Characterization of the Plasma Generated by Compact Theta Pinch

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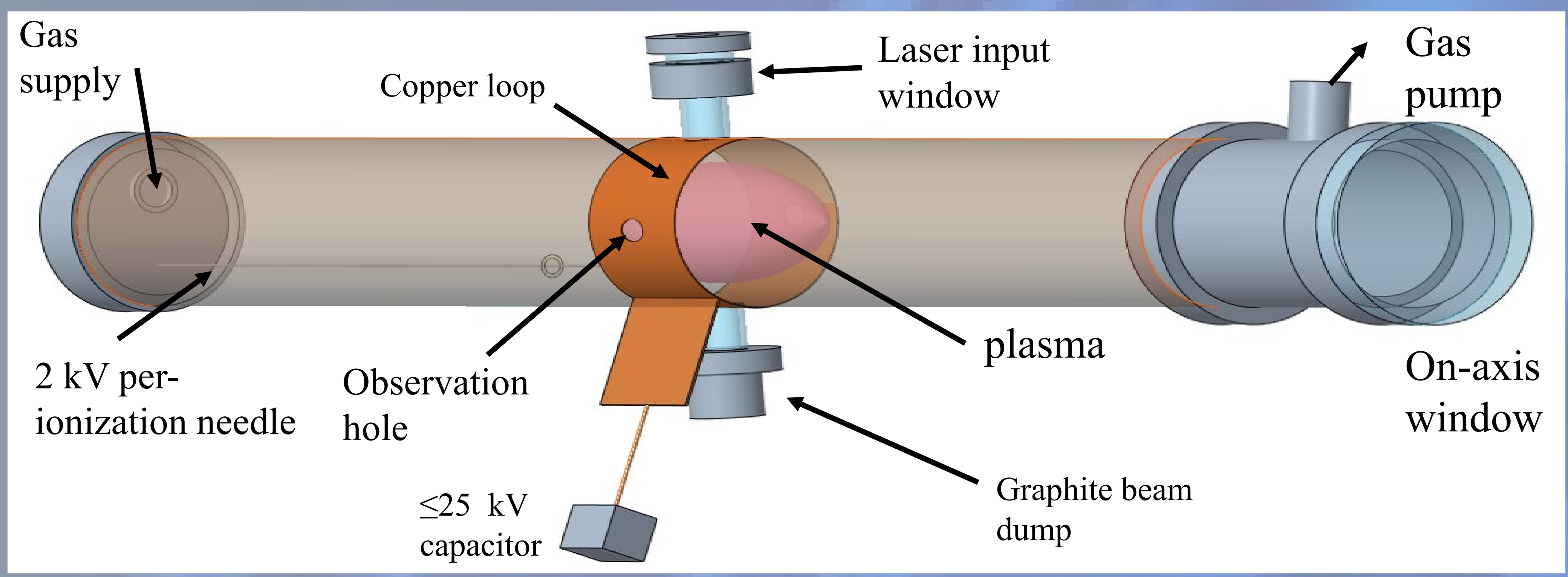
Abstract

Theta pinch is a well-known approach applicable for inertial fusion research. The theta pinch operation is based on plasma generation through gas ionization by induced electric field. The plasma radial compression occurs due to self-magnetic field pressure produced by an azimuthally driving current induced by the inductive coupling with a primary source. As a primary power supply, in our research, we use a 0.88 μF capacitor charged to 19 kV. This capacitor is discharged to a single loop, encompassing a glass tube filled with either hydrogen or helium gas, producing underdamped discharge with 0.7 μs rise-time and a peak current of 28 kA. We report on time- and space-resolved parameters of the hydrogen and helium plasmas during it compression which are obtained using frame images of the plasma light emission, microwave cut-off, laser interferometry, plasma spectroscopy, Thompson scattering and Laser induced fluorescence at pressures in the range of $0.1-3$ Torr.

