Polarization-Controlled Multi-Pass Thomson Scattering System in the Tandem Mirror GAMMA 10

Masayuki YOSHIKAWA, Ryo YASUHARA[1)], Seito SAKAMOTO, Ryo SEKIGUCHI, Yoriko SHIMA, Junko KOHAGURA, Mizuki SAKAMOTO, Yousuke NAKASHIMA, Tsuyoshi IMAI, Makoto ICHIMURA, Ichihiro YAMADA[1)], Hisamichi FUNABA[1)], Kazuo KAWAHATA[1)] and Takashi MINAMI[2)]

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

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An effective method to increase Thomson scattering (TS) signals is required in low-density plasmas. Multi-pass TS has the advantage of enhancing scattered signals. We constructed a double-pass TS system for a polarization-based system modelled on the GAMMA 10 TS system. In the second step, we have developed the multi-pass TS system based on the former double-pass TS system. In order to evaluate the effectiveness of the polarization-based configuration, the multi-pass system was installed in the GAMMA 10 TS system, which is capable of multi-pass scattering. We undertook Rayleigh scattering experiments. The integrated scattering signal was magnified to be approximately three times as large by using the multi-pass system with 6 passes.

Keywords: Thomson scattering, multi-pass, polarization-controlled, tandem mirror GAMMA 10

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The Thomson scattering (TS) diagnostic is one of the most reliable methods for measuring electron temperature and density profiles in fusion plasmas. However, for low-electron-density plasmas of less than 10^{19} m^{-3}, such as the GAMMA 10 plasma and the peripheral plasma in high-density fusion devices, an effective TS system is yet to be developed [1, 2]. A novel configuration for a multi-pass TS system is proposed for the improvement of both time resolution and accuracy of electron temperature measurements by using the polarization control technique [3–5]. This configuration can be used to realize perfect coaxial multi-passing at each pass. This new multi-pass TS system is being developed for the tandem mirror GAMMA 10. This multi-pass TS scheme effectively increases the scattering signal intensity from low-density plasmas. It allows a laser pulse to be focused multiple times onto the scattering volume in order to increase the number of scattering photons. Multi-pass TS systems have been developed for many devices. For instance, at the Tokamak Experiment for Technology Oriented Research (TEXTOR), the signal-to-noise ratio was improved by using a multi-pass TS system, which uses a pair of concave mirrors to recycle photons [6]. The confocal spherical mirror system is used in the TST-2 spherical Tokamak [7]. In the JT-60U, a double-pass system was constructed using a phase-conjugate mirror for reflection [3]. Although these approaches have increased the reliability of the TS system, they are limited by the optical system. Each laser beam pass is different in the concave-mirror-type TS system in TEXTOR and in the confocal spherical mirror type TS system in TST-2. The scattering volume must be set near the focal point of the concave mirror, and the system is required to be calibrated for each beam pass. Moreover, the phase-conjugate-mirror system in JT-60U requires high purity laser bandwidth.

In this paper, we present a new scheme for a multi-pass TS system that uses polarization optics, and we demonstrate the results of the multi-pass TS system installed in GAMMA 10 with Rayleigh scattering experiments. This scheme can be implemented by modifying a basic single-pass TS system with the addition of polarization devices, a high-reflection mirror, and lenses for the image relaying of the laser beam.

A schematic diagram of the new multi-pass method for a polarization-based system is shown in Fig. 1. This system is based on the GAMMA 10 TS system, which has been used to successfully observe the electron temperature and density of the GAMMA 10 plasma [1,2]. A horizontally polarized laser beam from the yttrium-aluminium-garnet (YAG) laser (Continuum, Powerlite 9010, 2 J/pulse, and 10 Hz) is focused onto the plasma center by the first convex lens (Shigmakoki, $f = 2000$ mm, $\phi = 50$ mm) from the downside port window, which has an anti-reflection (AR) coating, after passing a short-pass mirror (CVI, SWP-45-RS1064-TP633-PW-2025-C), two Faraday rotators (EOT, HP-12-I-1064-000-000) for isolation, two half-

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

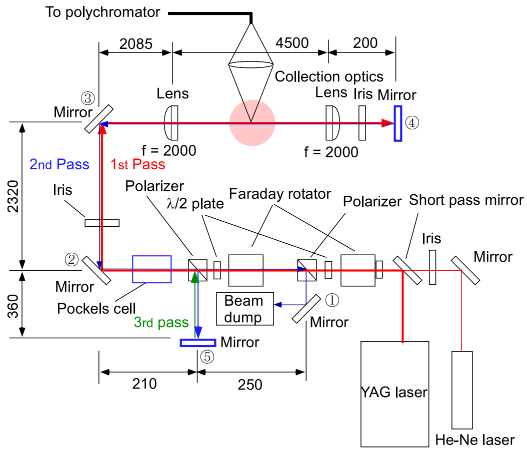

Fig. 1 Schematic of the multi-pass TS system.

