Measuring Non-Maxwellian Distribution Functions Using Expanded Thomson Scattering

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Abstract

A.B. Langdon[1] proposed that stable non-Maxwellian distribution functions are realized in coronal inertial confinement fusion (ICF) plasmas via inverse bremsstrahlung heating. For $Z\,v_{\mathrm{osc}}^2/v_{\mathrm{th}}^2 > 1$ the inverse bremsstrahlung heating rate is sufficiently fast to compete with electron–electron collisions. This process preferentially heats the subthermal electrons leading to super-Gaussian distribution functions.

A method to identify the super-Gaussian order of the distribution functions in these plasmas using collective Thomson scattering will be proposed. By measuring the collective Thomson spectra over a range of angles the density, temperature and super-Gaussian order can be determined. This is accomplished by fitting non-Maxwellian distribution data with a super-Gaussian model; in order to match the density and electron temperature to within 10%, the super-Gaussian order must be varied.

Background

- The study of plasma is based around the distribution function
- Maxwellian distribution is used because of the ease of use and physical significance, but it does not capture physics such as heat transport
- Super-Gaussian distribution functions are physically realized through inverse bremsstrahlung heating[2]

$$f_m(x,v,t) = C_m \exp\left[-(v/v_m)^m\right]$$

$$v_m^2 = \frac{3k_B T_e}{M_e}\frac{\Gamma(3/m)}{\Gamma(5/m)} \text{ and } C_m = \frac{n_e}{4\pi}\frac{m}{\Gamma(3/m)v_m^3}$$

Thomson Scattering

- A laser is scattered by a plasma wave yielding a spectrum containing information about the density and temperature of the plasma
- The scattered spectrum is given by

$$S(\vec{k},\omega) = \frac{2\pi}{k}\left|1-\frac{\chi_e}{\epsilon}\right|^2 f_{e0}\left(\frac{\omega}{k}\right) + \frac{2\pi Z}{k}\left|\frac{\chi_e}{\epsilon}\right|^2 f_{i0}\left(\frac{\omega}{k}\right)$$

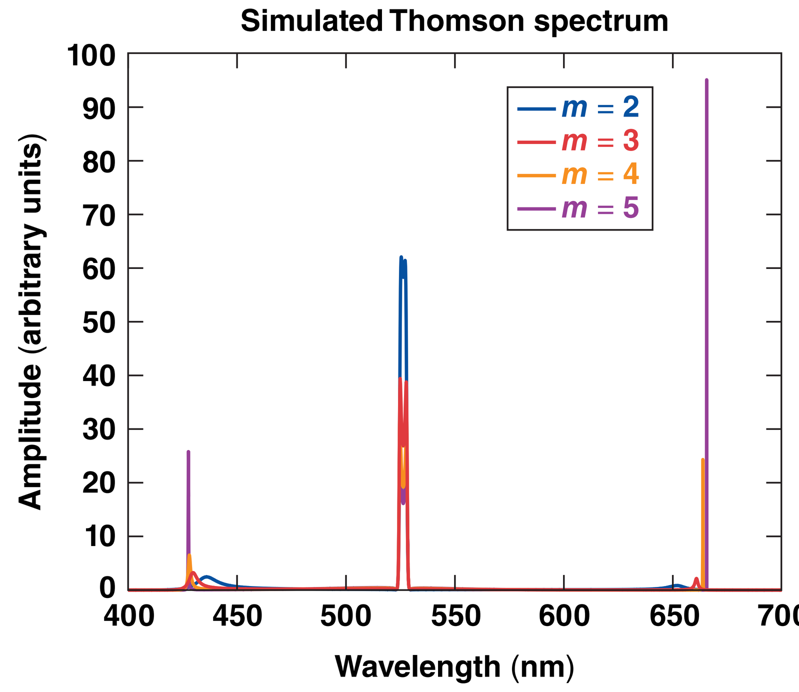
$$\chi_{e,i}(\vec{k},\omega) = \int_{-\infty}^{\infty} d\vec{v}\,\frac{4\pi e_{e,i}^2 n_{e,i}}{m_{e,i}k^2}\,\frac{\vec{k}\cdot\partial f_{e,i}/\partial\vec{v}}{\omega-\vec{k}\cdot\vec{v}-i\gamma}$$

