YAG-Thomson Scattering System in GAMMA 10/PDX Central and End Cells*)

Masayuki YOSHIKAWA, Tomoya MOURI, Junko KOHAGURA, Yoriko SHIMA, Tomoya YAMASAKI, Shun SUTO, Hiroyuki NAKANISHI, Mizuki SAKAMOTO, Yousuke NAKASHIMA, Ryutaro MINAMI, Naomichi EZUMI, Ichihiro YAMADA[1)], Ryo YASUHARA[1)], Hisamichi FUNABA[1)], Takashi MINAMI[2)] and Naoki KENMOCHI[3)]

Plasma Research Center, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan
[1)]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*
[2)]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*
[3)]*Graduate School of Frontier Sciences, University of Tokyo, Kashiwa, Chiba 277-8561, Japan*

(Received 25 September 2018 / Accepted 6 November 2018)

We developed an yttrium aluminum garnet (YAG)-Thomson scattering (TS) system for radial profile measurements of electron temperature and density in the GAMMA 10/PDX central cell. The optical collection system for TS light was constructed from three spherical mirrors and nine bundled optical fibers. The radial positions were intervals less than 5 cm in the range of ± 20 cm and were measured by moving the fixed fiber bundle position from shot to shot. We constructed a multi-pass TS system with laser amplification, which can increase the signal intensity and time resolution of the TS diagnostic system. In addition, we installed the end-TS system using the central-TS YAG laser in order to measure the electron temperature and density in a divertor simulation experimental module in the GAMMA 10/PDX end cell.

Keywords: Thomson scattering system, multi-pass Thomson, electron temperature, electron density, tandem mirror GAMMA 10/PDX

DOI: 10.1585/pfr.14.2402002

1. Introduction

Thomson scattering (TS) is one of the most useful diagnostic methods for measuring electron temperature and density in plasmas and fusion devices [1–10]. However, lower electron density areas, such as in GAMMA 10/PDX and spherical region of fusion plasmas, require large numerical aperture collection optics, longer scattering lengths, and high-sensitivity detection systems. In GAMMA 10/PDX, we installed an yttrium aluminum garnet (YAG)-TS system featuring large angle collection optics, a long scattering length optical system, and a high-sensitivity light detection system [8, 9]. The YAG-TS system can measure electron temperatures and densities in seven radial positions in a single laser shot at 10 Hz.

GAMMA 10/PDX is an effectively axisymmetric minimum-B anchored tandem mirror with a thermal barrier at both end mirrors [11]. The x-axis and y-axis are perpendicular to the magnetic field in the vertical and horizontal directions, respectively, and the z-axis is parallel to the magnetic field. Plasma is created by plasma guns and is heated and sustained using ion cyclotron heating (ICH) systems. In addition to ICH, electron cyclotron heating (ECH) is applied to produce the electron and ion confinement potential in the plug (P) and barrier (B) cells.

In the central cell, we performed direct electron heating by applying central (C) ECH [12]. We performed supersonic molecular beam injection (SMBI) in central and anchor cells to increase plasma density and produce a higher end-loss flux for divertor plasma experiments [13]. In the end region, we installed the divertor simulation experimental module (D-module) to perform divertor simulation experiments. To measure the electron temperature and density at the D-module, the new TS system must be installed in this region.

The electron density, electron temperature, and ion temperature in the central cell were measured using the YAG-TS system, microwave interferometers, a soft X-ray measurement system, and a charge exchange neutral particle analyzer system [14–17]. The typical electron density, electron temperature, and ion temperature were approximately 2×10^{18} m^{-3}, 100 eV, and 5 keV, respectively, during the application of P/B-ECH. In the D-module, the electron temperature and density were measured using electrostatic probes on the target plate and a helium line emission intensity ratio spectroscopic system. Using the TS system is therefore important for the direct measurement of electron temperature and density in the D-module.

