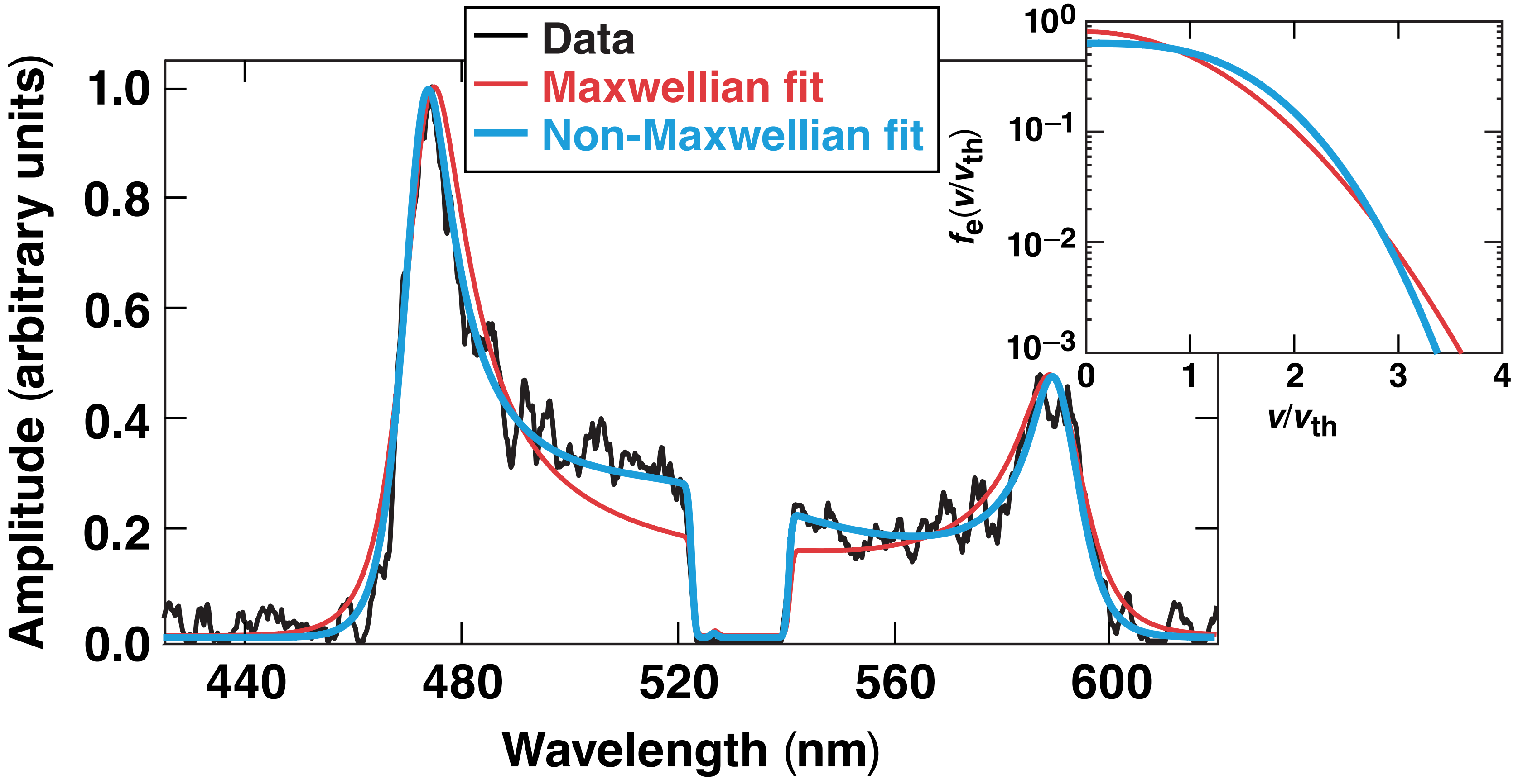
Measurement of the Langdon Effect in Laser-Produced Plasma Using Collective Thomson Scattering



A. L. Milder
University of Rochester
Laboratory for Laser Energetics

60th Annual Meeting of the American Physical Society Division of Plasma Physics
Portland, OR
5–9 November 2018

Summary

Experiments show evidence of the Langdon effect in a laser-produced plasma using collective Thomson scattering

- Electron plasma wave Thomson-scattering spectra were used to measure non-Maxwellian distribution functions driven by the Langdon effect
- Analyzing non-Maxwellian data as Maxwellian leads to significant errors in the inferred parameters
- The experimentally measured Langdon parameter agrees with theoretical predictions

E28073

Collaborators

P. Franke, J. Katz, J. P. Palastro, S. T. Ivancic, J. L. Shaw, A. S. Davies, I. A. Begishev, R. H. Cuffney, M. Spilatro, and D. H. Froula

University of Rochester
Laboratory for Laser Energetics

Inverse-bremsstrahlung (IB) heating is predicted to generate non-Maxwellian electron distribution functions

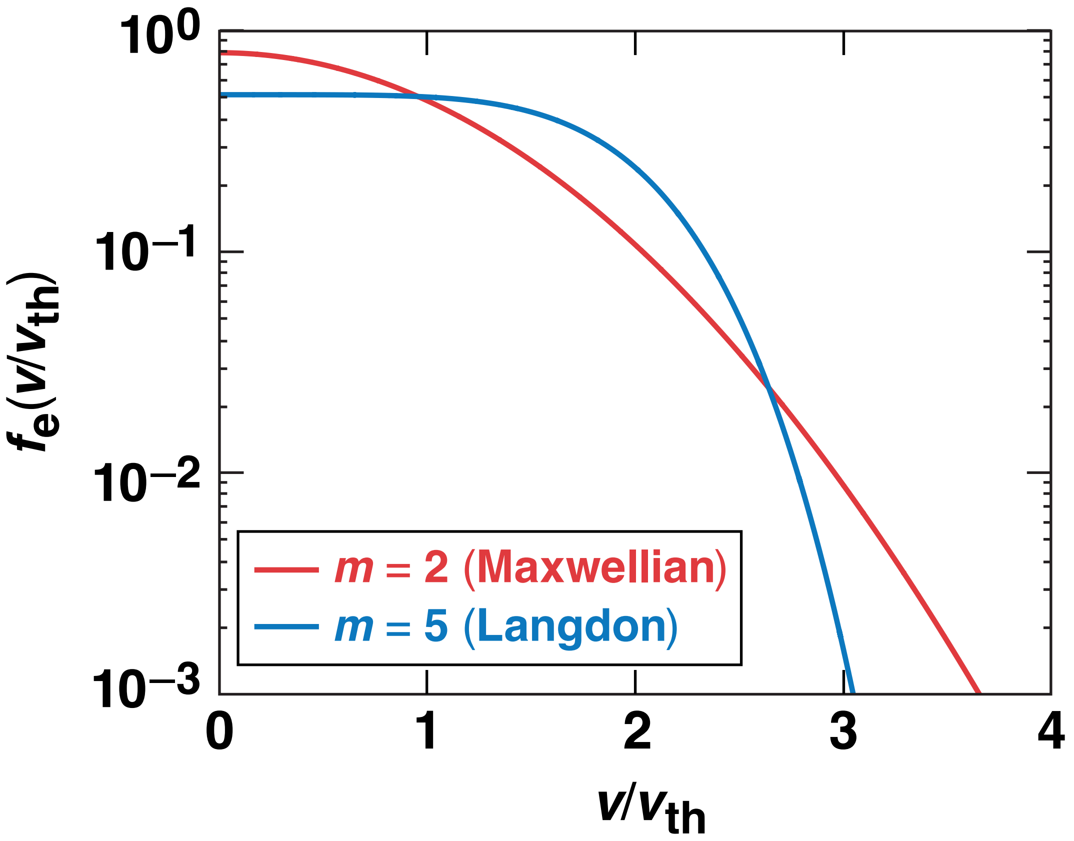
- IB heating causes the electron distribution function to go toward a fifth-order super-Gaussian* (Langdon Effect)

