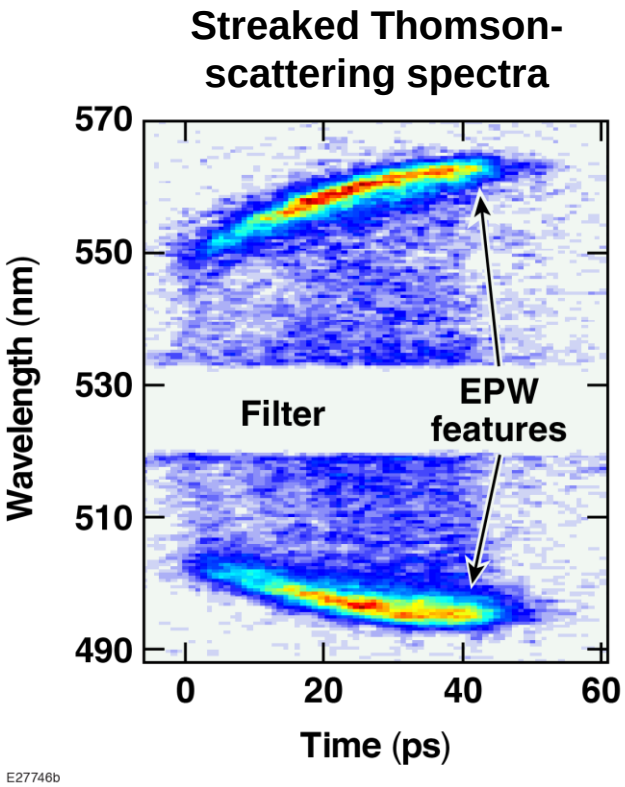
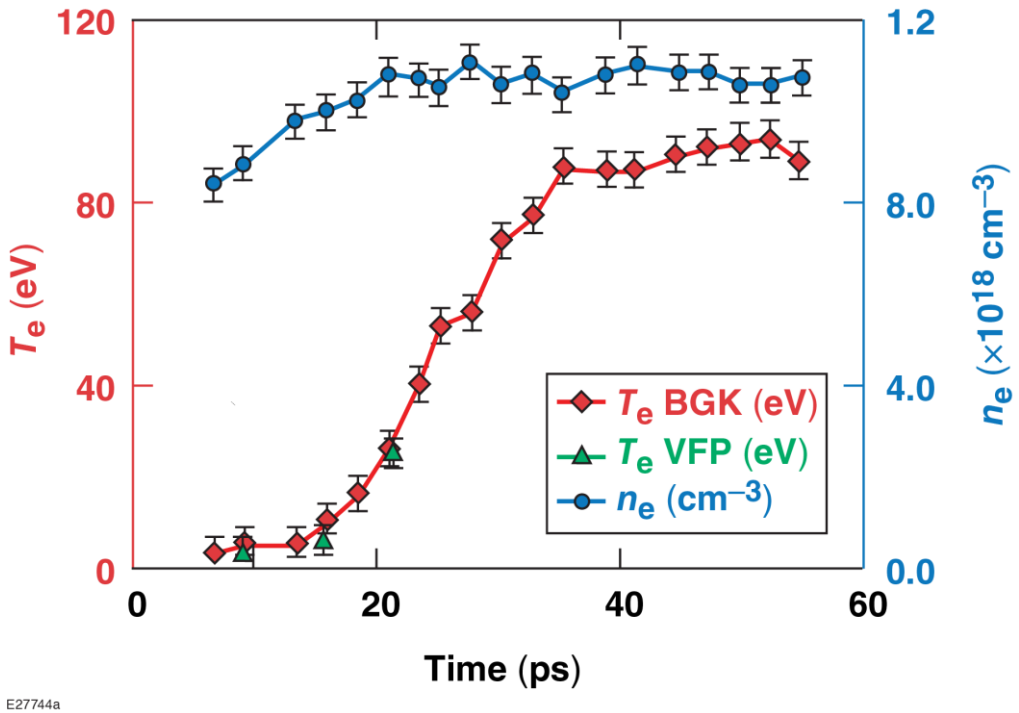
Investigation of Electron Plasma Waves and Picosecond Thermodynamics in a Laser-Produced Plasma Using Thomson Scattering





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Thomson Scattering Workshop
Rochester, NY
13 August 2019

Summary

Time-resolved Thomson scattering was used to measure the plasma creation and picosecond evolution of electron temperature and density

- A pulse-front–tilt-compensated streaked spectrometer was invented to measure the picosecond thermal and ionization dynamics
- For temperatures below ~35 eV, a collisional model was required to reproduce the measured spectrum
- Heat-equation calculations and measured equilibrium temperatures agree to within 15%

A. S. Davies *et al.*, Phys. Rev. Lett. 122, 155001 (2019).

A strong collaboration between computational and experimental physicists, engineers, and machinists made this research possible

J. Katz, S. Bucht, D. Haberberger, J. P. Palastro, J. L. Shaw, D. Turnbull, R. Boni, I. A. Begishev, S.-W. Bahk, J. Bromage, A. Sorce, J. Konzel, B. Cuffney, J. D. Zuegel, and D. H. Froula
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W. Rozmus
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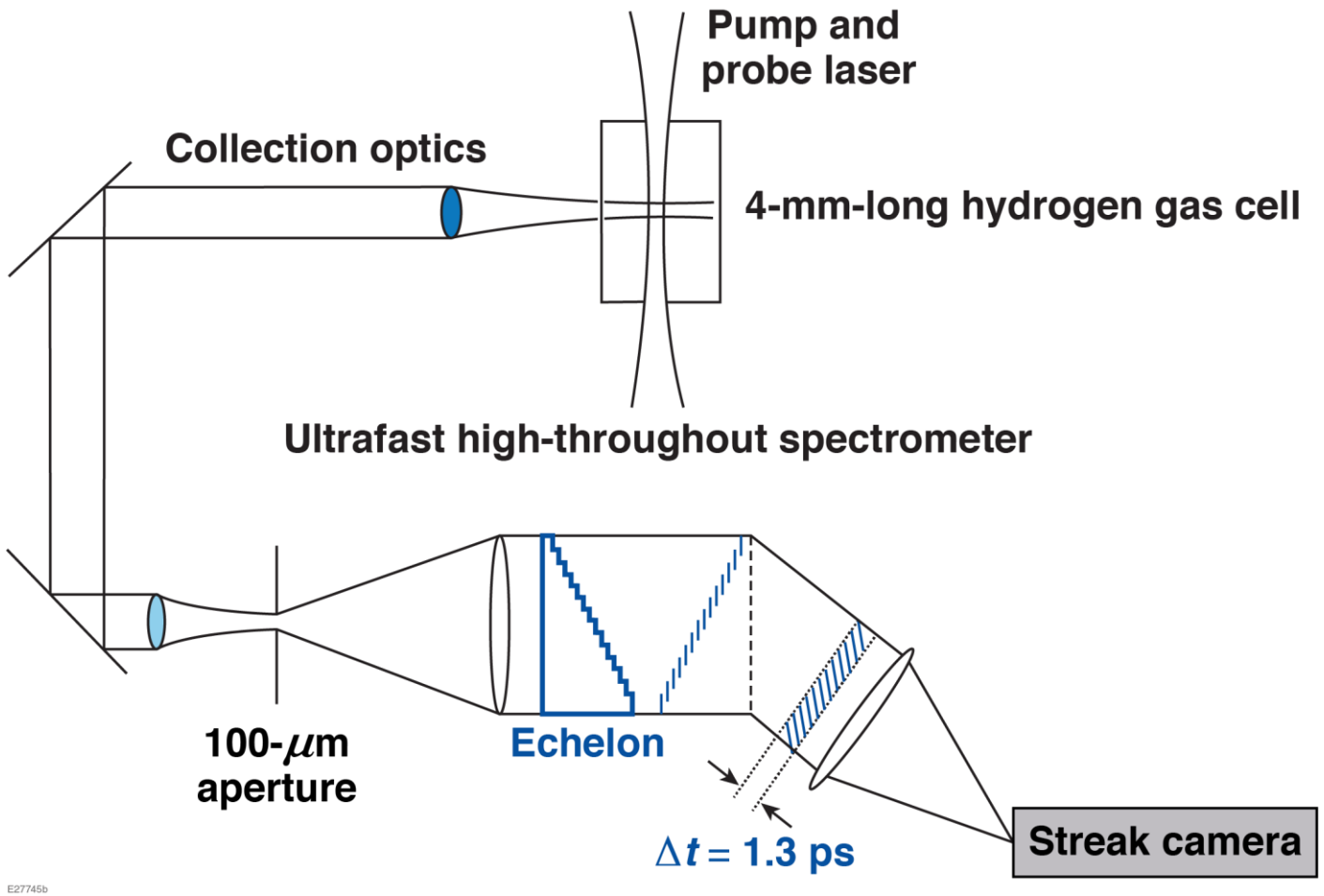
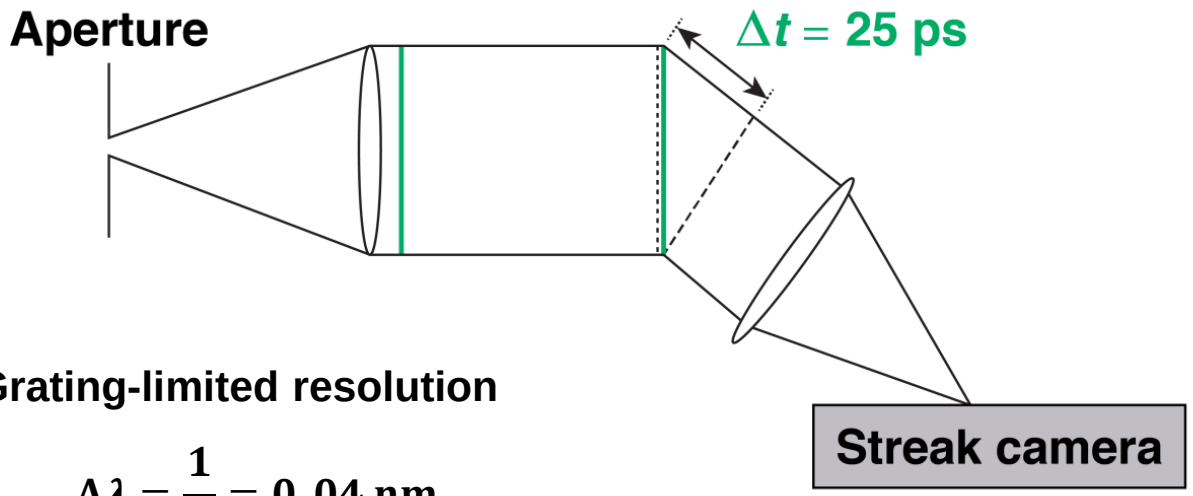
The experiments were conducted on the Multi-Terawatt (MTW) Laser System at the University of Rochester's Laboratory for Laser Energetics

- **Pump**
  - λ = 1053 nm
  - Δt = 60 ps
  - $I \sim 2 \times 10^{14}$ W/cm^2
- **Thomson-scattering probe**
  - λ = 526.5 nm
  - Δt = 55 ps
  - $I \sim 1 \times 10^{14}$ W/cm^2



