# Picosecond-Resolved Collective Thomson Scattering in Underdense Collisional Plasmas


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Summary/Motivation

## A principal difficulty in accurate descriptions of basic plasma processes is uncertain plasma thermal dynamics

- A pulse-front–tilt compensated streaked spectrometer was utilized for the first time to measure the underdense plasma thermal dynamics
- To fit the data for electron temperatures below ~30 eV, collisions must be included into the Thomson scattering simulation using the Bhatnagar–Gross–Krook (BGK) model
- The electron temperature was observed to rise from an initial 5 eV to 20 eV in 20 ps. Over this time the density increases from $0.8 \times 10^{19}$ $cm^{-3}$ to its plateau at $1.1 \times 10^{19}$ $cm^{-3}$
- The electron temperature was observed to plateau at ~100 eV after 40 ps


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## Thomson scattering at high temperatures is dominated by Landau damping and can be approximated as collisionless

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

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

Laplace transform variable

Collisionless: $\lim_{\gamma\to 0}(\chi_e)$

Collisional velocity dependent: $\gamma(v)$

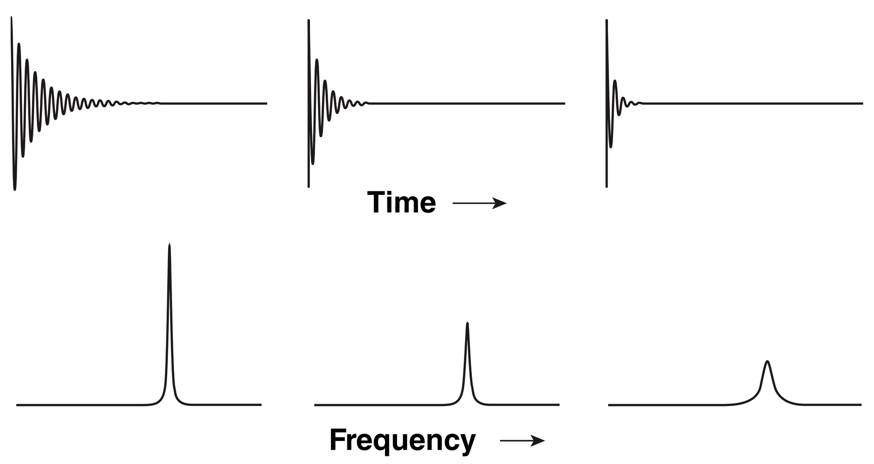
In the $\lim_{\gamma\to 0}(\chi_e)$, it can be shown that

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

where

$$x_e = \frac{w}{ak} \qquad a = \sqrt{\frac{2kT_e}{m_e}} \qquad \alpha = \frac{1}{k\lambda_{De}}$$

Damping in time causes spectral widening and lower spectral peaks

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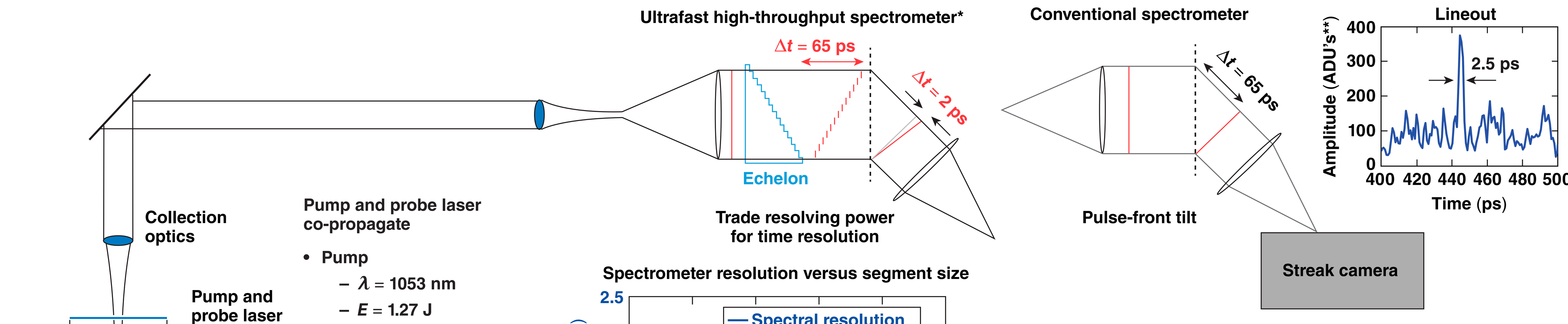
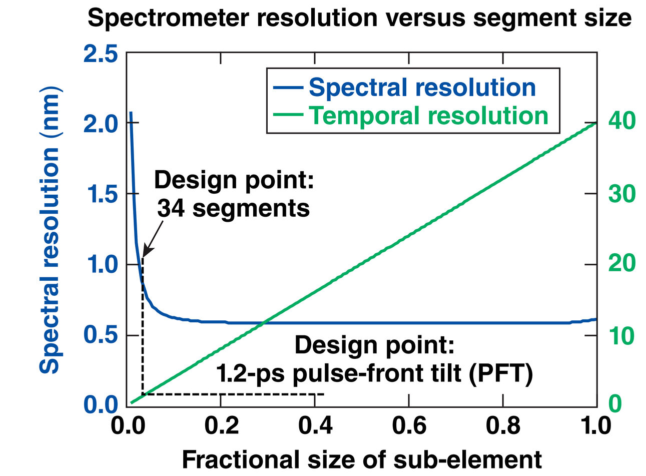