The optical collection system for TS light was constructed from three spherical mirrors and nine bundled op-

author's e-mail: yosikawa@prc.tsukuba.ac.jp

*) This article is based on the presentation at the 12th International Conference on Open Magnetic Systems for Plasma Confinement (OS2018).

tical fibers. The radial positions were measured by changing the fixed, bundled optical fiber slot position, set on a lab jack, in intervals less than 5 cm in the range of ± 20 cm. Three spherical mirrors for collecting TS light consisted of the first main spherical mirror and the top (second) and bottom (third) mirrors of the main collection spherical mirror for increasing the TS light intensity at the lower and upper edges of the plasma region, respectively.

In GAMMA 10/PDX, we developed a polarization-based multi-pass TS system with image-relaying optics for increasing the TS signal to allow for high-speed temporal measurements [18]. In a normal multi-pass TS system, in contrast, the signal intensity decreases with each pass due to the loss in laser power from reflection from multiple optical components. To address this problem, we upgraded the multi-pass TS system by adding a laser amplification system [19].

In this paper, we present the development of the YAG-TS system in GAMMA 10/PDX for measuring detailed radial profiles of electron temperature and density, a multi-pass TS system with laser amplification, and a newly installed end-YAG-TS system.

2. YAG-TS System in GAMMA 10/PDX

Figure 1 presents GAMMA 10/PDX and the YAG-TS system. The central cell (CC)-YAG-TS system and the end-YAG-TS system were installed at z = 0.6 m and z = 10.875 m, respectively. The YAG-TS system consisted of a laser, incident optics, light collection optics, signal detection electronics, and a data recording system.

2.1 CC-YAG-TS system

Figure 2 presents the side view of the CC-YAG-TS system. A 10 Hz Nd:YAG laser (Continuum, Powerlite 9010) with an energy per pulse of 2 J and a pulse width of approximately 10 ns, operating at a fundamental wavelength of 1064 nm, was used. The laser traveled through a short-pass half mirror, two Faraday rotators, two polarizers, two $\lambda/2$ plates, four mirrors, and an iris on the optical bench. The laser beam was injected into the plasma from the lower port though a focusing lens with f = 2.25 m in the central cell. The laser beam diameter at the plasma center was approximately 1 mm by the focusing lens. The polarization of the laser in the plasma was in the z-direction.

For light collection optics, three spherical mirrors coated with Al:SiO_2 were used. The main spherical mirror had a radius of 1.2 m and a diameter of 0.6 m. For light collection of the lower edge of the plasma, a second spherical mirror with a curvature radius of 1.2 m and a diameter of 0.2 m was set on top of the main spherical mirror [10].

The third collection mirror had a curvature radius of 1.1 m and a rectangular cross section of $0.12 \times 0.30\,m^2$ and was set on the lower side of the main spherical mirror to increase the TS light from the upper edge of the plasma region. This additional mirror system was useful for increasing the TS signal from the plasma edge. The distance between the center of the main mirror and the center of the additional mirror was approximately 0.34 m. The mirror size was optimized to obtain maximum collection efficiency, taking into consideration the solid angle and setting positions. Scattered light was collected by the spherical mirrors and reflected and reached a bundled optical fiber with a cross section of $2 \times 7\,mm^2$. The magnification of the collection optics was 1/2.2. The length of scattering volume along the laser was 15.4 mm, and the scattering angle was 90°.

The main collection mirror had a solid angle of 0.078 sr. After passing through the plasma, the laser beam exited the upper port and was absorbed by a beam dump through the mirror flipper system. A 6.67 m-long bundled optical fiber (Mitsubishi Densen, FS10-43001A) was connected to a 5-channel polychromator. The bundled optical fiber had a large numerical aperture of approximately 0.47. The fiber slot was located approximately 0.873 m away from the spherical mirror. The fiber positions were fixed by a fiber slot on the lab jack (Thorlabs, L490). The radial positions were measured by changing the fiber slot position from shot to shot in intervals less than 5 cm, in the range of ± 20 cm.