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



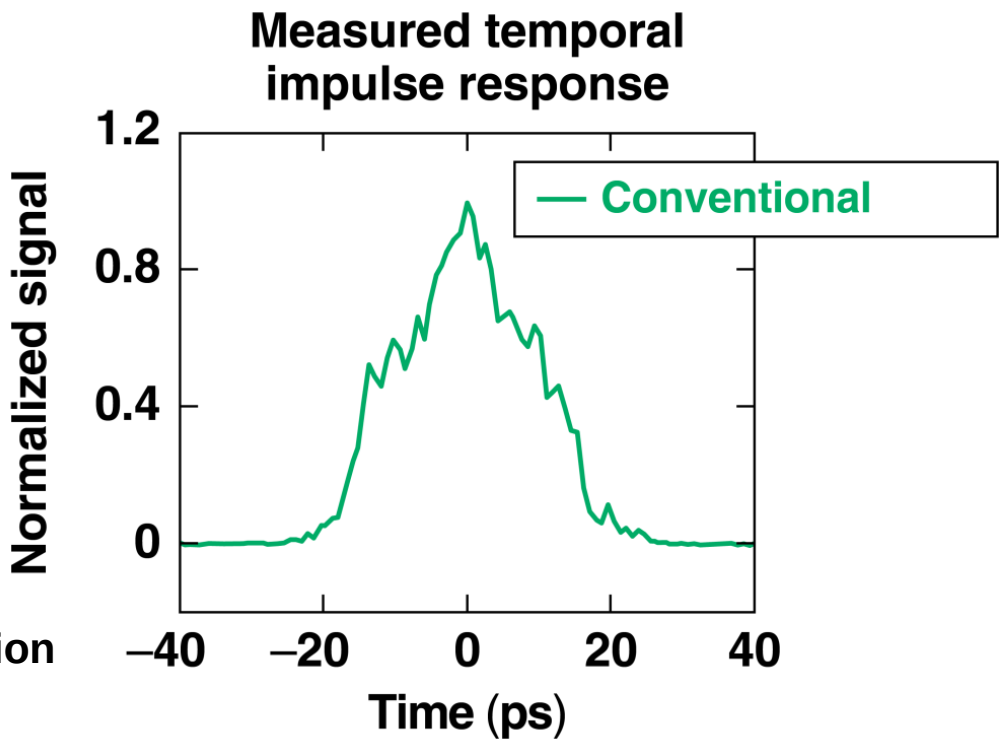
Grating-limited resolution

$$\Delta\lambda = \frac{1}{N} = 0.04\ \text{nm}$$

N = grooves illuminated

Streak-camera–limited resolution

$$\Delta\lambda \sim 1\ \text{nm}$$



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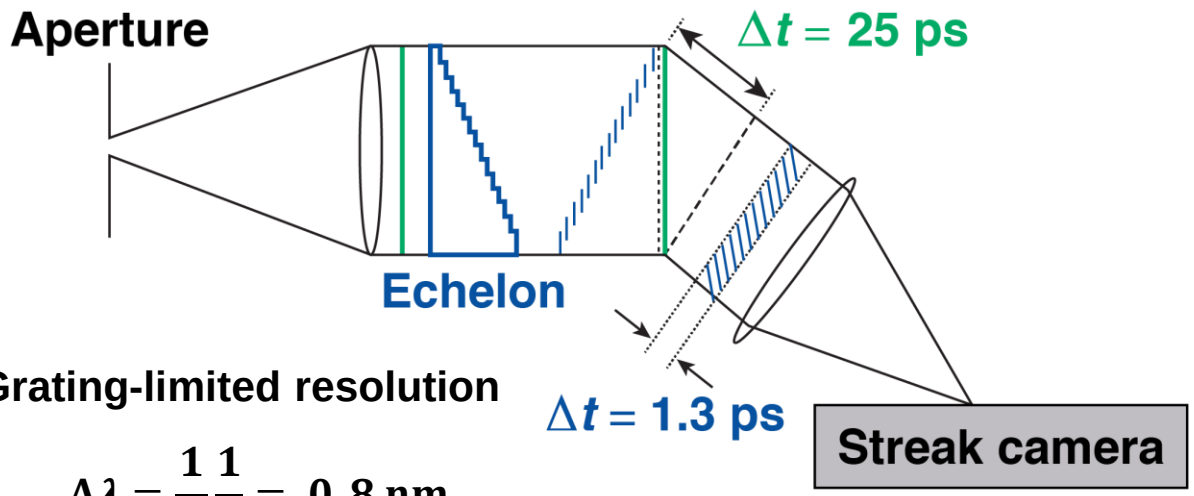
*J. Katz *et al.*, Rev. Sci. Instrum. 87, 11E535 (2016).

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



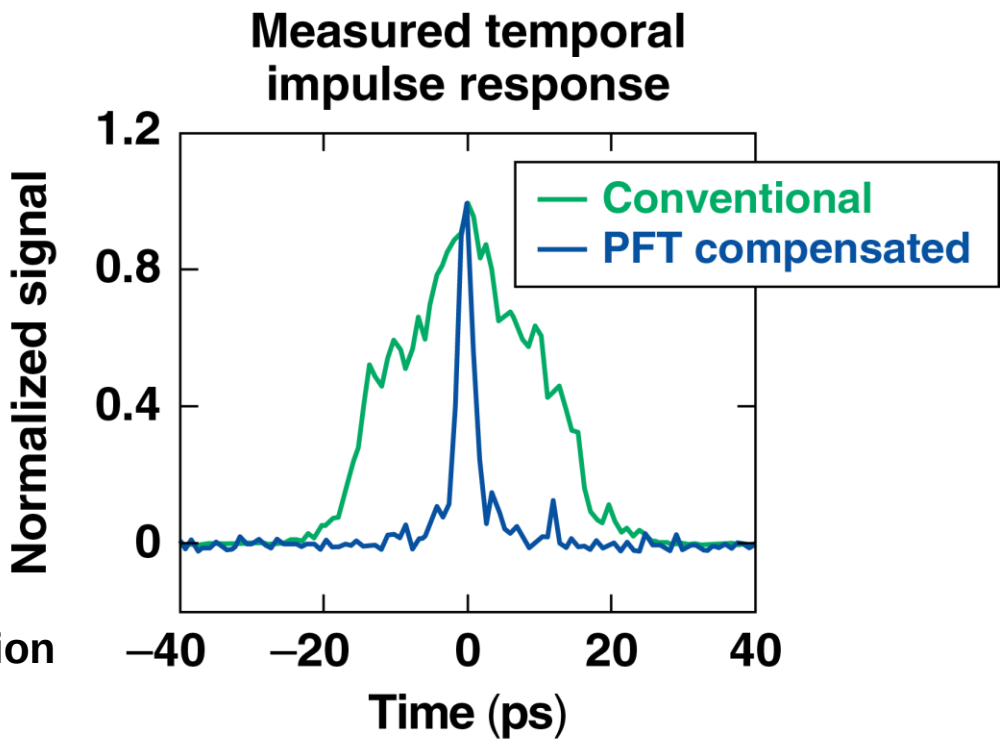
Grating-limited resolution

$$\Delta\lambda = \frac{1}{N}\frac{1}{n} = 0.8\ \text{nm}$$

n = Echelon steps

Streak-camera–limited resolution

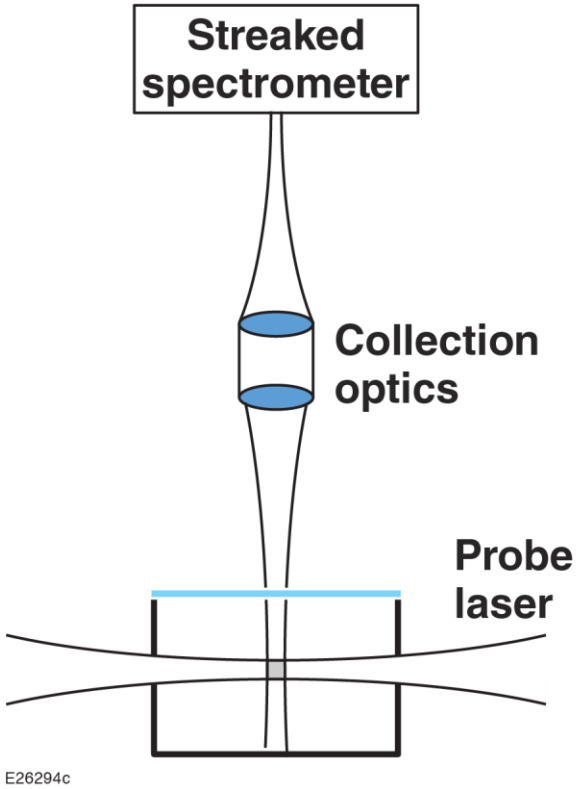
$$\Delta\lambda \sim 1\ \text{nm}$$



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

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

The electron temperature and density can be determined by scattering from thermal electron plasma waves



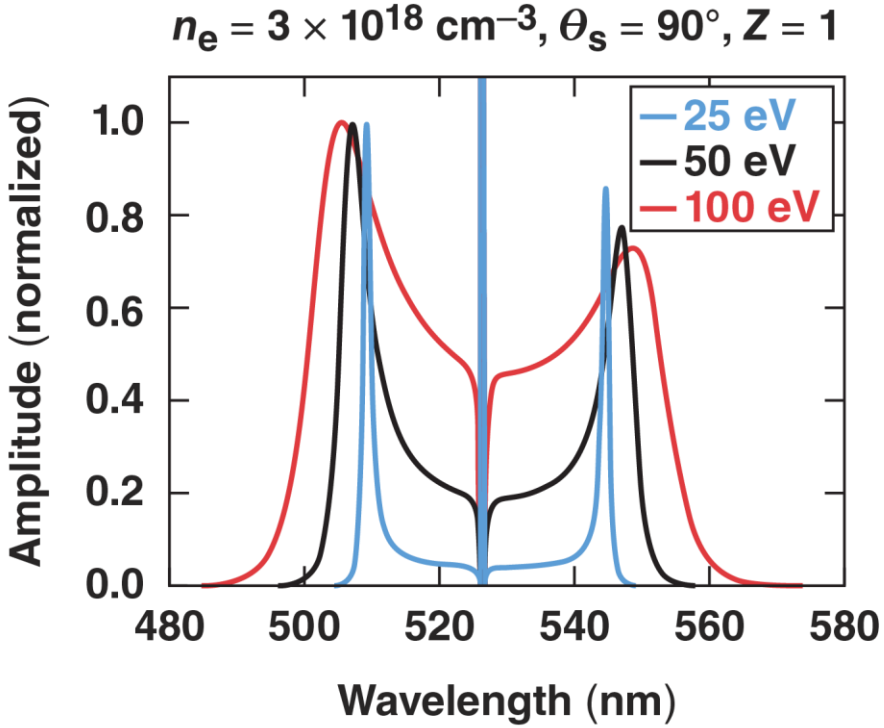
Expect to see

$$\omega_{\text{electron feature}} = \omega_{\text{probe}} \pm \omega_{\text{EPW}}$$

$$\omega_{\text{EPW}}^2 = \omega_{\text{pe}}^2 + 3v_{\text{th}}^2 k^2$$

$$= \frac{4\pi e^2}{m_e} n_e + \frac{3k_B k^2}{m_e} T_e$$

Predicted spectra



At high temperatures the shape of the Thomson-scattering spectra is dominated by Landau damping

$$P_s \propto S(\vec{k},\omega) = \frac{2k^2\lambda_D^2}{\omega}\,\mathrm{Im}\left[\frac{1}{\epsilon(\vec{k},\omega)}\right]$$

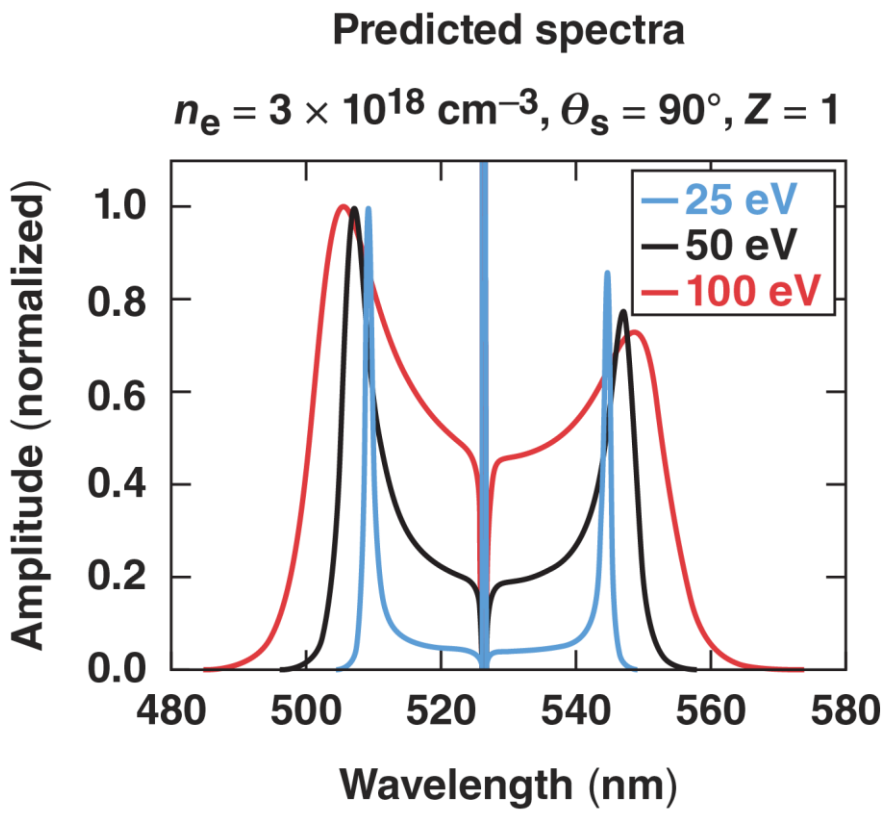
$$\epsilon(\vec{k},\omega) = 1 + \chi_e = 1 + \frac{4\pi e^2}{m_e k^2}\int d^3v\,\frac{1}{\omega - i\gamma - \vec{k}\cdot\vec{v}}\,\vec{k}\cdot\frac{\partial F_m^e}{\partial \vec{v}}$$