$$\epsilon(\vec{k},\omega) = 1+\chi_e(\vec{k},\omega)+\chi_i(\vec{k},\omega)$$

- Where $\vec{k}$ and ω are determined by the matching conditions

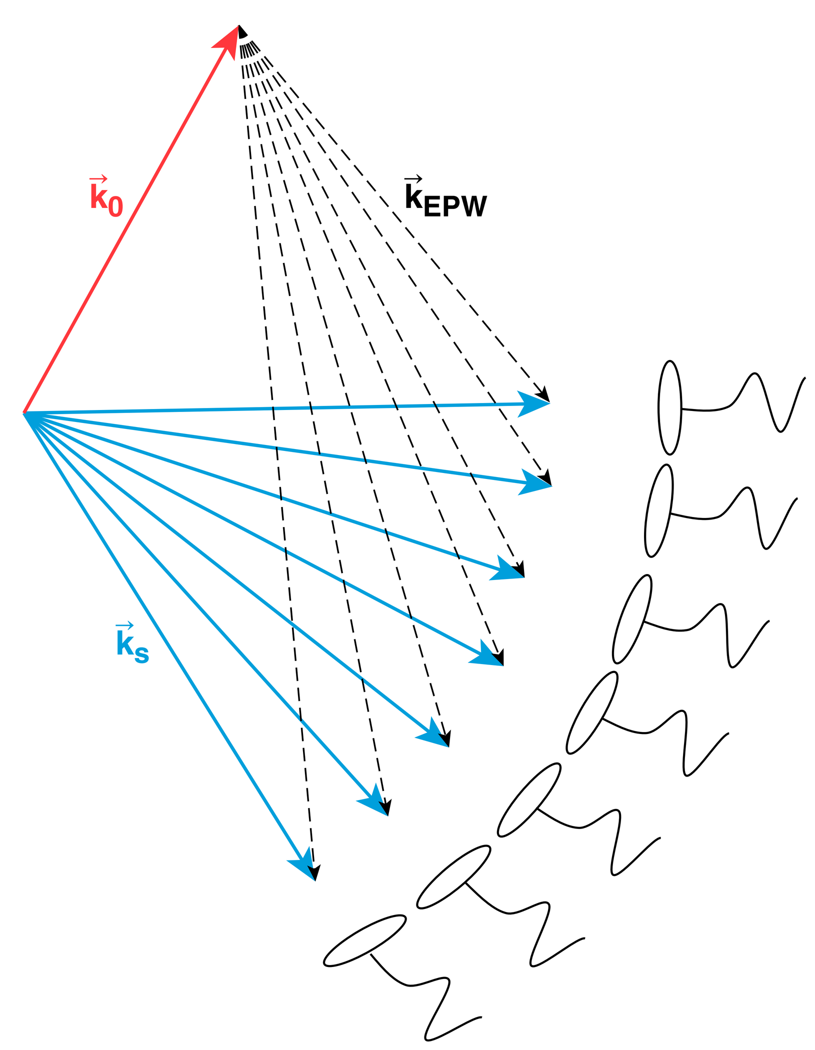
$$\vec{k} = \vec{k}_s - \vec{k}_0 \qquad \omega = \omega_s - \omega_0$$

- Therefore, the spectrum is a function of temperature, density and super-Gaussian order
- The effect of order can be seen by comparing spectra from $m = 2$ (Maxwellian) and $m = 5$

