Measuring Electron Temperature in the Tandem Mirror GAMMA 10 Plasma Using a Yttrium-Aluminum-Garnet Thomson Scattering System

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A yttrium–aluminum–garnet Thomson scattering (TS) system was constructed and applied to the tandem mirror GAMMA 10 plasma to measure the electron temperature. A large solid-angle TS light-collection system was set using a spherical mirror system and a large numerical aperture of bundled optical fiber. A five-channel polychromator with avalanche silicon photo diodes was employed after being calibrated with standard light. Calibration was performed by Rayleigh and Raman scattering. An electron temperature increase from 40 eV to 80 eV was observed with application of electron cyclotron heating to plug/barrier cells.

Keywords: tandem mirror, GAMMA 10, Thomson scattering

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GAMMA 10 is the world largest tandem mirror machine with which plasma confinement is achieved not only by a magnetic mirror configuration but also high potentials at both end regions [1–3]. The main plasma is produced and heated by ion-cyclotron range of frequency waves. The confinement potentials are produced by plug and barrier electron cyclotron heating (P/B-ECH) at the plug/barrier regions. During the formation of confinement potential, the typical electron density, electron temperature, and ion temperature are about 2×10^{18} m^{-3}, 0.1 keV, and 5 keV, respectively. Thomson scattering (TS) is the most reliable diagnostic for measuring electron temperature and electron density. In GAMMA 10, a ruby-laser TS system was installed to measure the electron temperature. However, the system experienced problems. Previously, electron temperature has been measured by soft X-ray measurement. Thus far, direct electron heating by ECH experiments have been conducted in the central cell. In addition, density and potential fluctuation suppressions during the formation of confinement potential have been studied using a gold neutral beam probe system [1–3]. 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 comparison with the ruby-laser system, operation of the YAG laser system is easier and the repetition rate of such a system is much larger. The YAG TS system is normally used in higher electron density plasmas, over 10^{19} m^{-3}. Moreover, an efficient TS system is necessary to measure low-density plasmas in the region of less than 10^{19} m^{-3}, such as the GAMMA 10 plasma and the peripheral plasma of high-density fusion plasmas. To obtain a TS signal with a good signal-to-noise ratio, we developed an optical-collection system with a large solid angle. In this paper, we describe the newly installed YAG TS system and the first results of electron temperature and density measurements in the tandem mirror GAMMA 10.

The YAG TS system is constructed with laser, incident optics, light-collection optics, signal-detection electronics, and a data-recording system. A 10-Hz Nd:YAG laser (Continuum, Powerlite 9010) with an energy per pulse of 2 J, a pulse width of about 10 ns, and operating at a fundamental wavelength of 1064 nm is used on loan from Japan's National Institute for Fusion Science (NIFS). The laser beam diameter at the plasma center is about 1 mm with a focusing lens $f = 2$ m. The light-collection optics is optimized with the help of the ZEMAX optical system design software program. For the light-collection optics, we use a spherical mirror with an Al:SiO_2 coating, curvature radius of 1.2 m, and a diameter of 0.6 m. The scattered light is collected by the spherical mirror and reflected until it reaches a bundled optical fiber having a cross section

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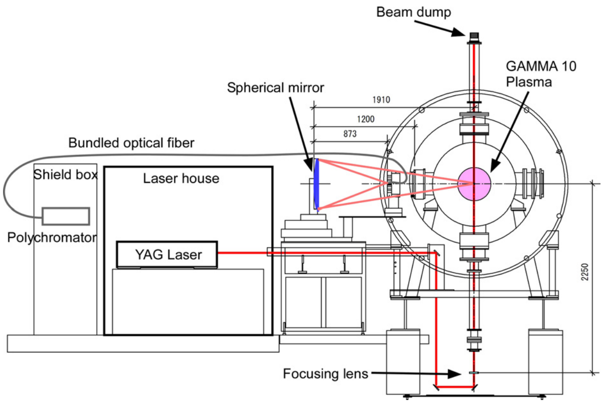

Fig. 1 YAG TS system in the tandem mirror GAMMA 10.