Collisionless limit: $\lim_{\gamma\to 0}\left[\epsilon(\vec{k},\omega)\right]$

$$\chi_e = -\frac{\alpha^2}{2}Z'(x_e) = \alpha^2\left[1 - \sqrt{\pi}x_e e^{-x_e^2}\mathrm{erf}(x_e) + i\pi\frac{1}{2}x_e e^{-x_e^2}\right],$$

where

$$x_e = \frac{v_{ph}}{v_{th}} \qquad v_{ph} = \frac{\omega}{k} \qquad v_{th} = \sqrt{\frac{2kT_e}{m_e}}$$



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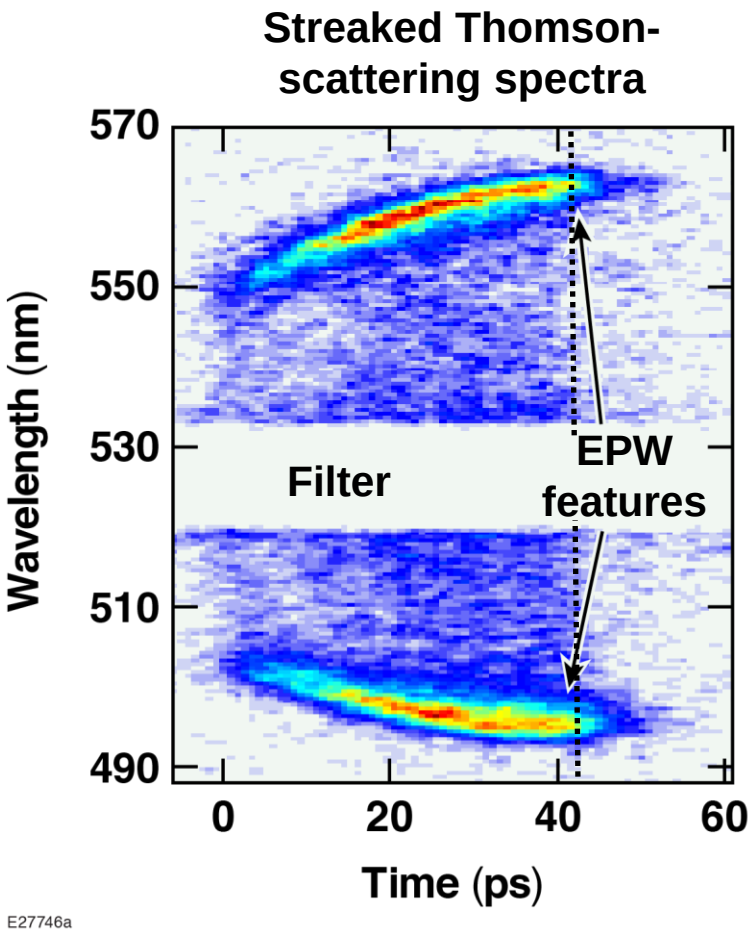
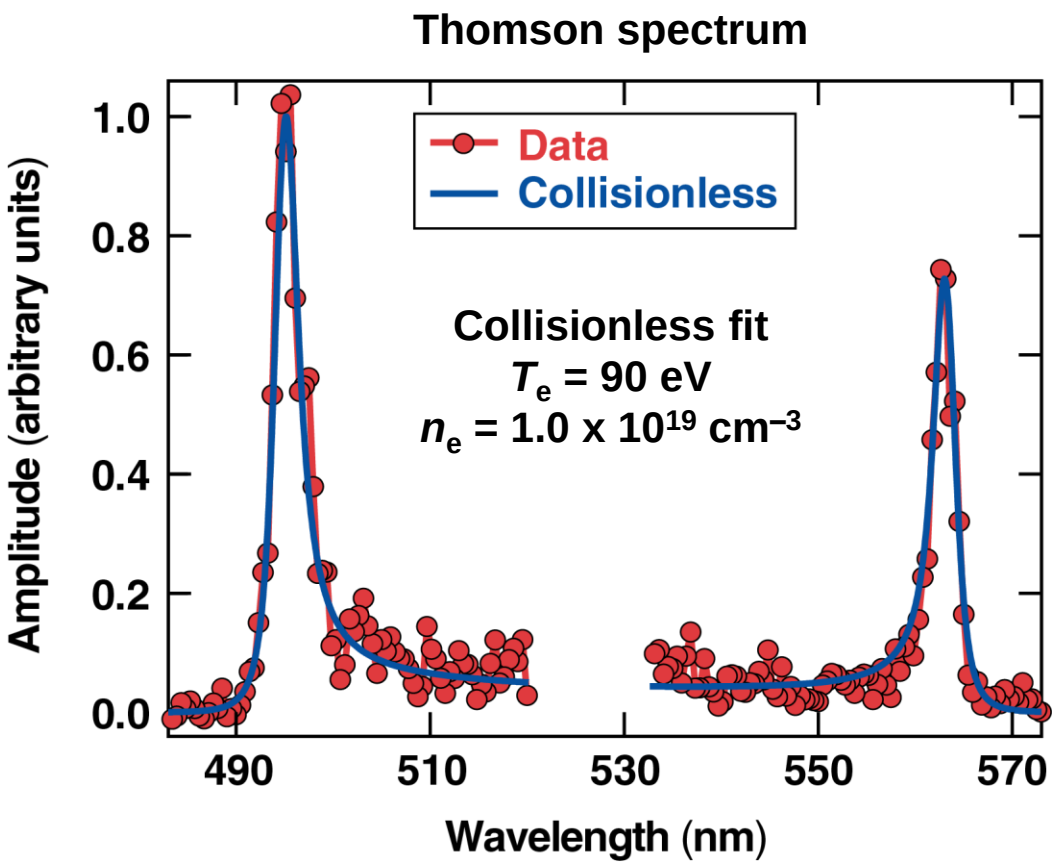
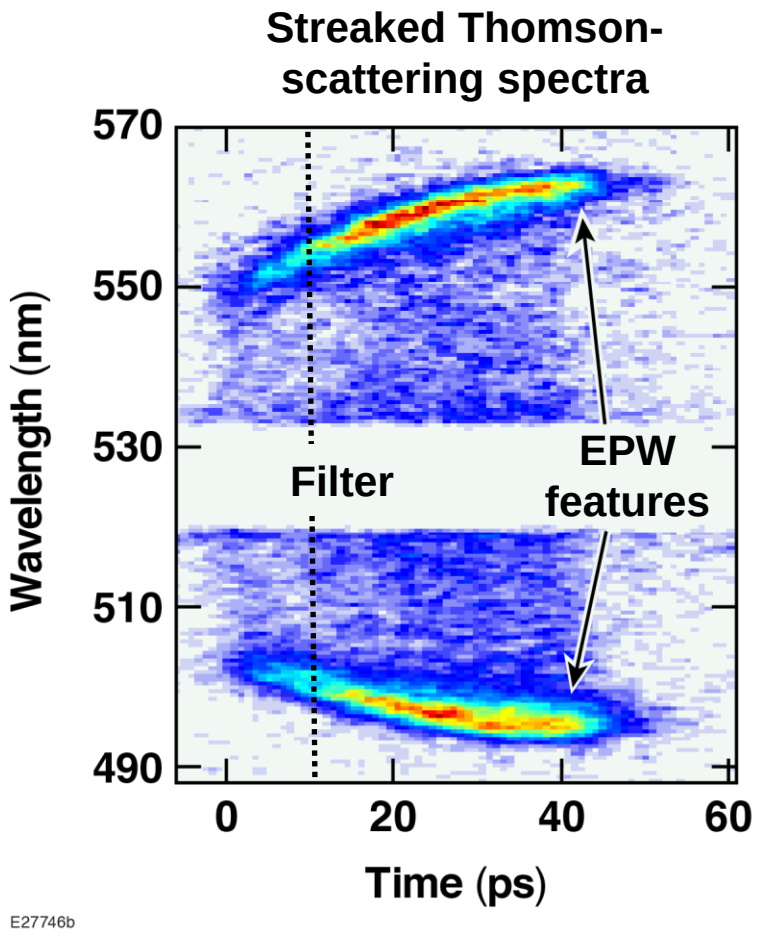
Thomson-scattering data and collisionless Thomson-scattering theory are in excellent agreement in the hot plasma conditions present late in time

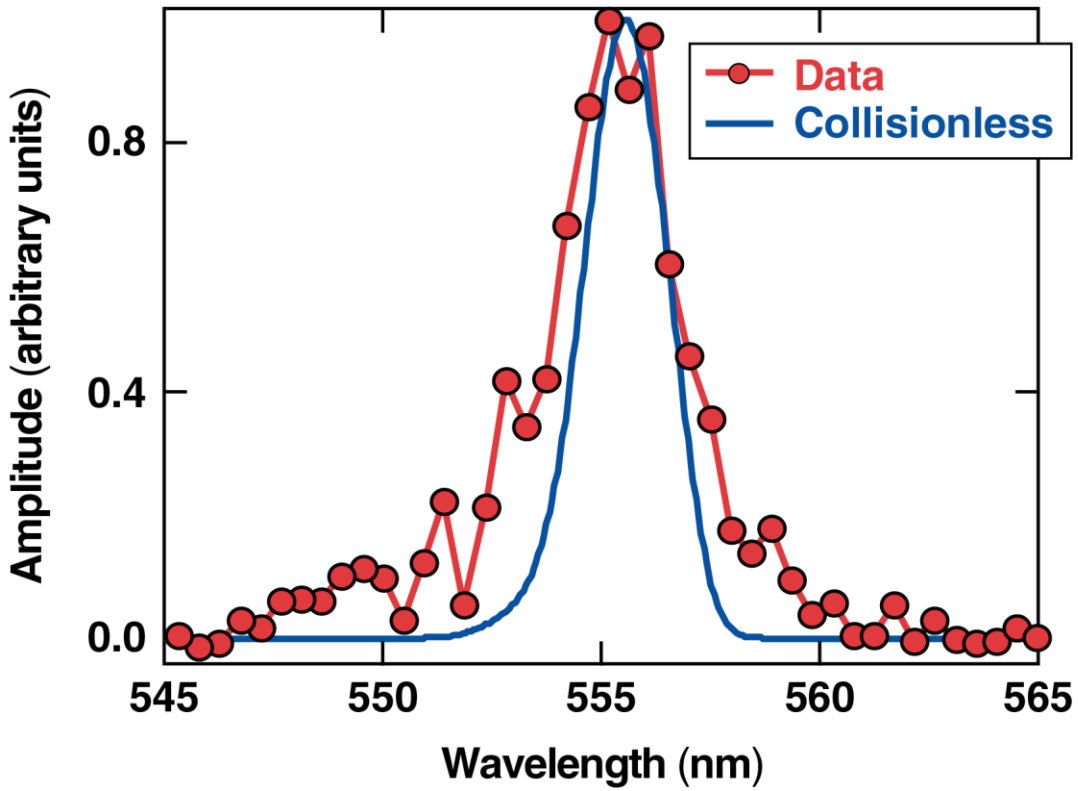




A. S. Davies *et al.*, Phys. Rev. Lett. 122, 155001 (2019).

In contrast, the collisionless theory fails to reproduce the data's spectral width in cold plasma present early in time





An additional damping term is required to model the data.

