Status of GAMMA 10/PDX-Thomson Scattering System

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Abstract. In the tandem mirror GAMMA 10/PDX, a neodymium-doped, yttrium-aluminium-garnet (Nd:YAG) Thomson scattering (TS) system have been constructed for electron temperature and density radial profile measurements. We can successfully measure the radial profiles of electron temperature and density in the central cell of GAMMA 10/PDX by using the YAG-TS system in a single laser shot. By using high speed oscilloscopes and their data collection program, we can measure time dependent electron temperatures and densities every 100 ms in a single plasma shot. Moreover, in order to increase the TS signal intensities, we have constructed a multi-pass TS system of the polarization based system with image relaying optics. The clear multi-pass TS scattering signals from first to eighth passing lasers through the plasma were successfully obtained. The five times larger TS signal intensity were indicated. The multi-pass TS system improves the measurement resolution and time resolution.

INTRODUCTION

Thomson scattering (TS) diagnostic is one of the most useful methods for measuring electron temperature and density of plasmas [1-14]. TS systems are normally applied to plasma densities of over 10^{19} m^{-3}. In lower-density plasmas, such as peripheral plasmas of tokamak devices or GAMMA 10/PDX plasma, an effective TS system for signal enhancement is required. GAMMA 10/PDX is an effectively axisymmetrized minimum-B anchored tandem mirror device having thermal barrier at both end-mirrors and an end divertor experimental module in the west end cell [15,16]. In GAMMA 10/PDX, the electron density, electron temperature and ion temperature are typically about 2×10^{18} m^{-3}, 0.04 keV and 5 keV, respectively.

TS signal depends linearly on the incident laser power, electron density, and solid angle of the TS collection optics. In GAMMA 10, a ruby-laser TS system was installed to measure the electron temperature in the 1980s [5]. However, the system experienced problems. After the aforementioned problems with the ruby-laser TS system, we planned to install a neodymium-doped, yttrium–aluminum–garnet laser (Nd:YAG) TS system to measure electron temperature directly in the central cell of GAMMA 10 in 2008. In GAMMA 10/PDX, a TS system with a large solid angle optical collection system was developed [6-9]. We have improved the TS system for six-position measurements in a single laser shot during a single plasma shot. In order to improve the TS signal intensity and time resolution, multi-pass (MP) TS systems were proposed [17-23]. The multi-pass Thomson scattering scheme effectively increases the scattering signal intensity from plasmas by the probing laser pulse to be focused multiple times onto the scattering volume [11-14, 17-23]. In this paper, we describe the current status of GAMMA 10/PDX-TS system and the results of time dependent radial electron temperature and density measurements in a single plasma shot.