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

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

- Super-Gaussian order varies continuously with the Langdon parameter**

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



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

E28076

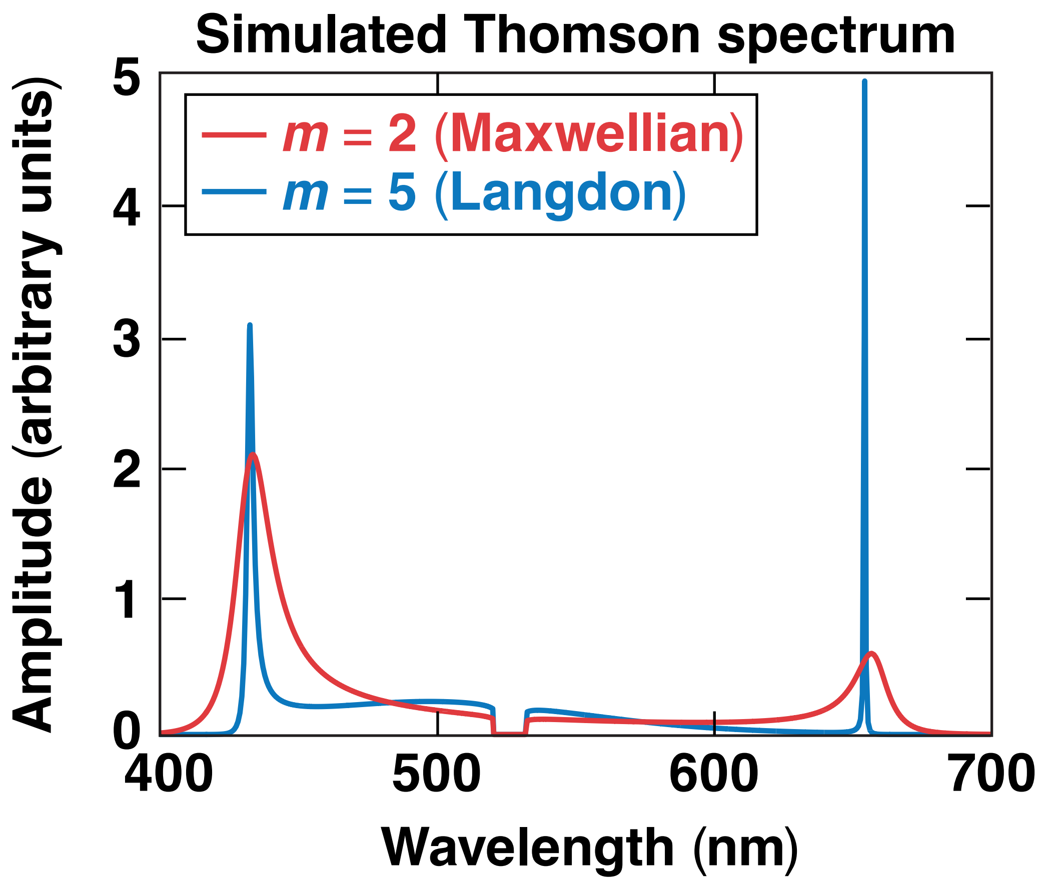
The Thomson-scattering spectrum can be used to determine a unique electron distribution function

- The spectral density function determines the shape of the scattered spectrum

$$S(\vec{k},\omega) \approx \frac{2\pi}{k} \frac{f_e(\omega/k)}{\left|1+\chi_e\right|^2}$$

$$\chi_e(\vec{k},\omega) = \int_{-\infty}^{\infty} d\vec{v} \, \frac{4\pi e^2 n_e}{m_e k^2} \frac{\vec{k} \cdot \partial f_e / \partial \vec{v}}{\omega - \vec{k} \cdot \vec{v} - i\gamma}$$

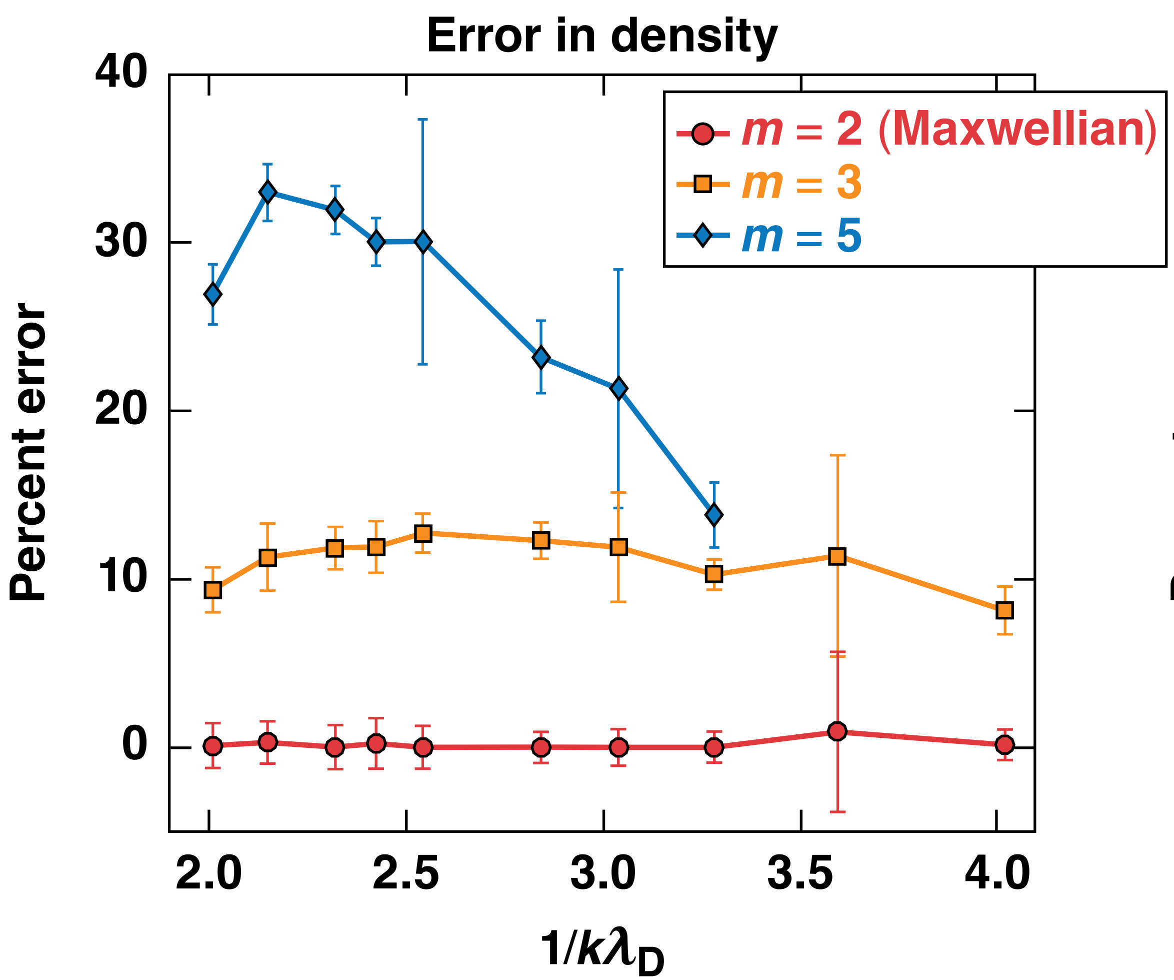
$$f_m(x, v, t) = C_m \exp\left[-(v/v_m)^m\right]$$

