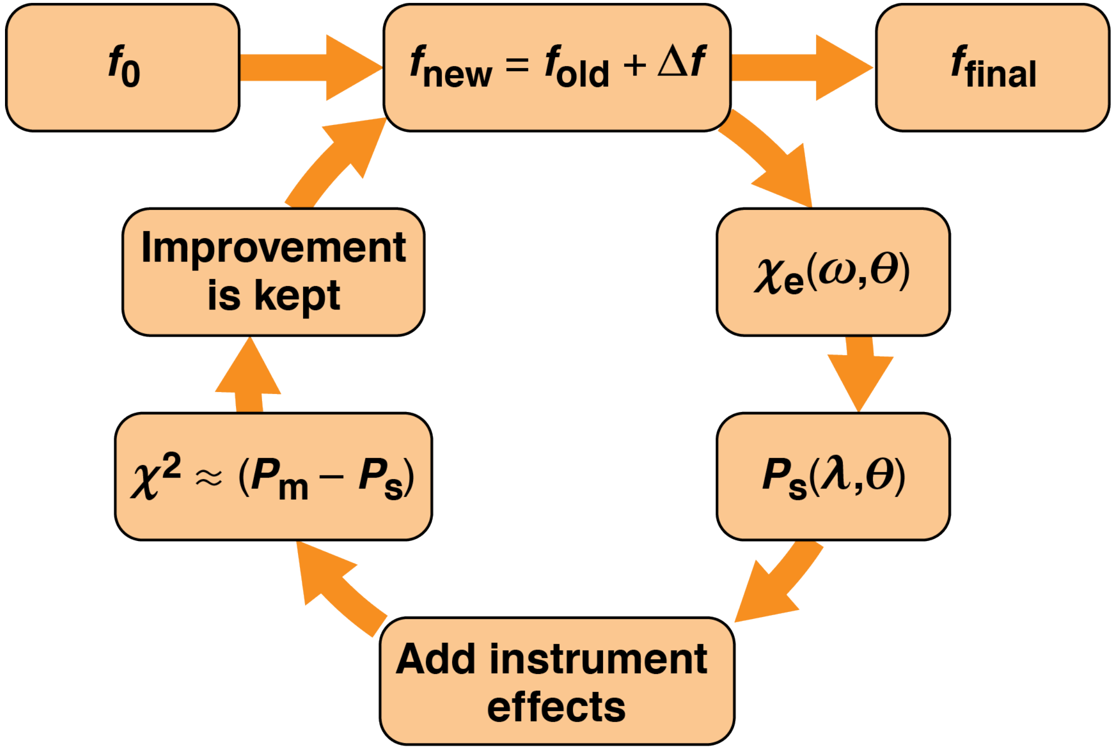
E29312

Distributions are extracted from the angularly resolved Thomson-scattering data using a forward-fitting algorithm

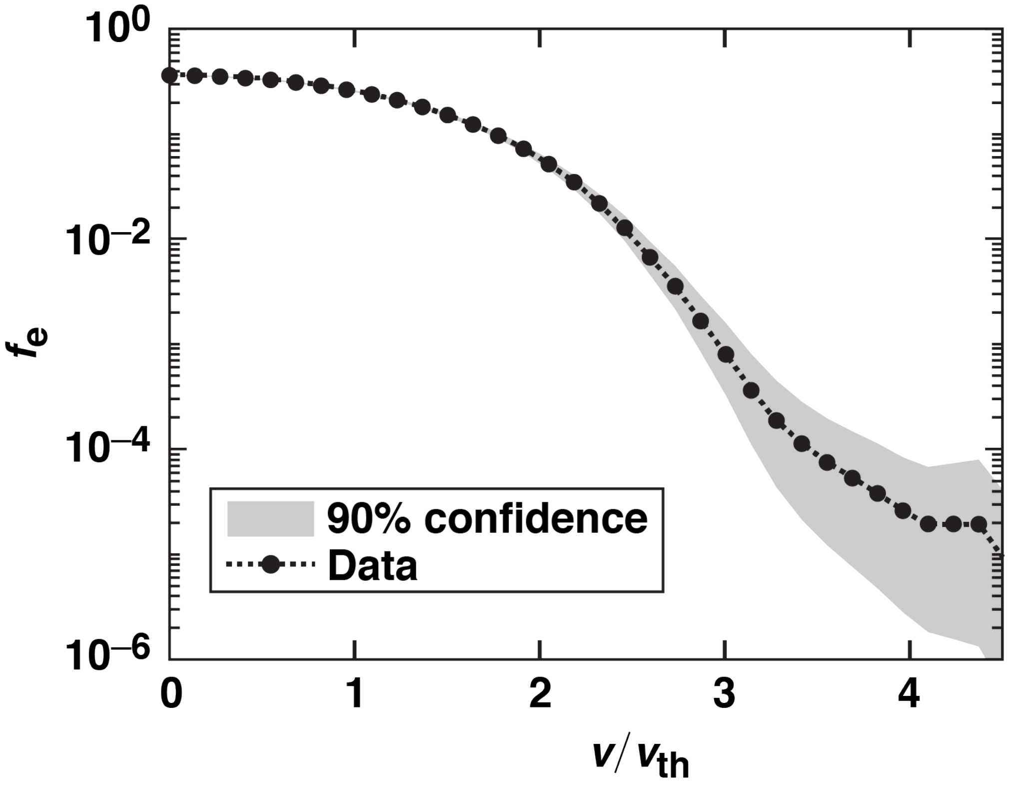


E29311

Distributions are extracted from the angularly resolved Thomson-scattering data using a forward-fitting algorithm