The polychromator was composed of five relay and

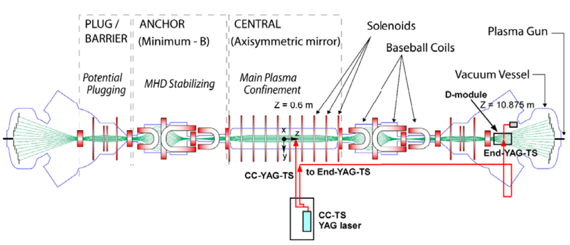

Fig. 1 Overall schematic of GAMMA 10/PDX and the TS system.

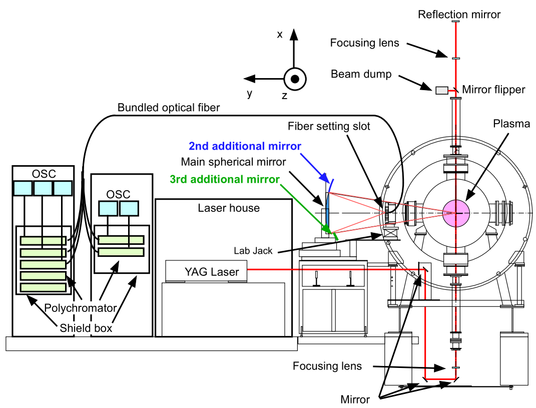

Fig. 2 Side view of TS system in GAMMA 10 central cell.

collection lenses, five interference filters, and five silicon avalanche photodiodes (Si-APD, PerkinElmer, C30950E, and C30659-1060-3AH) with a preamplifier (Tokyo Opto-Electronics, PLM12A001-3). The measured wavelengths of the polychromator were 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). Four-channel high-speed oscilloscopes (IWATSU, DS5524 and DS5524A) were used to measure four wavelength channels simultaneously with a bandwidth of 200 MHz and a sampling rate of 1 GS/s. The measured signals were recorded with IWATSU multi-oscilloscope control software (IWATSU, MultiVControl V2.23) on a Windows PC.

In a typical operation of GAMMA 10/PDX with a 0.2 s duration, two laser shots can be collected. We performed the spectral calibration of the sensitivities of 5-channel polychromators using standard light (Oriel, #66890) and a spectrometer (Oriel, CS130). In the CC-YAG-TS system, the electron temperature was deduced by a nonlinear least-squares fit procedure at the integrated output signals of each channel. The fit was obtained using a look-up table, which contains the calculated intensities expected in each channel for intervals from 1 to 500 eV. Electron temperatures were obtained by interpolating between the tabulated values that minimize the chi-square value.

2.2 End-YAG-TS system

The end-YAG-TS system was located at the end region, z = 10.875 m. The YAG laser beam was divided and sent to the end-TS system following the second polarizer, which changed the polarization from horizontal to vertical by a half-wave plate on the optical bench of the CC-YAG-TS system. The divided laser beam entered the end region through an aluminum pipe and was injected into the D-module through the horizontal end observation port. In the D-module, there was a hole with a diameter of 20 mm in the observation window. The laser passed through the opposite side of the D-module and was bent by the mirror to be absorbed by the beam dump. The TS light in the D-module was collected by an aluminum mirror with a diameter of 15 cm and a curvature radius of 30 cm, set at a distance of 56 cm away from the center axis, x = 0 cm. The 160° backscattered light was collected by a bundled optical fiber (Mitsubishi Densen, FS14-43601B) with a cross section of 7×2 mm^2 and a length of 10.2 m. The length of scattering volume along the laser was approximately 30 mm.