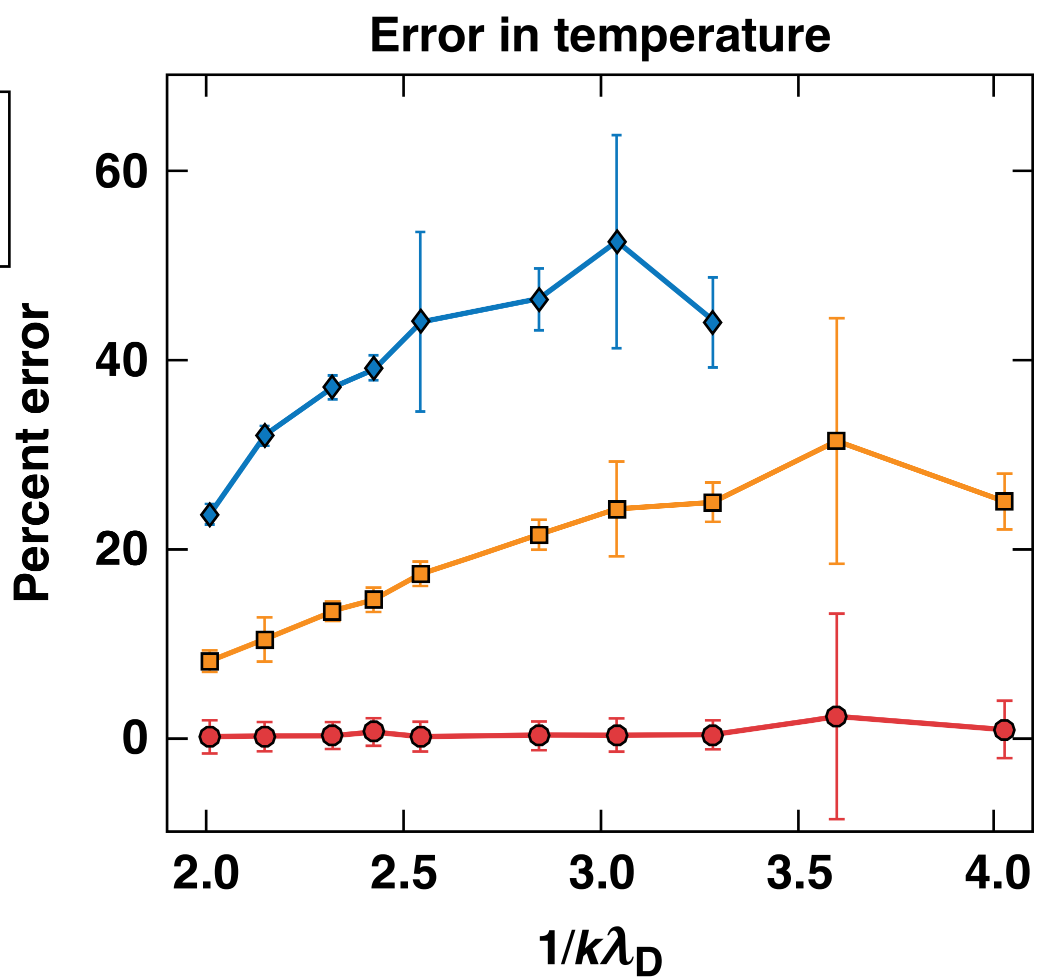


The Langdon effect has a large impact on the electron plasma wave spectrum.

E28077

Assuming a Maxwellian electron distribution function can result in large errors in the inferred electron temperature and density

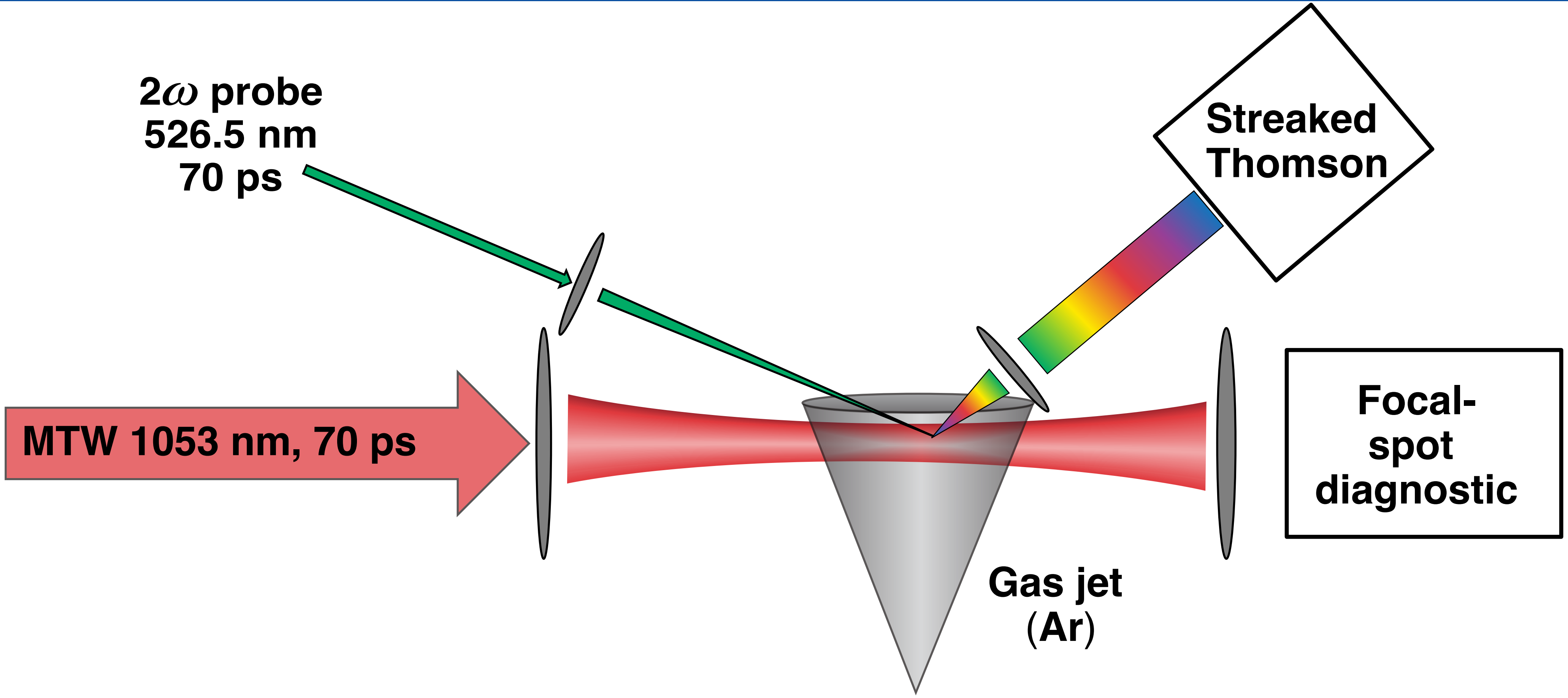




Including the super-Gaussian order in the fit recovers accurate measurements of the plasma conditions.

E28078

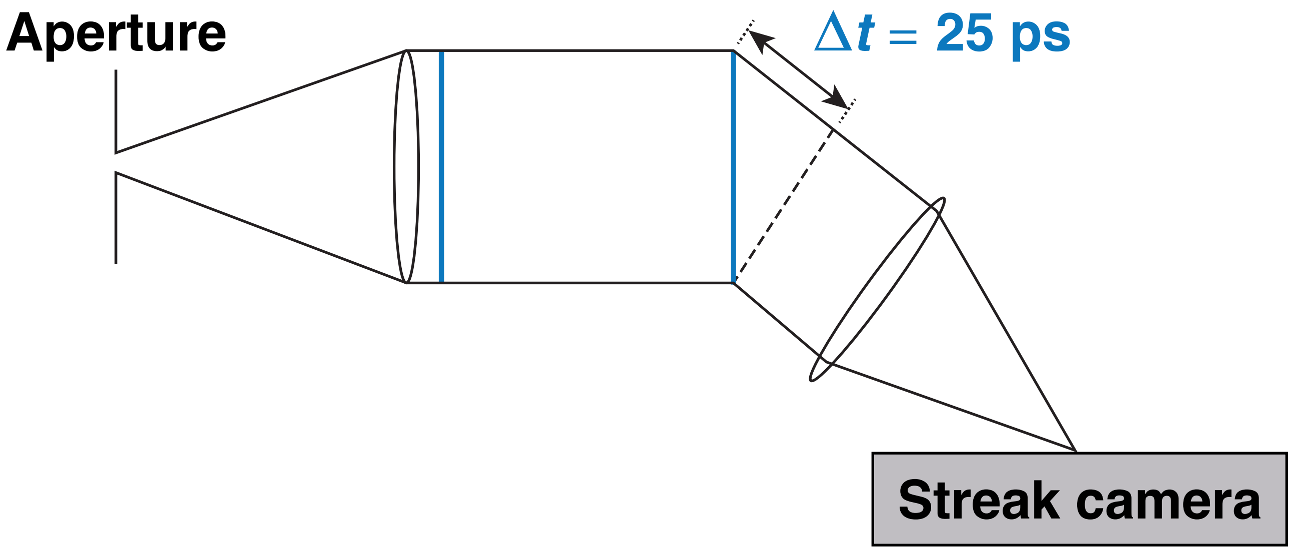
To measure non-Maxwellian electron distribution functions experimentally, Thomson scattering was performed on gas-jet plasmas using the Multi-Terrawatt (MTW) laser

