Dynamics of Optical-Field Ionized Helium Plasmas

C. K. Huang, C. J. Zhang, K. A. Marsh, C. E. Clayton, W. B. Mori and C. Joshi

University of California Los Angeles, Los Angeles, CA 90095, USA

UCLA

Abstract

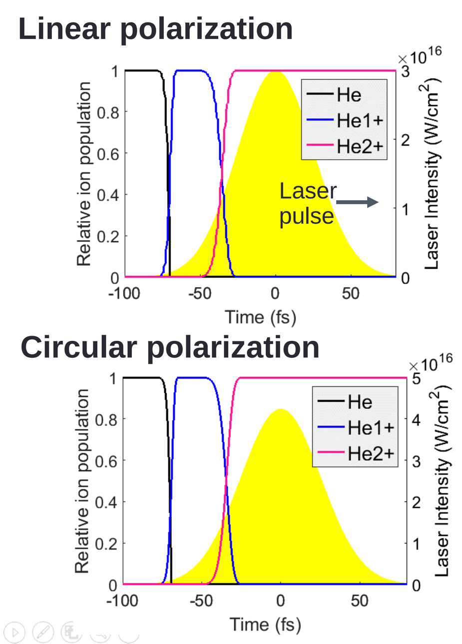
One unique feature of optical-field ionization (OFI) plasmas is that distinct non-Maxwellian electron distribution functions can be initiated by intense laser ionization of neutral gases depending on the laser polarization. In this work, we apply various Thomson scattering techniques to probe the evolution of optical-ionized helium plasmas produced by linearly and circularly polarized pulses. Polarization-dependent initial distributions have been inferred from collinearly-probe Thomson scattering of a second-harmonic probing pulse generated from a KDP crystal. A 90-degree probe Thomson scattering system with changeable wavelengths has been set up to probe plasma modes induced by nonequilibrium plasmas. Finally, we measured the plasma temperatures after the plasma become isotropic by fitting time-resolved scattering spectra. The results indicate the thermalization process of OFI helium plasmas involves the combination of collective plasma effects and collisions.

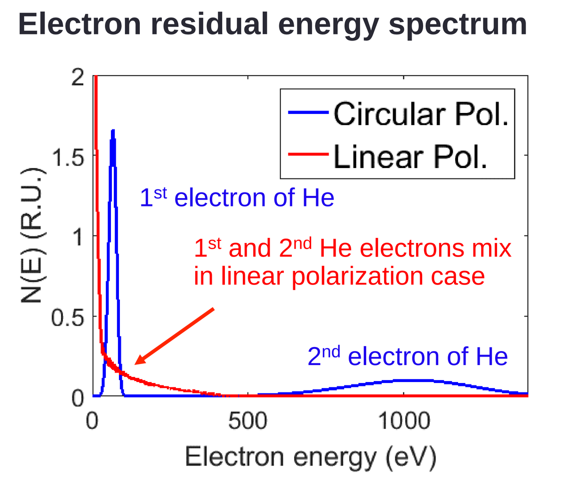
Introduction

When a high residual energy from tunnel ionization degas is ionized by an intense laser pulse, the plasma electrons can get very pending on the polarization of the incident laser pulse.

Energetic electrons emitted from optical-field ionized atoms have been measured in the past. However, no direct measurements of the resultant non-thermal electron distribution function in a high density plasma have been made.