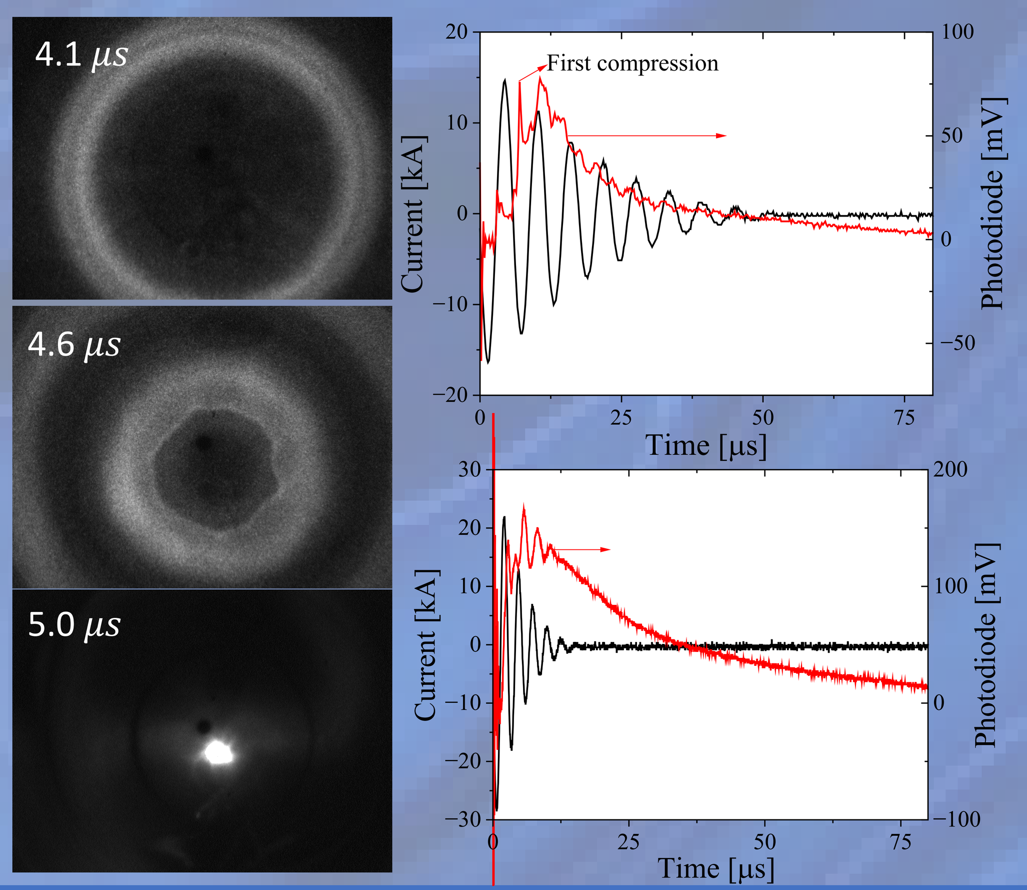


Theta pinch setup

Ionization occurs due to the induced azimuthal electric field which accelerate free electrons of pre-ionized gas resulting in avalanching process. The plasma is compressed to the center of the tube due to magnetic field pressure.
Observation windows and input and output openings were designed to allow different non-perturbative measurement methods of plasma parameters, which are crucial for fusion reactor research.

Plasma light emission and the discharge current time evolution

- Measurement of the discharge current and plasma light emission by a photo-diode for 1-loop and 3-loop schemes.
- A 10-ns duration images of the plasma light emission taken from the on-axis window helps us to understand plasma dynamics.