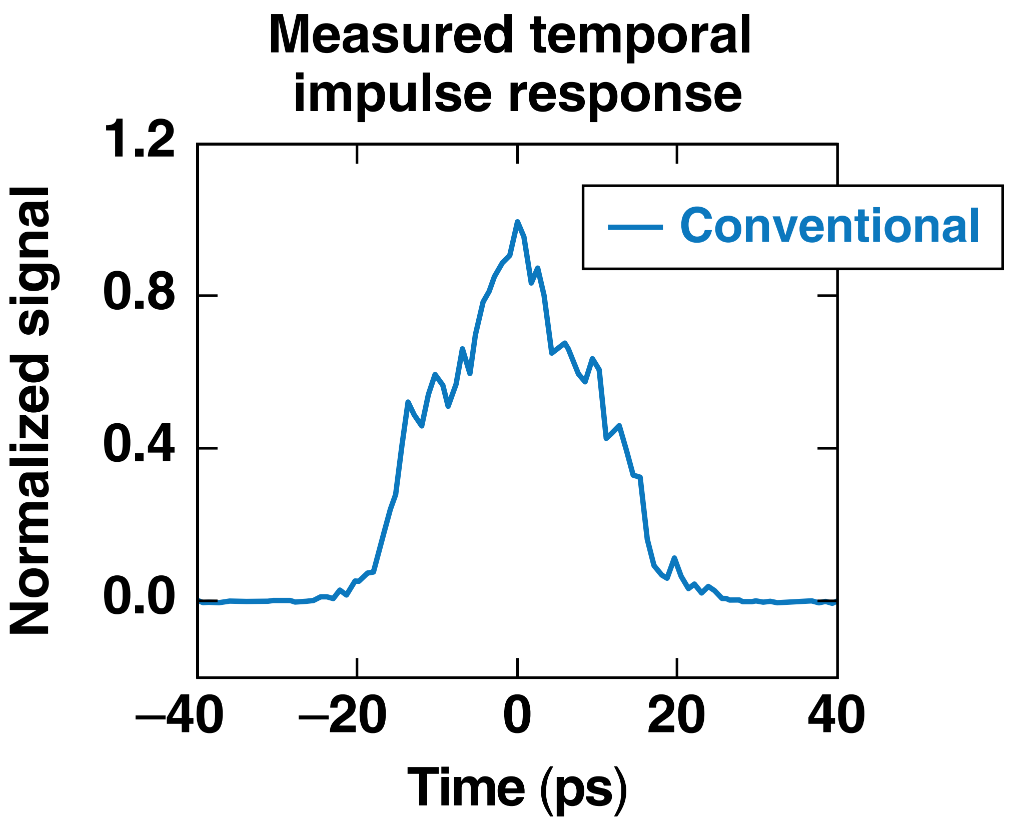


Laser intensity and gas were varied to study the Langdon effect.

E28079

A pulse-front–tilt compensated spectrometer* was invented to trade unutilized resolving power with temporal resolution