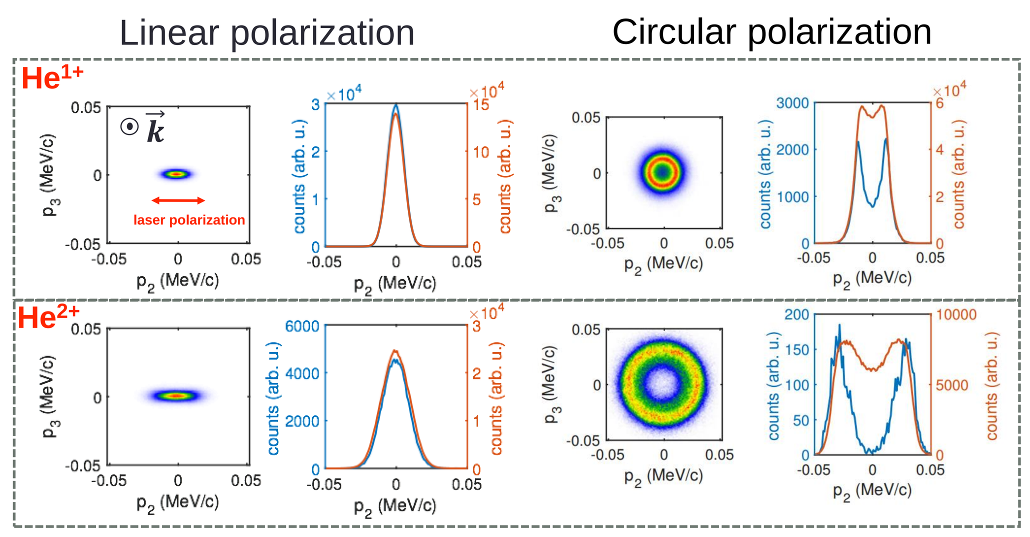
Electron Distribution of Helium Plasma from Tunnel Ionization : Quasi-classical Theory





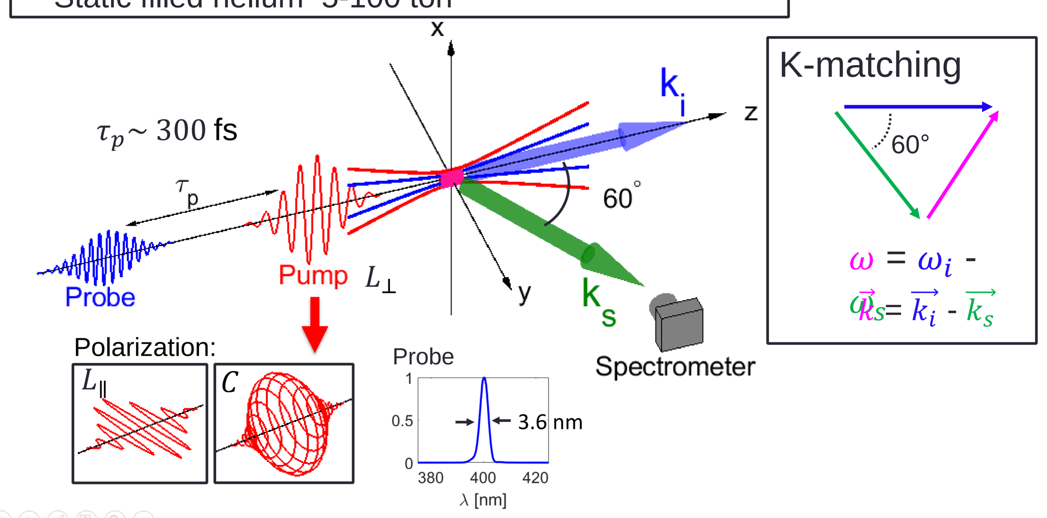
1. P. B. Corkum et. al., PRL **62**, 1259 (1989)
2. U. Mohideen et. al., PRL **71**, 509 (1993)

Expected Electron Distribution in a Helium Plasma: Osiris PIC Simulation



Determine the initial state of the plasma: Collinearly-probe Thomson scattering

Experiment parameters:
Pump: 0.8 μm, energy~10 mJ , τ_{FWHM}~50 fs, a_0~0.2
Probe: 0.4 μm, energy~1.5 mJ, τ_{FWHM}~50 fs
Static filled helium 5-100 torr



