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## AFFILIATIONS

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## ABSTRACT

The multipass Thomson scattering (MPTS) technique is one of the most useful methods for measuring low-electron-density plasmas. The MPTS system increases Thomson scattering (TS) signal intensities by integrating all multipass (MP) signals and improving the TS time resolution by analyzing each pass signal. The fully coaxial MPTS system developed in GAMMA 10/potential-control and diverter–simulator experiments has a polarization-based configuration with image-relaying optics. The MPTS system can enhance Thomson scattered signals for improving the measurement accuracy and megahertz-order time resolution. In this study, we develop a new MPTS system comprising a laser amplification system to obtain continuous MP signals. The laser amplification system can improve degraded laser power and return an amplified laser to the MP system. We obtain continuous MP signals from the laser amplification system by improving the laser beam profile adjuster in gas scattering experiments. Moreover, we demonstrate that more MP signals and stronger amplified MP signals can be achieved via multiple laser injections to the laser amplification system in the developed MP system comprising a laser amplification system.

## I. INTRODUCTION

The Thomson scattering (TS) method is one of the most useful techniques for measuring both the electron temperature and density of plasmas.[1–8] The time resolution of TS measurements is limited by the probing laser oscillation frequency. In high-frequency-fluctuation plasma experiments such as the Alfvén ion cyclotron modes, electron cyclotron heating experiments, edge localized mode simulation experiments, and pellet injection experiments, higher time-resolved TS measurements are required. Multipass Thomson scattering (MPTS) systems have been proposed for improving both the TS signal intensity and time resolution. The MPTS scheme effectively increases the scattering signal intensity from plasmas via the probing laser pulse to be focused multiple times onto the scattering volume. MPTS systems have been developed in several fusion plasma devices.[9–14] In GAMMA 10/potential-control and diverter–simulator experiments (PDX), a fully coaxial MPTS system has been developed using a polarization-based system with image-relaying optics.[15–23] GAMMA 10/PDX is an effectively axisymmetric minimum-B anchored tandem mirror with a thermal barrier at both end mirrors.[24] In the end region, a diverter simulation experimental module is used to perform diverter simulation experiments. By adding a polarization control device, polarizer, and high-reflection mirror to a normal single-pass TS system, we successfully constructed an MPTS system.[15–23] Subsequently, we developed a new MPTS system by adding a laser amplification system to achieve a continuous multipass (MP) signal.[25,26] The laser amplification system can increase the degraded laser power and the amplified laser beam can return to the normal MP configuration. We successfully obtained continuous MP signals via the laser amplification system in gas scattering experiments and TS measurements performed in GAMMA 10/PDX plasma. We have previously presented an MPTS system comprising a laser amplification system, which can obtain a significant amount of MPTS signals.[26] The laser amplification system can improve the degraded laser power after six passes in the MPTS system up to a high laser power. The amplification of the seventh pass signal via the amplification system rendered the integrated total signal intensity much larger than that of the single-pass configuration. Moreover, we measured the time-resolved electron temperature through megahertz sampling. However, in our previous study, the MPTS signals obtained after the laser amplification system were unclear in TS measurements performed in plasmas. The laser amplification in the later stage of the laser amplification system was low compared with that in the amplification module. We again added the laser beam profile adjuster before the laser amplifier and quarter wavelength plates to control the laser polarization. Moreover, we applied multiple laser amplification by performing multiple laser injections to the laser amplification system after the MP configuration.

Herein, we demonstrate the reconstructed MPTS system for obtaining stable MP signals in GAMMA 10/PDX. Additionally, we present the developed MP system that recurrently employs the laser amplification system to obtain stronger scattering signals and more stable MP signals over 12 passes.

## II. MPTS SYSTEM COMPRISING AMPLIFICATION SYSTEM

Figure 1 shows a schematic diagram of the reconstructed MPTS system comprising a laser amplification system. The basic system is the same as the former MPTS system comprising an amplification system.[26] However, the differences include the different polarizer position after the Faraday rotator, addition of a beam profile adjuster before the laser amplification system, and addition of two quarter-wavelength plates before and after the amplifier system. These are indicated in red in Fig. 1. A horizontally polarized laser beam from a yttrium–aluminum–garnet (YAG) laser (Continuum, Powerlite 9010, 2 J/pulse, pulse width of 10 ns, and repetition rate of 10 Hz) was focused onto the plasma center by the first convex lens from the lower port Brewster window after passing through a short-pass mirror, two Faraday rotators for isolation, two half-wave plates, two polarizers, the first Pockels cell (PC1, FastPulse, CF1043SG-1064), mirrors, and irises. After interacting with the plasma, the laser beam was emitted from the upper port Brewster window and then collimated by the second convex lens.

