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REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 11D801 (2014)

First results of electron temperature measurements by the use of multi-pass Thomson scattering system in GAMMA 10[a)]

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A multi-pass Thomson scattering (TS) has the advantage of enhancing scattered signals. We constructed a multi-pass TS system for a polarisation-based system and an image relaying system modelled on the GAMMA 10 TS system. We undertook Raman scattering experiments both for the multi-pass setting and for checking the optical components. Moreover, we applied the system to the electron temperature measurements in the GAMMA 10 plasma for the first time. The integrated scattering signal was magnified by approximately three times by using the multi-pass TS system with four passes. The electron temperature measurement accuracy is improved by using this multi-pass system. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4885542]

I. INTRODUCTION

The Thomson scattering (TS) diagnostic is one of the most reliable methods to measure electron temperature and density in fusion plasmas. However, for low-electron-density plasmas, such as the GAMMA 10 plasma and the peripheral plasmas in fusion devices, an effective TS system is required.[1,2] The GAMMA 10-TS system can measure the radial profiles of electron density and temperature for the electron density region of over about 5×10^{17} m^{-3}. However, in the lower electron density region, the measurement accuracy is low. Moreover, TS measurements with increased time resolutions are required for future studies on turbulence. GAMMA 10 is an effectively axisymmetric minimum-B anchored tandem mirror with thermal barriers located at both end-mirrors.[3,4] In the tandem mirror GAMMA 10, the lengths of the central, anchor, and plug/barrier cells are 6.0, 4.8, and 2.5 m, respectively. The magnetic field strength at the mid-plane of the central cell under standard operation is 0.41 T, and the mirror ratio is 5. The plasma diameter is approximately 0.36 m. The typical electron density, electron temperature, and ion temperature are approximately 2×10^{18} m^{-3}, 40 eV, and 5 keV, respectively. Multi-pass TS systems were originally proposed with the aim of improving both the time resolution and the accuracy of electron temperature measurements.[5–12] At the Tokamak Experiment for Technology Oriented Research (TEXTOR), the signal-to-noise ratio was improved by using a multi-pass TS system, which is equipped with a pair of concave mirrors to recycle photons.[11] The confocal spherical mirror system is used in the TST-2 spherical Tokamak.[10,12] In the JT-60U, a double-pass system was constructed using a phase-conjugate mirror for reflection.[5] 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 by using the polarisation control techniques. We develop a new multi-pass TS system for the tandem mirror GAMMA 10. This multi-pass TS scheme effectively increases the scattering signal intensity from plasmas and can be implemented by modifying a basic single-pass TS system with the addition of polarisation device, a high-reflection mirror, and lenses for the image relaying of the laser beam. The system allows a laser pulse to be focused multiple times onto the scattering volume to increase the number of scattering photons. The double-pass TS system was constructed and the TS signal increased twice and electron temperature resolution improved in GAMMA 10.[6,8] In LHD, the double-pass TS system, which is the same design as the GAMMA 10 double-pass TS system, was installed and operated.[7] The configuration of the multi-pass TS system in GAMMA 10 can be used to realize perfect coaxial multi-passing at each pass. By adding the polarisation control device, a polariser and a high reflection mirror to the double-pass TS system, we can successfully construct the multi-pass TS system.[9]

In this paper, we present the first electron temperature measurements acquired by using the new multi-pass TS system that uses polarisation optics and the image relay system. In previous research, the Rayleigh scattering experiments in the multi-pass configuration were carried out with the lower laser power condition.[9] We carried out the Raman scattering experiments for optical system checking and evaluation of the multi-pass configurations with a typical laser power

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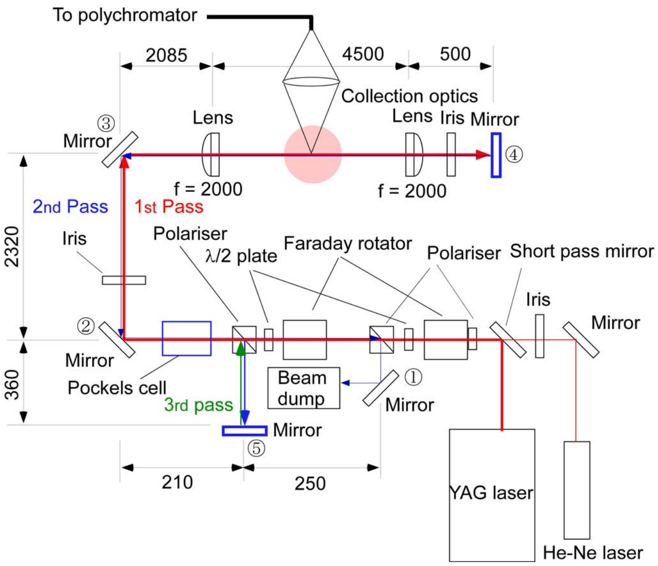

FIG. 1. Schematic of the multi-pass TS system.

condition. Moreover, we applied it to the electron temperature measurement in the GAMMA 10 plasma for the first time.