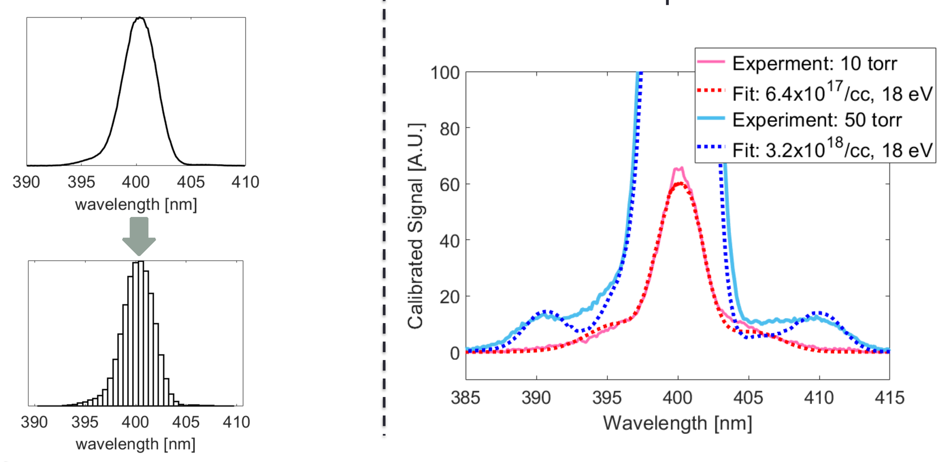
Fitting the initial distribution using Thomson scattering theory for Maxwellian plasmas

TS spectral density function:

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

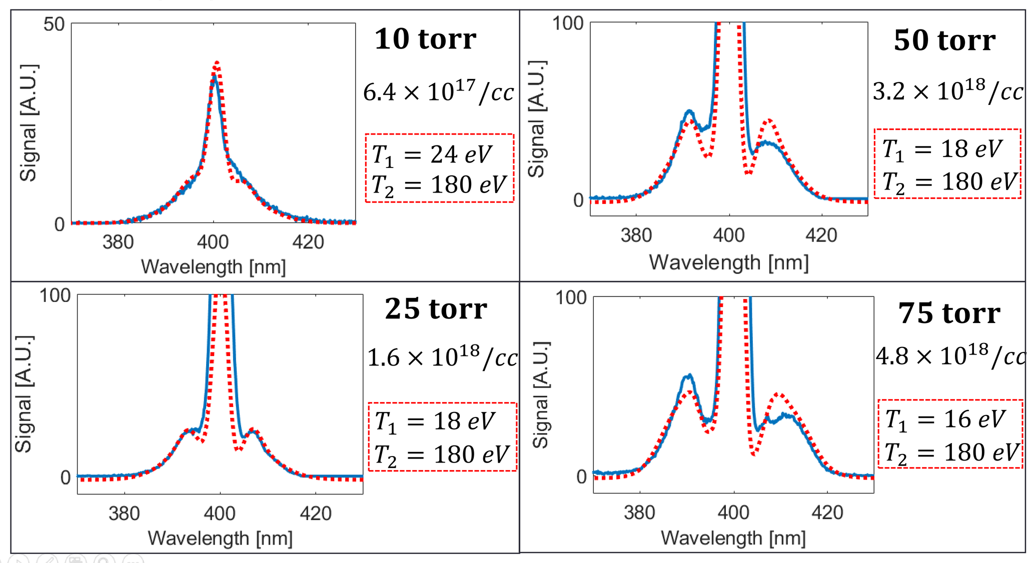
$$S(\mathbf{k},\omega) \propto \sum_n W_n S_n(\mathbf{k},\omega)$$

For $L_\perp$ polarization, most of the electrons momentum will distribute perpendicular to the scattering plane. The scattering spectra resemble to the ones from cold plasmas.