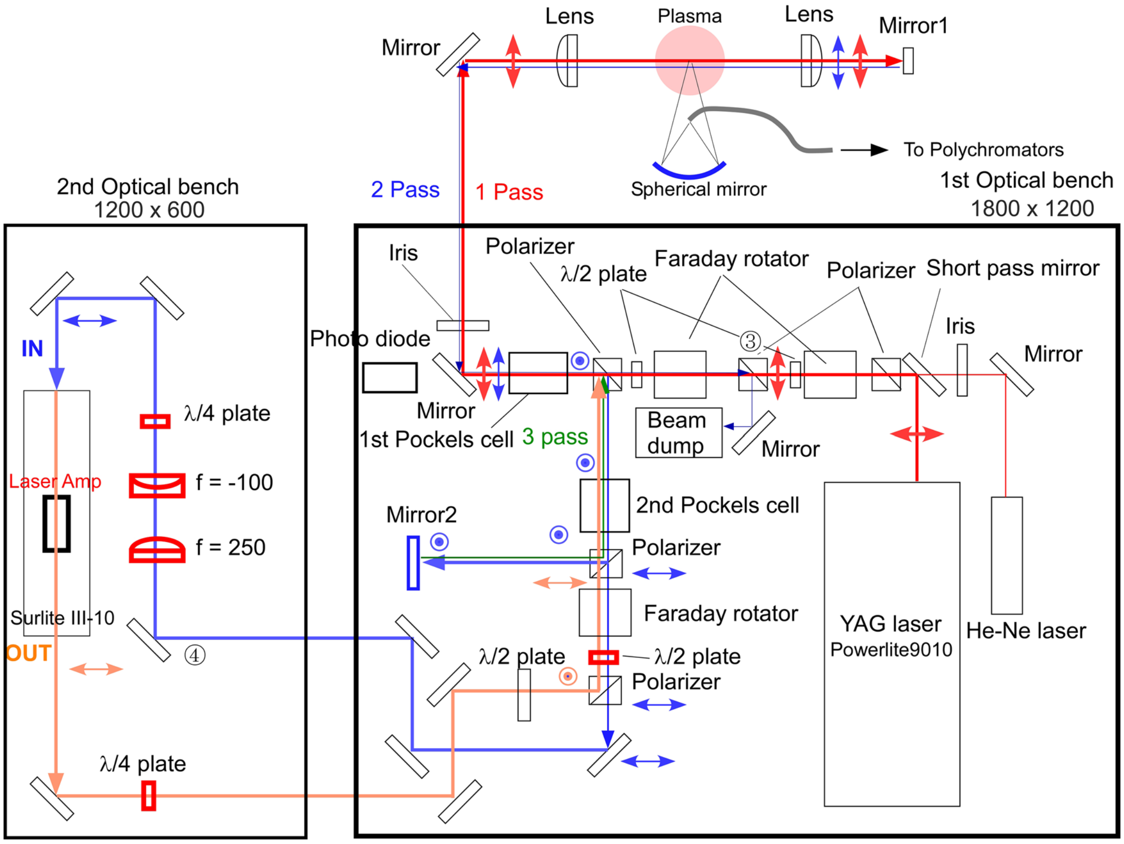

**FIG. 1.** Schematic diagram of the MPTS system with the amplification system.

These lenses maintained the laser beam quality during MP propagation through the image-relaying optical system. The spot diameter of the focused laser was ~1 mm, and the spot was located at the plasma center. In Fig. 1, the bold red lines with arrows indicate the first passing laser trajectory. The laser beam was reflected by reflection mirror 1 for the second pass and then refocused onto the plasma. The path length from the YAG laser to mirror 1 was 10.80 m. The distance between mirror 1 and mirror 2 was 10.75 m. The deviation in the laser position can be absorbed in the collection optics. The blue lines with arrows indicate the second passing laser trajectory. PC 1 switched the polarization of the laser beam from horizontal to vertical for the reflected passes during the gate pulse (10 kV and duration of ~550 ns). The horizontal laser polarization directions are indicated by red, blue, and orange left–right arrows. Before introducing reflection mirror 2, the second Pockels cell (PC 2) and polarizer were used to allow the third laser to pass through (green line with arrow). PC 2 was turned off, and the laser polarization was maintained in the vertical direction. The laser beam was focused toward reflection mirror 2. The laser light was confined between reflection mirror 1 and mirror 2 for MP propagation when PC 2 was turned off. To increase the degraded MP laser power, we added the laser amplification system to the normal MP configuration. We switched on PC 2 to change the laser beam polarization from vertical to horizontal during the gate pulse (10 kV and duration of ~80 ns) to focus the laser beam toward the laser amplification system. The laser reached the amplification system through the polarizers, Faraday rotator, half-wave plate, and mirrors. We added the quarter-wavelength plates before and after the laser injection of the amplification system to control the laser beam polarization more precisely. Without those wavelength plates, the amplified laser beam was not polarized. Moreover, we added a plano–convex lens (f = 250 mm) and plano–concave lens (f = −100 mm) to adjust the beam diameter before injecting it into the laser amplifier system. We used an amplifier (Continuum, Surelite-III amplifier system of 821V-09) in the laser amplification system. After PC 2 was switched on, the laser amplification system functioned as intended. Subsequently, the amplified laser beam returned to the normal MPTS system through the half-wave plate, polarizer, Faraday rotator, and polarizer. In Fig. 1, the orange line indicates the amplified laser trajectory to the normal MPTS system. For the TS light collection optics, we used three Al:SiO$_2$-coated spherical mirrors. The collected and reflected lights reached nine channel optical fiber bundles of cross sections measuring 2 × 7 mm$^2$. The scattering angle was 90°. The measurable radial positions were X = 0, ±5, ±10, ±15, and ±20 cm. Each channel of the 6.67-m-long optical fiber bundle was connected to a five-channel polychromator, which comprised five relay and collection lenses, five interference filters, and five silicon avalanche photodiodes with preamplifiers. The measured wavelengths of the polychromator were 1059 ± 2 (CH. 1), 1055 ± 2 (CH. 2), 1050 ± 3 (CH. 3), 1040 ± 7 (CH. 4), and 1020 ± 14 nm (CH. 5). Four-channel high-speed oscilloscopes (IWATSU, DS5524A) were used to measure the TS signals of four wavelength channels with a bandwidth of 200 MHz and a sampling rate of 1.0 GS/s. The electron temperatures were calculated using the chi–squared method after using the improved signal fitting analysis method.[8,23] Furthermore, we performed high-speed electron temperature and density measurements using the fitting analysis method.