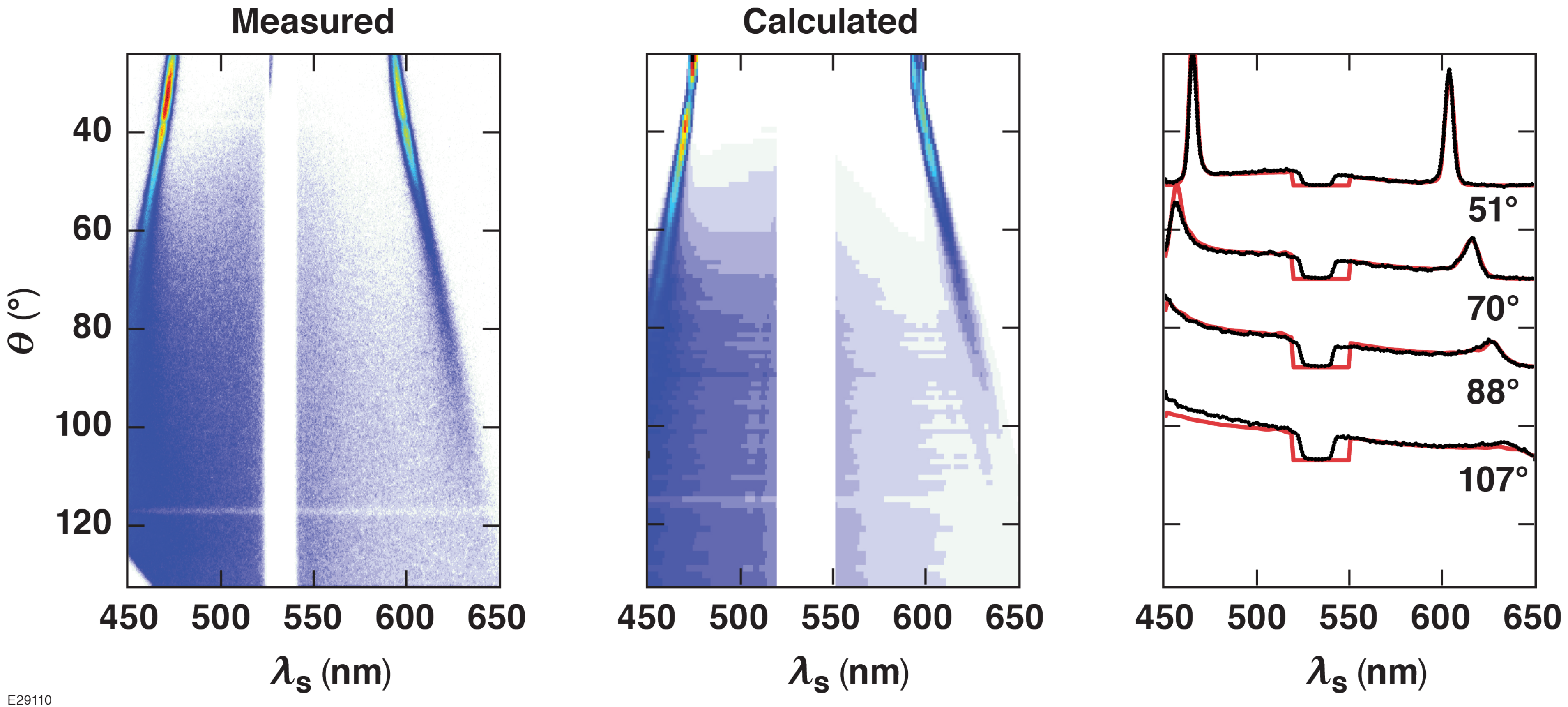


E29311



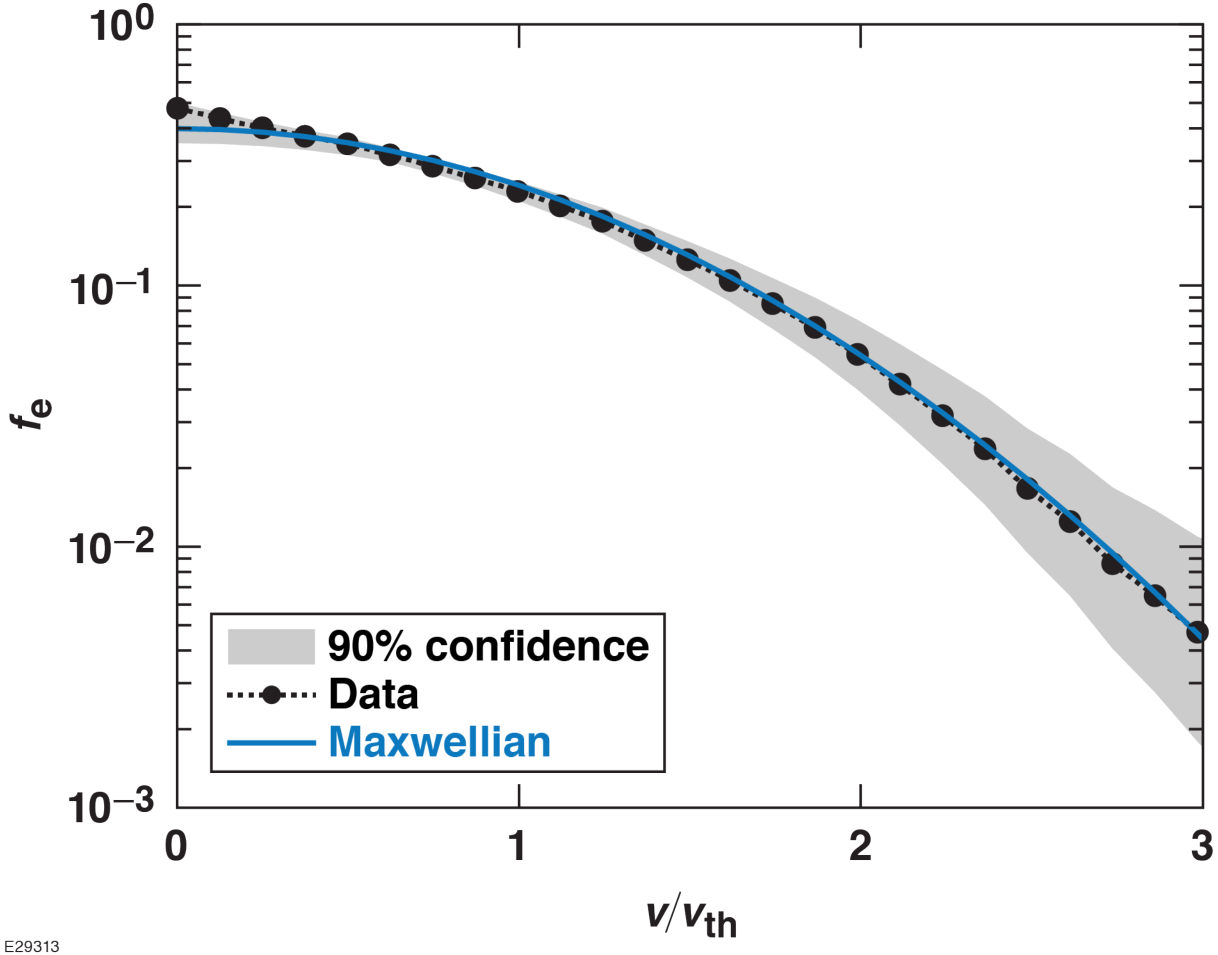
The result is an electron distribution that represents the data without specifying the relevant physics.

The measured electron distribution function reproduced the measured Thomson-scattering spectrum