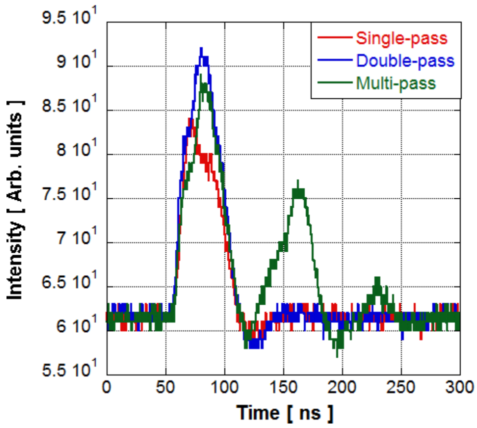

Fig. 2 Single, double and multi-pass Rayleigh scattering signals.

wave plates (CVI, QWPO-1064-08-2-AS10), two polarizers (Glan-Laser Calcite Polarizer), a Pockels cell (Fast-Pulse, Q1059P12SG-1064), mirrors ② and ③ (CVI, YH-2037-45), and irises (Thorlabs, ID25/M). After interacting with the plasma, the laser beam is emitted from the upper-side port window, which also has an AR coating, and is collimated by the second convex lens (Shigmakoki, f = 2000 mm, ϕ = 50 mm). A pair of lenses forms a key component of this optical system. 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. The laser beam is reflected by the reflection mirror ④ (CVI, Y1-1037-0) 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. The third laser pass is produced by a Pockels cell for polarization control and the reflection mirror ⑤. The laser light is confined between 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. The scattered light is collected and reflected by the spherical mirror, after which, it reaches an optical fiber bundle with a cross-section of $2 \times 7\ \mathrm{mm}^2$. The scattering angle is 90°. A solid angle of 0.078 sr can be realized by the light collection optics. The 6.67-m-long optical fiber bundle (Mitsubishi Densen, FS10-25301B) is connected to a 5-channel 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 (EG&G, C30950-CD1161). A four-channel high-speed oscilloscope (Tektronix, DPO4034B) is simultaneously used to measure four wavelength channels with a bandwidth of 350 MHz and a sampling rate of 2.5 GS/s. The measured signals are recorded by a Windows PC using the LabVIEW analyzing software.

Rayleigh calibration experiments are carried out for setting up the optical system and the measurement of stray light in the evaluation of the multi-pass GAMMA 10 YAG-TS system. In Rayleigh scattering experiments, we used 1/1000 of laser power that is normally used at TS experiments. Nitrogen gas is used, and the pressure in the GAMMA 10 device is increased to 400 hPa. In Fig. 2, the measured single-pass (red line), double-pass (blue line), and multi-pass signals (green line) are shown. We can see the six-pass scattering signals in the multi-pass TS system. In the multi-pass system, the scattered signals from the first to sixth laser passes are added. The integrated scattering intensity of the multi-pass is about three times that of the single pass. The integrated intensity of the double pass signal is about 1.5 times larger than that of the single pass one. The reason for the low second-pass signal intensity is the reflection of laser in the optical lens system, because, unfortunately, the optical lens was not AR coated. Moreover, optimization of the second pass orbit is required. The measured scattering signal is proportional to the gas pressure. The scattering signal intensities depend on the gas pressure and injected laser power. In these experiments, the precision of coaxial alignment is almost less than 1 mm. We have successfully constructed the multi-pass TS scattering system. In order to apply this system to measure TS signals in GAMMA 10 plasma, we have to check the damages on the optical systems in the multi-pass configuration carefully.

[1] M. Yoshikawa *et al.*, Plasma Fusion Res. **6**, 1202095 (2011).
[2] M. Yoshikawa *et al.*, Journal of Instrumentation **7**, C03003 (2012).
[3] T. Hatae *et al.*, Rev. Sci. Instrum. **77**, 10E508 (2006).
[4] R. Yasuhara *et al.*, Rev. Sci. Instrum. **83**, 10E326 (2012).
[5] M. Yoshikawa *et al.*, Rev. Sci. Instrum. **83**, 10E333 (2012).
[6] M. Yu Kantor *et al.*, Plasma Phys. Control. Fusion **51**, 055002 (2009).
[7] J. Hiratsuka *et al.*, Plasma Fusion Res. **5**, 044 (2010).