A. S. Davies *et al.*, Phys. Rev. Lett. 122, 155001 (2019).

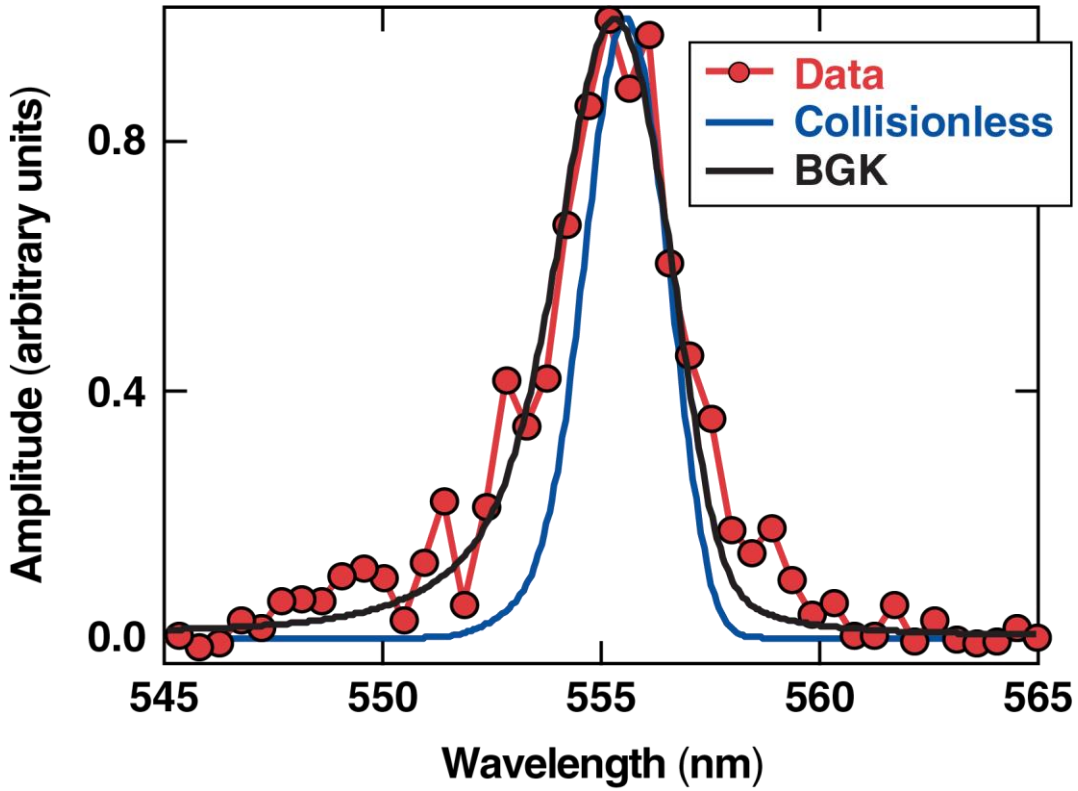
The collisional Bhatnagar–Gross–Krook (BGK) model reproduced the cold measured spectrum

$$S(\vec{k},\omega) = -\frac{2k^2\lambda_D^2}{\omega}\,\mathrm{Im}\left[\frac{1}{\epsilon^{BGK}(\vec{k},\omega)}\right]$$

$$\epsilon^{BGK}(\vec{k},\omega) = 1 + \frac{4\pi e^2}{m_e k^2}\int d^3v\,\frac{1}{\omega - i\vec{v}_{ei} - \vec{k}\cdot\vec{v}}\,\vec{k}\cdot\frac{\partial F_e}{\partial \vec{v}}$$

$$\vec{v}_{ei} = 4\pi Z e^4 n_e \Lambda_{ei}/m_e^2\, v^3$$

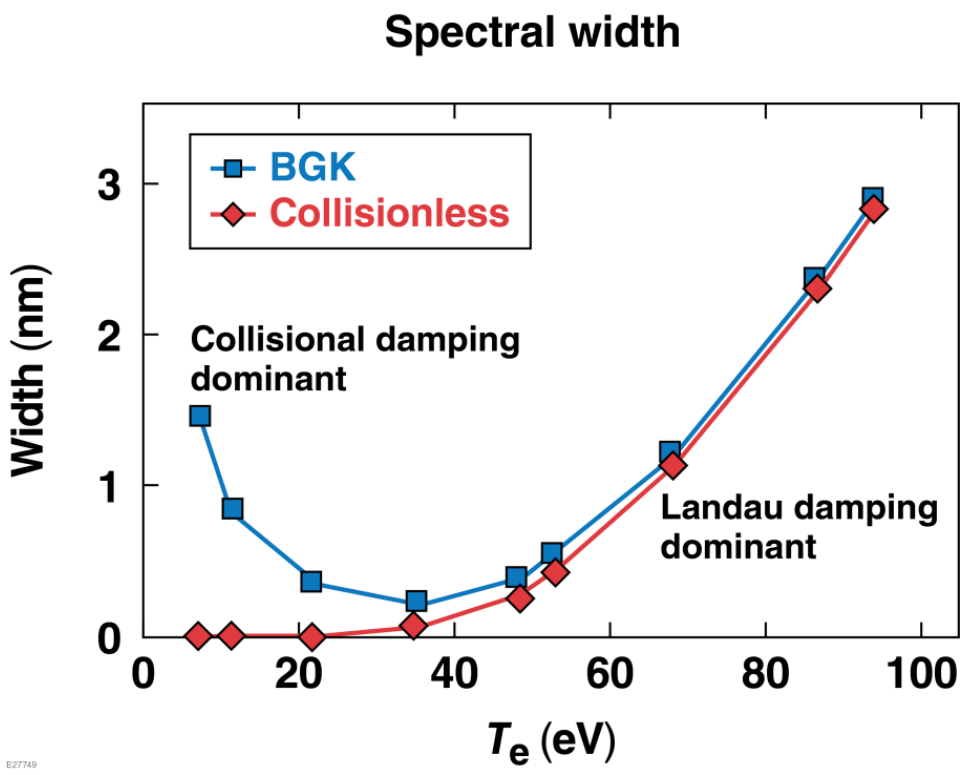
$$T_e^{BGK} = 10\ \mathrm{eV}$$
$$n_e^{BGK} = 1.0 \times 10^{19}\ \mathrm{cm}^{-3}$$



E27746c

P. L. Bhatnagar, E. P. Gross, and M. Krook, Phys. Rev. 94, 511 (1954).

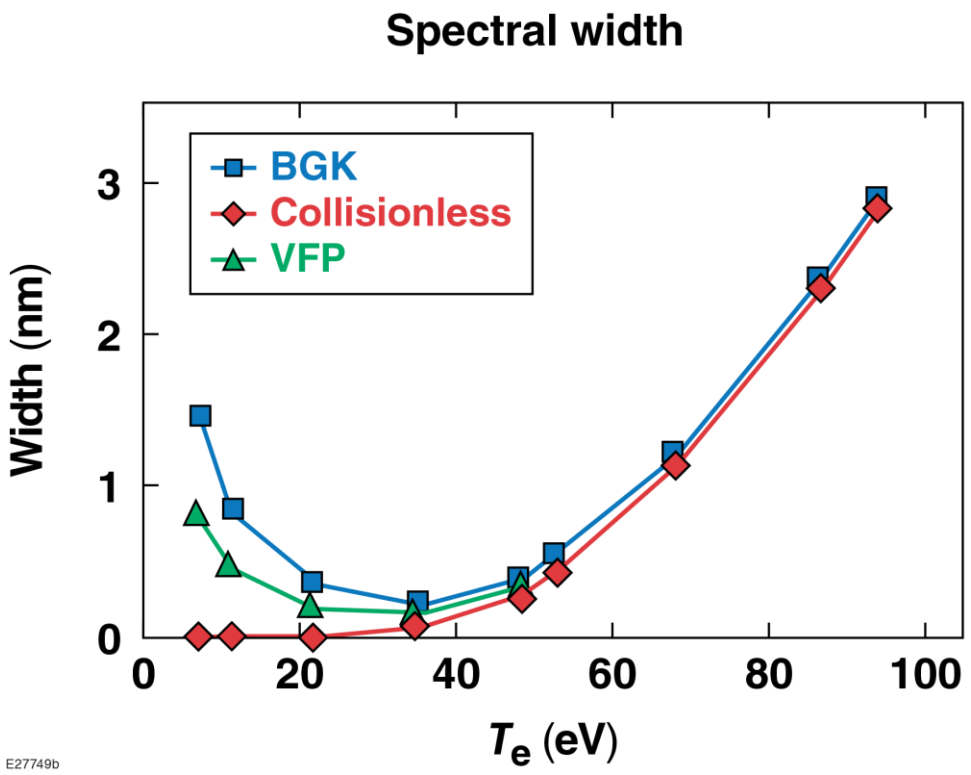
Collisional damping dominates the width of the electron plasma wave features at electron temperatures below ~35 eV

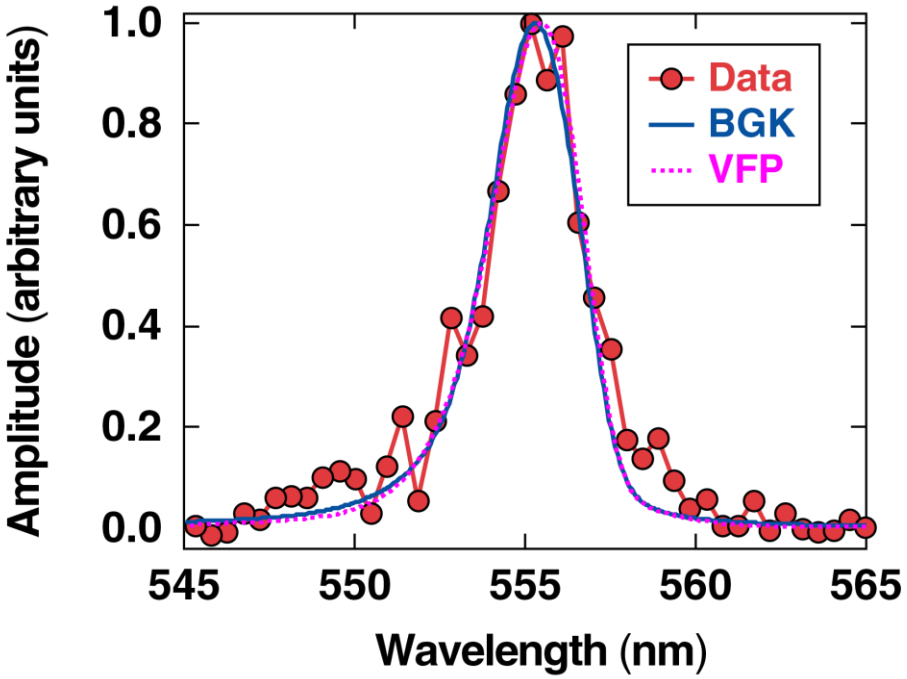


To understand the impact of using the BGK model to approximate collisions, a more-complete but computationally expensive Vlasov–Fokker–Planck (VFP) model* was fit to three spectra

$T_e^{BGK} = 10$ eV $\quad T_e^{VFP} = 5$ eV

$n_e^{BGK} = 1.0 \times 10^{19}$ cm^{-3} $\quad n_e^{VFP} = 1.0 \times 10^{19}$ cm^{-3}



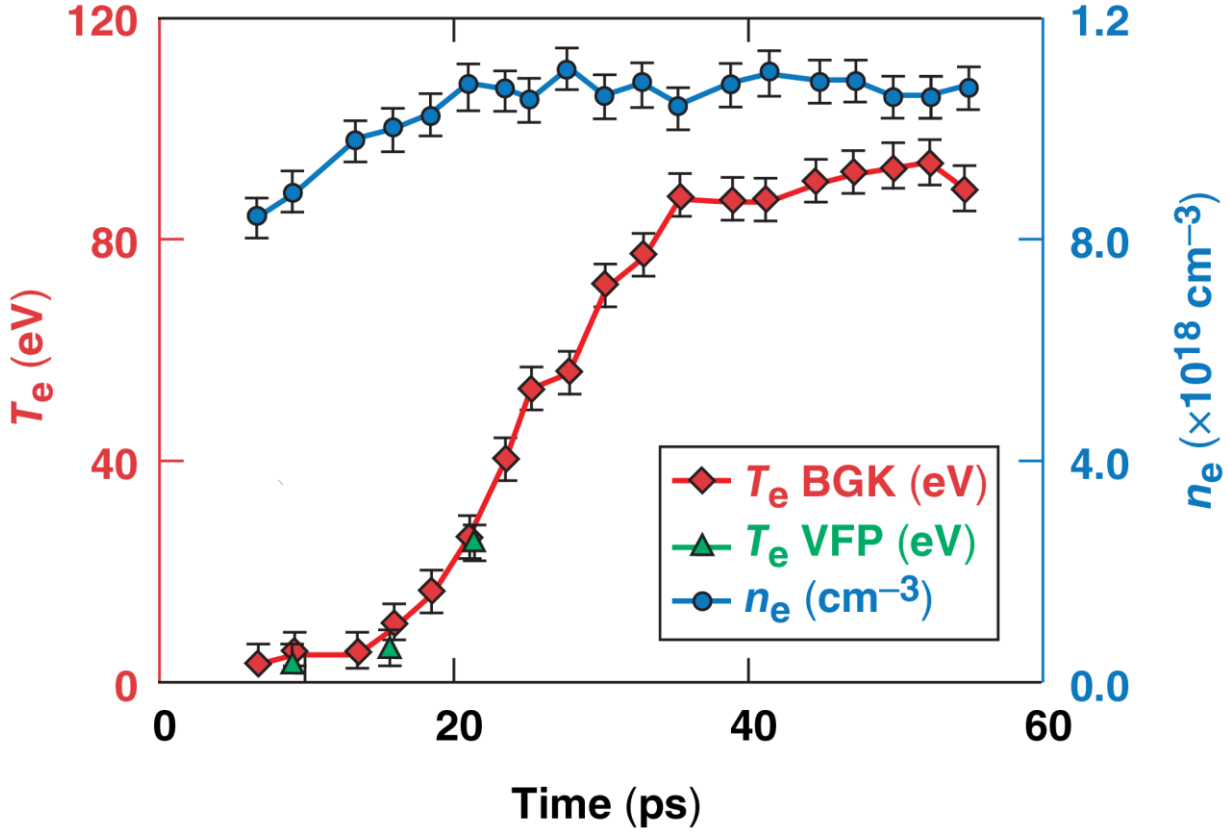


The BGK model overestimates the spectral width at low temperatures.

