22C09

Temperatures of Electron, Ion and Gas in Low Temperature Recombining Plasmas Measured Using Laser Thomson Scattering and Stark Spectroscopy
レーザートムソン散乱法およびシュタルク分光法を用いた低温再結合プラズマの電子温度・イオン温度・ガス温度

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Development of the laser Thomson scattering system in the MAP-II steady-state linear divertor/edge plasma simulator intended for the study of low-temperature recombining plasmas (also referred to as the detached plasma), having electron temperature below 0.1 eV, is reviewed. In addition, a method to determine the neutral temperature, electron density, and ion temperature in the recombining plasmas from the spectral line shapes with Doppler and Stark broadenings of three different transitions, 2^1S–3^1P (501.567 nm), 2^1S–7^1P (335.455 nm), and 2^3P–7^3D (370.500 nm) was proposed. The results from both diagnostics were compared at the recombining front of the helium plasma.

1. Introduction

Recombining plasma in the divertor/edge region in magnetically confined fusion-relevant plasma can be a sink of particle and heat fluxes due to the neutralization of the plasma before reaching the divertor plate (this phenomenon being referred to as "detachment"). Characteristics of the recombining plasma, such as electron-ion recombination (EIR) consisting of radiative and three-body recombination, or molecular assisted/activated recombination (MAR) induced by hydrogen or hydrocarbons are determined by the atomic and molecular processes that are strongly dependent on the electron temperature. Moreover, in the recombining plasmas, because there is no external energy input, such as discharge electric field or additional heating, ions and neutral atoms are also expected to influence and to be influenced by the electron temperature because of their high collisionality.

In spite of its importance, however, conventional diagnostics methods are difficult to be applied to the recombining plasma.

The electron current of the single probe exhibits values anomalously lower than those expected from the ion saturation current (known as an anomalous current-voltage characteristic)[1,2]. The spectroscopic measurement, such as atomic Boltzmann plot method for the electron temperature in a partial local thermal equilibrium (pLTE) - one of the typical properties of the volumetric recombining plasmas - always reflects the brightest point. In addition, there is a transition layer between the ionizing and EIR regions where the excitation rates are so low that the line emissivity is small.

This paper thus reviews the development of the Laser Thomson Scattering (LTS), and Doppler-Stark Spectroscopy of He I lines at MAP-II divertor simulator at the University of Tokyo[3] as shown in Fig. 1. The former was designed specifically for the measurement of electron temperature and density in the recombining plasma, while the latter was applied for the measurement of both ion and atomic temperatures, when applied to the brightest point of the He EIR plasmas.

2. Laser Thomson Scattering for the plasma below 0.1 eV

LTS is regarded as being a reliable electron temperature measurement. However, since the 1 eV electron temperature corresponds to about 1.5 nm in the Doppler half-width at 1/e maximum at 532 nm for an orthogonal viewing chord, it is difficult for commercially available narrow-band interference filters (which typically have a pass band broader than about 1 nm) to resolve the Doppler profiles. For this reason, a double monochromator equipped with a physical notch filter, called a Rayleigh block, at the intermediate slit have been adopted.

First the author and his collaborators (A. Okamoto et. al) developed a conventional double monochromator, homo-tandem type, with dispersion addition, using four commercial photographic lenses (Nikon, f = 135 mm, F/2.8). This system could measure the electron temperature down to 0.13 eV covering the MAR plasma[4]. However, it was still insufficient for the EIR region.