II. MULTI-PASS THOMSON SCATTERING SYSTEM

A schematic diagram of the new multi-pass method is shown in Fig. 1. System details are discussed elsewhere.[9] 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 polarised 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, AR coated) from the downside port window after passing a short-pass mirror, two Faraday rotators for isolation, two half-wave plates, three polarisers, a Pockels cell (FastPulse, Q1059P12SG-1064), mirrors ② and ③, and irises. After interacting with the plasma, the laser beam is emitted from the upper-side port window and is collimated by the second convex lens (Shigmakoki, $f = 2000$ mm, $\phi = 50$ mm, AR coated). The pair of lenses forms a key component of this optical system in that the 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 for the second pass and is focused again onto the plasma. The Faraday rotator and the Pockels cell are used for polarisation control. The Pockels cell switches the polarisation of the laser beam from horizontal to vertical for reflected passes made during the gate pulse (~550 ns). The third laser pass is produced by a Pockels cell and the reflection mirror ⑤. The distance between the lens and the reflection mirror ④ was changed from 200 mm to 500 mm in these experiments. The laser light is confined between the reflection mirrors ④ and ⑤ for the multi-pass propagation, and its distance between the reflection mirrors is 9975 mm. 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 at scattering angle 90° is collected and reflected by the spherical mirror, after which it reaches an optical fiber bundle with a cross-section of 2×7 mm^2. The measurable radial positions are X = 0, ±5, ±10, ±15, and ±20 cm. The 6.67 m-long optical fiber bundle 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 (PerkinElmer, C30659-1060-3AH) with preamplifiers. 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). Four-channel high speed oscilloscopes (Tektronix, DPO4034B, and IWATSU, DS5524) were used to measure the four wavelength channels simultaneously with bandwidths of 350 MHz and 200 MHz, and sampling rates of 2.5 GS/s and 1 GS/s, respectively. The measured signals were recorded by a Windows PC using the LabVIEW analyzing software.

III. EXPERIMENTAL RESULTS

A. Raman scattering experiments

Raman gas scattering experiments were carried out to assist in the setup of the optical system and ultimately for the evaluation of the multi-pass GAMMA 10 YAG-TS system. In the Raman scattering experiments, we used a laser power of 2 J/pulse, a value that is typical of TS experiments. The lowest damage threshold of energy density of the optical components within the multi-pass configuration is the Pockels cell at about 5 J/cm^2. This value is large relative to the laser energy fluence and is therefore not of great concern. Nitrogen gas is used, and the pressure in the GAMMA 10 device is increased to 19.4 hPa. In Fig. 2, the measured single-pass (green dotted line) and multi-pass signals (red line) of CH. 1 shown are measured by DPO4034. We can clearly see the six-pass scattering signals in the multi-pass

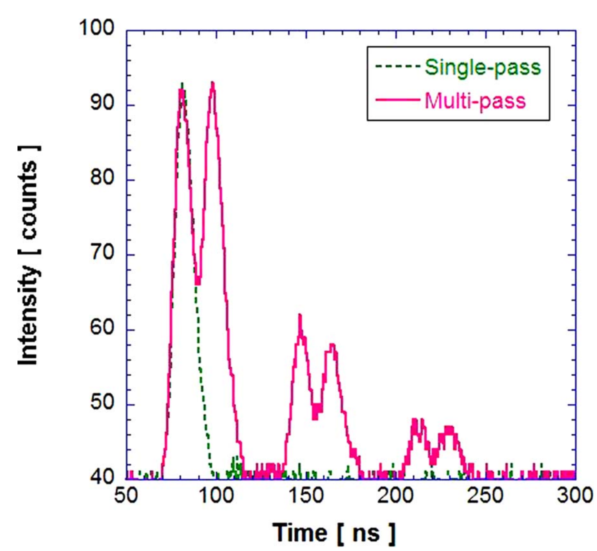

FIG. 2. Single (green dotted line) and multi-pass (red line) Raman scattering signals of CH. 1.