Figure 3 shows a schematic representation of the end-TS system. The collection optics of the main collection mirror had a solid angle of 0.050 sr. The optical fiber was connected to a polychromator system. The measured wavelengths of the polychromator were 1060.5 ± 0.5 nm (CH. 1), 1059 ± 1 nm (CH. 2), 1055 ± 2 nm (CH. 3), 1050 ± 3 nm (CH. 4), and 1040 ± 7 nm (CH. 5). A four-channel high-speed oscilloscope (IWATSU, DS5624A) was used to measure four wavelength channels simultaneously with a

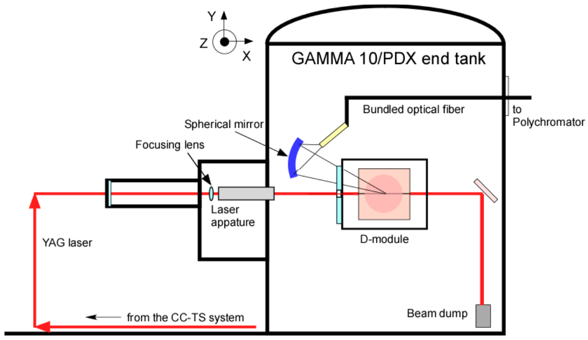

Fig. 3 Schematic view of the end-TS system.

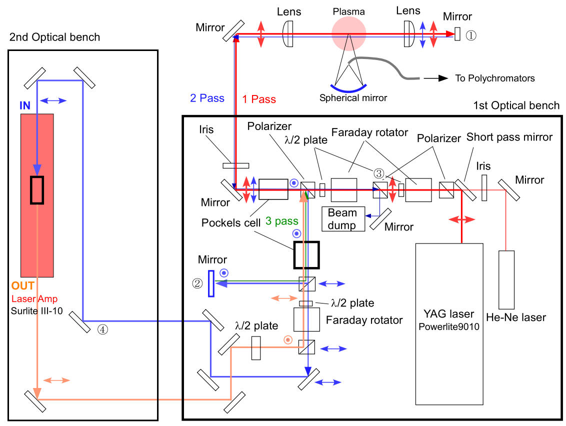

Fig. 4 Schematic diagram of the multi-pass TS system with the amplification system.

bandwidth of 200 MHz and a sampling rate of 1 GS/s. The measured signals were recorded by the IWATSU multi-oscilloscope control software on a Windows PC. The calibration of the wavelength sensitivity of the system was performed using the same method as in the CC-YAG-TS system. In the end-YAG-TS system, we encountered a large amount of stray light. This prevented gas scattering calibrations from being performed for density measurements.

2.3 Multi-pass TS system

A schematic diagram of the new multi-pass (MP) system with amplification is shown in Fig. 4. This system is based on the GAMMA 10/PDX-TS system. A horizontally polarized laser beam from the YAG laser was focused on the plasma center by the first convex lens from the lower port window after passing a short-pass mirror, two Faraday rotators for isolation, two half-wave plates, two polarizers, a Pockels cell (FastPulse, CF1043SG-1064, aperture of 16 mm), mirrors, and irises. After interacting with the plasma, the laser beam was emitted from the upper port window and collimated by the second convex lens. These lenses maintained laser beam quality during the MP propagation through the image-relaying optical system from the iris to reflection mirror ①.

In Fig. 4, bold red lines with arrows represent the first passing laser trajectory. The laser beam was reflected by reflection mirror ① for a second pass and was once again focused on the plasma. Blue lines with arrows represent the second passing laser trajectory in Fig. 4. The Pockels cell changed the polarization of the laser beam from horizontal to vertical for the reflected passes during the gate pulse (peak to peak of 10 kV and duration of ~500 ns). We added a second Pockels cell and a polarizer before introducing toward the reflection mirror ② to perform the third laser pass. The laser light was confined between reflection mirrors ① and ② for the MP propagation when the second Pockels cell was off.

To increase the degraded MP laser beam power, we added a new laser amplification system to the normal MP configuration. The second Pockels cell was turned on to change the laser beam trajectory toward the laser amplification system after passing the polarizer, half-wave plate, Faraday rotator, and mirrors. In the laser amplification system, we set an amplifier (Continuum, Surelite-III amplifier system) and a half-wave plate. When turning on the second Pockels cell (peak to peak of 10 kV and duration of ~100 ns), the laser amplification system became operational. The amplified laser beam then returned to the normal MP system through the polarizer. In Fig. 4, the orange line represents the amplified laser trajectory to the normal MPTS system. Thus, we have successfully constructed a new MPTS system with amplification.