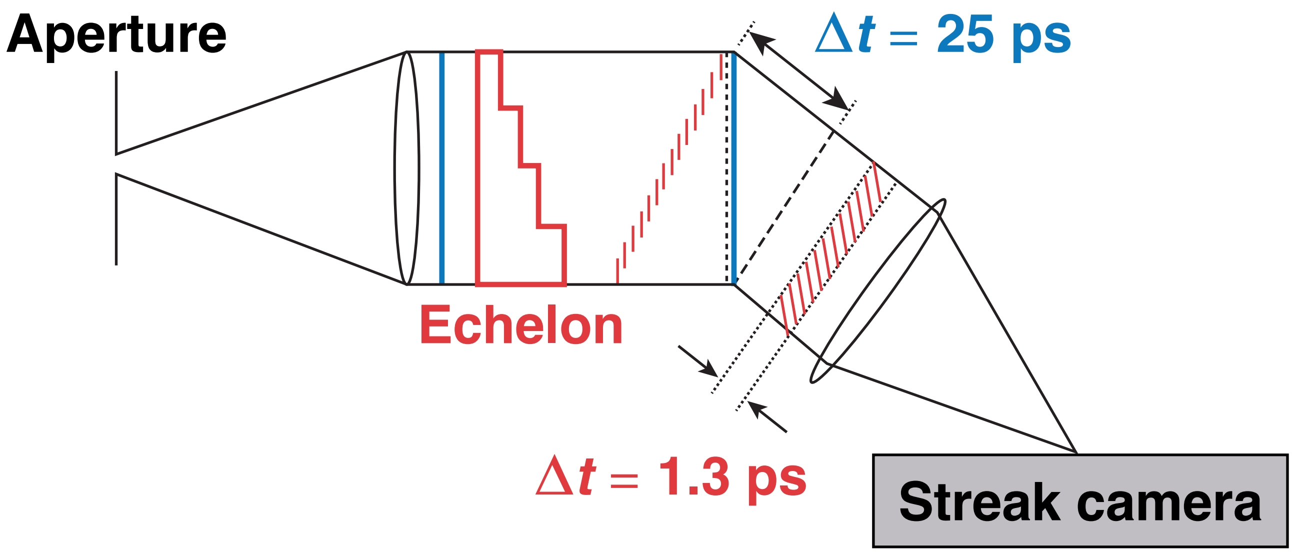


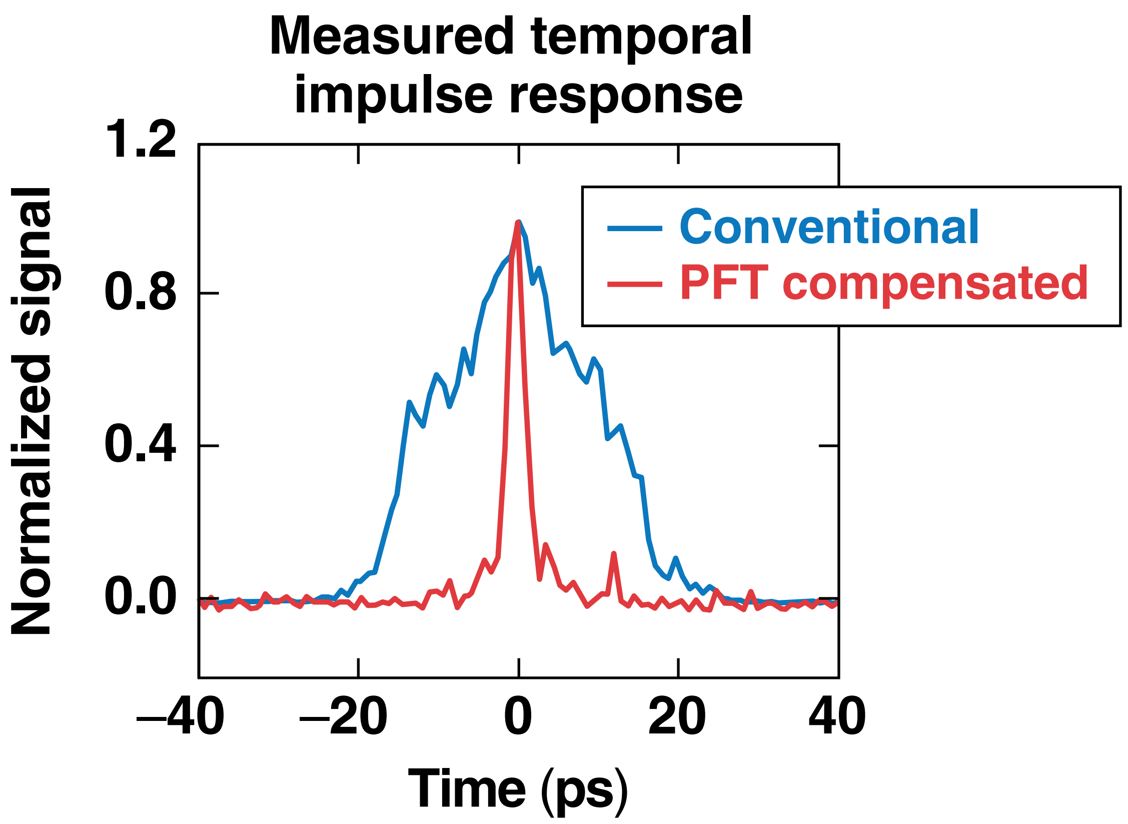


E27204c

*J. Katz *et al.*, Rev. Sci. Instrum. 87, 11E535 (2016).

A pulse-front–tilt (PFT) compensated spectrometer* was invented to trade unutilized resolving power with temporal resolution



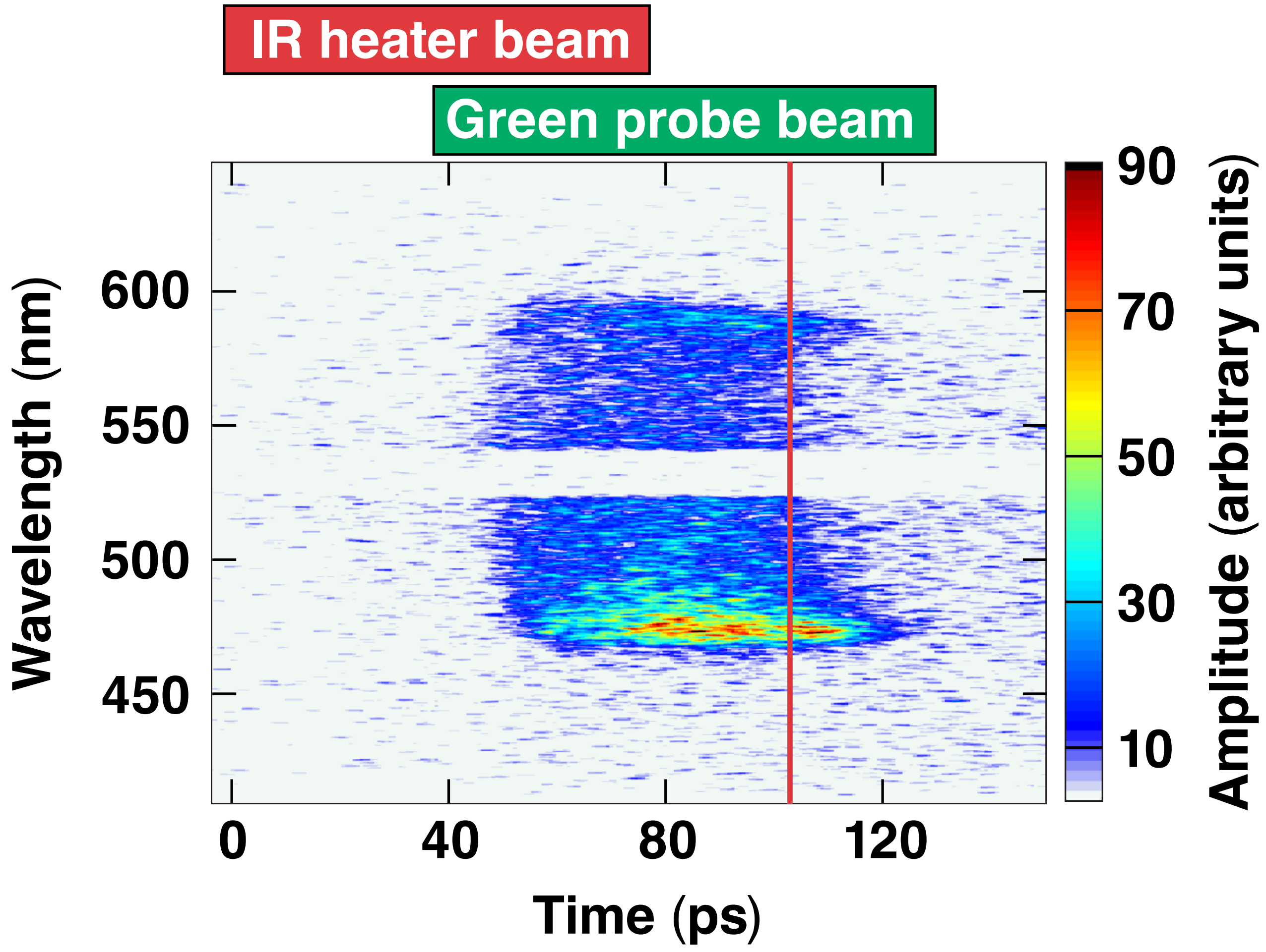


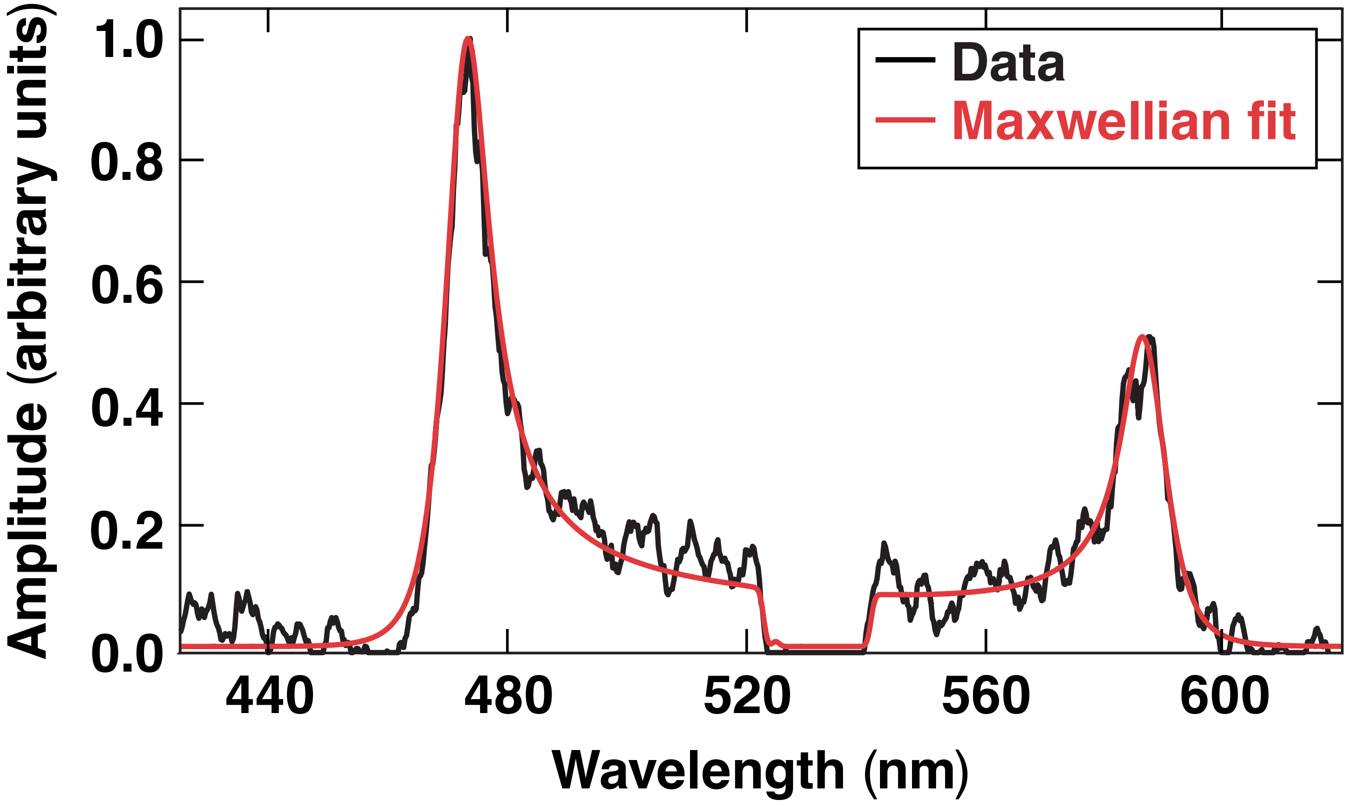
This system is greater than 10× faster than an equivalent (*f*/5) conventional streaked-spectrometer diagnostic while maintaining 1-nm spectral resolution.