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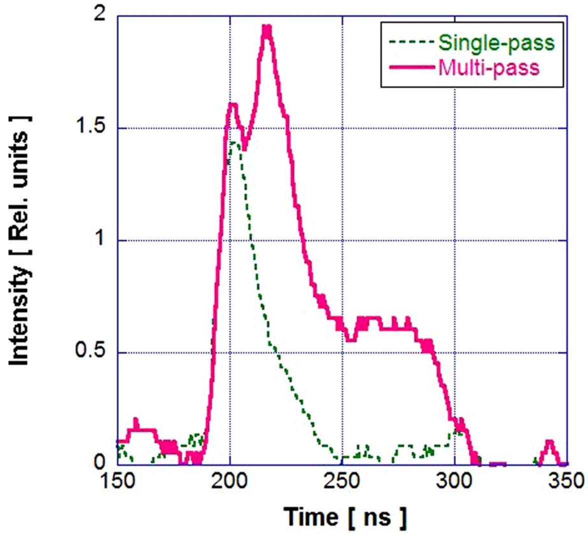

FIG. 3. Single (green dotted line) and multi-pass (red line) TS signals.

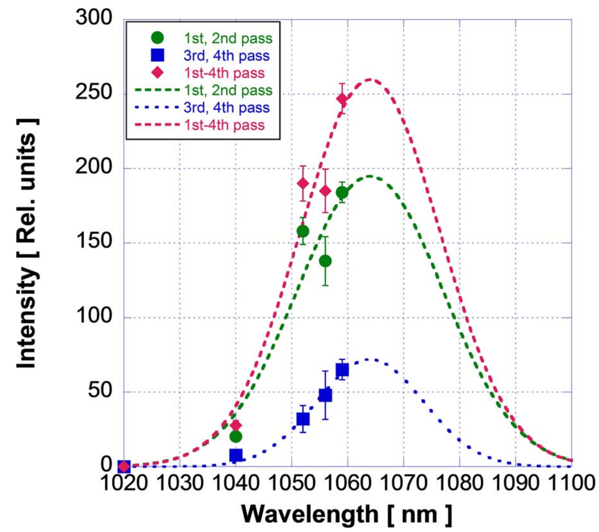

FIG. 4. TS spectra of the multi-pass configuration.

system. In the multi-pass system, the scattered signals from the first through sixth laser passes are added. The integrated scattering intensity of the multi-pass is about 3.5 times larger than that of the single-pass. The measured scattering signal is also proportional to the gas pressure.

B. Electron temperature measurements

We applied this system to the GAMMA 10 plasma for electron temperature measurements. Figure 3 shows the measured TS signals of single-pass (green dotted line) and multi-pass signals (red line) of CH. 1 measured by DS5524. The single-pass and multi-pass configurations were measured at the radial position of $X = 0$ cm and $X = 5$ cm, respectively. We can clearly confirm the first through forth passing TS signals in the multi-pass configuration. The integrated TS signals in the multi-pass configuration were about three times larger than in the single-pass configuration. Figure 4 shows the integrated TS spectra of the first and second pass signals (green circles, integration time of $\Delta t = 60$ ns), the third and fourth pass signals (blue squares, $\Delta t = 60$ ns), the first through fourth pass signals (red diamonds, $\Delta t = 120$ ns), respectively, and Gaussian curves fitted to them (dotted lines) as measured by DS5524. The integrated TS signal intensity from the first through fourth pass in the multi-pass configuration is about 3 times larger than that of single pass TS signal. The electron temperatures are obtained by using chi-squared method.[1] The obtained electron temperatures by the single-pass and the multi-pass (first through fourth pass integration) TS signals were about 47 ± 7 eV and 28 ± 2 eV, respectively. The error in the electron temperature obtained by the single-pass TS signal, ±7 eV, is more than two times larger than that of the first through fourth pass, ±2 eV, in the multi-pass configuration. The resolution of electron temperature measurement was improved by the multi-pass TS system. We have successfully constructed the multi-pass TS scattering system and obtained the first multi-pass TS signals for electron temperature measurements.

IV. SUMMARY

We have successfully constructed the multi-pass TS scattering system and obtained the multi-pass TS signals for electron temperature measurements in the GAMMA 10 plasma. We carried out Raman scattering experiments, clearly obtained the multi-pass Raman scattering signals and applied them to the electron temperature measurements in the GAMMA 10 plasma for the first time. The integrated scattering signal was magnified by three by using the multi-pass TS system with four passes; additionally the resolution of electron temperature measurement is improved.

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