3. Calibration Experiments

Raman and Rayleigh calibration experiments were performed to evaluate the optical system and stray light in the GAMMA 10/PDX-YAG-TS system. Nitrogen gas was used and the pressure in the GAMMA 10 device was raised to 300 Torr. The measured scattering signal was proportional to the gas pressure. The linear component indicated the scattering light, and the offset indicated the stray light. We conducted a Raman scattering calibration for radial position measurements of $x = 0, \pm 5, \pm 10, \pm 15$, and ± 20 cm, simultaneously. We changed the fiber slot position by ± 1.25 cm and ± 2.5 cm to obtain detailed radial density calibration parameters. The electron density can be obtained by comparing the linear components of the Rayleigh and Raman scattering experiments in each position to the total TS signal intensity. The estimated increase rates of signal intensity with the second and third mirrors are approximately 50% and 10%, respectively, at a radial position of $|x| = 15$ cm.

The additional mirrors were useful for increasing the TS signal intensities of the plasma edge region. MP signal calibration experiments were also performed to obtain the calibration parameters along the pass signals. Figure 5

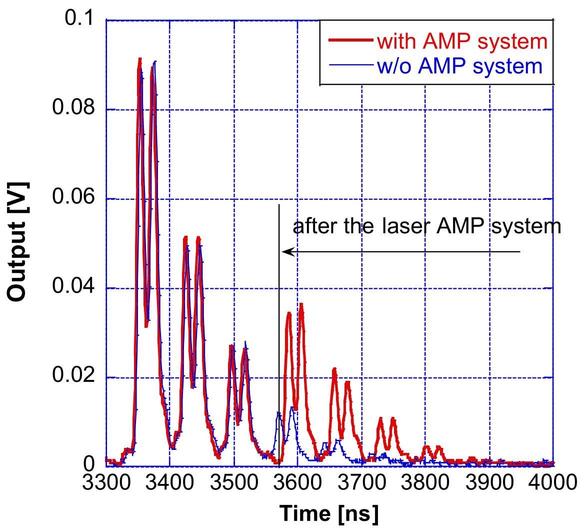

Fig. 5 Rayleigh scattering signals of the multi-pass system.