E27204d

*J. Katz *et al.*, Rev. Sci. Instrum. 87, 11E535 (2016).

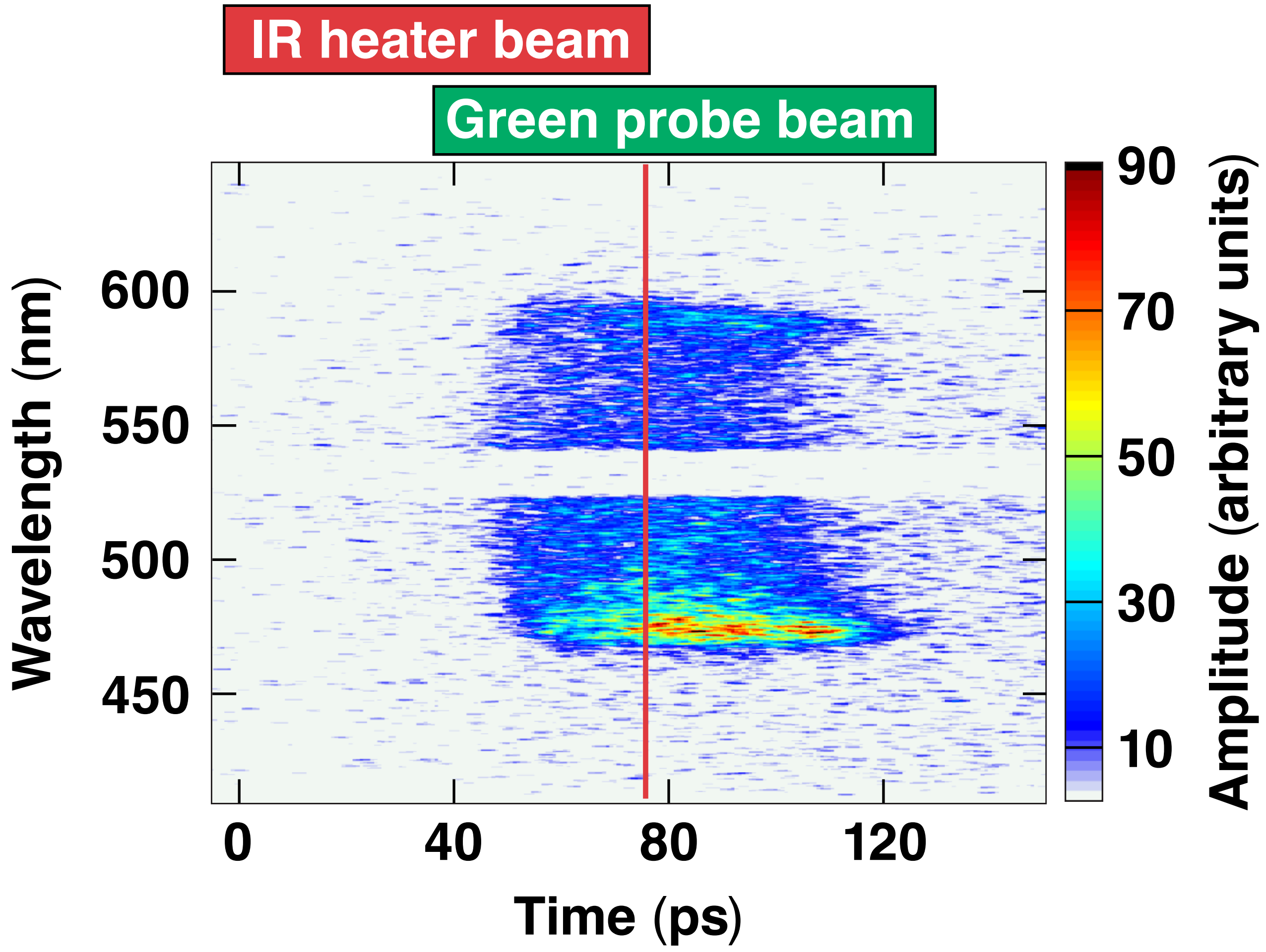
Maxwellian theory shows good agreement with measurements late in time and allows an accurate measurement of the plasma conditions