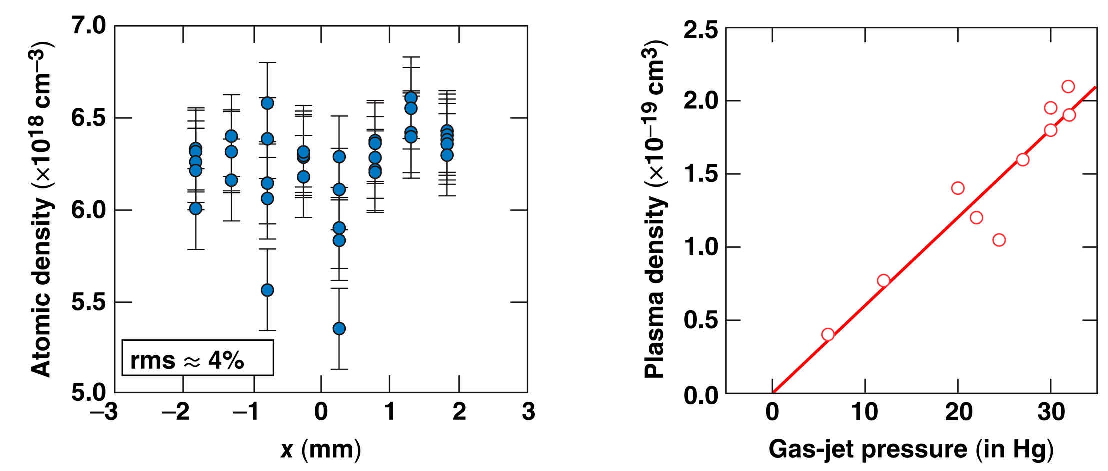

$$\delta\lambda = \frac{d\beta}{d\lambda}FL\sqrt{OBJ^2 + GEO^2 + DIF^2 + SC^2}$$

| Spot size parameter | Typical size ($\mu$m) |
|---|---|
| Object size | 50 |
| Geometric aberrations | 15 |
| Diffraction limit | 2.5 |
| Streak camera | 40 |

$$\Delta t = \frac{N\lambda}{c} \qquad \Re = \frac{\lambda}{\Delta\lambda} = N = G \times d \qquad \Delta t\Delta\lambda = \frac{\lambda^2}{c}$$

$$dt_{corrected} = \frac{dt}{n}$$

| | Resolving power | G (ll/mm) | dx/dλ (mm/nm) | d (mm) | f# | Δt (ps) |
|---|---|---|---|---|---|---|
| Conventional | 20,000 (0.025 nm) | 300 | 0.125 | 65 | 5 | 65 |
| Ultrafast | 600 (1 nm) | 300 | 0.125 | 2 | 5 | 2 |




Interferometry indicates a neutral gas uniformity of less than 4% rms.

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*J. Katz *et al.*, Rev. Sci. Instrum. 87, 11E535 (2016).
**ADU: Analog-to-digital unit

## The collisional dielectric function, $\epsilon(\vec{k}, \omega)$, can be solved in an analogous manner to the collisionless case except it requires two inputs: $x_e$ and $y_e$

Velocity-dependent BGK mode

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

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

It can be shown that the dielectric function reduces to

$$\epsilon^{BGK} = 1 + \frac{32e^2 n_e \pi^{1/2}}{m_e a^2 k^2}\int du\, u^2 e^{-u^2}\left\{1 - Y(u)\coth^{-1}[Y(u)]\right\},$$

where

$$a = \sqrt{\frac{2kT_e}{m_e}} \qquad u = \frac{v}{a} \qquad Y(u) = \frac{1}{u}\left(x_e + i\frac{y_e}{u^3}\right)$$

Landau damping

$$x_e = \frac{w}{ak}$$

Collisional damping

$$y_e = \frac{Z\ln(\Lambda_{ei})n_e}{a^4 k}$$

This function has collisional damping at low temperatures and Landau damping at high temperatures.