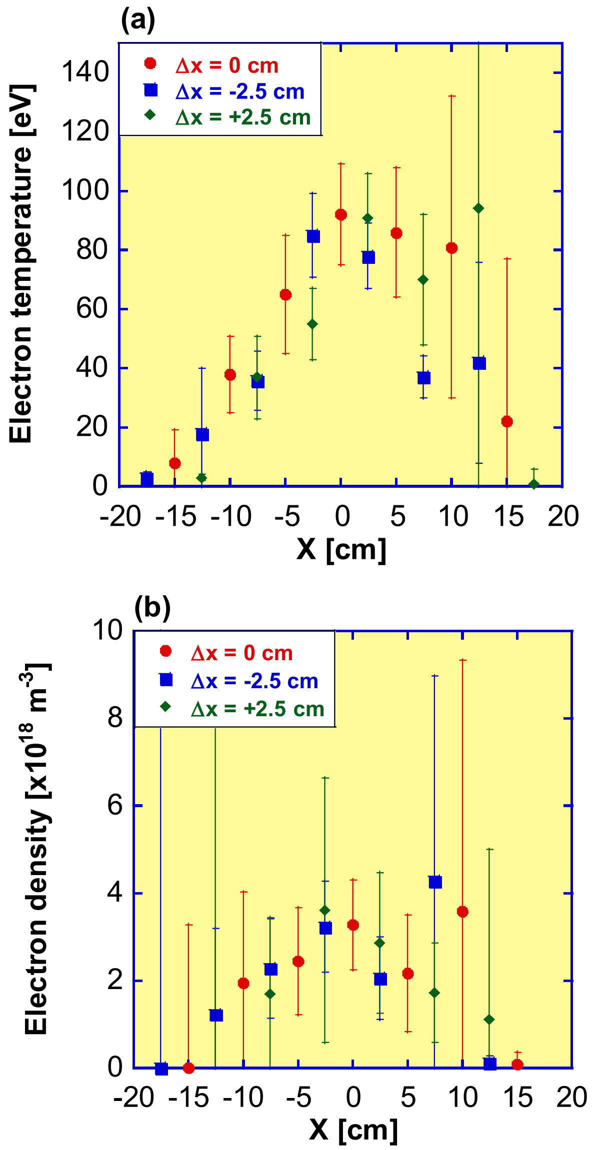

Fig. 6 Radial (a) electron temperature and (b) density.

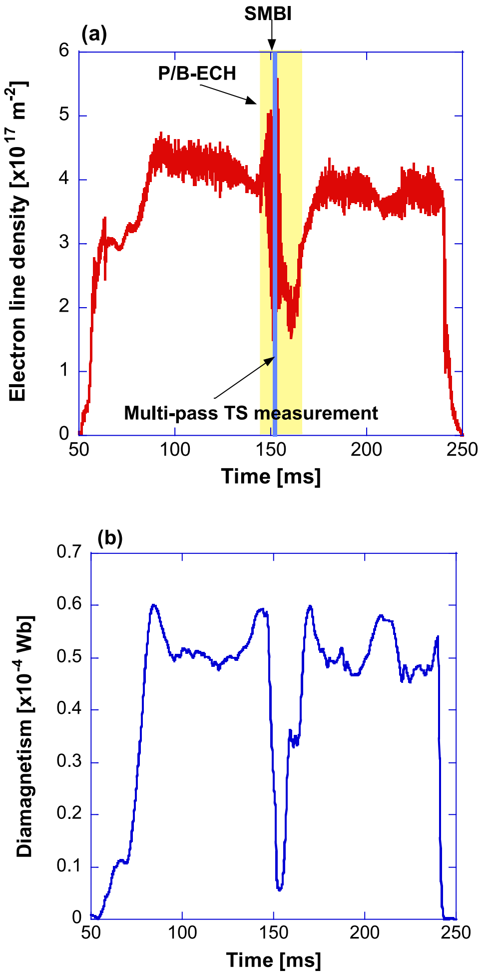

Fig. 7 Time-dependent (a) electron line density and (b) diamagnetism.

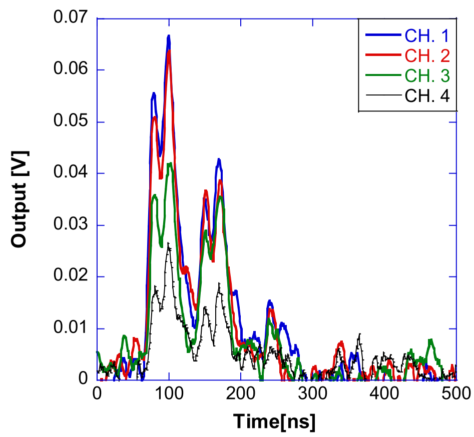

Fig. 8 Multi-pass TS scattering signals.

illustrates the MP Rayleigh scattering signals without the amplification system (blue line) and with the amplification system (red line), respectively. It can be seen that using the amplification system leads to improvements.