Fitting for slightly non-Maxwellian plasmas: Linear polarization in scattering plane

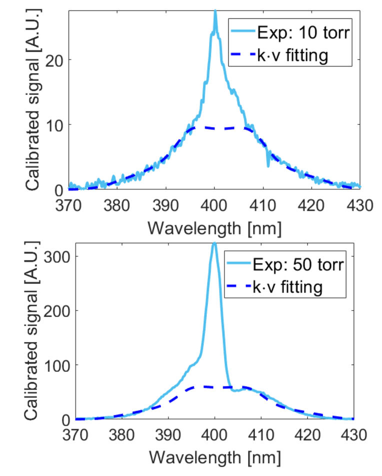
For $L_\parallel$ polarization, the first electron and the second electron will distribute in Maxwellian respectively, we can apply this distribution to spectral density function S(k,ω).



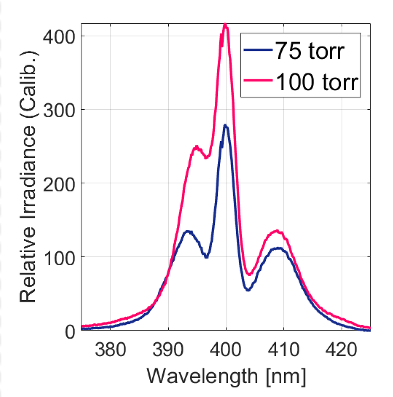
Fitting for strongly non-Maxwellian plasmas: Circular polarization

Circular polarization will yield electrons with high momentum, forming a plasma deviated far from Maxwellian distribution.

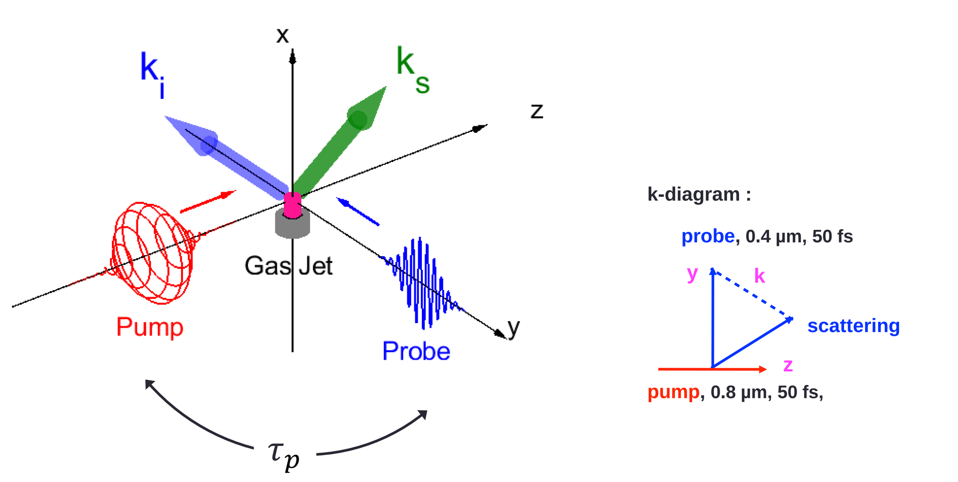
For low densities, fitting with the velocity distribution from simulations.



For high densities, the k·v fitting does not work at all.