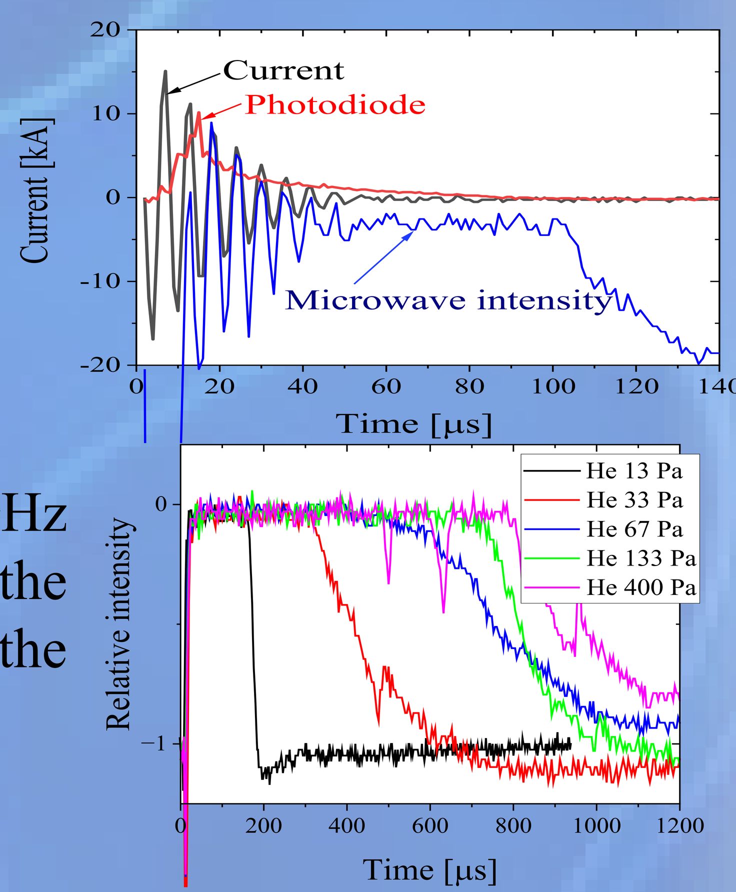
Microwave cutoff

E/m wave dispersion relation:

$$c^2k^2 = \omega^2 - \omega_p^2$$

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$$

Measuring the intensity of a 70 GHz microwaves propagating through the plasma shows the life time of the plasma with electron density: $\geq 5 \cdot 10^{13}\ cm^{-3}$



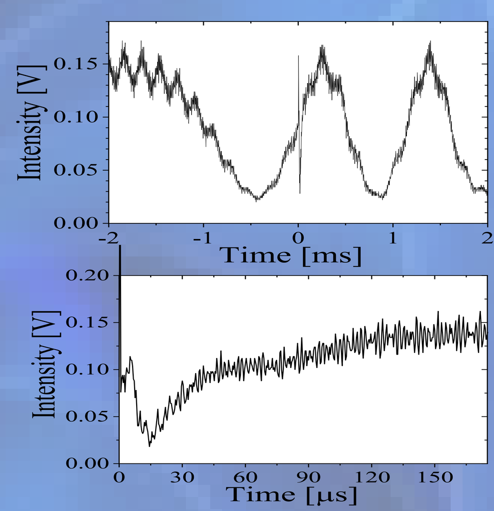
Spectroscopy

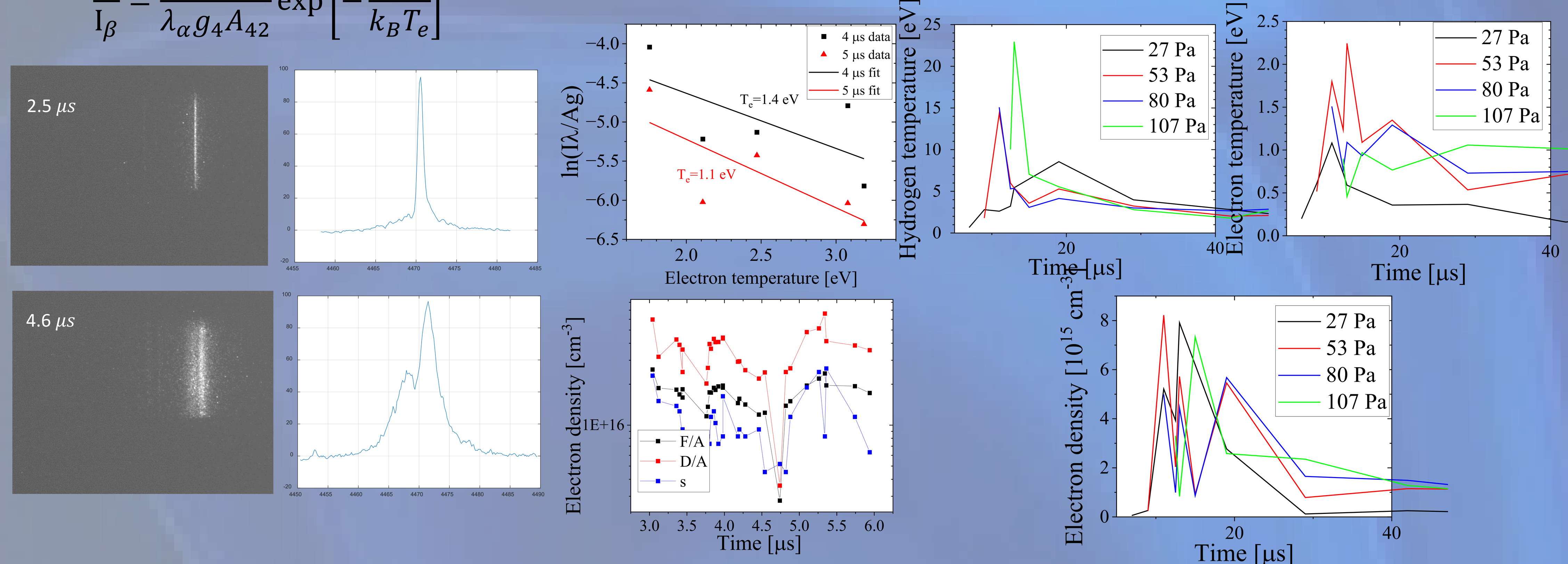
Light emission from the plasma is focused into a spectrometer and recorded at its output by a fast framing camera. Line broadening and intensity of the H_α and H_β and several He I lines allows estimation of the plasma ion and electron temperatures and density.