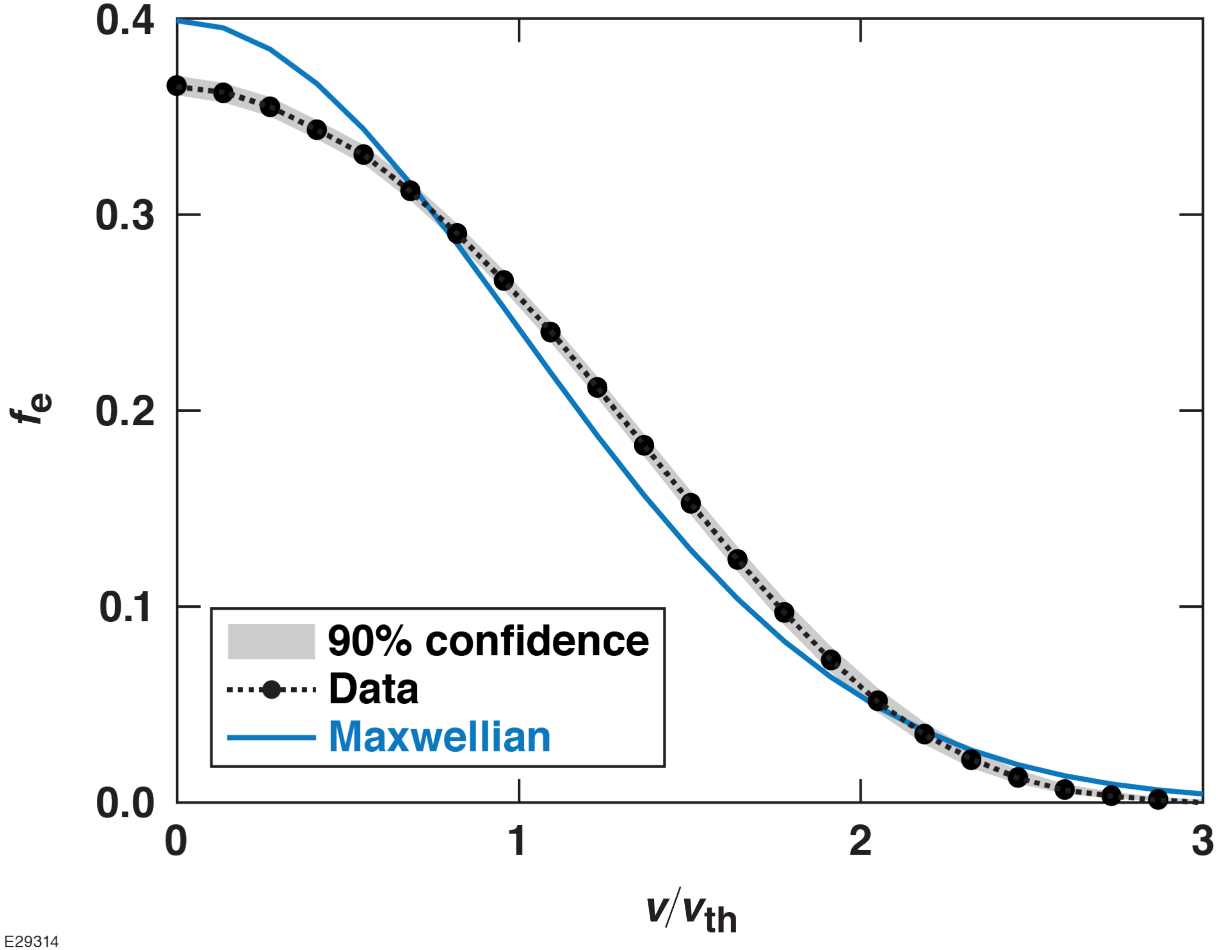
E29110

Angularly resolved Thomson-scattering measurements show Maxwellian distributions 200 ps after the heating lasers are turned off



E29313

During laser heating the distribution was measured to be non-Maxwellian



E29314

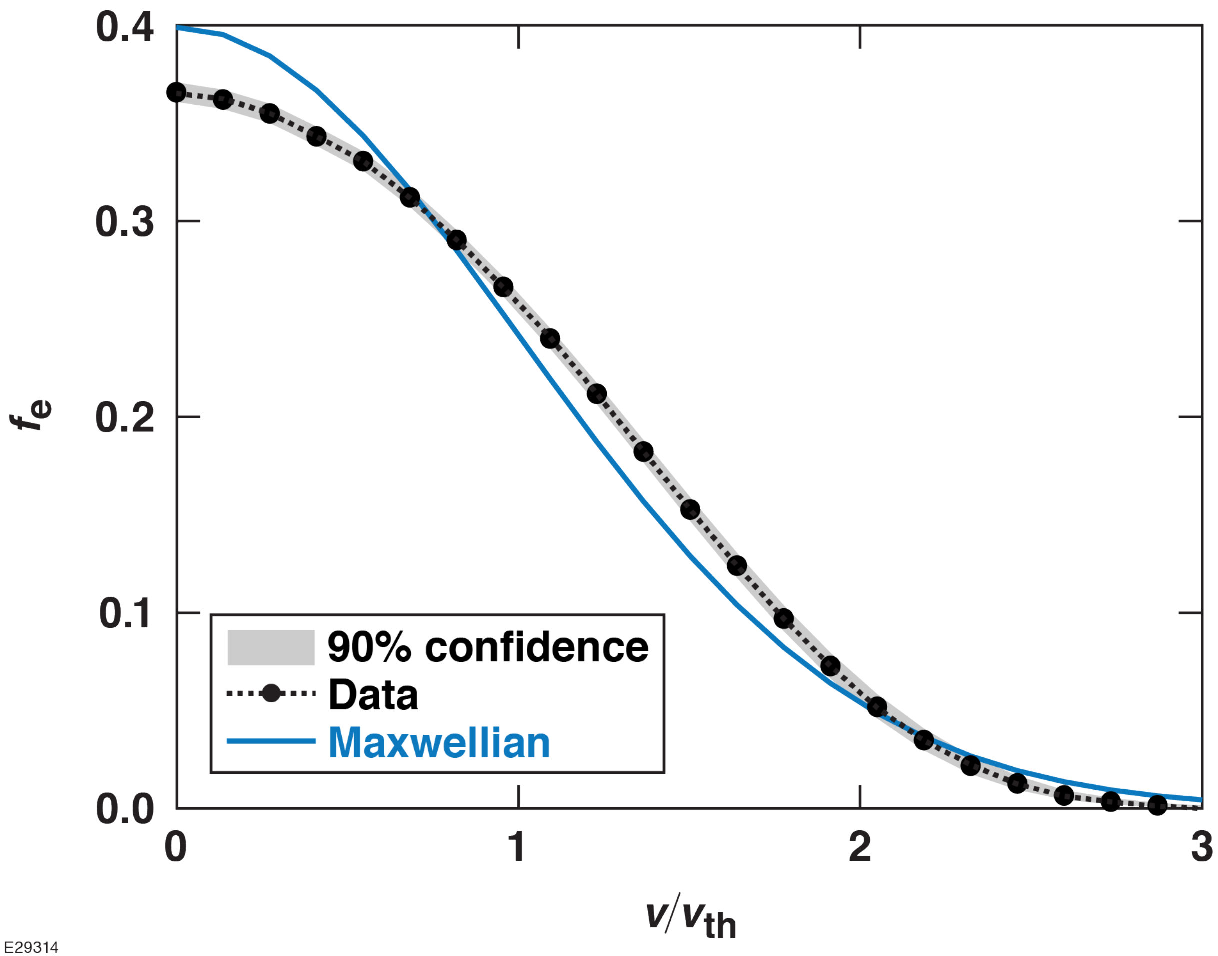
Non-Maxwellian distribution functions result from inverse bremsstrahlung heating

- **Langdon effect***

$$f_m(v) \propto \exp[-(v/v_m)^m]$$

- **Super-Gaussian order varies continuously with the ratio of inverse bremsstrahlung heating to electron–electron collision rate (Langdon parameter)****

$$\alpha = Z\left(\frac{v_{\mathrm{osc}}}{v_{\mathrm{th}}}\right)^2 \qquad m = 2 + \frac{3}{1 + 1.66/\alpha^{0.724}}$$



E29314

* A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).
** J. P. Matte *et al.*, Plasma Phys. Control. Fusion 30, 1665 (1988).

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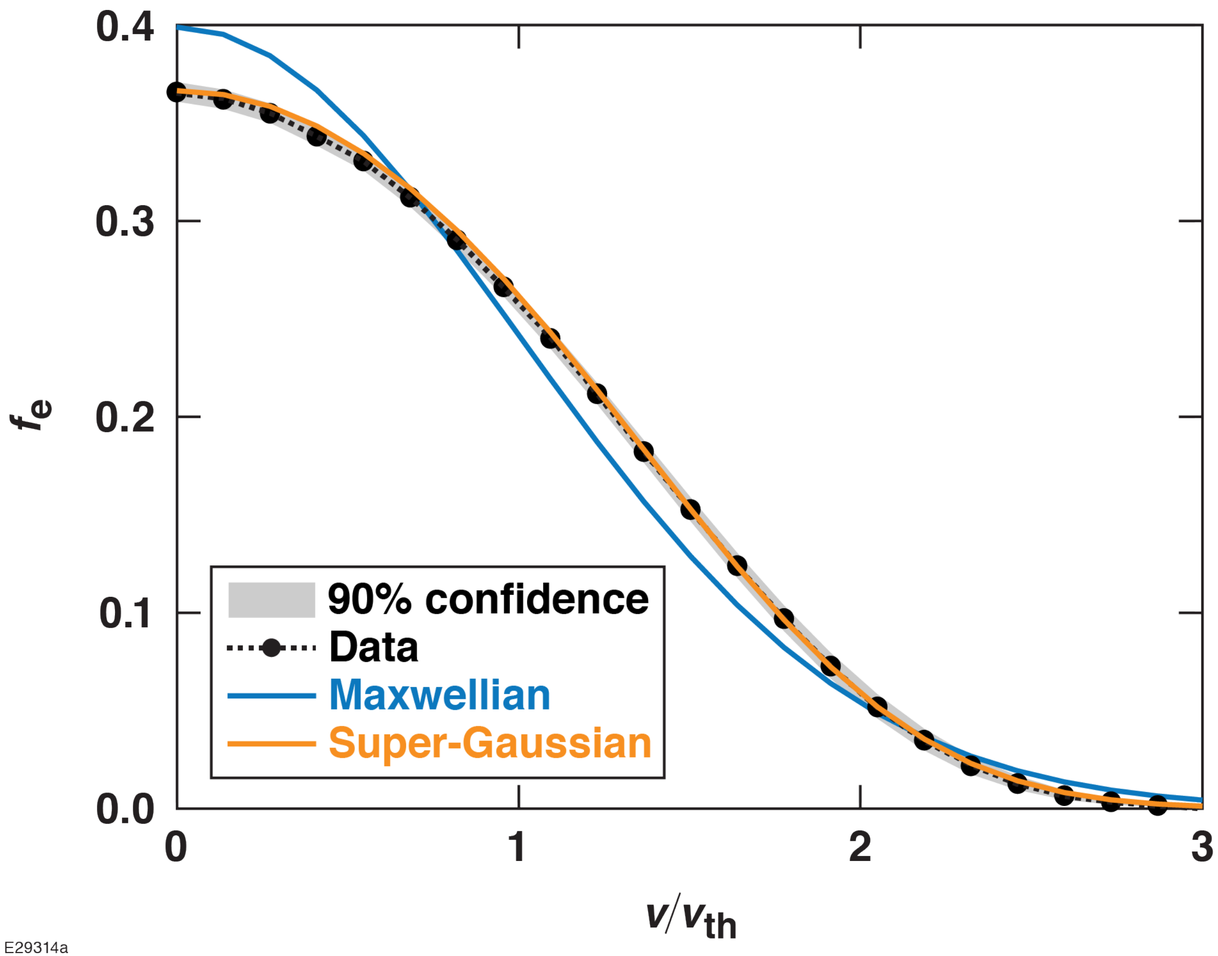
Super-Gaussian functions are in excellent agreement with the measured distribution function.