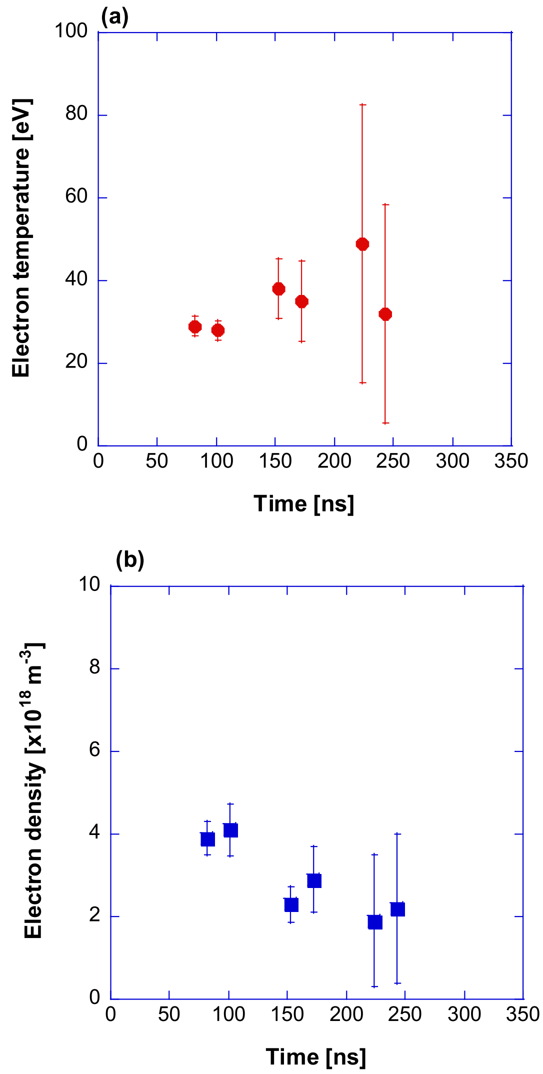

Fig. 9 Time-dependent (a) electron temperature and (b) density measured by the multi-pass TS system at t = 151.5 ms.

4. Electron Temperature and Density Measurements

4.1 Radial profile measurements

Plasma was produced from t = 50 to 240 ms with ICH applied from t = 51 to t = 240 ms. Figure 6 shows the radial electron temperature (a) and density (b) resulting from changing the fiber position from 0 to ±2.5 cm from shot to shot, with laser injection time t = 122.5 ms. The red circles, blue squares, and green diamonds represent the results measured at fiber slot positions Δx = 0 cm, −2.5 cm, and +2.5 cm, respectively. We successfully obtained detailed radial profiles of electron temperature and density with three plasma shots.

4.2 MP measurements

Figure 7 demonstrates the electron line density (a) and diamagnetism (b) in SMBI experiments. The plasma was produced from t = 50 to 240 ms with ICH from t = 51 to

240 ms. To produce the confinement potential, we applied plug and barrier ECH from $t = 145$ to 165 ms. The SMBI was injected at $t = 150.0$ ms with a pressure of 0.3 MPa and a pulse duration of 0.5 ms. Figure 8 shows MP TS signals for each channel at measuring position $x = 0$ cm in the SMBI experiment. In Fig. 8, red, blue, green, and black lines represent the outputs of CH. 1, CH. 2, CH. 3, and CH. 4, respectively. The calculated time-dependent electron temperature and density measured by each pass are shown in Figs. 9 (a) and (b), respectively. Using the MP TS system made it possible to successfully measure time-dependent electron temperature and density.

5. Summary

We developed a YAG-TS system to measure the radial electron temperature and density in GAMMA 10/PDX plasma. Using additional collection mirrors for improving the TS signals from the plasma edge region and a movable fiber slot position on a lab jack allowed us to measure a detailed radial profile. The MP TS system successfully measured time-dependent electron temperature and density in SMBI experiments. To increase the pass number of the MP system, a laser amplification system was installed. Comparing Rayleigh scattering experiments with and without the amplification system reveals a clear improvement when the amplification system was used. In addition, the end-TS system was installed in the divertor simulation experiment (D-module) of GAMMA 10/PDX.

Acknowledgments

The authors thank the members of the GAMMA 10/PDX group of the University of Tsukuba for their collaboration. This study was conducted with the support and under the auspices of the NIFS Collaborative Research Program (NIFS11KUGM056) and the Bidirectional Collaboration Research Programs (NIFS14KUGM086, NIFS14KUGM088).

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