of 2 × 7 mm. The magnification of the collection optics is 2.2. The length of scattering volume along the laser is 15.4 mm, and the scattering angle is 90°. A solid angle of 0.078 sr can be realized from the light-collection optics. This value is larger than those achieved on other plasma devices, which are typically less than about 0.020 sr. The 6.67-m bundled optical fiber (Mitsubishi Densen, FS10-25301B) is connected to the five-channel polychromator. The bundled optical fiber is constructed of 48 fibers with a core diameter of 0.4 mm and a very large numerical aperture of approximately 0.47. The fiber aperture should be located at approximately 0.873 m from the spherical mirror. The YAG TS system in GAMMA 10 is shown in Fig. 1. The five-channel polychromator is on loan from NIFS [4]. This polychromator is composed of five relay and collection lenses, five interference filters, and five avalanche photodiodes. A four-channel, high-speed oscilloscope (Tektoronix, DPO4034B) was used to measure four wavelength channels simultaneously. Raman and Rayleigh calibration experiments were conducted to set the optical system and evaluate the stray light in the GAMMA 10 YAG TS system. Nitrogen gas was used, and the pressure in the GAMMA 10 device was increased to 2.33×10^4 Pa. Figure 2 shows the signal intensities of the Raman scattering measurement as a function of target pressure. The measured scattering signal is proportional to gas pressure. The linear component indicates the scattering light and the offset indicates the stray light. The stray light in this system is very small, less than 3% of the TS signals. In the GAMMA 10 YAG TS system, 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 200 eV. By interpolating between the tabulated values, the values of the electron temperature that minimize the chi-squared value are obtained.

We applied the YAG TS system to measure the electron temperature of the GAMMA 10 plasma. The obtained TS spectrum with four channels and normalized calculation fitting curve before application of P/B-ECH is shown in Fig. 3. The signal-to-noise ratio is approximately 3. We obtain an electron temperature of about 40 eV before applying P/B-ECH. With application of P/B-ECH, the electron temperature increased to about 80 eV. Considering the minimized chi-squared value analysis, the error of the electron temperature measurement by the system is about 13%. Electron density by TS is about $(2.5 \pm 0.8) \times 10^{18}$ m^{-3}.

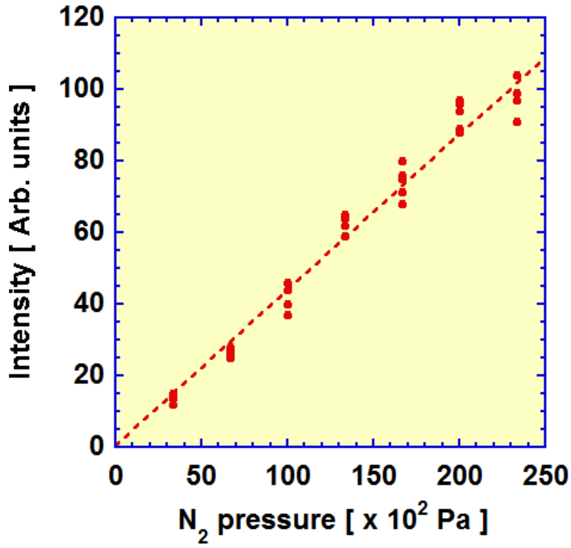

Fig. 2 Signal intensities of Raman scattering measurement as a function of target pressure.

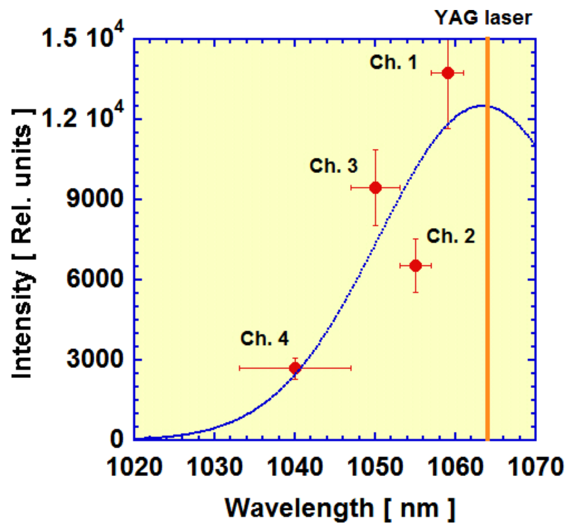

Fig. 3 Thomson scattering spectra with four channels and normalized calculation-fitting curve.

In summary, a YAG TS system was installed to the tandem mirror GAMMA 10. This system can be operated to measure electron temperature in the very low-density plasma region, which is less than 2×10^{18} m^{-3}. We were able to measure the electron temperature and density in the tandem mirror GAMMA 10 by using a YAG TS system for the first time. The electron temperature was obtained at one position and for one period. We measured the radial electron temperature profile by changing the bundled optical fiber position.

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