E29314a

* A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).
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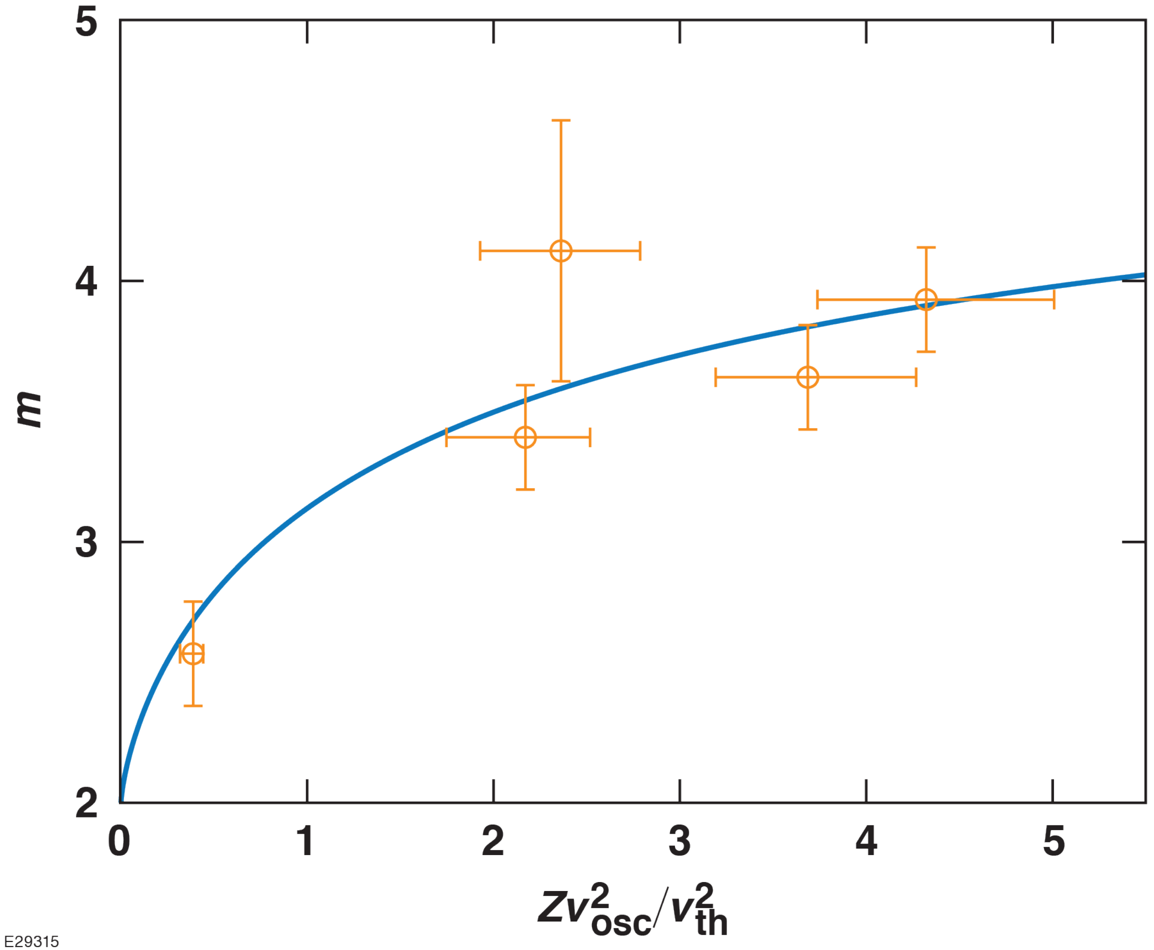
Agreement of the scaling law with measurements provides confidence in its use for predictive modeling .



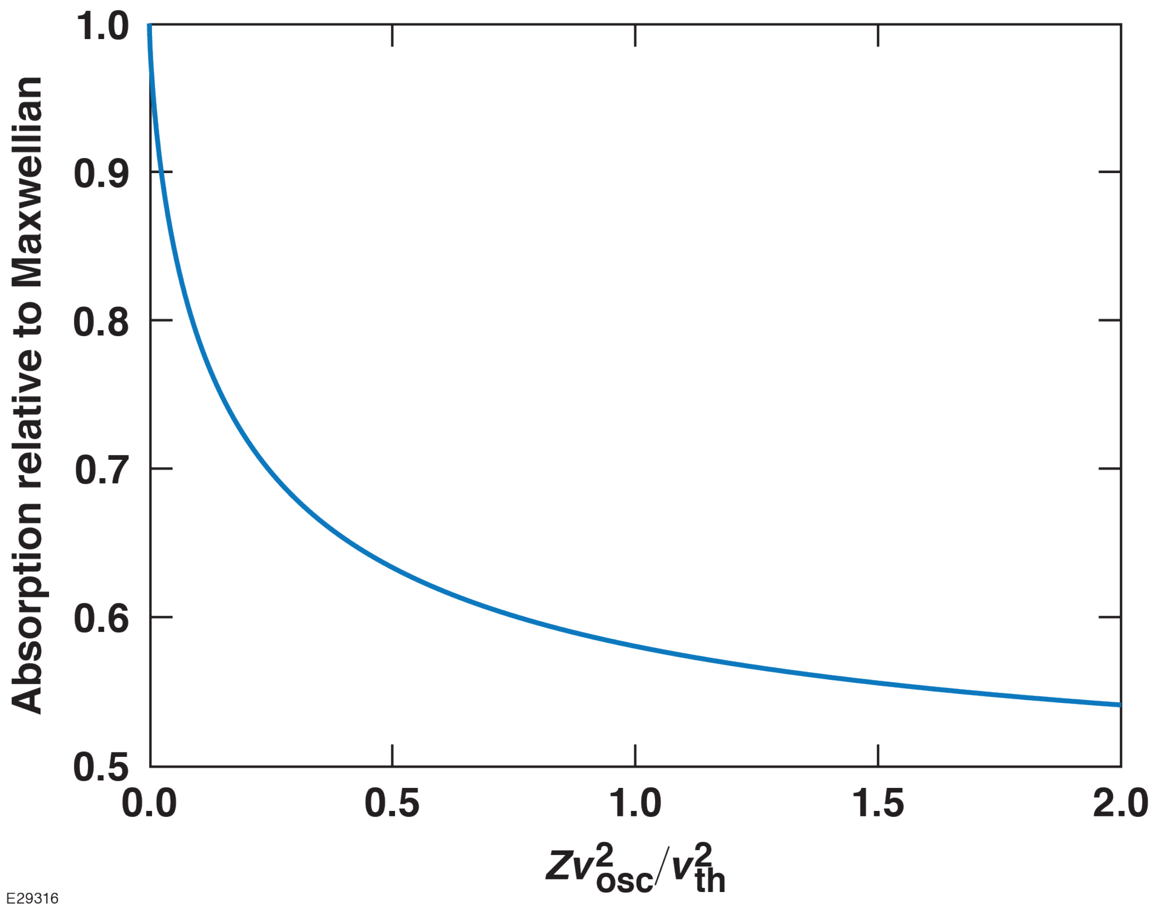
E29315

* A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).
** J. P. Matte *et al.*, Plasma Phys. Control. Fusion 30, 1665 (1988).

