Enhancing Low-Temperature Plasma Diagnostics: Ultra-High Resolution Spectroscopy with Signal Amplification

Franciszek Sobczuk[1*], Krzysztof Dzierżęga[1], Wojciech Talik[1], Robin Flaugère[2]

[1] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Poland*

[2] *GREMI, UMR 7344, Université d'Orléans/CNRS, F-18020, Bourges Cedex, France*

(*) franciszek.sobczuk@uj.edu.pl

The application of laser light scattering technique for low-temperature plasma diagnostics offers a reliable means to determine critical plasma parameters such as temperature and particle concentrations. This method involves analyzing the scattering signal, which encompasses contributions from Thomson, Rayleigh, and Mie scattering processes — reflecting interactions with free electrons, atoms and ions, and dust particles respectively. However, distinguishing between these contributions necessitates ultra-high spectral resolving power ($\mathcal{R} > 10^5$) spectroscopy, a challenge due to the extremely low intensity of scattered light within the apparatus's solid angle. With scattered light pulses often falling below 0.1 fJ within their 6 ns duration, the signal-to-noise ratio (SNR) drops to an exceptionally low level.

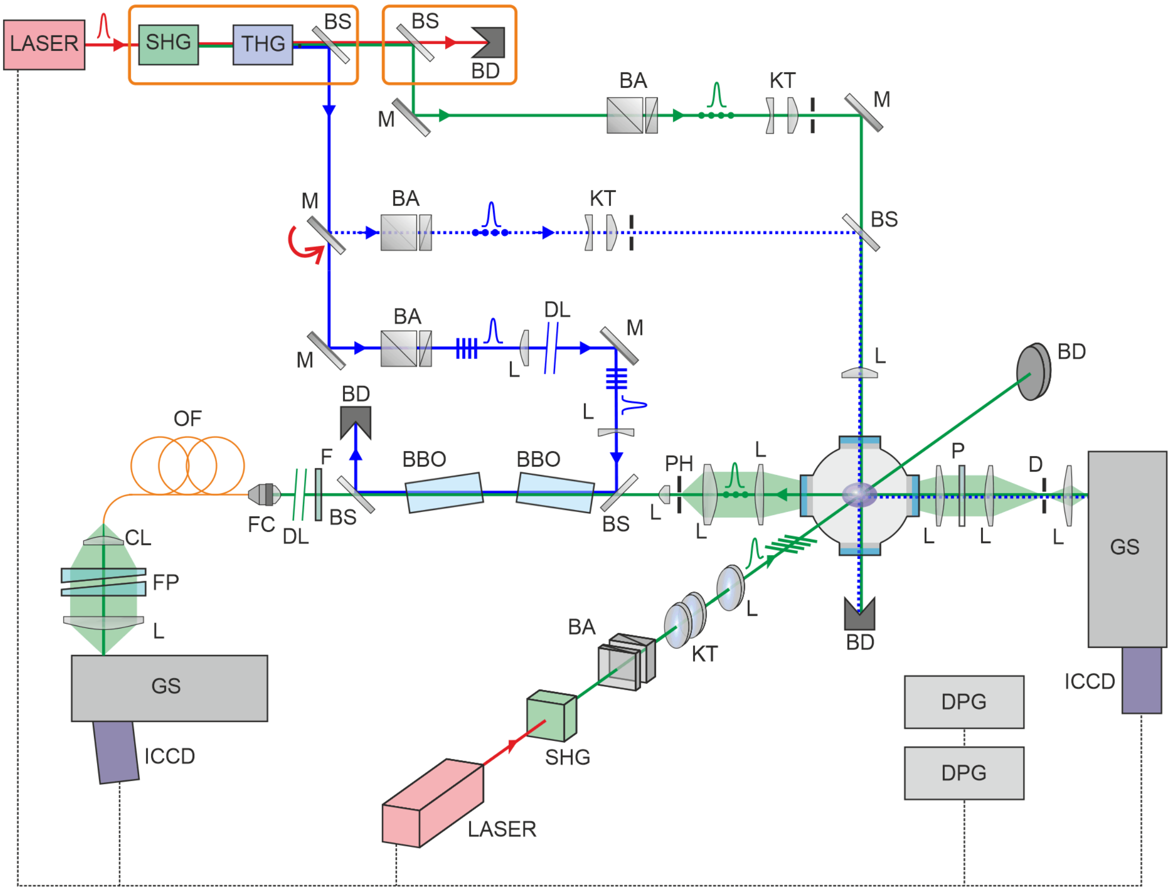

Fig. 1: Scheme of the experimental setup. SHG — 2nd harmonic generator, THG — 3rd harmonic generator, M — mirror, BA — beam attenuator, BS — dichroic mirror, DL — delay line, KT — telescope, L — lens, CL — cylindrical lens, BD — beam dump, D — diaphragm, PH — pinhole, FC — fiber coupler, OF — optical fiber, FP — Fabry-Pérot etalon, GS — grating spectrometer, BBO — beta-barium-borate crystal. The laser at the bottom of the picture generates the plasma in the vacuum chamber. The laser at the top generates the probe beam. The ICCD camera on the right side collects the scattered light in a standard way (using grating spectrometer as a spectrum analyzer). The camera on the left side collects the scattered light amplified by the OPA system and analyzed with a high spectral resolving power by a FP etalon.