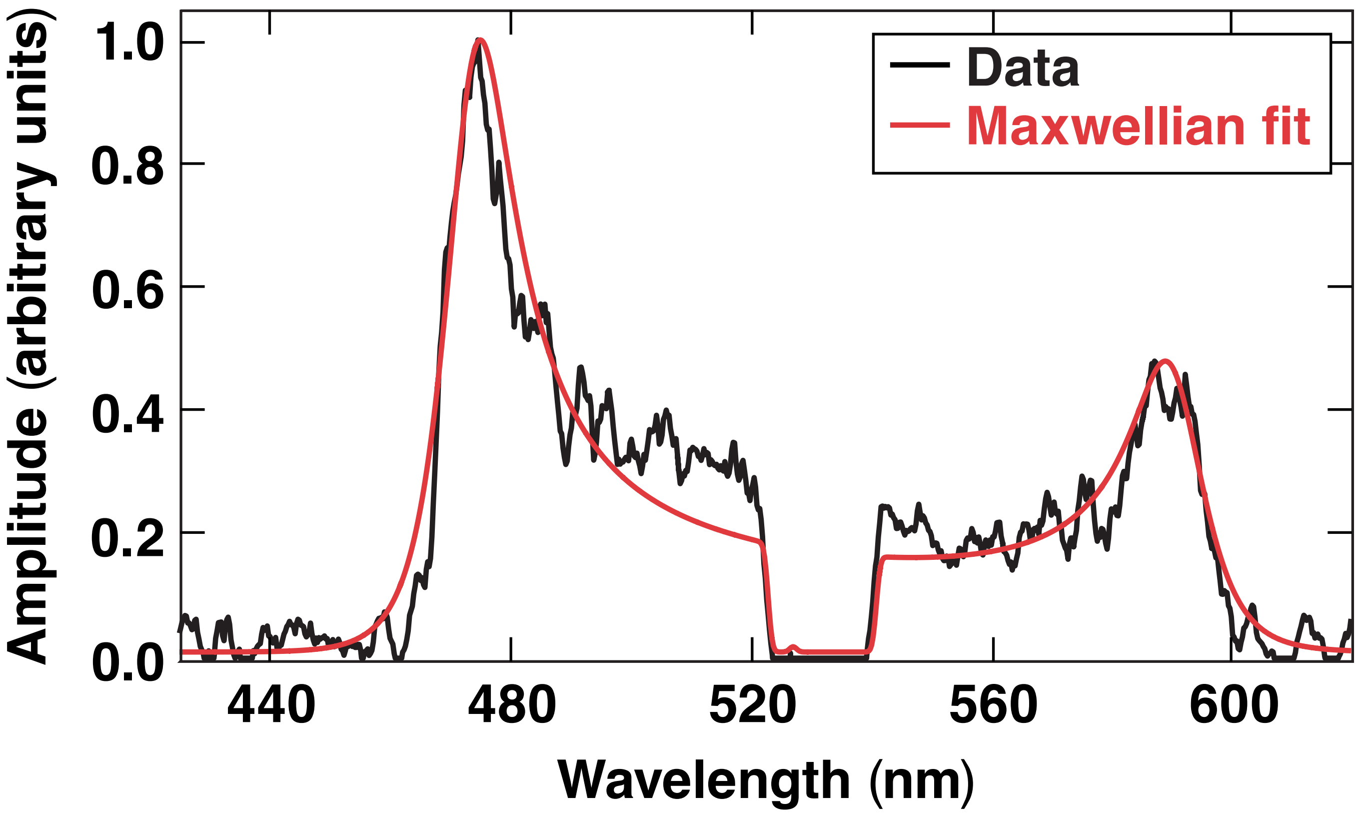




n_e = 2.71±0.04 × 10^{19} 1/cm^3 T_e = 288±5 eV

Maxwellian theory shows discrepancies with the measurements early in time

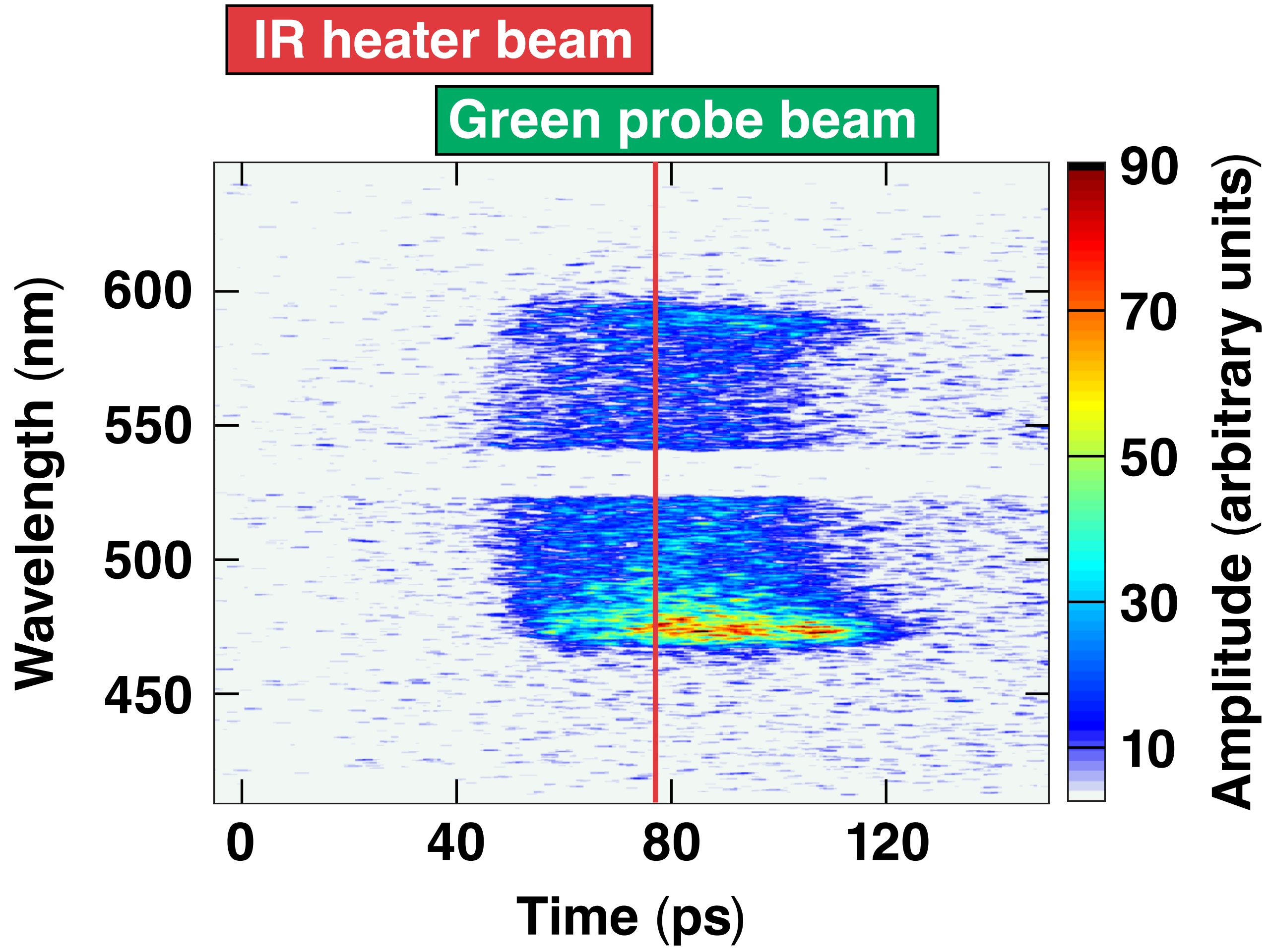


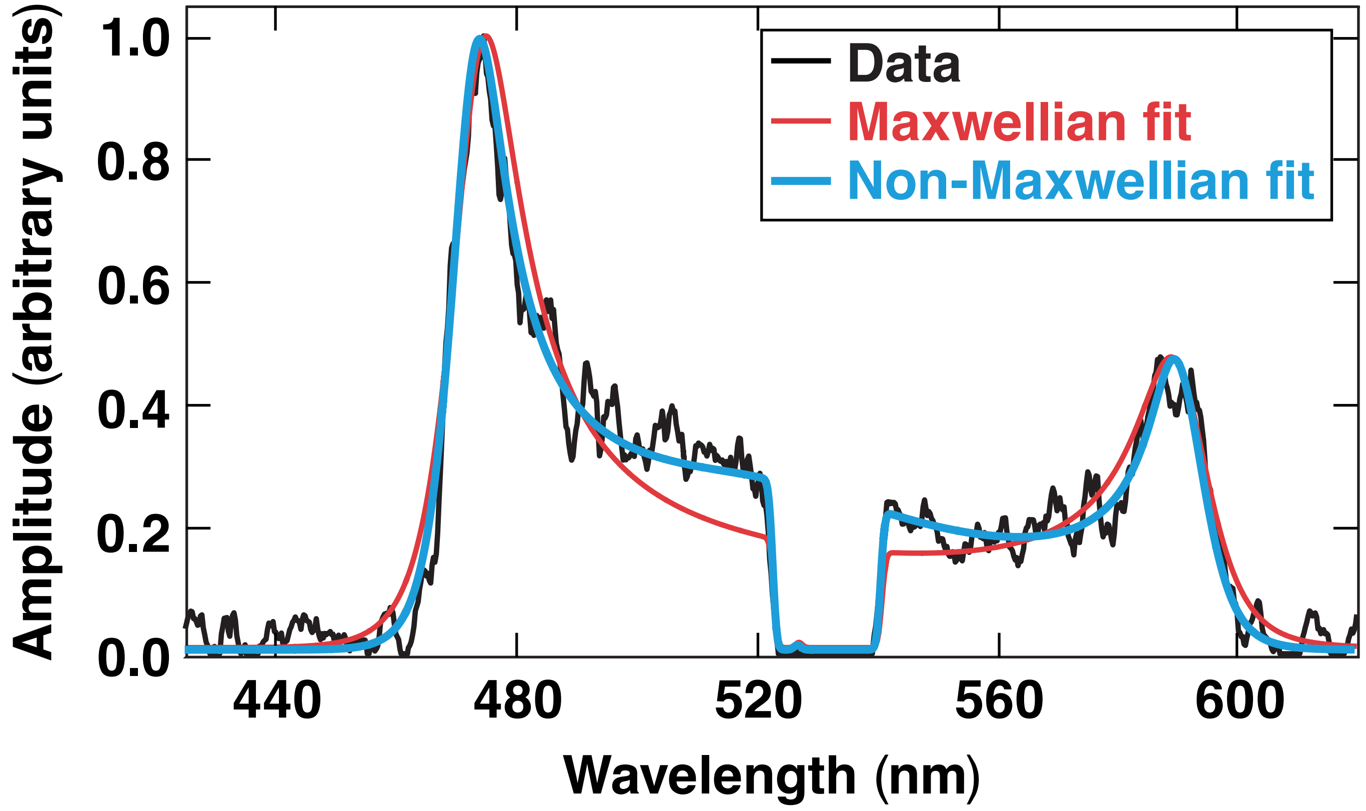


$n_e = 2.41 \pm 0.04 \times 10^{19}$ 1/cm^3 $T_e = 364 \pm 5$ eV

E28080a

Data early in time is fit well when including non-Maxwellian electron distribution functions