* W. Rozmus *et al.*, Phys. Rev. E 96, 043207 (2017).

Armed with the new diagnostic and the BGK model, the picosecond time history of the plasma conditions can be determined

- During ionization the electron temperature raised modestly
  - T_e is suppressed by ν_{e-H}
- Once fully ionized, the temperature rapidly increased to an equilibrium temperature
  - inverse bremsstrahlung = thermal conduction
- Below 20 eV the BGK model has a high percent error (~10% to 50%), but the absolute value is bounded to a small range (1 to 5 eV)



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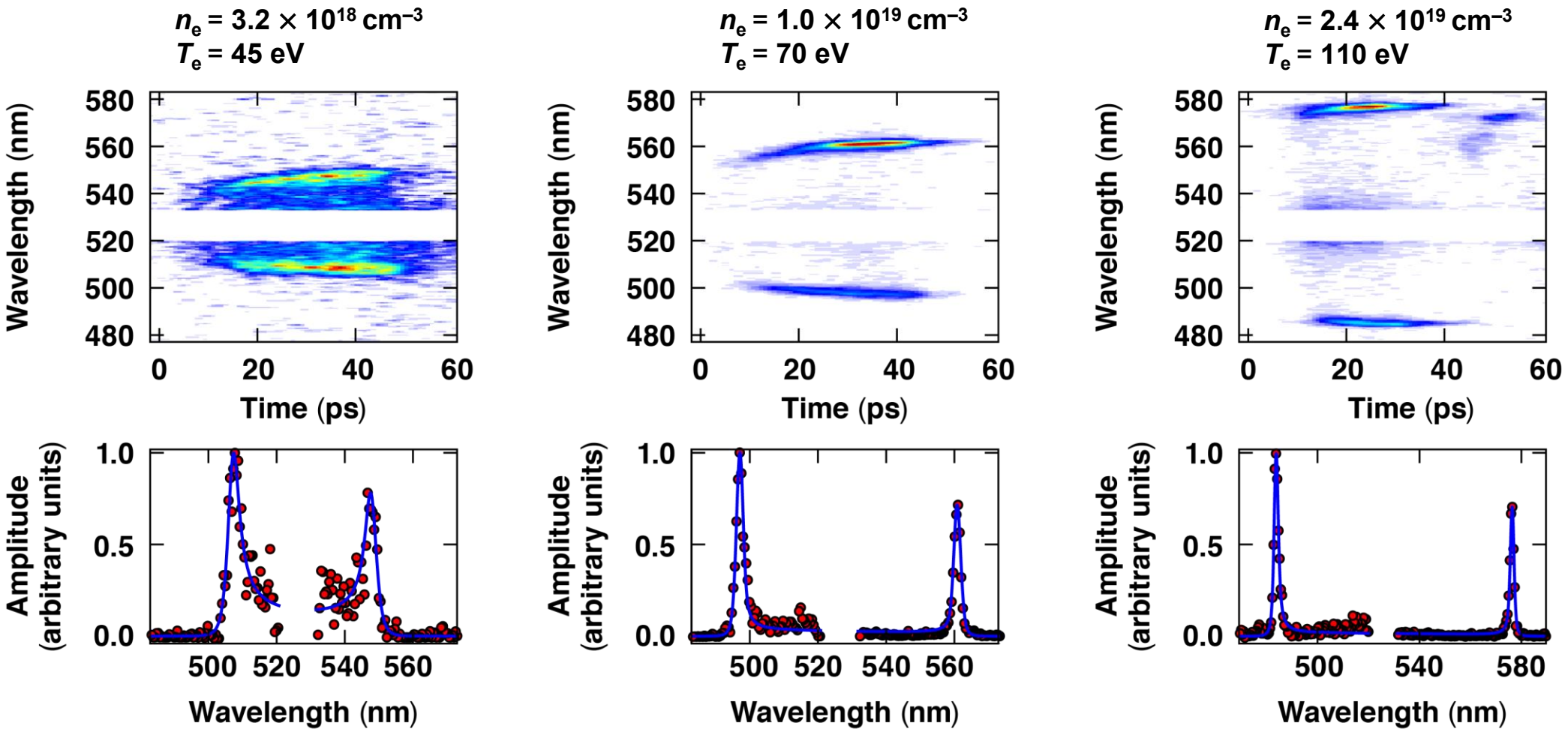
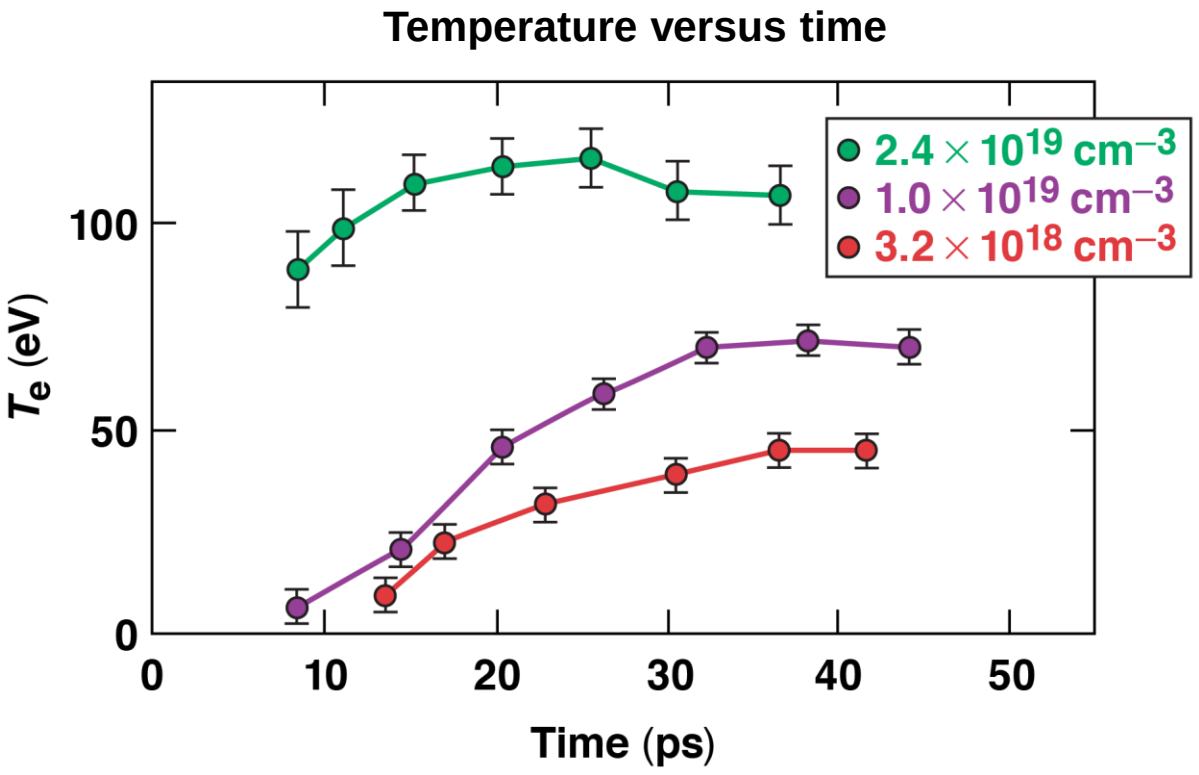
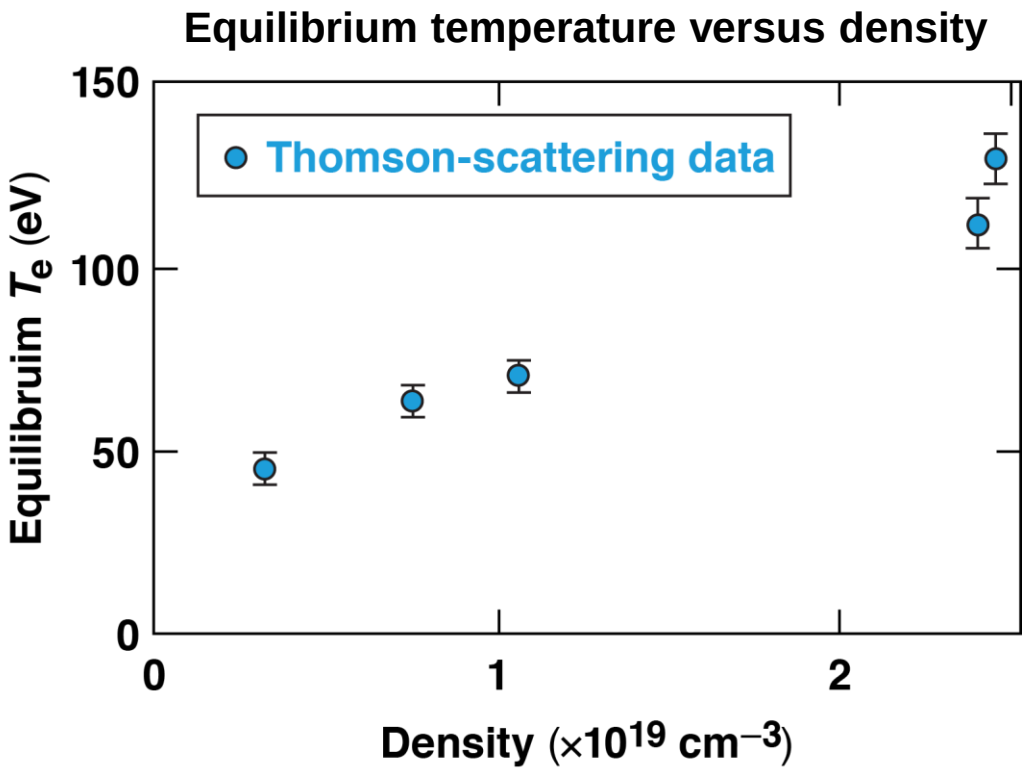
Thomson-scattering measurements were used to study the plasma evolution as a function of density for a 2×10^{14} W/cm^2 pump laser