$$n_e = 10^{-17}\left(\frac{\Delta\lambda_S^{FWHM}}{48}\right)^{1.46808}\ [cm^{-3}]$$

$$\log n_e[m^{-3}] = 22.563 + 1.658\log\left(\frac{F}{A}\right) + 0.257\left[\log\left(\frac{F}{A}\right)\right]^2$$

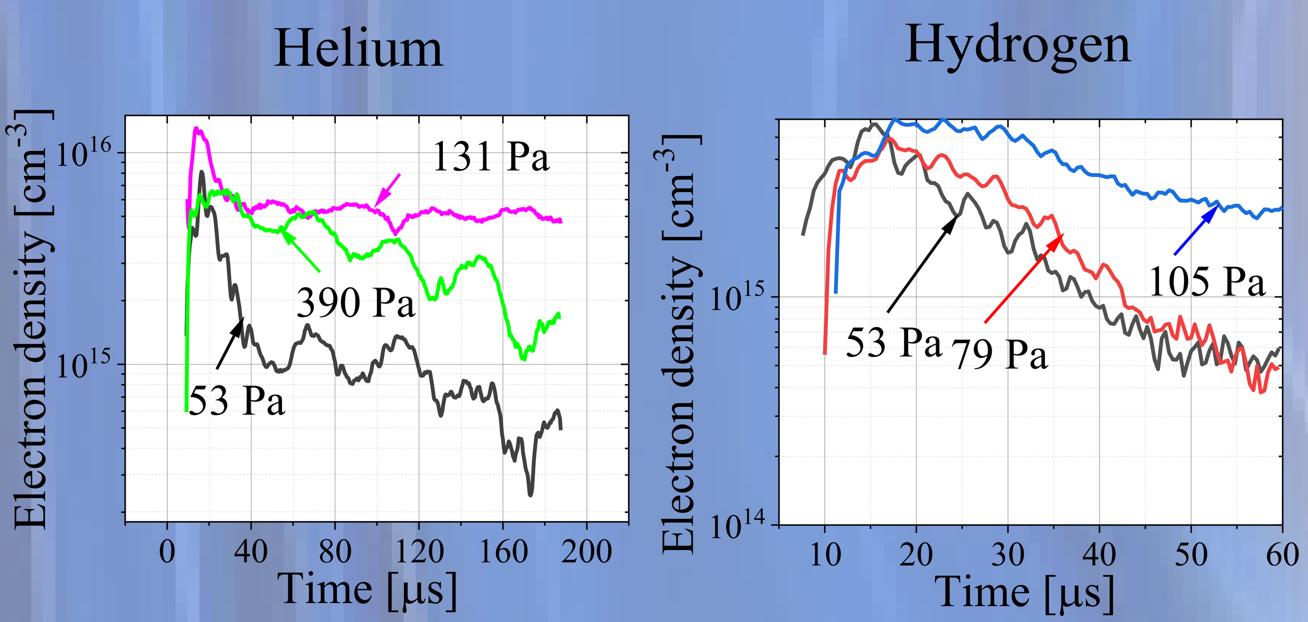
$$\frac{I_\alpha}{I_\beta} = \frac{\lambda_\beta g_3 A_{32}}{\lambda_\alpha g_4 A_{42}}\exp\left[-\frac{\Delta E}{k_B T_e}\right]$$





