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Thomson Scattering Diagnostics of Plasmas for Various Applications
様々な応用プラズマのトムソン散乱計測

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The laser Thomson scattering technique has been developed as a diagnostics method for plasmas for various applications. Those plasmas includes low-pressure discharge plasmas such as an ECR plasma, an inductively-coupled plasma, and a capacitively-coupled plasma, and high pressure micro-plasmas such as the capacity-coupled-discharge plasma, a dielectric-barrier-discharge plasma and the plasma for the extreme ultra-violet light source. In this presentation, it is reviewed how successfully those Thomson scattering diagnostics have been performed.

1. Introduction

Thomson scattering is the light scattering by free electrons in plasmas. Quantitative measurements of the intensity and the spectrum of the scattered lights give the absolute values of electron density and electron temperature. [1]

The authors have been developing the laser Thomson scattering (LTS) as a diagnostic method for industrially applied plasmas. First, we have applied LTS to low-pressure processing plasmas, and recently, are extending to micro-discharge plasmas. In this article, we will describe about these our efforts. For the application of LTS to industrially applied plasmas, we are often faced with following problems. First, signals are sometimes difficult to be detected due to low signal intensities. In order to solve this problem, we adopt the signal accumulation over many laser shots because plasmas are maintained continuously or produced repeatedly at a high frequency. Second, the strong stray lights which are the laser lights scattered by windows and chamber walls can easily swamp the scattered signal lights. Because the spectral spread of the stray lights is determined by the instrumental function of the spectrometer used for the detection optics system, the problem can be resolved by using a triple-grating spectrometer which has high stray-light rejection characteristics. Third, the high laser energy may change values of electron density and temperature. For this problem, we must examine the laser conditions (energy, wavelength, pulse width, and so on) which do not induce laser perturbations.

The application of LTS to low pressure plasmas is reviewed in Refs. [2], [3] and described briefly in section 2. For micro-plasmas which are recently being developed, LTS is the unique diagnostic method for some cases. As an example, the application of LTS to a pulsed micro-discharge produced at around atmospheric pressure is presented in section 3.

2. Application to Low Pressure Plasmas

We first applied LTS to an ECR processing plasma produced in an argon gas about twenty years ago. [4] Because the electron density was of the order of 10^{18} m^{-3}, the analog detection was adopted and the signals were observed using an oscilloscope. Since the plasma was continuously maintained, signal accumulations over many laser shots were demonstrated to be effective to obtain an enough signal-to-noise ratio. The photon-counting method was used to measure the detailed structure of the scattered spectrum. When the electron energy distribution function (EEDF) of the inductively-coupled plasma was examined, it was found that argon plasmas have the Maxwellian EEDF and, on the other hand, EEDFs of plasmas produced in molecular gases such as methane and oxygen deviated remarkably from the Maxwellian. [5] For capacitively-coupled plasmas, the lowest detection limit was pursued and the electron density as low as 5×10^{15} m^{-3} was proved to be detectable by LTS after a longtime signal accumulation. [6]

In the reactive plasmas, the interaction between laser lights and plasma particles sometimes induces problems for LTS measurements. We must examine the particle composition of the plasma and evaluate the possible laser perturbations to the plasma. The strategy for such situation is reviewed in Ref. [3]. When the Raman scattering, whose spectrum overlaps with the LTS spectrum, was the problem, the LTS spectrum was separated from the Raman spectrum by observing both spectra from two different scattering angles. [7]

3. Application to Micro-discharge Plasmas

We are now applying LTS to diagnose some micro-plasmas such as a capacity-coupled-discharge (CCD) plasma, a dielectric-barrier-discharge (DBD) plasma, and a laser produced plasma for the extreme-ultraviolet light source.[8] In the followings, the experiment for the CCD plasma is described.

The CCD plasma was created between a set of tungsten electrodes composed of a needle and a hemisphere (ϕ=2.4 mm) with a gap of 500 μm. The discharge was triggered by a high-voltage semiconductor switch with fast rising characteristics and we could produce the CCD plasma with excellent reproducibility. The discharge gas was a neon gas at a pressure of 400 Torr. For the LTS measurement, the Nd:YAG laser beam with a output energy of about 5 mJ was injected to the discharge perpendicularly to the discharge axis. Then, we could obtain LTS spectra along with the laser beam path in the radial direction of the discharge. Figure 1 (a) shows a two-dimensional image of the LTS signal recorded by an ICCD camera when the laser beam was injected to the center of the electrode gap. In order to obtain enough SN ratios, LTS signals were averaged over 2000 laser shots for this image. The measurement time was at 25 ns after the beginning of the discharge. From this image, we can obtain

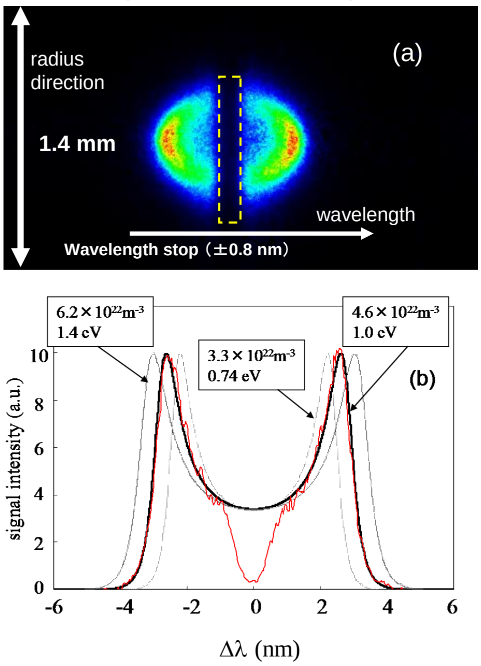

Fig. 1 (a) Two-dimensional image of the LTS signal measured at 25 ns after the start of the discharge. (b) Thomson scattering spectrum at r=0 extracted from Fig. 1 (a).

radial profiles of electron density (n_e) and electron temperature (T_e). Figure 1 (b) shows an example of a LTS spectrum obtained at the radial centre position (r=0). Since the LTS spectrum was in the collective regime, n_e and T_e could be evaluated from the spectral shape and the peak wavelength. It can be seen from Fig. 1 (b) that the theoretical curve which corresponds to $n_e = 4.6\times10^{22}\,\mathrm{m}^{-3}$ and T_e = 1.0 eV is most close to the measured spectrum and so those were fixed as measured values. The laser beam was injected at 5 different axial positions and two-dimensional distributions of n_e and T_e were obtained with the spatial resolution of 50×50×50 $\mu\mathrm{m}^3$.

Based on the results obtained for the CCD plasma, the lower detection limit of the LTS signal of the present detection system was estimated. Then, the result suggested that the lower limit of the electron density could be as low as $10^{18}\,\mathrm{m}^{-3}$ if we use the ICCD camera in the photon-counting mode. Therefore, we have a possibility to examine the streamer phase of the pulsed discharges at atmospheric pressure.

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