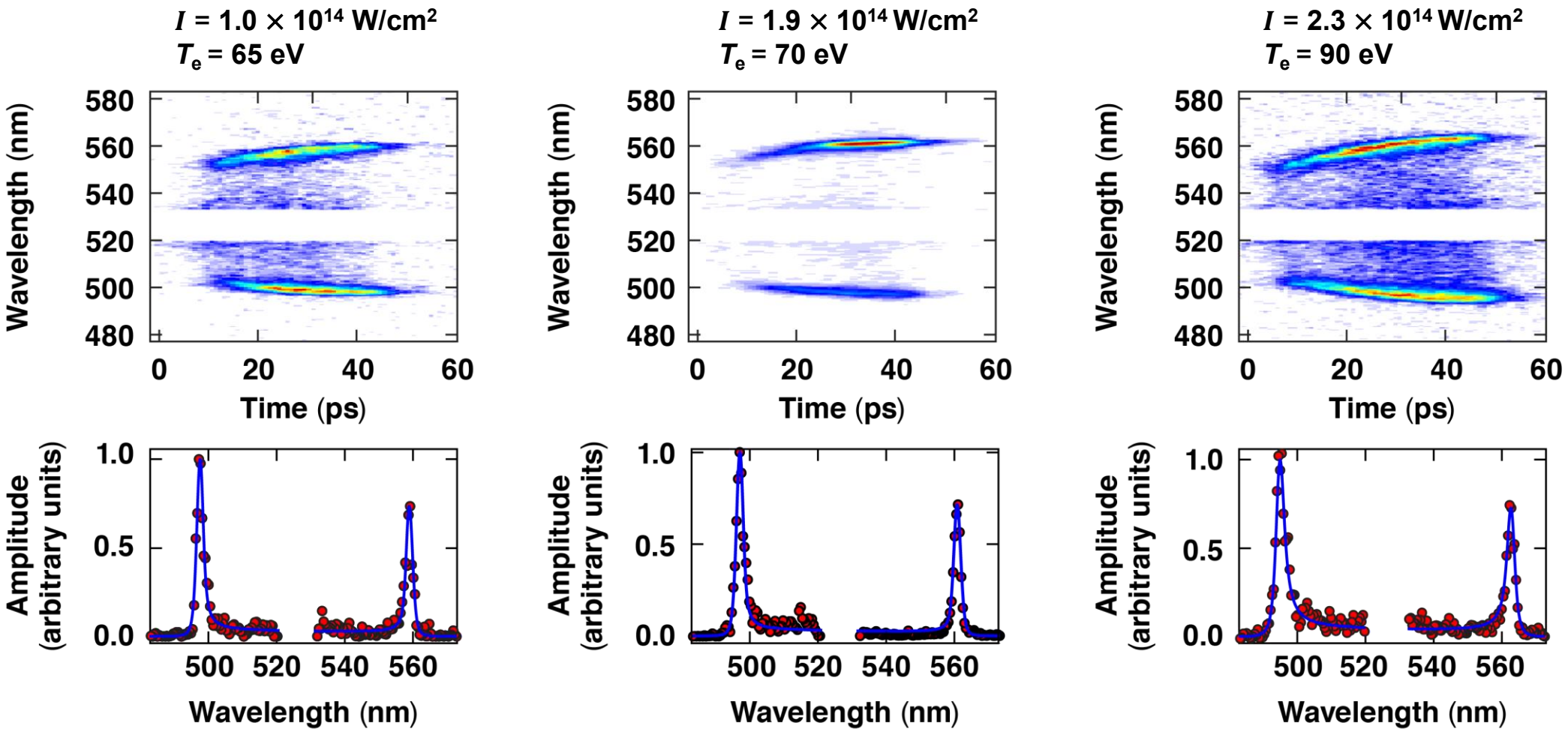
The electron heating rate and equilibrium temperature are found to increase with higher densities



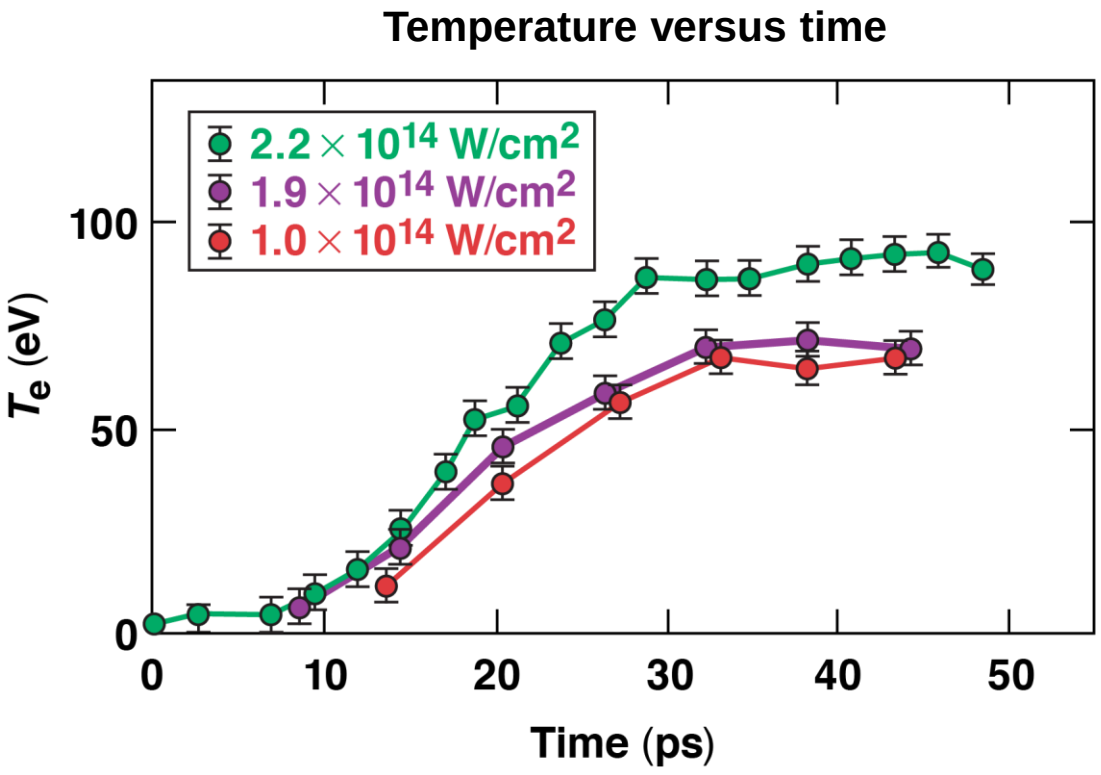


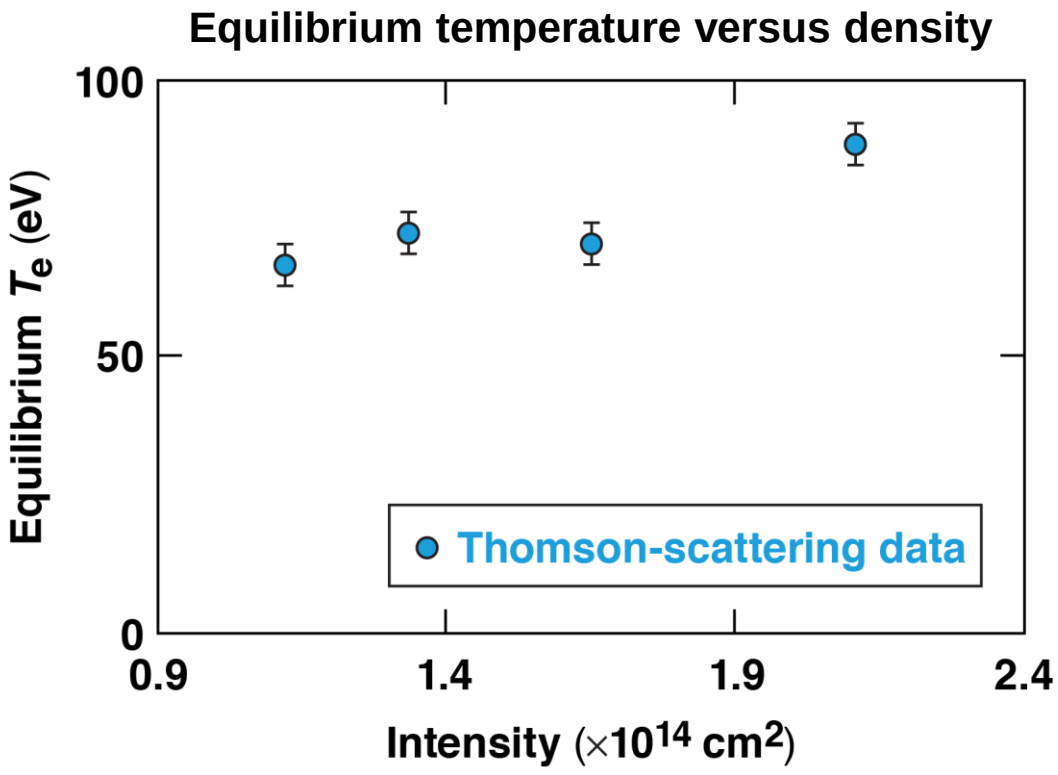
E28327

The plasma evolution was studied as a function of laser intensity for a plasma density of 1×10^{19} cm^{-3}



The electron heating rate and equilibrium temperature are found to modestly increase with higher laser intensities



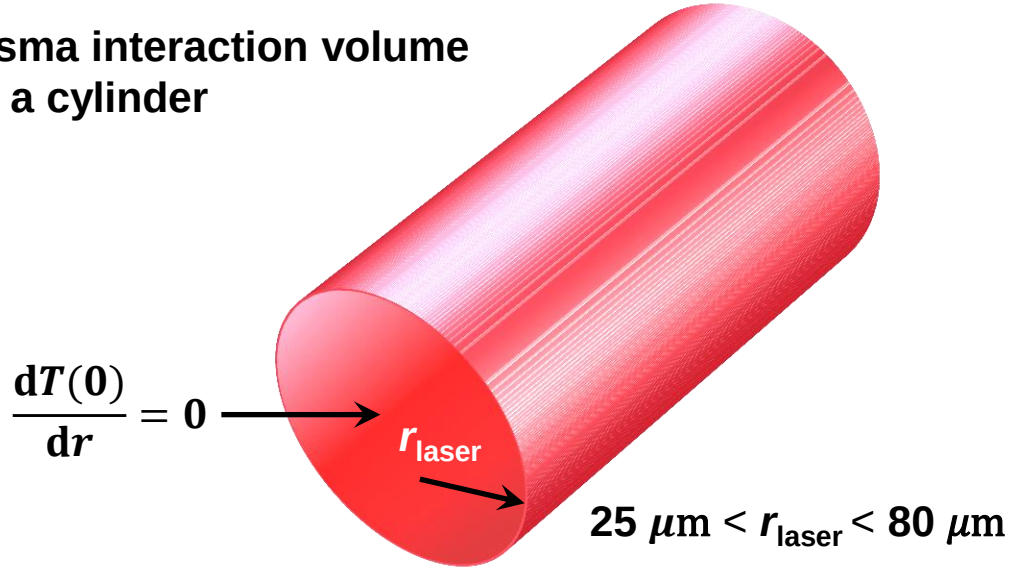


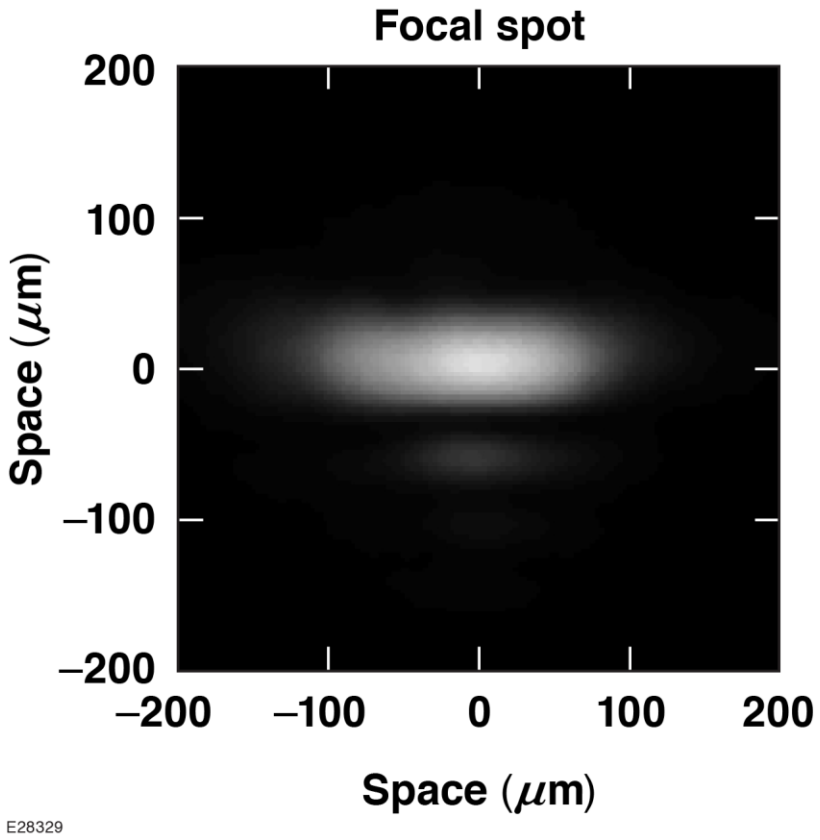
E28328a

The thermodynamics of the laser-plasma system can be modeled with the generalized heat equation

$$\underbrace{\frac{\partial}{\partial t}\left(\frac{3}{2}n_e k_B T_e\right)}_{\text{Energy density}} = \underbrace{\frac{\bar{v}_{ei}}{c}\frac{\omega_p^2}{\omega_0^2} I}_{\text{Laser heating}} + \underbrace{\nabla\left(k\nabla T_e\right)}_{\text{Heat conduction}} - \underbrace{3\frac{m_e}{m_i}\bar{v}_{ei} n_e k_B (T_e - T_i)}_{\text{Ion heating}}$$

The laser–plasma interaction volume approximates a cylinder





The thermodynamics of the laser-plasma system can be modeled with the generalized heat equation