THOMSON SCATTERING SYSTEM IN GAMMA 10/PDX

The TS system is installed in the central cell of GAMMA 10/PDX. A schematic of the TS system is shown in Fig. 1. A horizontally polarized laser beam from Nd:YAG laser (Continuum, Powerlite 9010, 10 Hz and 2 J/pulse) is focused by the first convex lens (CVI, f = 2229 mm, ϕ = 50.8 mm) from the downside port window after passing a short-pass mirror, two Faraday rotators for isolation, two half-wave plates, three polarizers, a Pockels cell (Gooch&Housego, QX1630), mirrors ② and ③, and irises. After interacting with the plasma, the laser beam is emitted from the upper-side port window. In the single-pass TS configuration, a closed mirror flipper leads the laser beam to the beam dump. In the multi-pass TS configuration, the output laser beam from the upper-side port is collimated by the second convex lens (CVI, f = 2229 mm, ϕ = 50.8 mm). These lenses maintain the laser beam quality during the multi-pass propagation through the image-relaying optical system from the iris to the reflection mirror ④. The laser beam is reflected by the reflection mirror ④ for the second pass and is focused again onto the plasma. The Faraday rotator and the Pockels cell are used for polarization control. The Pockels cell switches the polarization of the laser beam from horizontal to vertical for the reflected passes during the gate pulse. In the double-pass TS configuration, gate pulse is off. Then, the second pass laser goes through the polarizers, half-wave plate, Faraday rotator and mirror ① to beam dump. In the multi-pass TS configuration, the third laser pass is produced by a Pockels cell for polarization control and the reflection mirror ⑤. The laser beam is confined between the reflection mirrors ④ and ⑤ for the multi-pass propagation. For the TS light collection optics, we used an Al:SiO$_2$-coated spherical mirror with a curvature radius of 1.2 m and a diameter of 0.6 m, and a second collection mirror of a curvature radius of 1.2 m and a diameter of 0.2 m. The scattered light is collected and reflected by the spherical mirror, after which, it reaches the nine channels of optical fiber bundle with a cross-section of 2 × 7 mm^2 having the length of 6.67 m. The scattering angle is 90°. The measurable radial positions are X = 0, ±5, ±10, ±15, and ±20 cm. Each channel optical fiber bundle is connected a 5-channel filter-type polychromator. The fiber aperture is located at about 0.873 m away from the spherical mirror. The polychromator is comprised of five relay and collection lenses, five interference filters, and five silicon avalanche photodiodes (PerkinElmer, C30659-1060-3AH, bandwidth of 50 MHz) with preamplifiers (Tokyo Opto-Electronics, PLM12A001-2). Measured wavelengths of the polychromator are 1059±2 nm (CH. 1), 1055±2 nm (CH. 2), 1050±3 nm (CH. 3), 1040±7 nm (CH. 4), and 1020±14 nm (CH. 5). A four-channel high-speed oscilloscope (IWATSU, DS5524A) is used to measure four wavelength channels with a bandwidth of 200 MHz and a sampling rate of 1.0 GS/s. The measured signals are recorded by a Windows personal computer using the IWATSU multi-oscilloscope control software (IWATSU, MultiVControl V2.23). The electron temperature is deduced by a nonlinear least-squares fit procedure at integrated output signals of each channel. The fit is obtained using a lookup table that contains the calculated intensities expected in each channel for 1 eV intervals up to 500 eV. By interpolating between the tabulated values, the values of the electron temperature that minimize the chi-squared value are obtained.

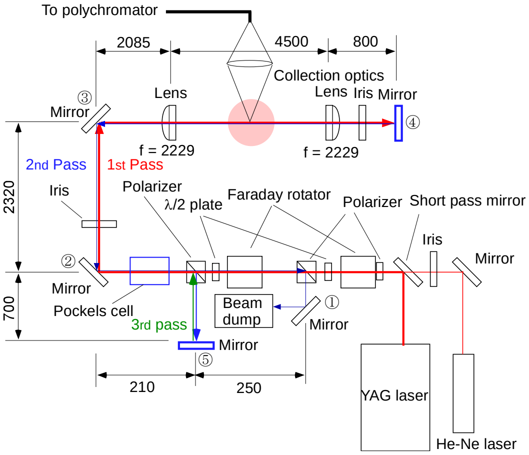

FIGURE 1. Schematic of the GAMMA 10/PDX Thomson scattering system.

RADIAL ELECTRON TEMPERATURE AND DENSITY MEASUREMENTS

We use the TS system to measure radial profiles of electron temperature and density in the GAMMA 10/PDX plasma. The hydrogen plasma is produced from t = 50 to 440 ms with heating by RF1 from t = 51 to t = 440 ms and RF2 from t = 53 to t = 440 ms. These plasmas are long-pulse discharge experiments for divertor plasma experiments. The Nd:YAG laser was injected at t = 100.0, 200.0, 300.0 and 400.0 ms. In Fig. 2, the red circles, blue squares, green diamonds, and brown triangles show the radial electron temperatures (a) and densities (b) at t = 100.0, 200.0, 300.0, and 400.0 ms, respectively. At the plasma center, the electron temperature and density are about 30 eV and 1.7×10^{18} m^{-3}, respectively, during the observing periods. By changing the Nd:YAG laser injection time shot-by-shot, we can obtain the time evolution of electron temperature and density. By using the TS system, we successfully obtained the time-dependent electron density and temperature with few plasma shots.