Outline

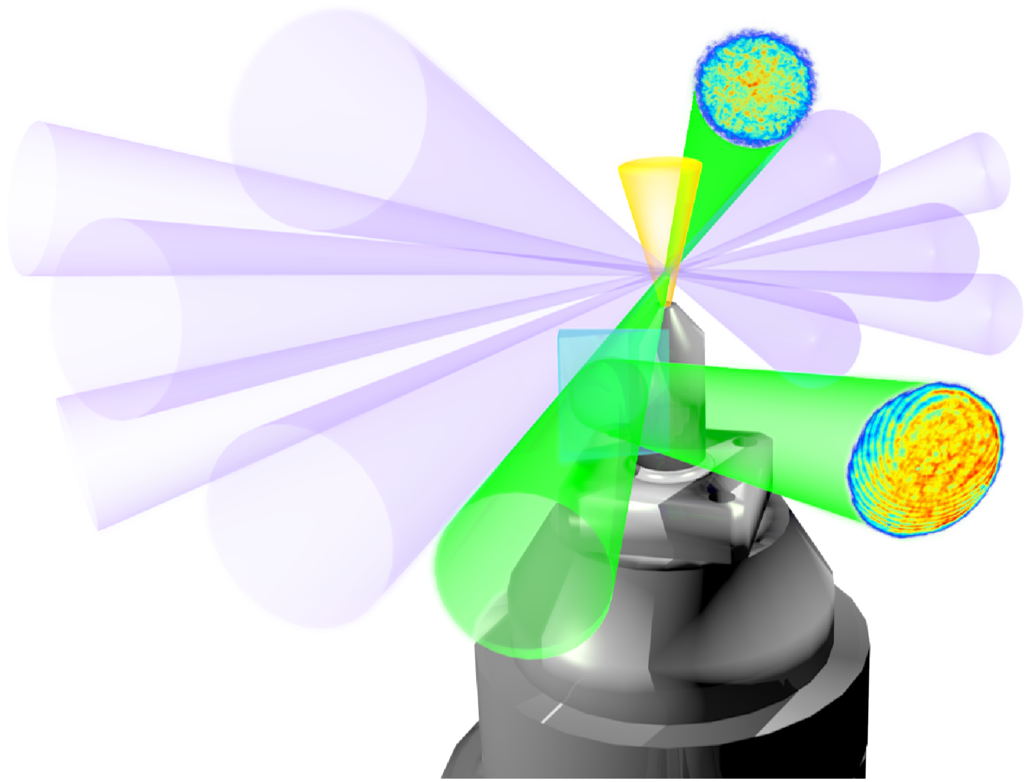
- Electron distribution functions impact ICF through LPI
- Measurements of electron distribution functions with angularly resolved Thomson scattering
- **Measured distributions (bulk) and the impact on**
  - **absorption**
  - **CBET**
- Measured distributions (tail)

The reduced number of slow electrons in a super-Gaussian distribution was predicted to reduce the absorption rate

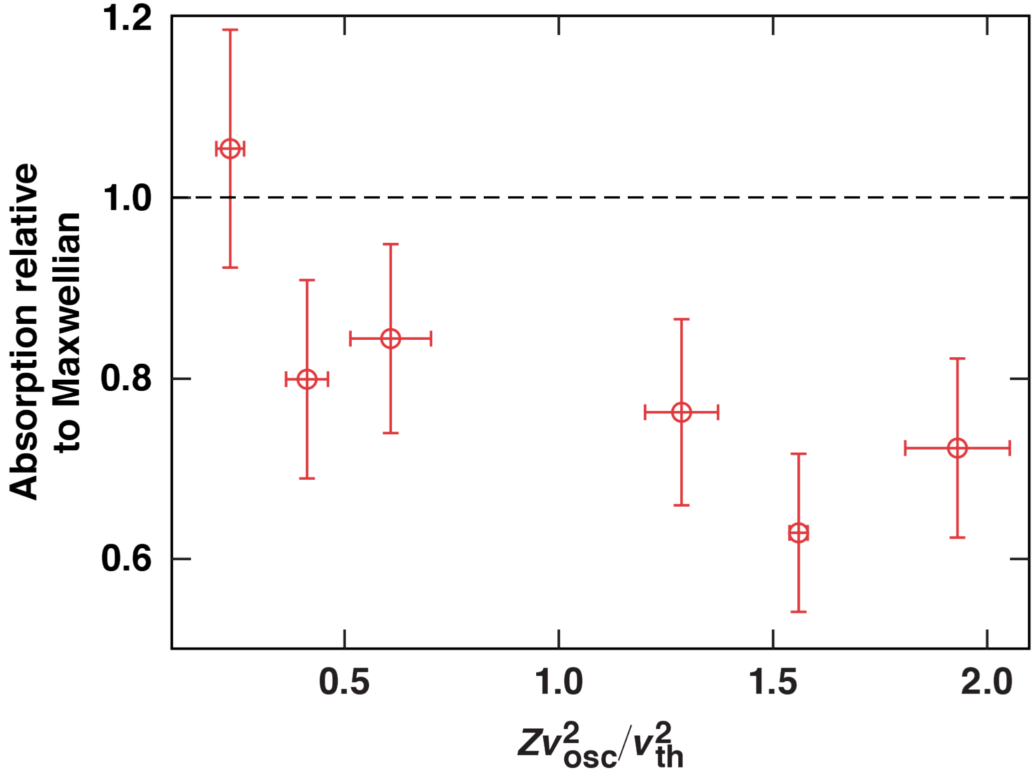


A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).

The absorption was quantified by the measuring the energy of the green beam before and after interacting with the plasma



E29308d



The measurements show reduced absorption relative to a Maxwellian plasma.

A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).