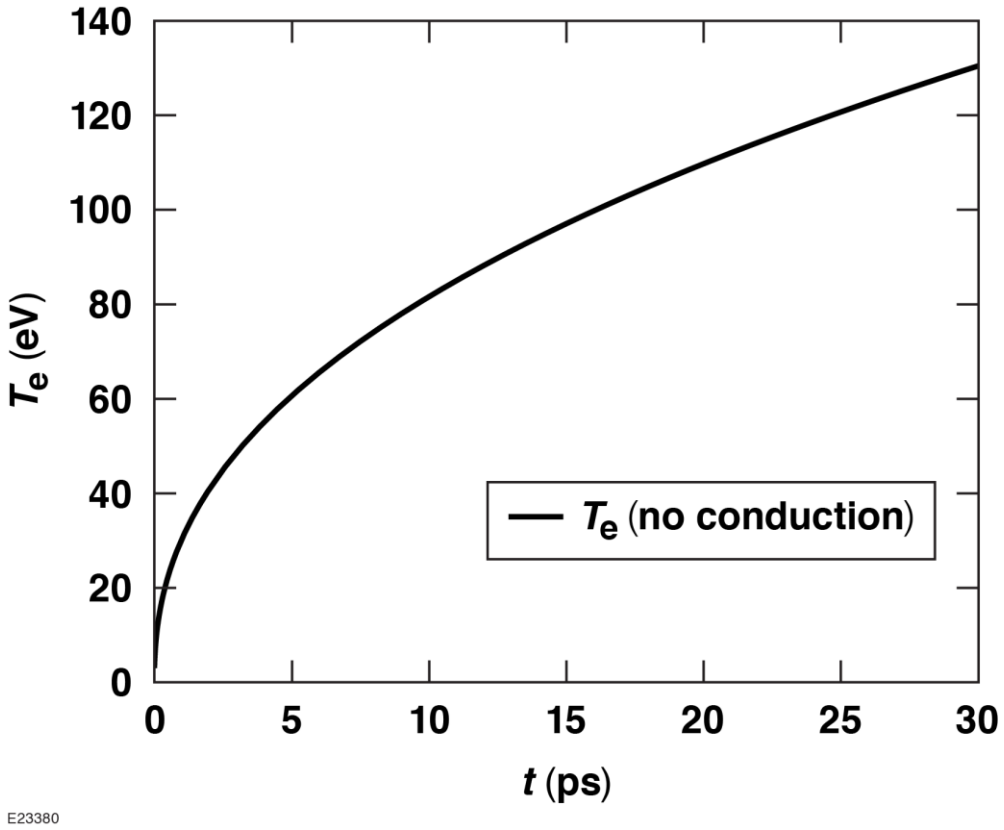
Energy density | Laser heating | Heat conduction | Ion heating

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e k_B T_e\right) = \frac{\bar{v}_{ei}}{c}\frac{\omega_p^2}{\omega_0^2} I + \cancel{\nabla\left(k\nabla T_e\right)} - \cancel{3\frac{m_e}{m_i}\bar{v}_{ei} n_e k_B (T_e - T_i)}$$

Time-dependent laser heating

$$k_B T_e = \left(\frac{\bar{v}_{ei}^{con}}{3 n_e c}\frac{\omega_p^2}{\omega_0^2} I\right)^{2/5} t^{2/5}$$

$n_e = 1 \times 10^{19}\ \mathrm{cm}^{-3}, I = 1.4 \times 10^{14}\ \mathrm{W/cm}^2$



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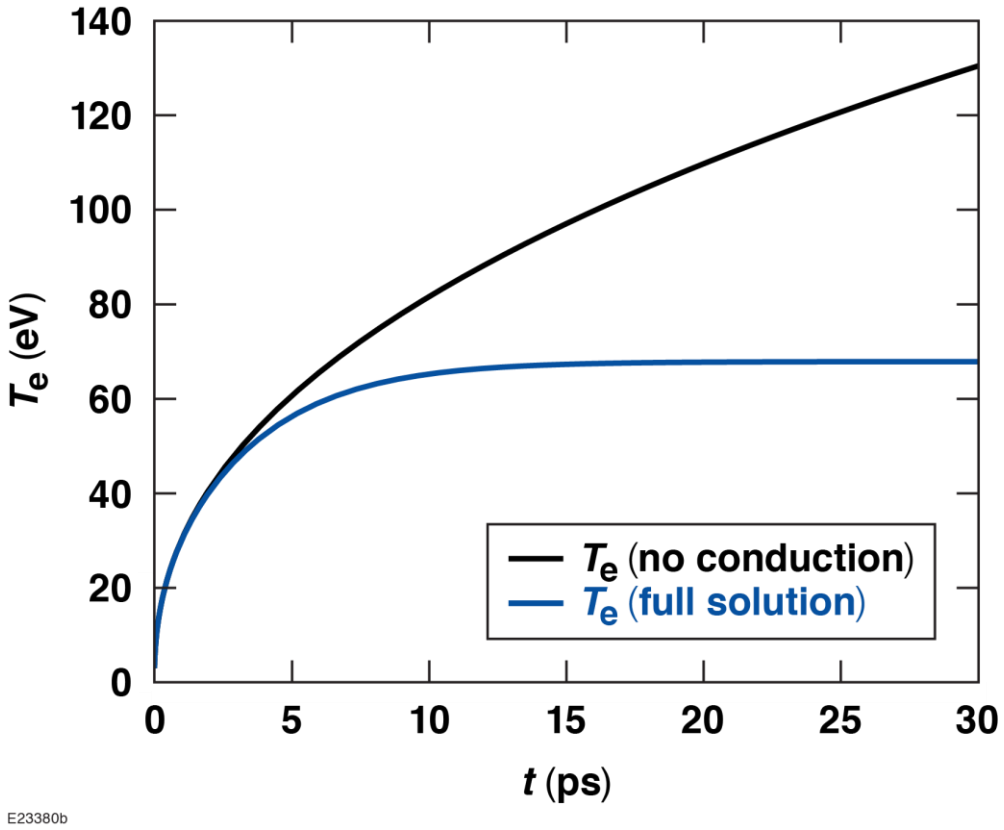

The thermodynamics of the laser-plasma system can be modeled with the generalized heat equation

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Equilibrium temperature

$$k_B T_e = \left(\frac{5}{4}\frac{r_0^2}{c}\frac{n_e Z^2 e^8 \ln(\Lambda)^2}{3.2\cdot 72\pi^3\varepsilon_0^4}\frac{\omega_p^2}{\omega_0^2}I\right)^{1/5}$$

$$k_B T_e \propto n_e^{2/5}$$

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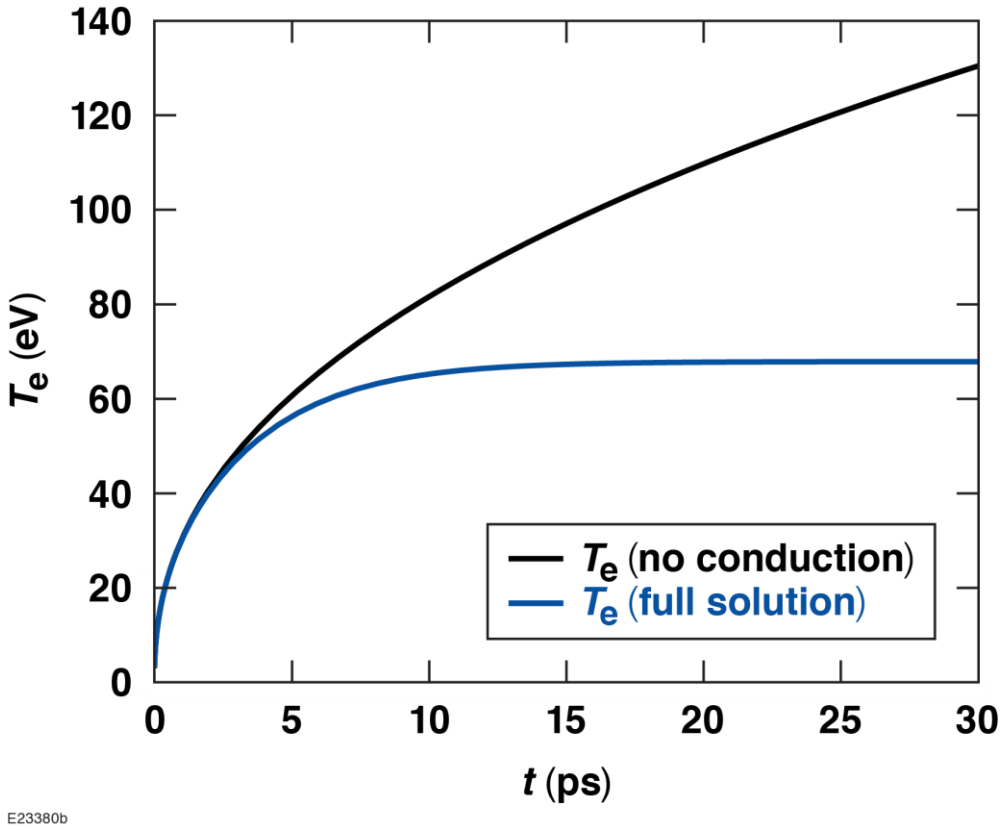

The electron equilibrium temperature as a function of density can be modeled with the heat equation

Equilibrium temperature

$$k_B T_e = \left(\frac{5}{4} \frac{r_0^2}{c} \frac{n_e Z^2 e^8 \ln(\Lambda)^2}{3.2 \cdot 72\pi^3 \varepsilon_0^4} \frac{\omega_p^2}{\omega_0^2} I \right)^{1/5}$$

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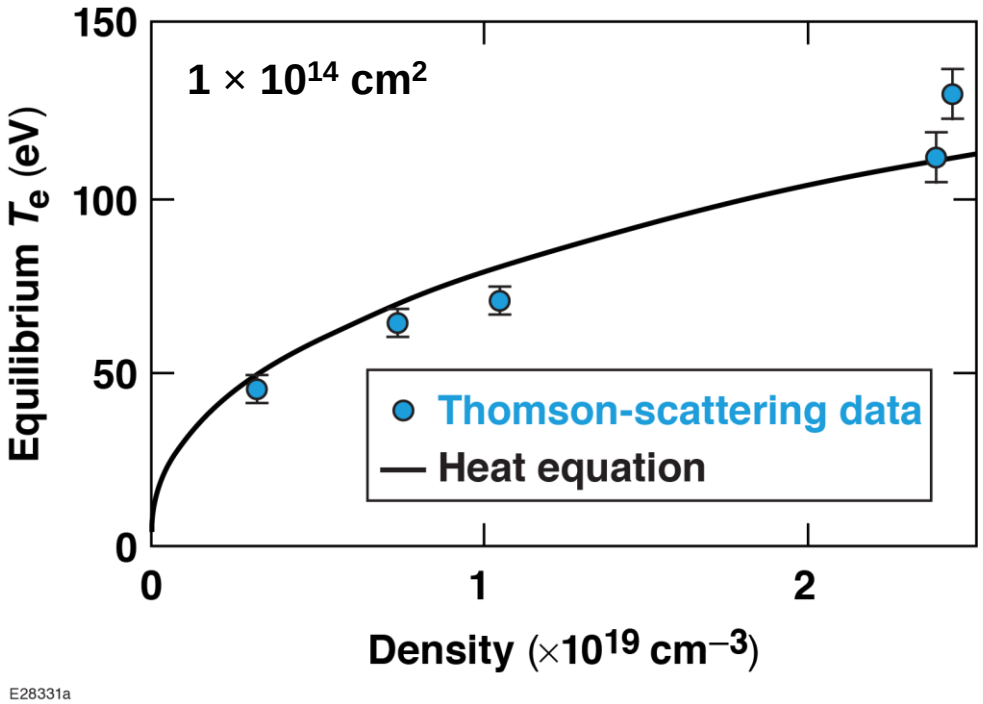


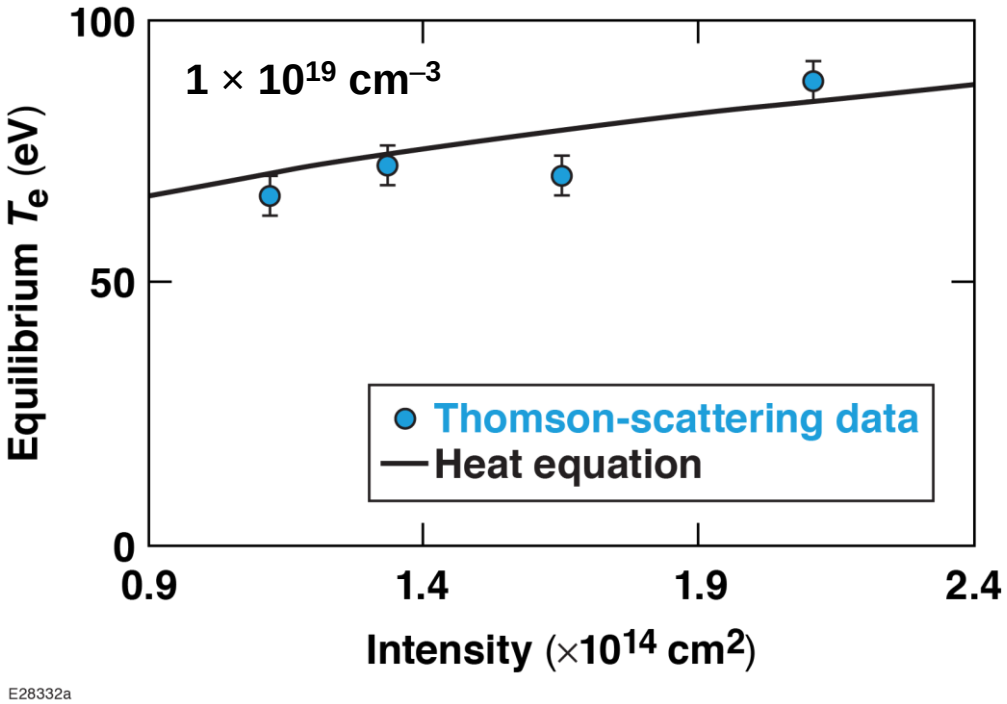
The measured equilibrium temperature and heat equation agree to within 15%.