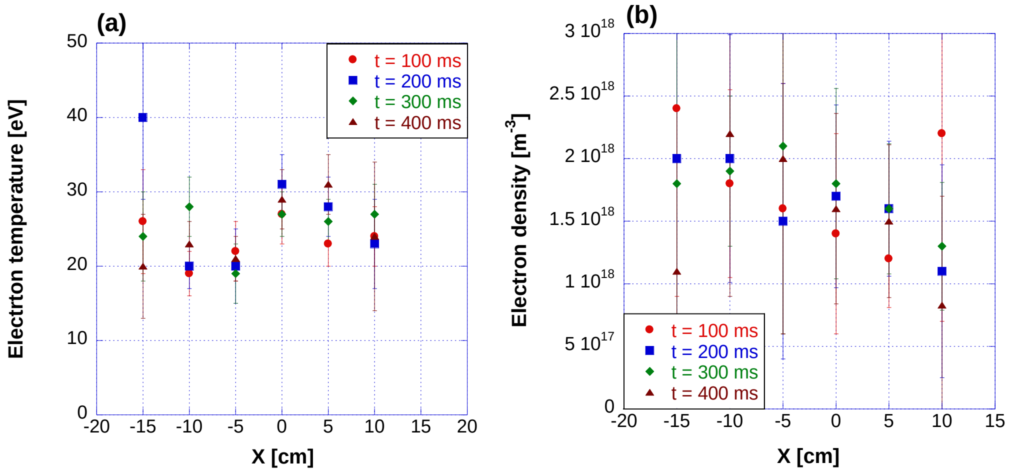

FIGURE 2. (a) and (b) show the radial profiles of electron temperatures and densities at t = 100, 200, 300 and 400 ms, respectively.

MULTI-PASS THOMSON SCATTERING SYSTEM

By using the multi-pass TS configuration, we can improve the TS signal intensity. We apply the MPTS system to the GAMMA 10/PDX plasma. The single-pass (red thin line) and multi-pass (blue line) TS raw signals of the polychromator CH. 1 are shown in Fig. 3. In Fig. 3, the indicated pass numbers of multi-pass TS signals are also

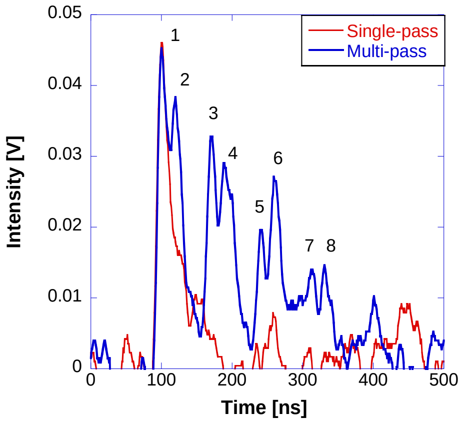

FIGURE 3. TS raw signals in the single-pass (red thin line) and multi-pass (blue line) configurations.

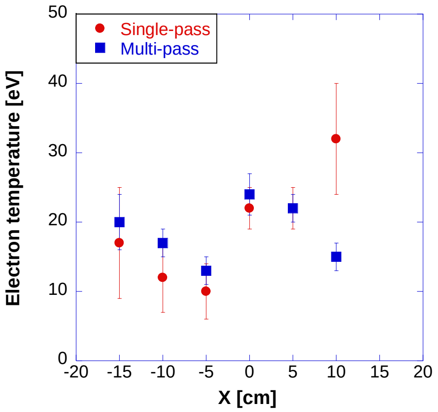

FIGURE 4. Radial profiles of electron temperatures obtained by the single-pass (red circles) and multi-pass (blue squares) TS systems.

shown. The integrated intensity of the multi-pass TS signal is about five times larger than that of single-pass TS signal. The obtained radial electron temperatures by the single-pass (red circles) and multi-pass (blue squares) TS configurations are shown in Fig. 4. The obtained electron temperatures at X = 10 cm have large differences between the single-pass and multi-pass configurations. The reason of it is thought that the small TS signal intensity at the X = 10 cm in the single pass configuration and shot difference make the large difference. The errors of electron temperatures in the multi-pass configuration are smaller than those in the single-pass configuration. The errors at X > |5| cm in the multi-pass configuration are about less than 50 % of those in the single-pass configuration.

SUMMARY

We have developed the GAMMA 10/PDX-TS system for electron temperature and density measurements. We can successfully obtain the time dependent radial electron temperatures and densities in a single plasma shot. With the integrated scattering signal by using the multi-pass configuration, we can obtain about five times larger TS signal intensity than that in the single-pass configuration. Moreover, the measurement accuracy is improved in the multi-pass TS configuration.

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