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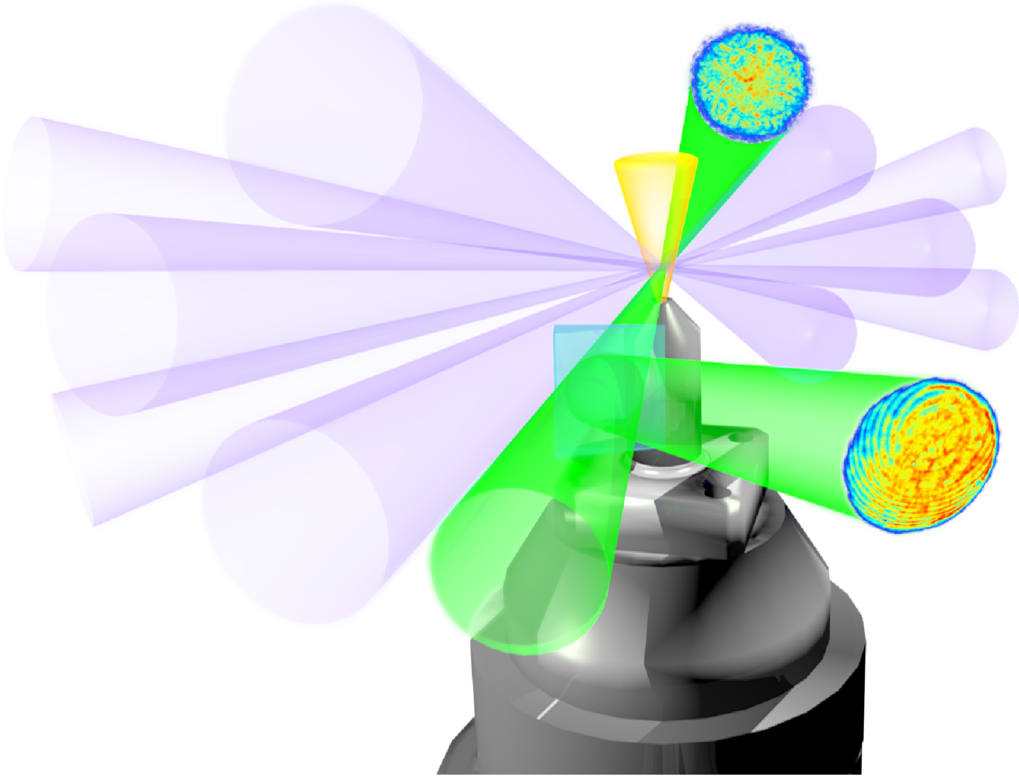
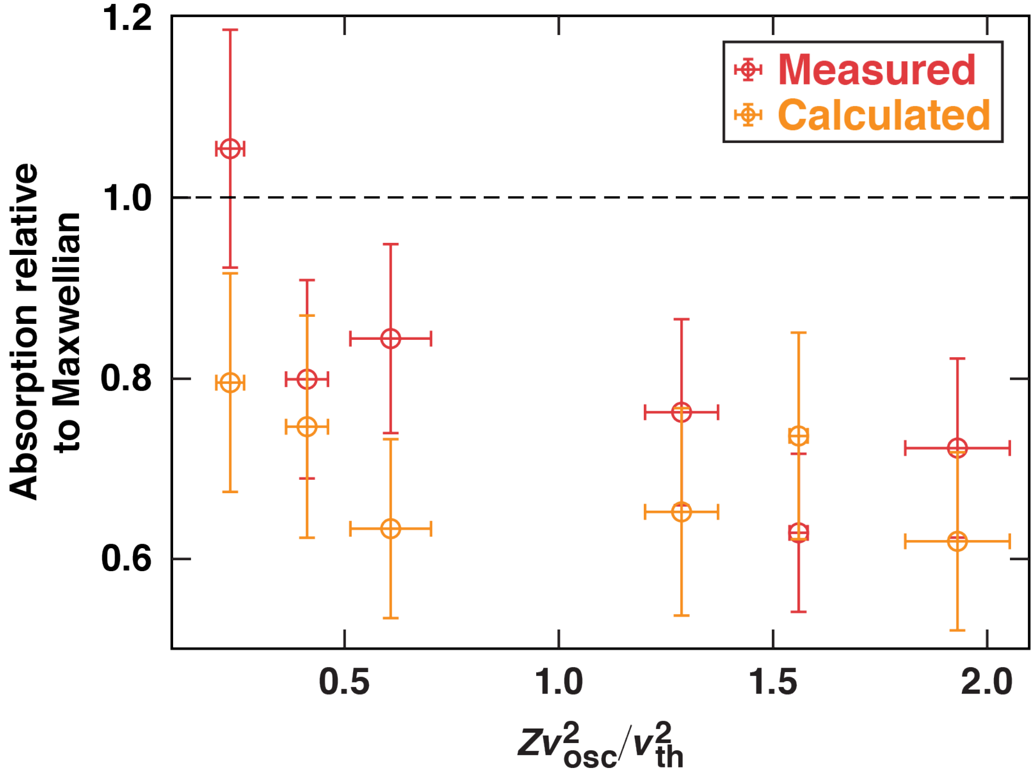