The electron equilibrium temperature as a function of laser intensity can be modeled with the heat equation

Equilibrium temperature

$$k_B T_e = \left(\frac{5}{4} \frac{r_0^2}{c} \frac{n_e Z^2 e^8 \ln(\Lambda)^2}{3.2 \cdot 72\pi^3 \varepsilon_0^4} \frac{\omega_p^2}{\omega_0^2} I \right)^{1/5}$$

$$k_B T_e \propto I^{1/5}$$



The measured equilibrium temperature and heat equation are consistent.

Summary/Conclusions

Time-resolved Thomson scattering was used to measure the plasma creation and picosecond evolution of electron temperature and density

- A pulse-front–tilt-compensated streaked spectrometer was invented to measure the picosecond thermal and ionization dynamics
- For temperatures below ~35 eV, a collisional model was required to reproduce the measured spectrum
- Heat-equation calculations and measured equilibrium temperatures agree to within 15%
- The density-dependent electron heating rate and equilibrium temperature are found to evolve on a 25-ps time scale, resulting in Raman resonance detuning

A. S. Davies *et al.*, Phys. Rev. Lett. 122, 155001 (2019).

Backup

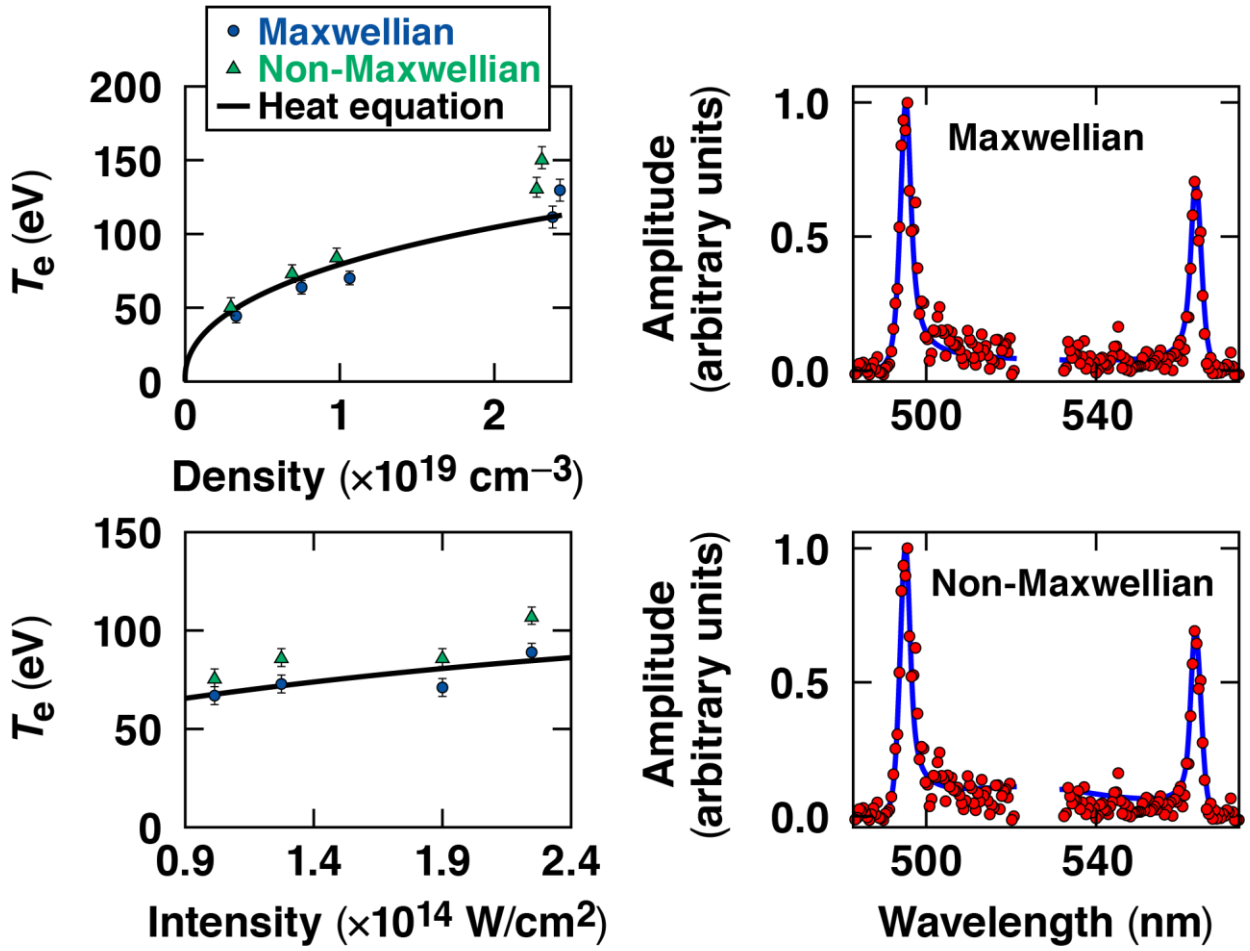
Langdon theory predicts non-Maxwellian ($m \sim 3$) distribution functions that are produced by inverse Bremsstrahlung heating

Langdon parameter

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

Super-Gaussian order

$$m(\alpha) = 2 + 3/\left(1 + 1.66/\alpha^{0.724}\right)$$



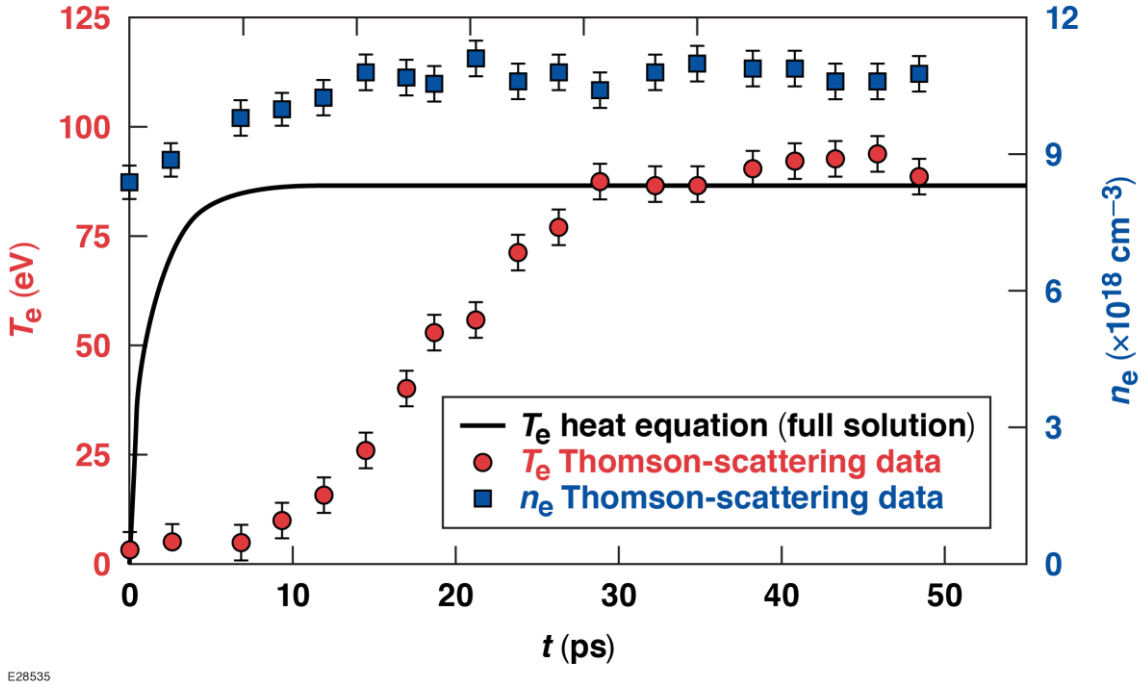
J. P. Matte *et al.*, Plasma Phys. Control. Fusion 30, 1665 (1988).

The plasma evolution was model with the heat equation and showed qualitative agreement with the measurements

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e k_B T_e\right) = \frac{\bar{v}_{ei}}{c}\frac{\omega_p^2}{\omega_0^2}I + \nabla\left(k\nabla T_e\right) - 3\frac{m_e}{m_i}\bar{v}_{ei}n_e k_B\left(T_e - T_i\right)$$

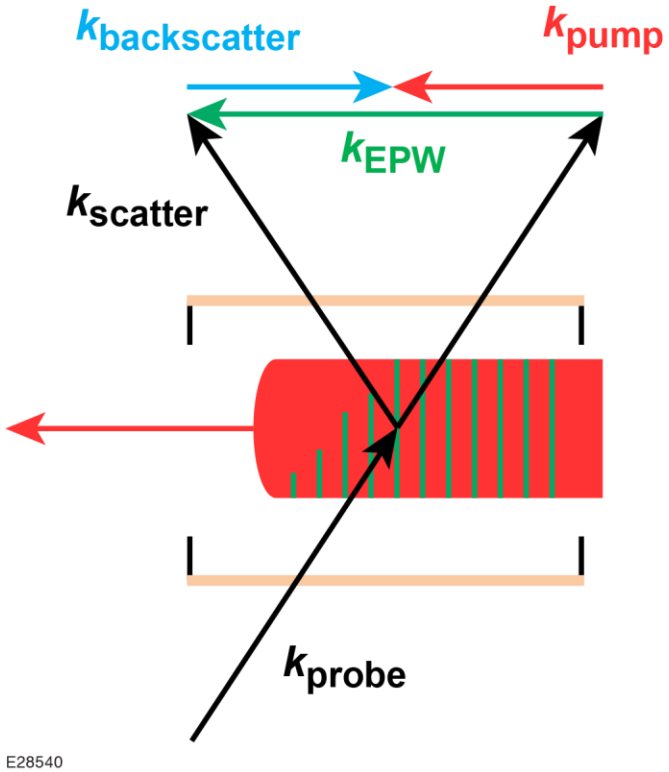
Time-dependent laser heating

$$k_B T_e = \left(\frac{\bar{v}_{ei}^{con}}{3n_e c}\frac{\omega_p^2}{\omega_0^2}I\right)^{2/5} t^{2/5}$$



The heat equation's equilibrium temperature showed good agreement with measurements but did not replicate the heating rate.

A dynamic Thomson-scattering diagnostic could measure the frequency and amplitude of driven electron plasma wave



$$\vec{k}_{\text{scatter}} = \vec{k}_{\text{probe}} + \vec{k}_{\text{EPW}}$$

$$\omega_{\text{scatter}} = \omega_{\text{probe}} + \omega_{\text{EPW}}$$

$$\omega_{\text{EPW}} = \omega_{\text{p}} \pm \Delta\omega_{\text{NL}}$$

Diffraction efficiency η for linear plasma waves

$$\eta = \sin^2 \frac{\pi L_{\text{p}} \frac{\Delta n_{\text{e}}}{2 n_{\text{c}}}}{\sqrt{\lambda_{\text{probe}} \lambda_{\text{scatter}}} \cos\theta}$$

These experiments would quantify the effects of trapping ($\Delta\omega_{\text{NL}}$) and the wavebreaking threshold in a well-characterized plasma.