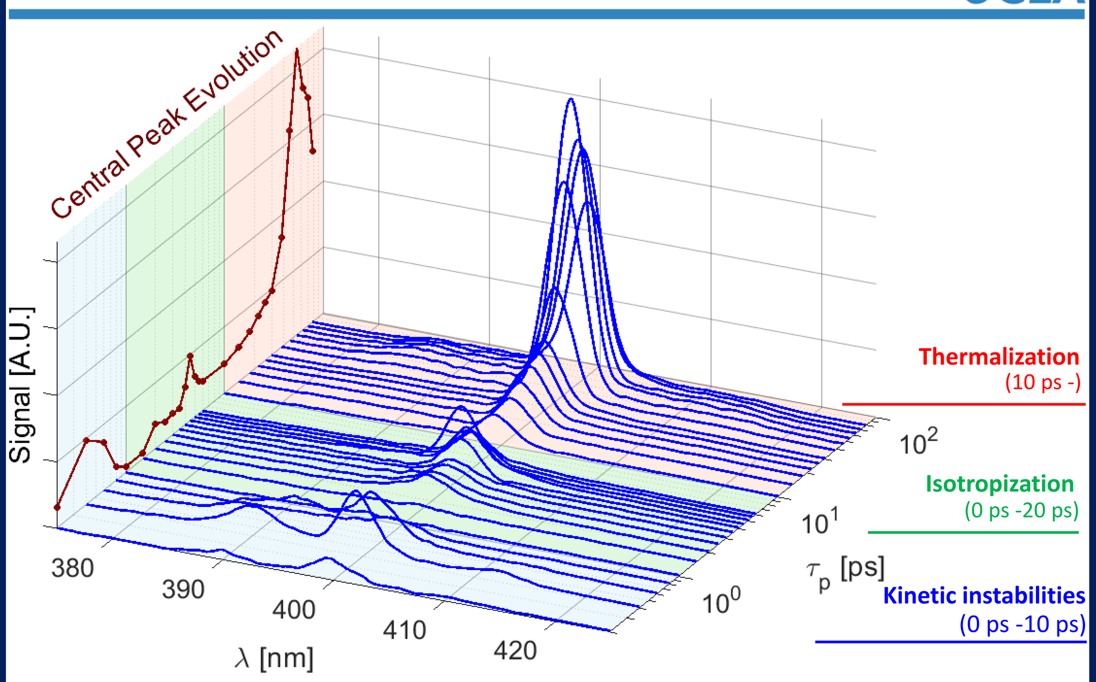


Thomson scattering setup for measuring plasma evolution



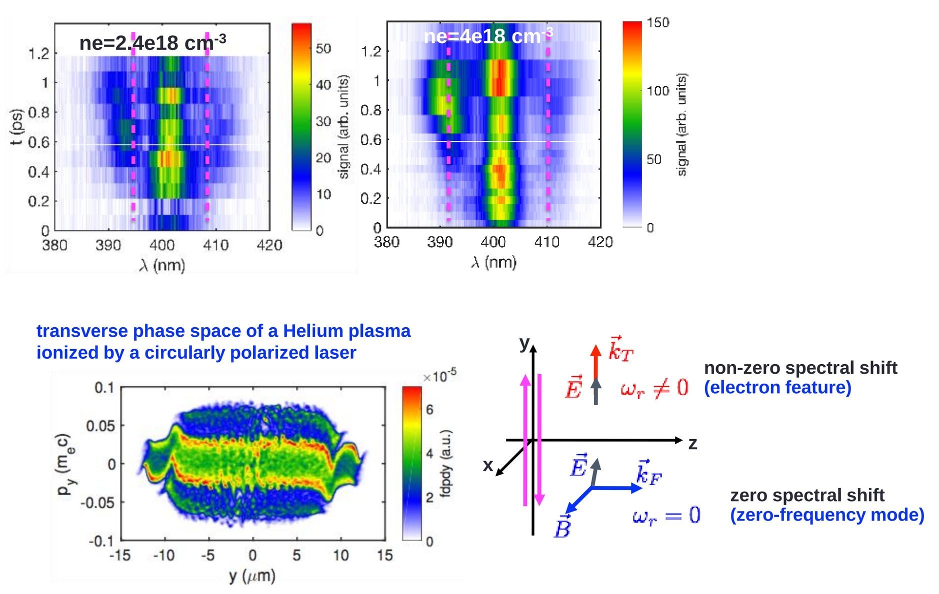
τ_p is controlled by a delay line, maximum delay is 100 ps