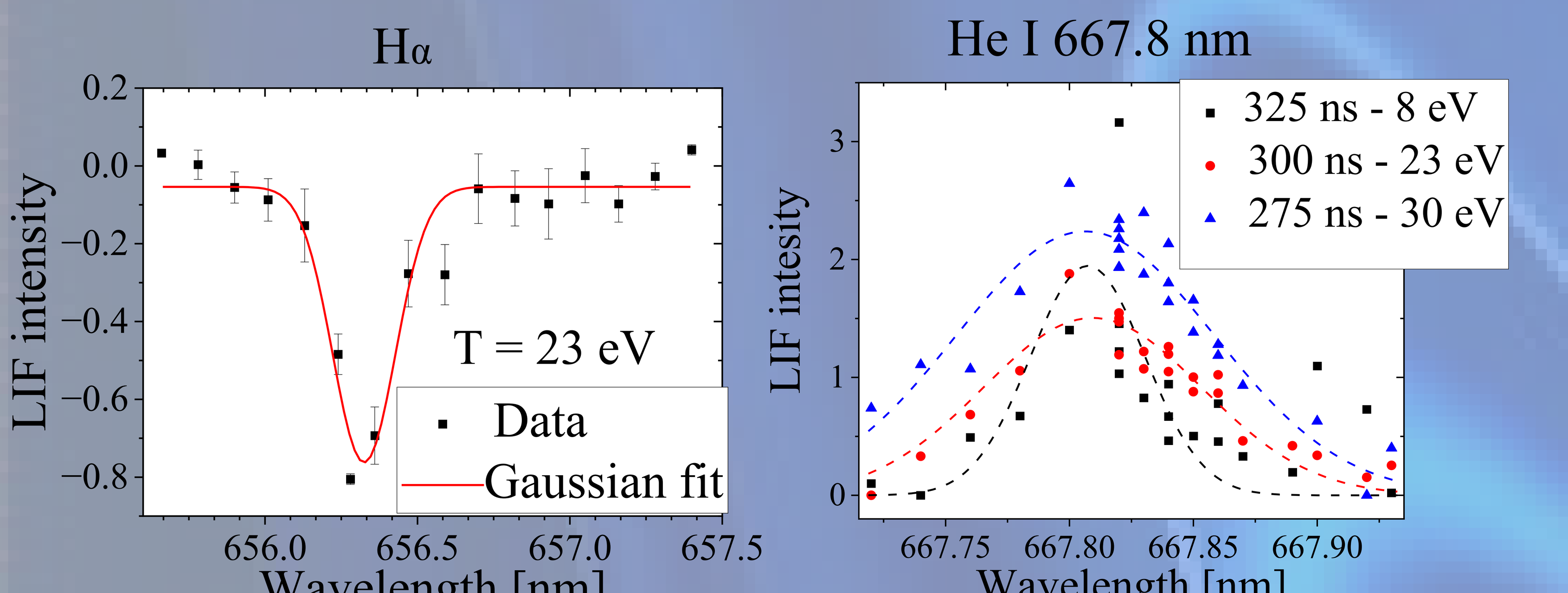
Laser interferometry

Plasma refraction index is proportional to the plasma electron density.
Using a Michelson-Rayleigh interferometer with 532 nm and 632 nm lasers we measure the phase accumulation of e/m wave propagating through the plasma and calculate the average plasma electron density temporal evolution at $\geq 10^{15}\ cm^{-3}$.



Laser induced fluorescence

Excitation of a specific energy level transition by high power laser pulses, H_α in Hydrogen and 667.8 nm line in He. Varying wavelengths in ~0.01 Å scale and measurement of the emitted line intensity from the higher level, allows one to obtain a high resolution image of the emission line and respectively, calculate temperature frome line width.



Thompson scattering

A laser pulse of 532 nm with 10 ns duration and 300 mJ energy is focused at the plasma compression center. The Thompson scattered light by free electrons in a 90° angle with respect to the laser direction is measured in a high (0.14 $\frac{Å}{pixel}$) and a low (1.7 $\frac{Å}{pixel}$) resolution spectrometers. Analysis of the spectral profile allows estimation of electron and ion temperatures and free electron density. Collective plasma behavior strongly effects the spectral profile and is expected when:

$$\alpha = (k\lambda_D)^{-1} \geq 1$$

At maximum compression our analysis suggest ion temperature of $\sim 20\ eV$ while electron temperature $\sim 1-1.5\ eV$ with electron density up to of $\sim 5 \cdot 10^{17}\ cm^{-3}$.