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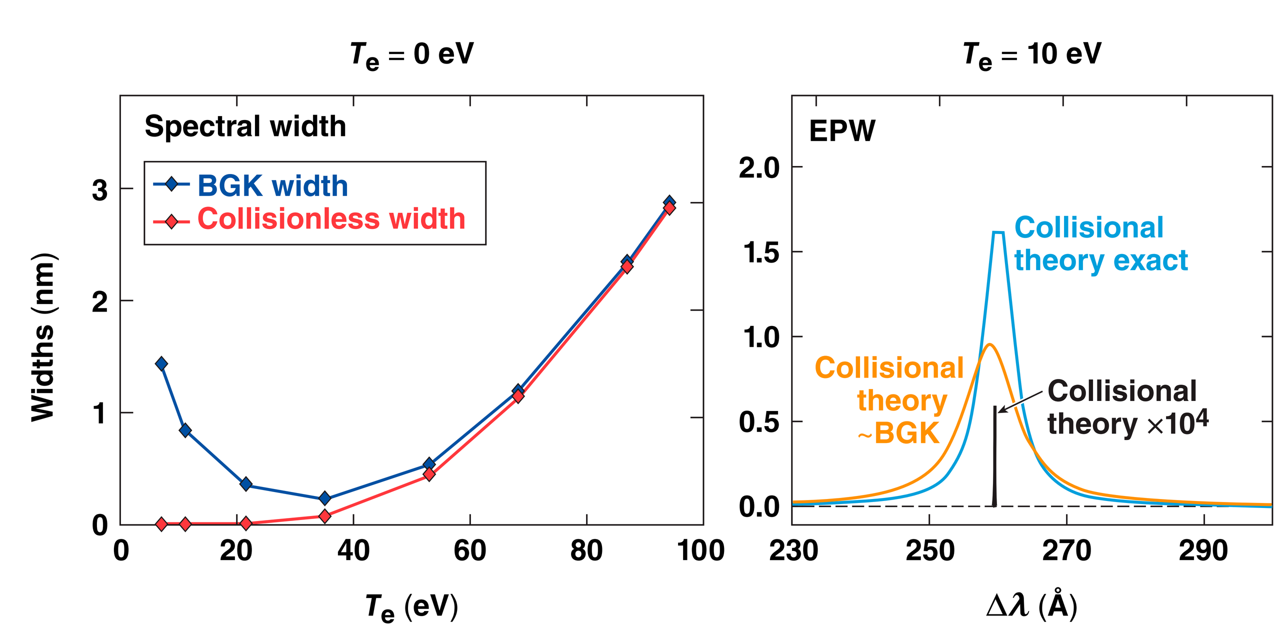
## The Thomson scattering peak width of the BGK and collisonless model diverge for electron temperatures below ~30 eV