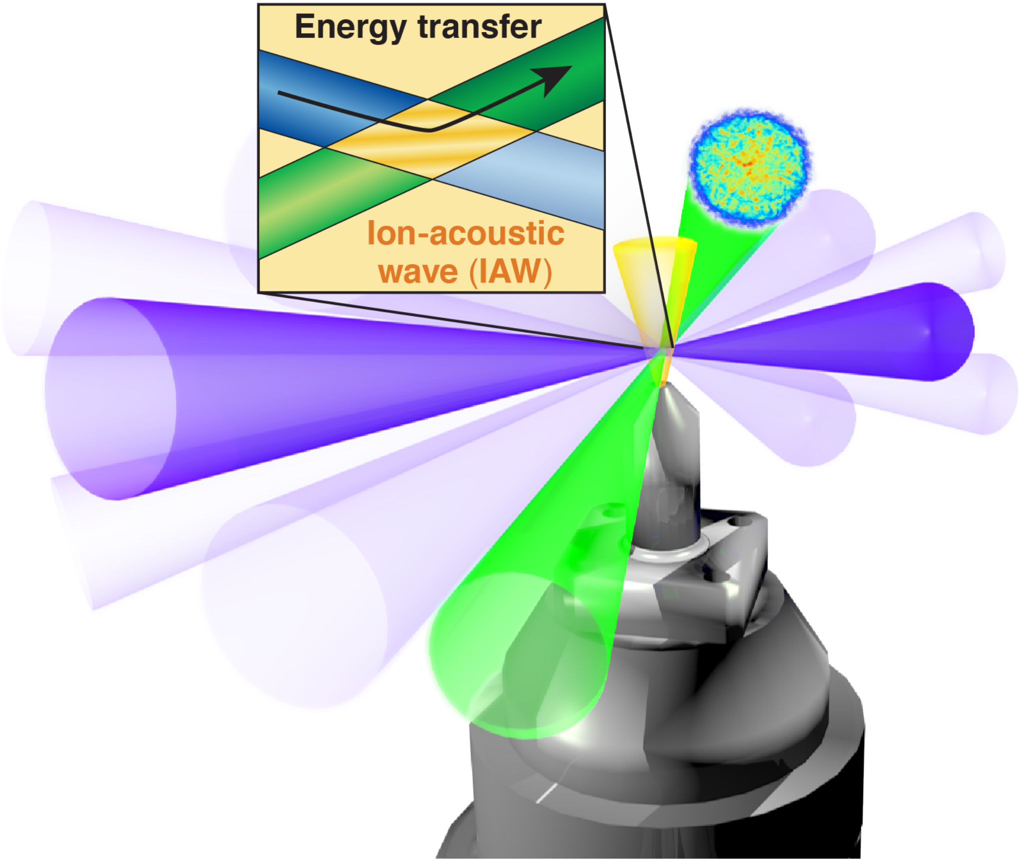
E29308e

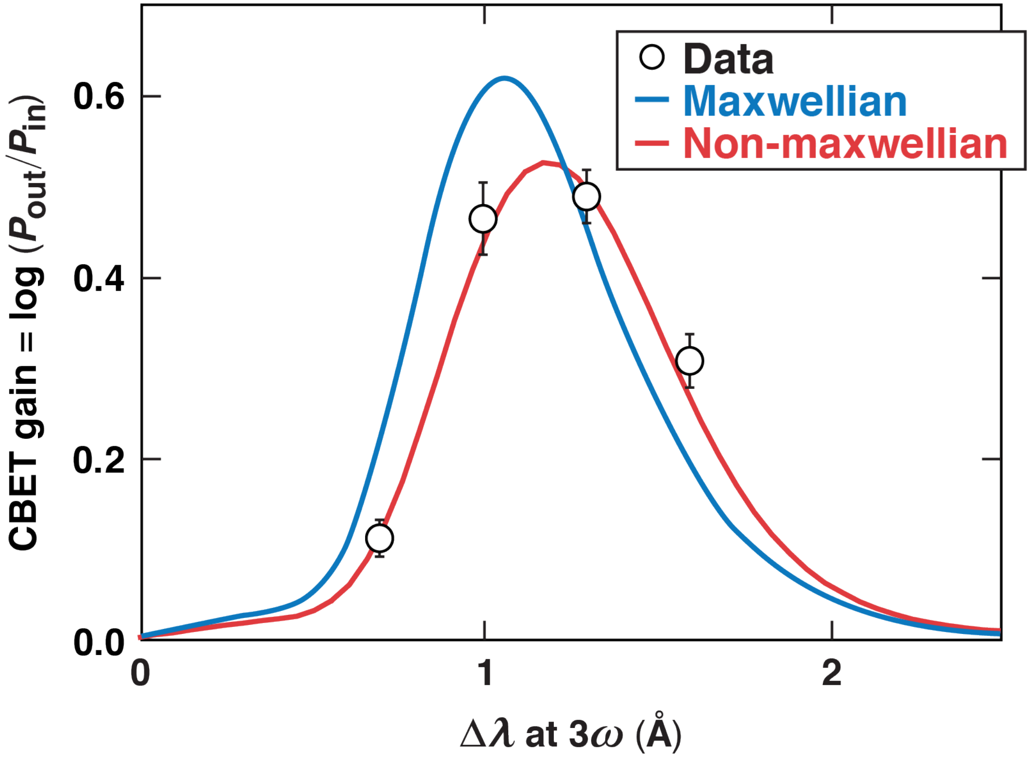


Langdon's theory provides good agreement with the measured absorptions.

A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).

To measure the effects of non-Maxwellian electron distribution functions on ion-acoustic waves, CBET experiments were performed





E29308f

Including the electron distribution function in calculations reproduces the measurement; this can be used to improve ICF modeling.

D. Turnbull *et al.*, Nat. Phys. 16, 181 (2020).

Outline

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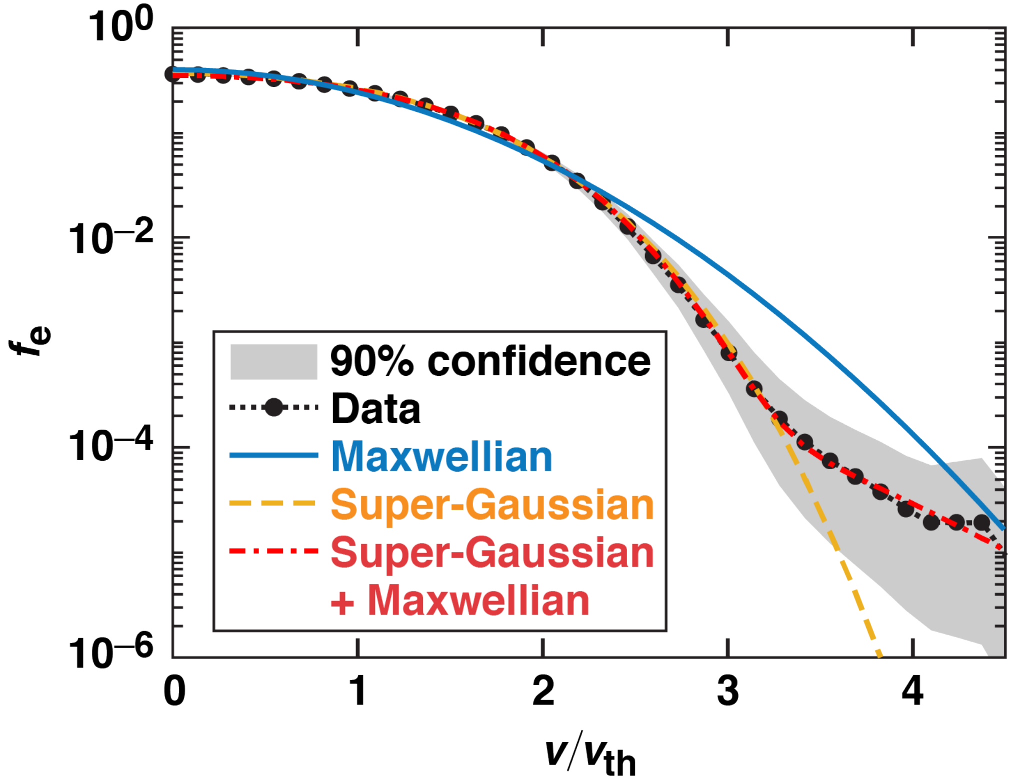
- Measured distributions (bulk) and the impact on
  - absorption
  - CBET
- **Measured distributions (tail)**

Measured electron distribution functions are super-Gaussian in the bulk and Maxwellian in the tail ($v/v_{th} > 3$)

- **A simplified super-Gaussian + Gaussian model was used determine the shape of the tail**

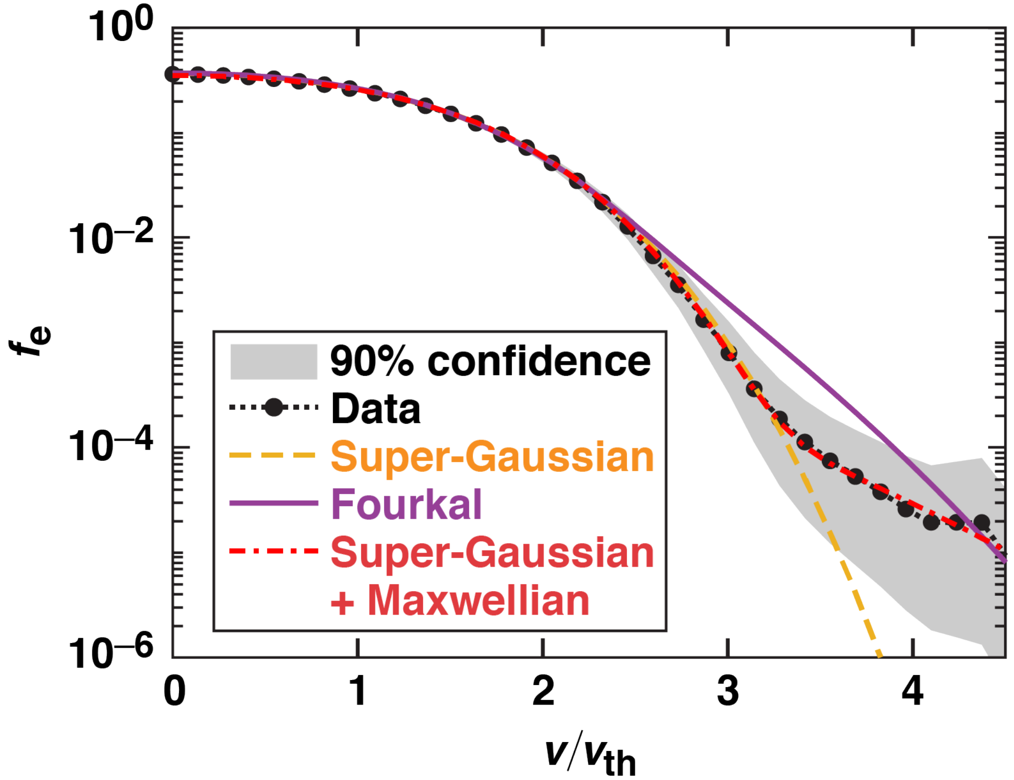
$$f_e(x) = a_1 \exp\left[-\left(\frac{x}{x0_1}\right)^m\right] + a_2 \exp\left[-\left(\frac{x}{x0_2}\right)^2\right]$$



E29311b

Electron–electron collisions involving electrons oscillating in the laser field lead to a Maxwellian tail