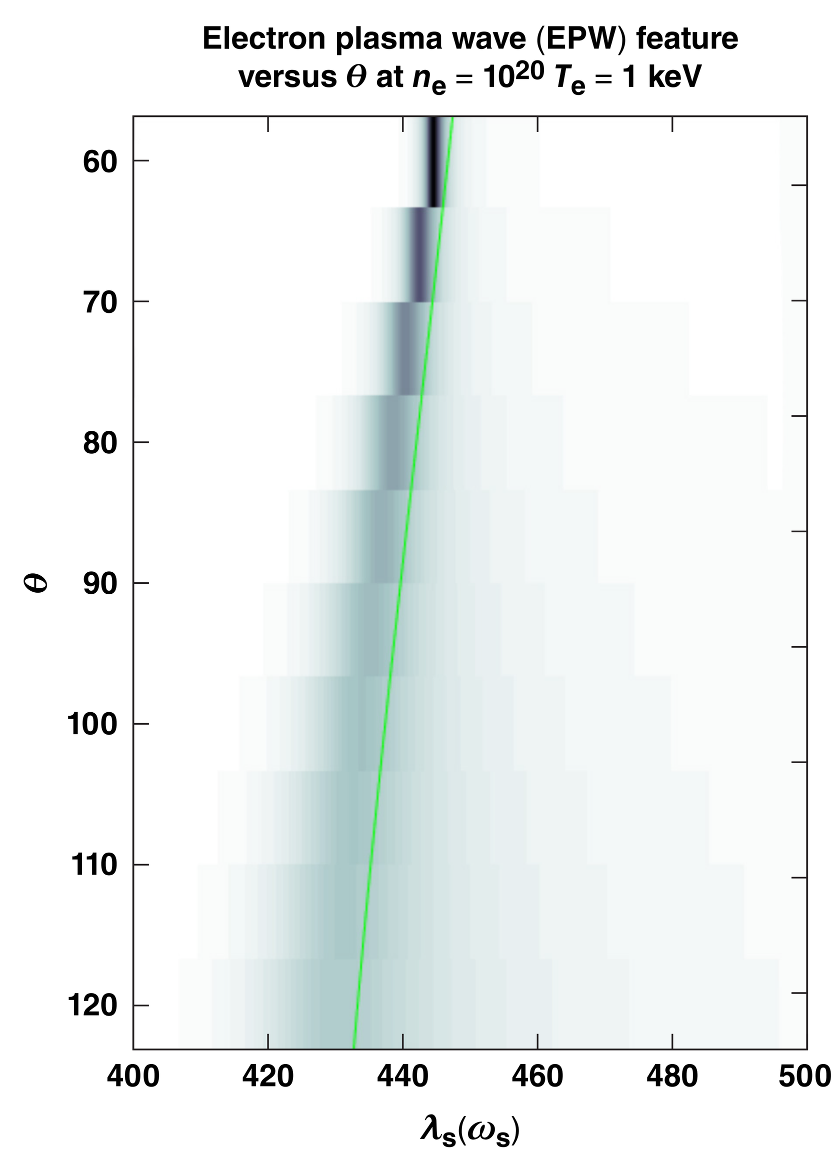


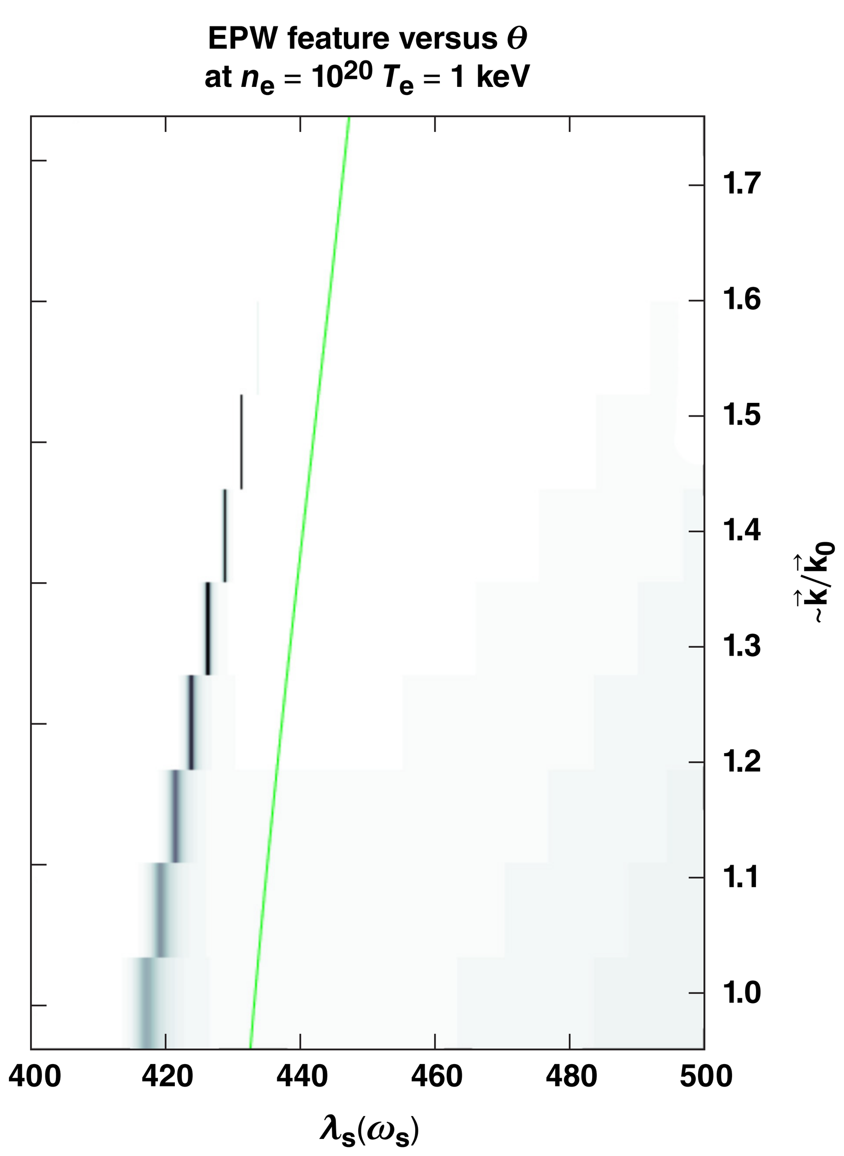
Expanded Thomson Scattering

- While the discrepancy shown above is large it is greatly reduced through order, noise, and additional physics
- More information can be gained through measuring multiple $\vec{k}$ vectors



- Here it is easiest to compare with the Bohm–Gross dispersion relation



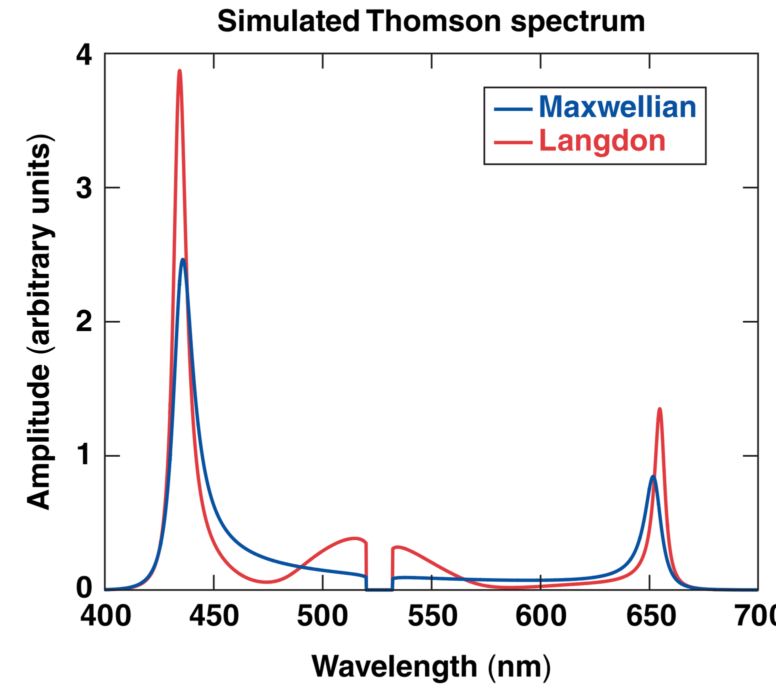


Langdon Effect and Gaussian Tails

- A. B. Langdon[1] found that inverse bremsstrahlung heating leads to a fifth-order super-Gaussian distribution
- He identifies this effect with the competition between heating and electron–electron collisions

$$\alpha = \frac{\tau_{ee}}{\tau_{IB}} = \frac{Zv_{osc}^2}{v_{th}^2}$$

- Further work by E. Fourkal *et al.*[3] shows the distribution function is only modified for low-energy electrons leading to Gaussian tails
- This results in less discrepancy between the spectra for different orders



Conclusions and Future Work

- Non-Maxwellian distribution functions allow for additional physics, which is important to many areas of plasma physics
- Collective Thomson scattering is sensitive to distribution function
- Expanded Thomson scattering can be used to determine the distribution and map dispersion relations
- The next steps are to examine the sensitivity of the spectrum with respect to order and determine constraints for measurements

References

[1] A. B. Langdon, Phys. Rev. Lett. 44, 575 (1980).
[2] J. P. Matte *et al.*, Plasma Phys. Control. Fusion 30, 1665 (1988).
[3] E. Fourkal *et al.*, Phys. Plasmas 8, 550 (2001).

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