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High time resolved electron temperature measurements by using the multi-pass Thomson scattering system in GAMMA 10/PDX

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High time resolved electron temperature measurements are useful for fluctuation study. A multi-pass Thomson scattering (MPTS) system is proposed for the improvement of both increasing the TS signal intensity and time resolution. The MPTS system in GAMMA 10/PDX has been constructed for enhancing the Thomson scattered signals for the improvement of measurement accuracy. The MPTS system has a polarization-based configuration with an image relaying system. We optimized the image relaying optics for improving the multi-pass laser confinement and obtaining the stable MPTS signals over ten passing TS signals. The integrated MPTS signals increased about five times larger than that in the single pass system. Finally, time dependent electron temperatures were obtained in MHz sampling. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4955287]

I. INTRODUCTION

Thomson scattering (TS) diagnostic is one of the most useful methods for measuring electron temperature and density of plasmas.[1–7] However, the time resolution of TS measurement is limited by the probing laser frequency of the TS system. In the high frequency fluctuation plasma experiments, such as Alfvén ion cyclotron (AIC) modes, electron cyclotron heating experiments for edge localized modulation (ELM) simulation, and pellet injection experiments, the higher time resolved TS measurements are required. Multipass (MP) TS systems were proposed for the improvement of both increasing the TS signal intensity and time resolution. 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. The MPTS systems have been developed in several fusion plasma devices. For instance, at Tokamak Experiment for Technology Oriented Research (TEXTOR) and TST-2 tokamak devices, the MPTS systems were constructed by using a pair of concave mirrors to recycle photons.[8–12] In JT-60U, a double-pass system was built with a phase-conjugate mirror for laser reflection.[13] In GAMMA 10/PDX, the MPTS system of the polarization based system with image-relaying optics has been developed. In our MPTS system, the multi-pass configuration scheme can be easily 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. The configuration of MPTS system in GAMMA 10/PDX can be used to realize perfect coaxial multi-passing on each pass. In GAMMA 10/PDX, a double-pass TS system was constructed, doubling the TS signal intensity and improved the resolution of electron temperature measurements.[14,15] In LHD, the double-pass TS system, which is the same design as the GAMMA 10/PDX double-pass TS system, was installed and operated.[16] By adding a polarization control device, a polarizer, and a high-reflection mirror to the double-pass TS system, we have successfully constructed over three passing MPTS systems.[17–20] We successfully obtained about 3.6 times increased TS signals by first to sixth passing probing lasers through the plasma in a single laser shot.[20] Moreover, the time dependent electron temperature measurement every 65 ns was successfully obtained.[20]

In this paper, we present the high time resolved electron temperature measurement system with using the MPTS system, which can obtain the better TS signal intensities and the time dependent TS signals to improve the accuracy and time resolution of electron temperature measurements. The MPTS system can obtain ten passing TS signals and the integrated MPTS signals increased about five times larger than that of the single-pass TS signal.

II. MULTI-PASS THOMSON SCATTERING SYSTEM

A schematic diagram of the multi-pass method 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.[6,7] 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 (CVI, f = 2229 mm, ϕ = 50.8 mm) from the downside port window after passing a short-pass mirror, two Faraday

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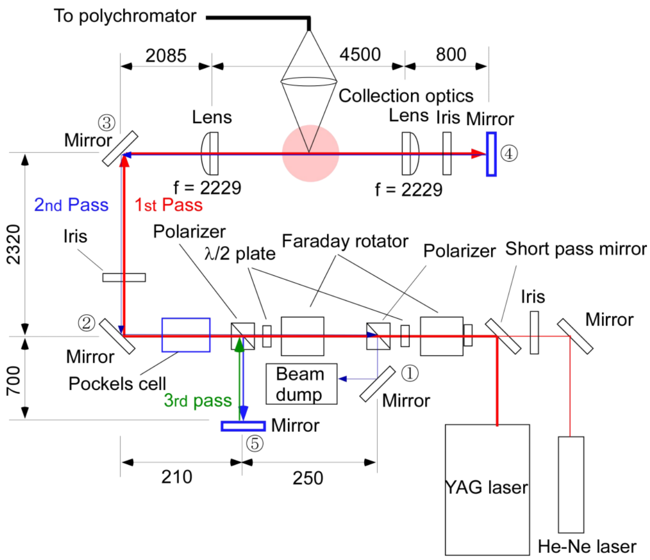

FIG. 1. Schematic of the MPTS system.

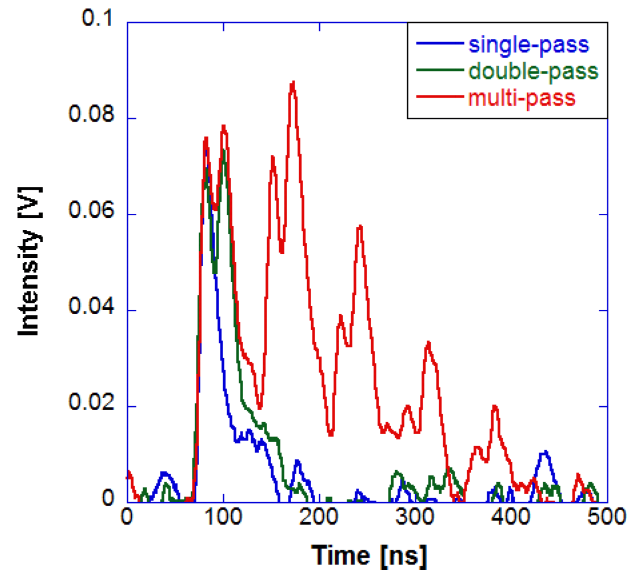

FIG. 2. A single-pass, a double-pass, and a multi-pass signals are shown in blue, green, and red lines, respectively.