$n_e = 2.41 \pm 0.04 \times 10^{19}$ 1/cm^3 $T_e = 364 \pm 5$ eV $\chi^2 = 11.518$
$n_e = 2.30 \pm 0.04 \times 10^{19}$ 1/cm^3 $T_e = 379 \pm 5$ eV $m = 2.9 \pm 0.2$ $\chi^2 = 4.434$

E28080b

The non-Maxwellian electron distribution functions measured from the early time data are in good agreement with Langdon theoretical predictions

$$L = 0.042 \frac{I_0}{10^{14}\ \mathrm{W/cm^2}} \frac{\lambda_0^2}{(1.06\ \mu m)^2} \frac{1}{k_B T_e\,(\mathrm{keV})} Z$$

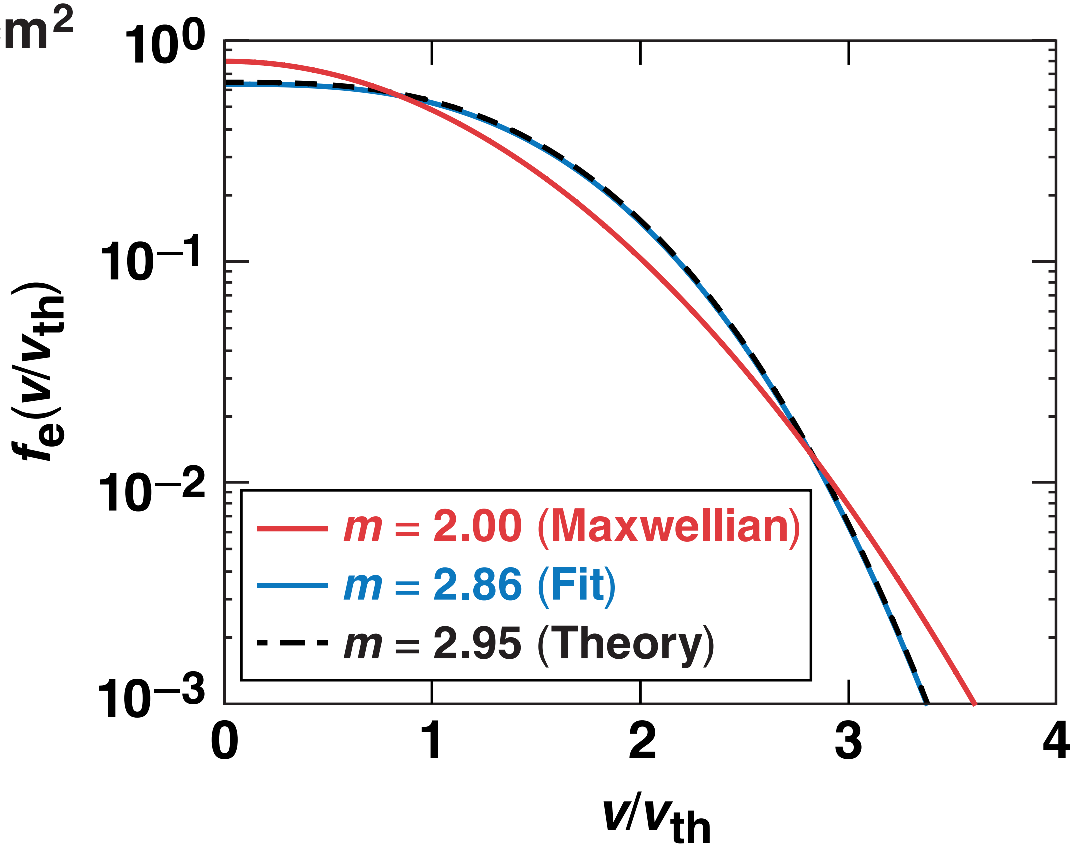
$$m = 2 + \frac{3}{1 + 1.66/L^{0.724}}$$

$I_0 = 1.3 \times 10^{14}\ \mathrm{W/cm^2}$

$\lambda_0 = 1053\ \mathrm{nm}$

$Z = 5$

$T_e = 377\ \mathrm{eV}$



The fit shown gives m = 2.86 while the formula gives m = 2.95.

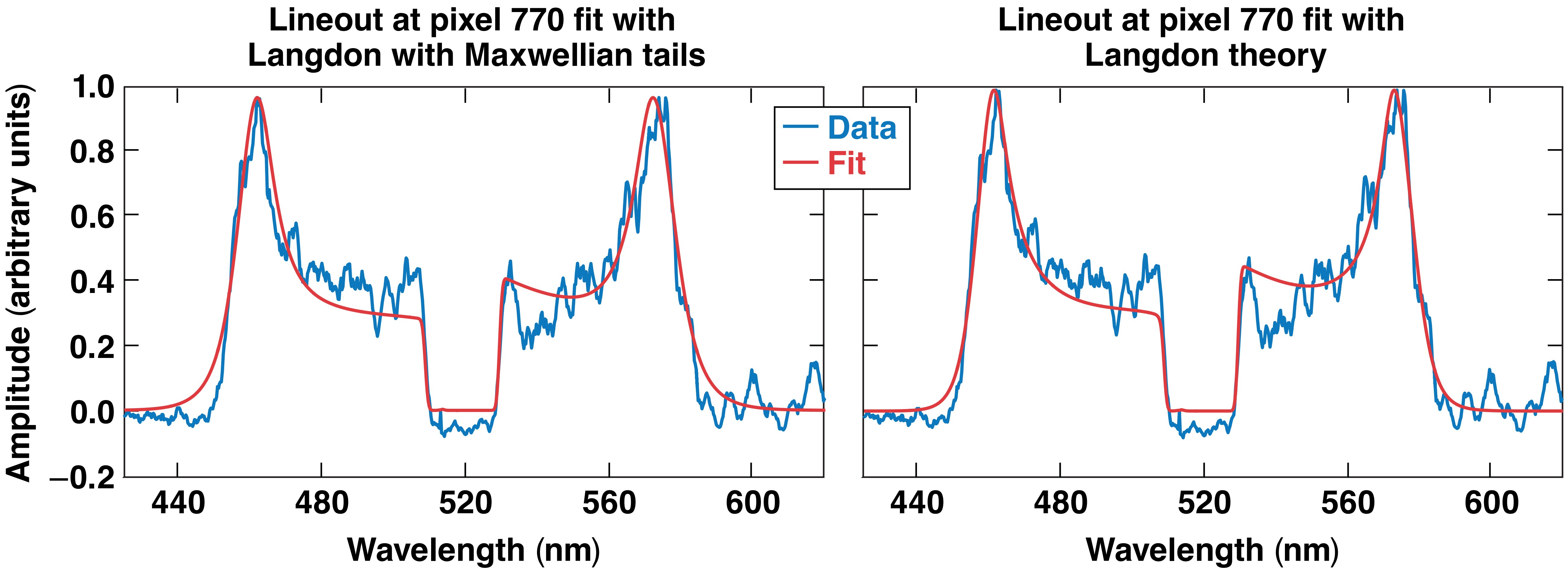
*J. P. Matte *et al.*, Plasma Phys. Control. Fusion 30, 1665 (1988).

Experiments show evidence of the Langdon effect in a laser produced plasma using collective Thomson scattering

- Electron plasma wave Thomson-scattering spectrum were used to measure non-Maxwellian distribution functions driven by the Langdon effect
- Analyzing non-Maxwellian data as Maxwellian leads to significant errors in the inferred parameters
- The experimentally measured Langdon parameter agrees with theoretical predictions

Theory including Maxwellian tails does a worse job fitting data

- This is likely because the data are at low α
- This example is at α = 1.75 while crossover appears to be around 2.35



E28082