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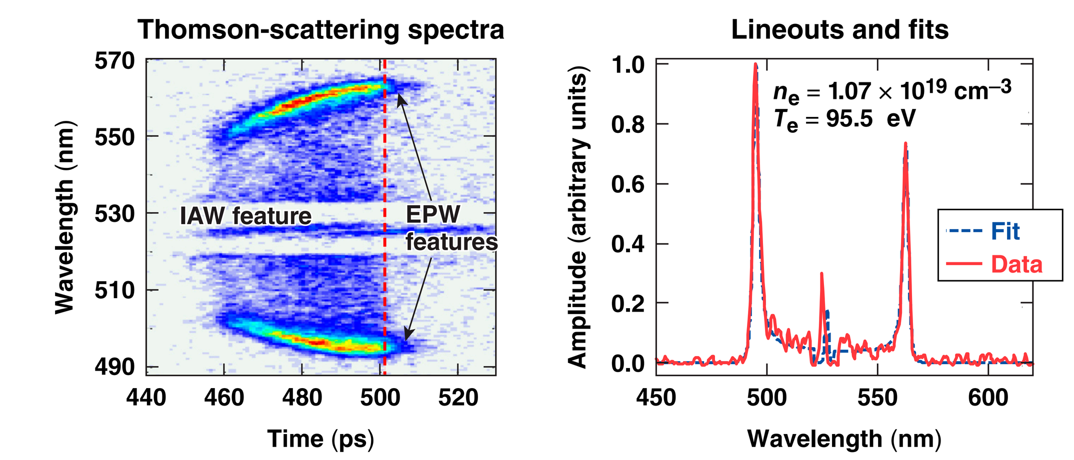
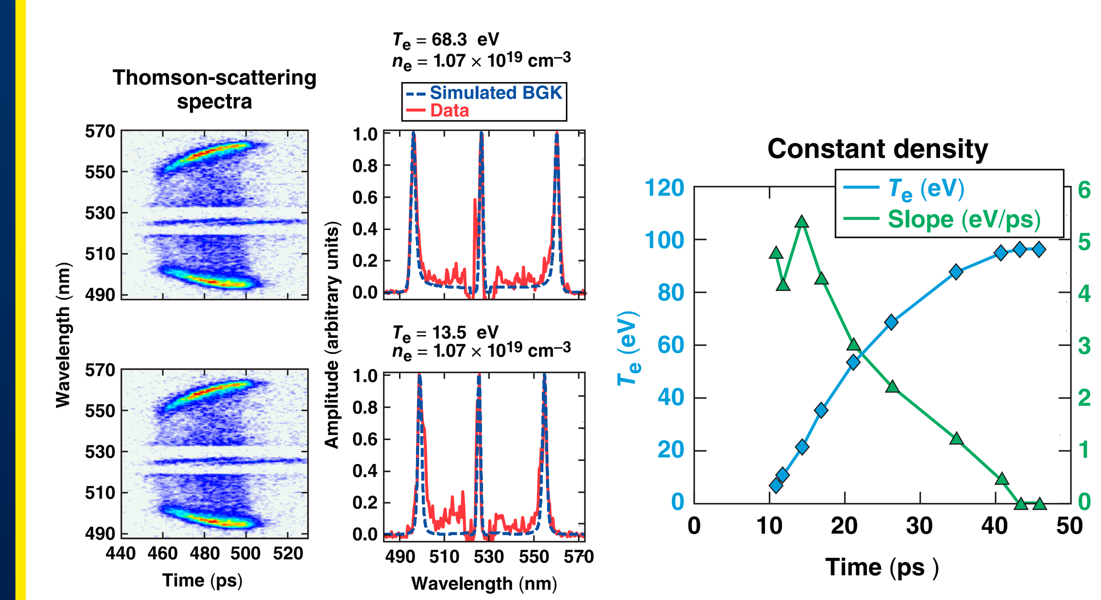
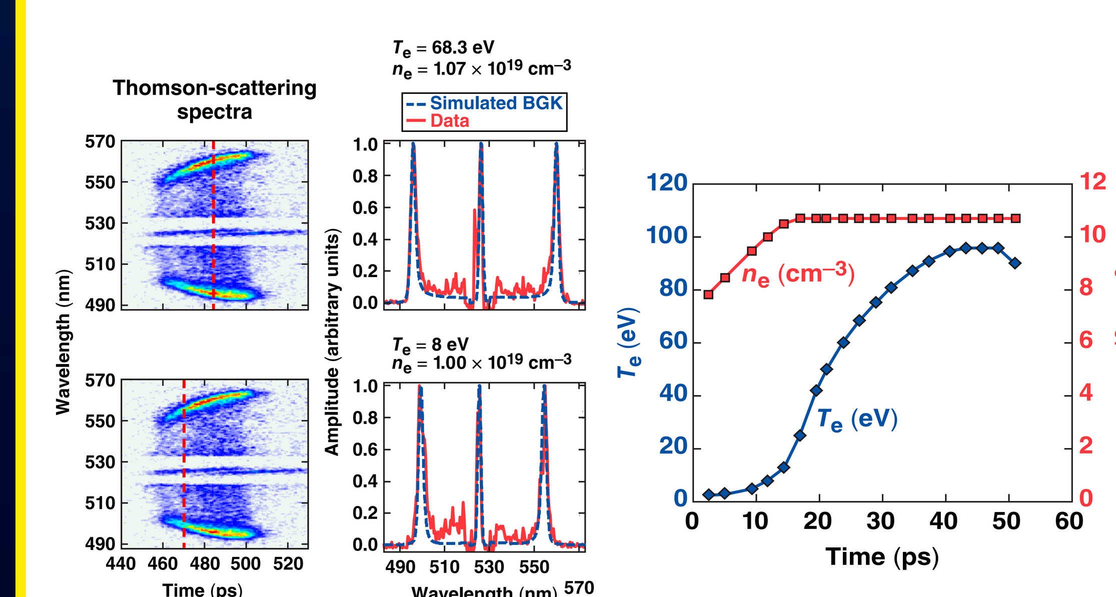
## The Thomson-scattering data were fit late in time to find both the electron temperature and density




## The spectra are then fit for a second time taking into account the effects of temporal temperature gradients using the heating rate from the first fit

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