rotators for isolation, two half-wave plates, two polarizers, a Pockels cell (Gooch & Housego, QX1630, aperture of 15 mm), 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 (CVI, $f = 2229$ mm, $\phi = 50.8$ mm). We changed the focal length of these focusing lenses from the previous system to improve the image relay characteristics. 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 distance between the second lens and the reflection mirror ④ is extended to 800 mm from 500 mm in the former system. 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 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). The third laser pass is produced by a Pockels cell for polarization control and the reflection mirror ⑤. The distance between the first lens and the reflection mirror ⑤ is also extended to 700 mm from 360 mm in the former system. The laser light is confined between the reflection mirrors ④ and ⑤ for the multi-pass propagation, and its distance between them is 10 615 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 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 scattering angle is 90°. The measurable radial positions are X = 0, ±5, ±10, ±15, and ±20 cm. The each channel of 6.67-m-long optical fiber bundle is connected 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, 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). Electron temperatures are obtained by the chi–square method.[6]

III. EXPERIMENTAL RESULTS

We applied this MPTS system to the GAMMA 10/PDX plasma for electron temperature measurements. Figure 2 shows the measured TS signals of single-pass (blue line), double-pass (green line), and multi-pass (red line) signals of CH. 1 of polychromator (TS149) measured by DS5524. We can clearly confirm the first to tenth passing TS signals in the multi-pass configuration. The integrated TS signals in

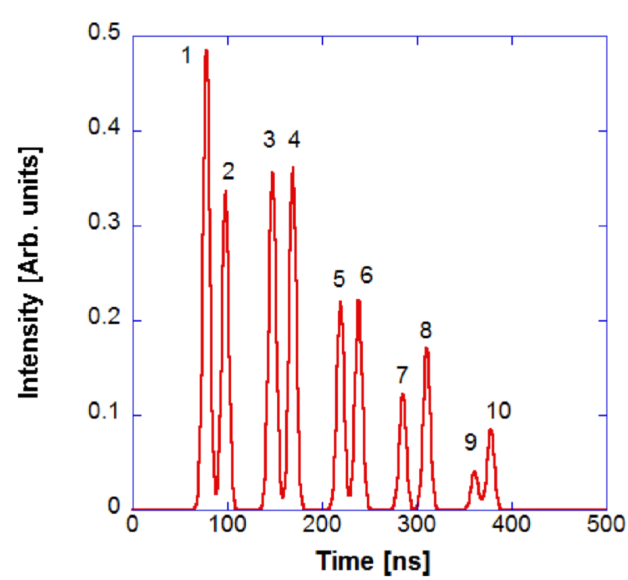

FIG. 3. Time dependent TS signals obtained by using analyzed methods.

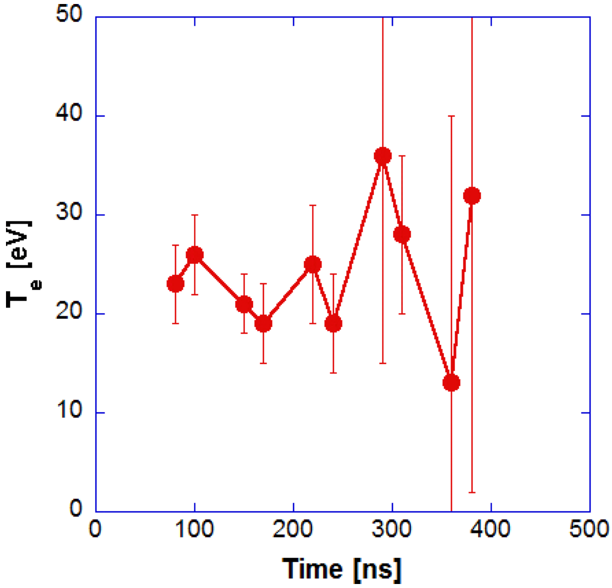

FIG. 4. Time dependent electron temperature obtained by the MPTS.

the multi-pass configuration are about five times larger than that in the single-pass configuration. Figure 3 shows the clear multi-pass TS signals of summed with all TS signals from all output channels of the polychromator after subtracting the noises and polychromator pre-amplifier characteristic decay signals using the newly constructed analyzing method which is shown in Ref. 21, with the pass numbers. The 8 and 10 passing TS signal intensities are larger than those of 7 and 9, respectively. The reason of it is not clear but it is thought that it is caused by the density fluctuation. Integrated TS signals intensity from 1st-pass to 10th-pass in the multi-pass configuration is about five times larger than that of single pass TS signal. By calculating each passing TS signal, we can obtain the time dependent electron temperature. In Fig. 4, time evolution of electron temperature is shown. The calculated electron temperatures from 7th-pass to 10th-pass have large errors and large differences because of low signal to noise ratio. In GAMMA 10/PDX plasma, the electron collision time is about 0.7 μs. Then the electron temperature is almost constant of 22 ± 2 eV during 400 ns from 1st-pass to 10th-pass. We successfully constructed the high time resolved electron temperature measurement system by MPTS in the order of MHz sampling.

IV. SUMMARY

We have constructed the high time resolved TS scattering system by constructing the multi-pass TS system. We have successfully obtained the time dependent multi-pass TS signals in the order of MHz sampling and measured the time dependent electron temperatures for the first time. The integrated scattering signal was magnified to be approximately five times as large by using the multi-pass TS system with ten passes and the resolution of electron temperature measurement is improved.

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