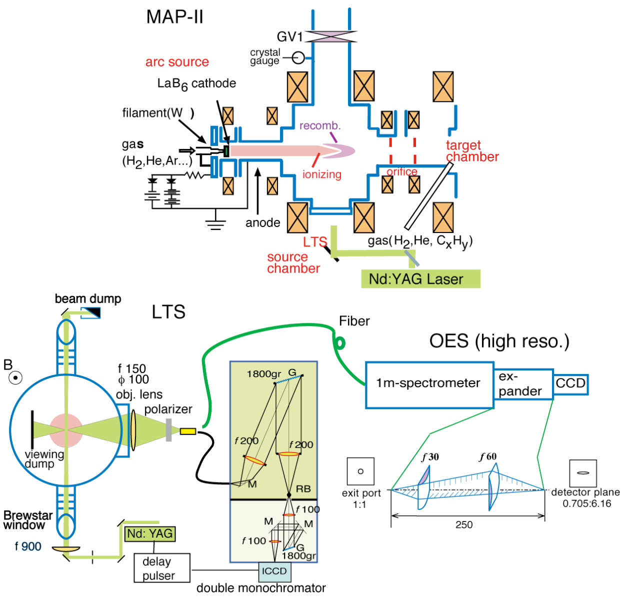

Fig.1. Schematic diagrams of the source chamber in the upstream of MAP-II divertor simulator and optical arrangement of LTS and high-resolution OES.

The author and his student (F. Scotti) then upgraded the double monochromator to a bright (using F/2 chromatic lenses) hetero-tandem type, composed of two non-symmetric stages - f = 200 mm for the first one to increase the dispersion and f = 100 mm for the second one to conserve the total dispersion [5].

A frequency-doubled Nd:YAG laser beam (532 nm in wavelength, a 10 Hz repetition rate, 7 ns pulse duration, and typically 400 mJ of energy per pulse, 8 mm in diameter) was used as the probe beam and an image-intensified charge-coupled device (ICCD) detector (Hamamatsu C4078+C4742, 1344 × 1024 pixels) was adopted for the gating and accumulating the scattered component.

3. Doppler-Stark Spectroscopy for EIR plasmas

The authors and his students (K. Suzuki et al.) have observed that the Doppler broadening of the He I lines gives different atomic temperature depending on the quantum states and that as the electron density increases, the difference becomes more remarkable even though the Stark broadening is taken into consideration. For example, ^{1}D and ^{3}D series temperatures increase with the principal quantum number but with different rates.

A high-resolution visible spectrometer, 1 m in focal length and 2400 lines/mm in groove frequency, with image expander optics [6] attached with a cooled CCD detector with electron multiplier technology (Andor DU971N of 1600 × 400 pixels and 16μm × 16μm in pixel size) is applied for the line-broadening measurement for the He-EIR plasmas in the upstream chamber of MAP-II.

Reciprocal linear dispersion and instrumental width at 492 nm were 0.86 pm/pixel and 8.2 pm (9.5 pixels) (FWHM), respectively.

Highly excited states (principal quantum number n ≥ 6) of helium atoms are dominated by the recombining component, except the ^{1}P states that are optically coupled with the ground state. Therefore, the authors have proposed a method to determine the neutral temperature, electron density, and ion temperature in the recombining plasmas from the spectral line shapes with Doppler and Stark broadenings of three different transitions, 2^1S -3^1P (501.567 nm), 2^1S -7^1P (335.455 nm), and 2^3P -7^3D (370.500 nm) [7].

4. Results and Conclusions

The author had expected that in the recombining plasmas, the thermal equilibrium is likely to be achieved among electron, ion and atom. Indeed, the previous work [5] has revealed that the measured electron temperature using both LTS and the Rydberg series spectra yields the similar values about 0.05 - 0.07 eV.

As the measurement position approached the recombination front, both ion and atomic temperatures deduced from the Doppler component became close to the electron temperature by LTS, indicating the achievement of the thermal equilibrium between electrons, ions, and neutral atoms[7].

Acknowledgments

The author acknowledges A. Okamoto, F. Scotti K. Suzuki and the other MAP-II group members for their contributions presented here. This work was supported partially by NIFS collaborative research program (NIFS04KOAB009, NIFS10KLMH002), and by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid, for Young Scientists (B), 16740311, 2004 and for Scientific Research (C), 21540507, 2009.

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