To address this issue, we employ a high-finesse ($\mathcal{F} > 100$) Fabry-Perot (FP) etalon as a spectrum analyzer integrating it with an optical parametric amplifier (OPA). Positioned in front of the FP etalon, this OPA boosts the analyzed light by a factor of approximately 5000, resulting in a 50-fold enhancement of SNR and reducing measurement times from hours to minutes.

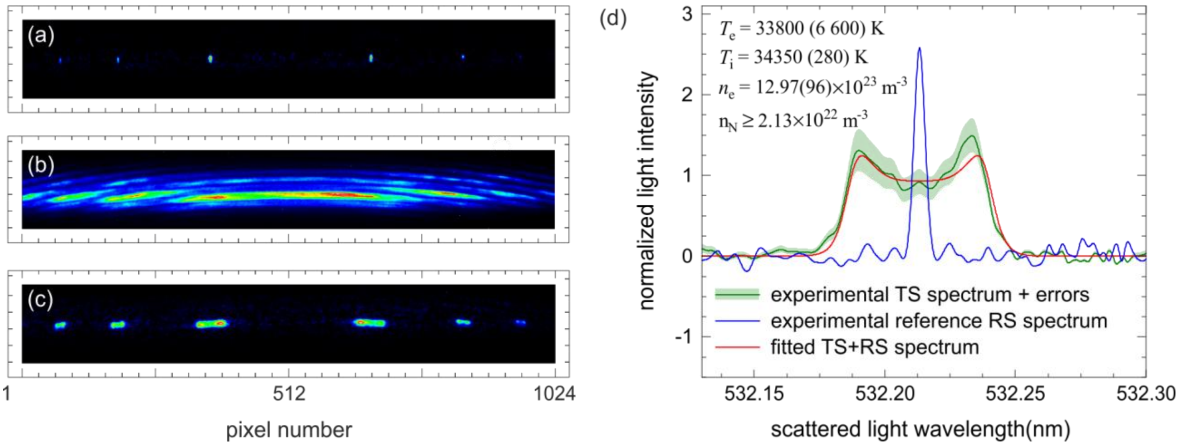

Fig. 2: Interferograms of light scattered on the reference gas (a), light emitted by the laser-induced plasma (b), light scattered on this plasma (c). Example spectrum of the light scattered on the nitrogen plasma (d). This spectrum was used to infer plasma parameters: electron concentration n_e, electron temperature T_e, ion temperature T_i and to estimate concentration n_N of neutral atoms.

During my presentation I will show details of the design of the combined setup for ultrahigh resolution spectroscopy with amplification of weak signals. It is based on the optical parametric amplifier pumped by the 3rd harmonic of Nd:YAG pulsed nanosecond laser and the FP etalon equipped with a grating spectrometer used as a narrow-banded filter. I will present example of laser light scattering spectra registered using this setup. Next, I will consider main limitations of the presented technique. Especially, I will describe the spontaneous parametric down conversion (SPDC) process, which produces majority of the apparatus noise. In principle, it should be possible to obtain near one-photon accuracy of light detection using OPA setup. I will show how it could be possible to approach this quantum-mechanical limitation.