TS Spectral evolution for the plasma generated by a circularly polarized pump

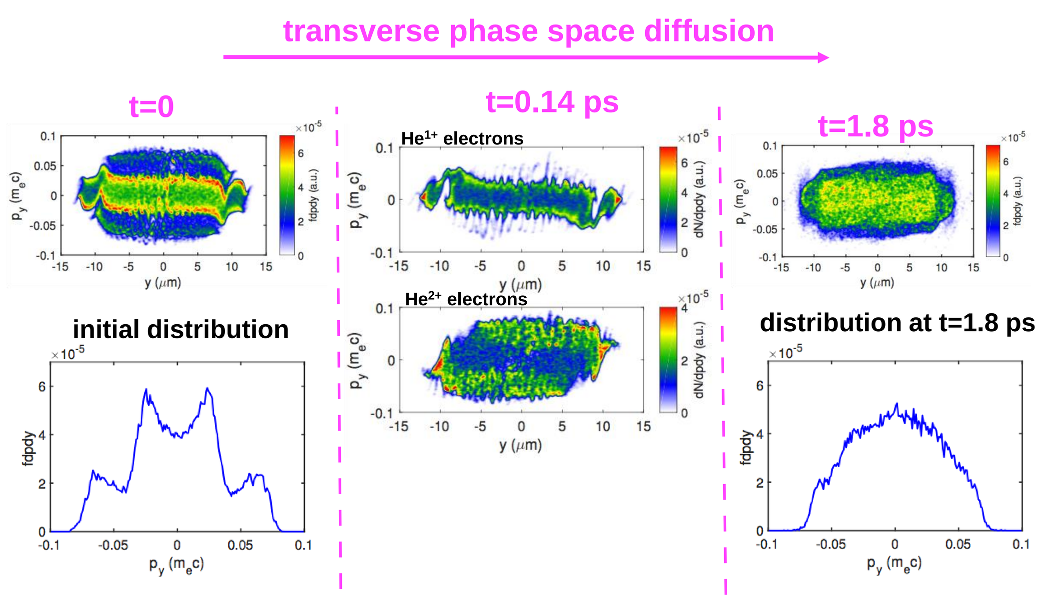


Each line represents averaged spectrum, Backing pressure: 150 psi

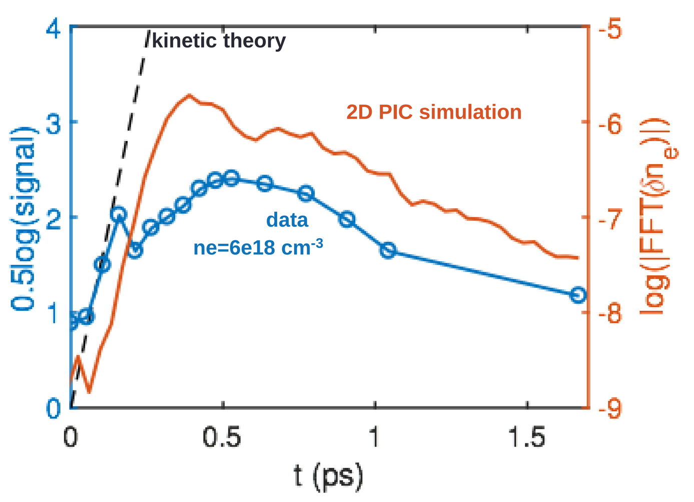
Kinetic instabilities in OFI plasmas



Transverse phase space diffusion caused by two-stream instability

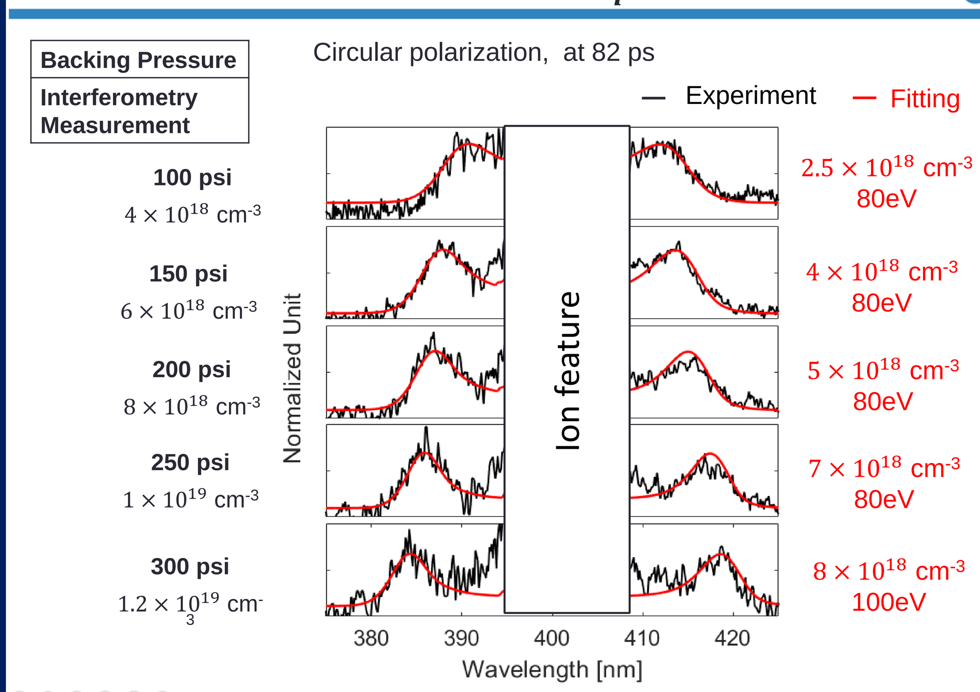


Nonlinear stage of the two-stream instability

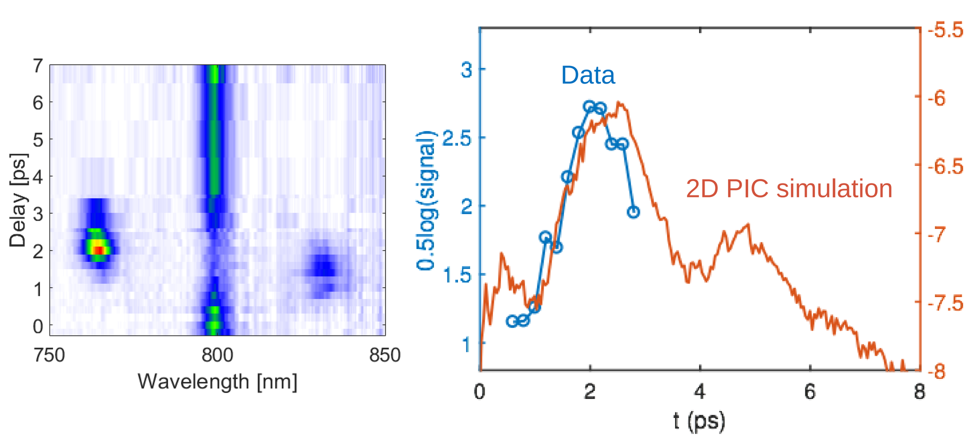


- The two-stream instability reaches saturation at ≈0.5 ps
- Then quickly damps in ~1 ps through Landau damping
- The overall evolution of the measured data agrees well with the 2D simulation (fully kinetic theory)

Electron feature of Thomson scattering spectra can be fitted at latter delays ($\tau_p > \sim40$ ps)



Kinetic instabilities for linear polarization



- saturates at t≈2 ps (t≈0.5 ps in the CP case)
- signal lasts for a slightly longer time
- different mechanism of generating counter-streaming beams

Conclusions

- Thomson scattering of a ultrashort probe pulse has shown to be an effective tool to study the plasma instabilities as well as plasma evolution with sub-picosecond temporal resolution.
- Polarization-dependent initial distributions have been measured.
- The evolution of OFI plasma generated by circularly polarized pulses involves the development of kinetic instabilities which rapidly isotropize plasmas.

2018 Advanced Accelerator Concepts

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