- Fourkal's calculations considered the anisotropy from polarization
- Electrons oscillated in the field of a single laser, modifying the electron–electron collisions
- The modified collisions lead to a modified tail in the cycleaveraged isotropic distribution function
- This model deviates from the data around 2.5 v_{th}

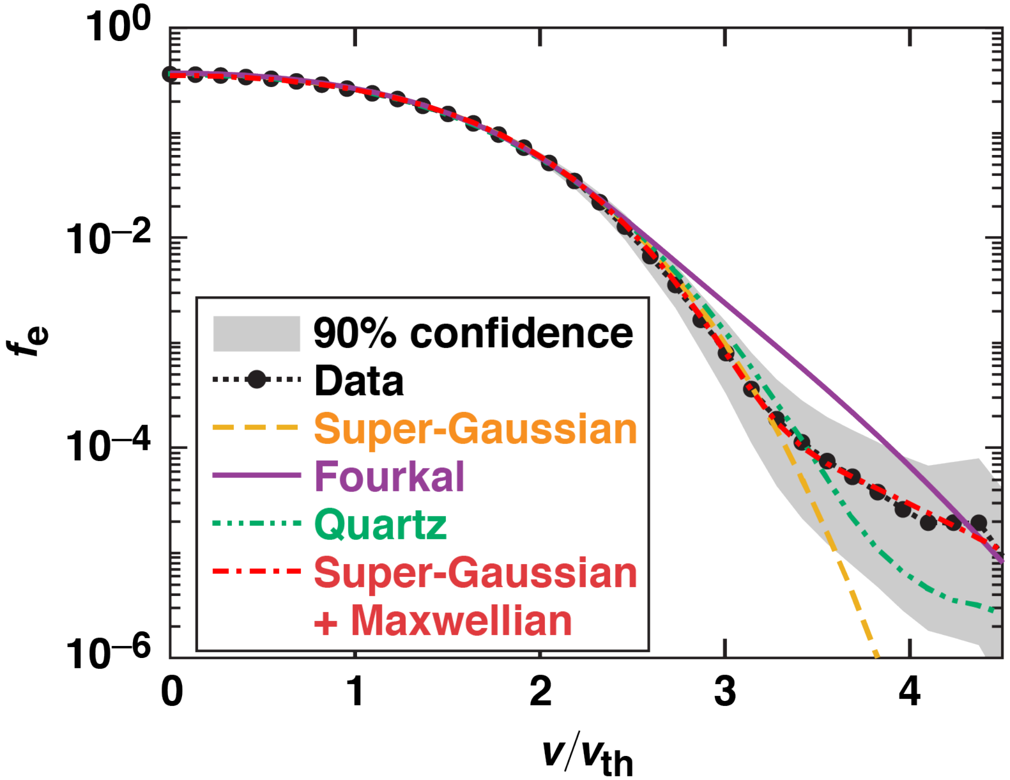


E29311a

While this model, considering a single plane wave, results in a Maxwellian tail, it is not consistent with the measured shape.

E. Fourkal *et al.*, Phys. Plasmas 8, 550 (2001).

These experiments were simulated with the particle code *Quartz* to investigate the effects of multiple beams on the distribution function



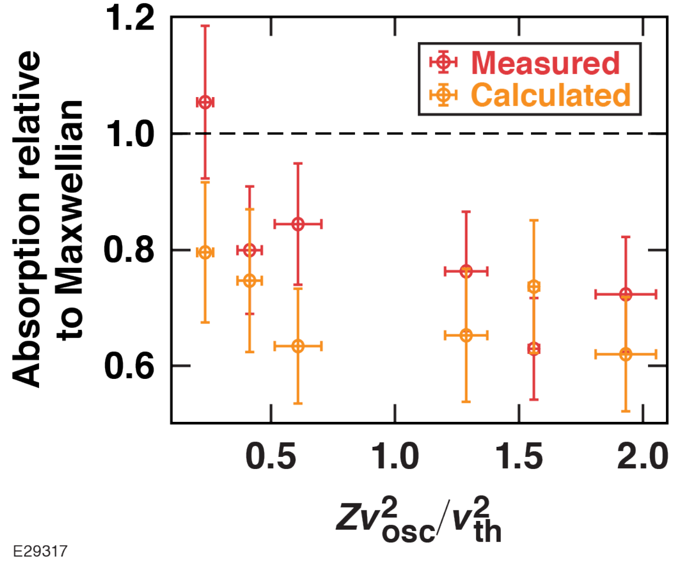
E29311c

Results suggest that uniformity introduced by multiple overlapped beams can dictate the energy transfer to the high-velocity electrons.

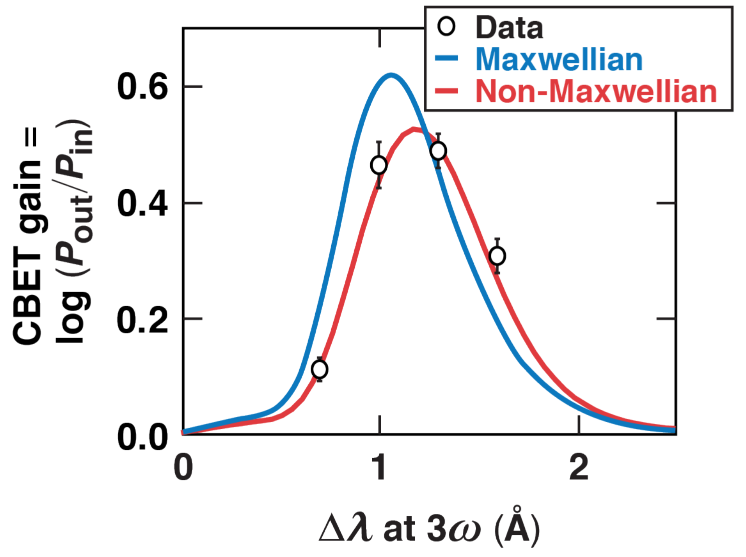
The measured distribution functions show some of the ways the electron distribution function can affect inertial confinement fusion

UR LLE

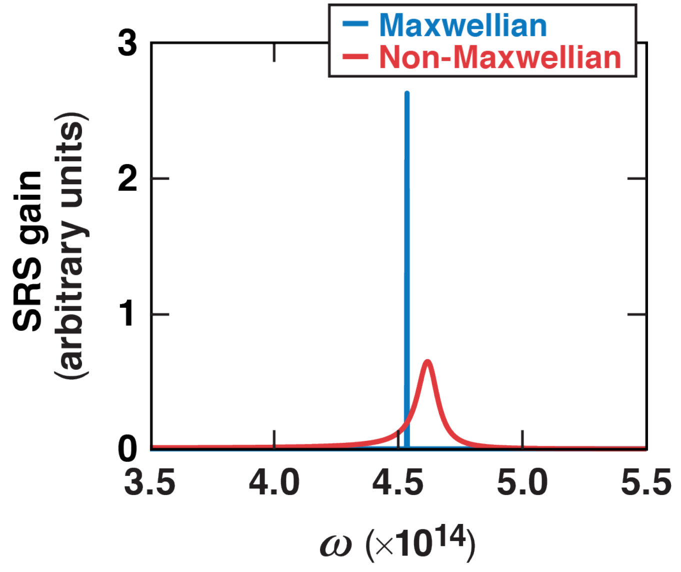
Reduced absorption



Altered CBET transfer and location



Increased SRS gain



Measuring distribution functions can improve predictive capability and open the ICF design space.

Angularly resolved Thomson scattering allows the first direct measurement of the electron velocity distribution over many orders of magnitude

- Electron velocity distribution function plays an important role in governing laser–plasma interactions and setting the conditions in inertial confinement fusion
- Measured distributions are super-Gaussian in the bulk due to inverse bremsstrahlung heating and Maxwellian in the tail
- Reduction in laser absorption and shift in ion-acoustic resonance due to super-Gaussian distributions were measured

Measurements of electron distribution functions can improve agreement between modeling and experiment.