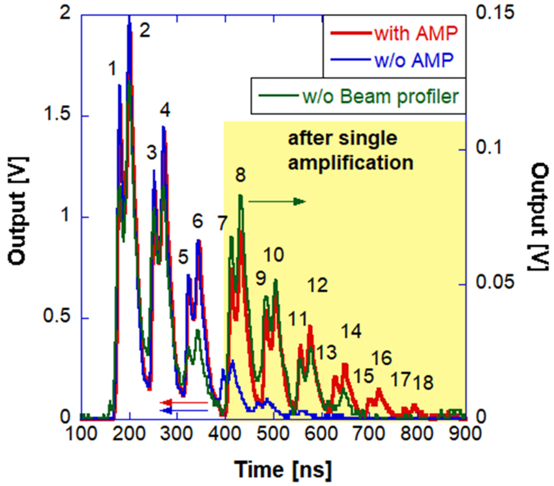

**FIG. 2.** MP signals with (red line) and without the amplification system (blue line) and that (green line) without the laser beam profile adjuster on old MPTS. Pass numbers are shown.

## III. GAS SCATTERING EXPERIMENT

We applied the new MPTS system to Raman gas scattering experiments. Figure 2 shows the typical MP signals of CH. 1 at X = 0 cm with (red line) and without the new MPTS system (blue line), where the initial laser power was 14.0 W and the gas pressure was 6.7 kPa, and the typical MP signal (green line) without the laser beam profile adjuster in the old MPTS, where the initial laser power was 1.0 W. Additionally, the number of passes is presented. The signal intensity of the second pass signal was larger than that of the first pass because of the pile-up on the first pass signal. A laser was introduced to the amplification system after the sixth pass through the laser beam profile adjuster. In the figure, the signals obtained after single amplification via the laser amplification system are indicated by the yellow hatched region. The differences in the peak times of the seventh pass signals with and without the amplification system originated from the path length corresponding to the amplification system. Using the laser amplification after the sixth pass laser, we obtained a seventh pass signal that had the same intensity as the fifth pass signal. The amplification rate of the laser power under the lower initial laser power condition (1.0 W) was much larger than that under the higher initial laser power condition (14.0 W). The signal intensity amplification rates calculated by the integrated intensity of the total multi-pass signals with and without amplification system divided by the integrated intensity of the first pass signal are ~7.3 and 4.7, respectively. The total signal intensities with the amplification system are 1.6 times larger than that without the amplification system.

## IV. NEW MP SYSTEM

We attempted to increase the MP signal pass numbers by changing the laser trajectory. In a normal MTPS with an amplification system, the laser beam passes through the laser amplification system only once. Under the lower-laser-power conditions, we can reuse the laser amplification system. The stored energy of the laser amplification system is restricted. If we used the initial laser power of 14 W, the multiple laser injection to the laser amplification system works like a single amplification because the stored energy is completely used for only one amplification. We attempted to introduce the laser after the sixth pass to the laser amplification system. The amplified laser returned the MP system to generate a double pass, and the laser propagated toward the laser amplification system again when PC 2 was switched on with a long gate pulse of PC 2. Subsequently, the laser beam was injected into the laser amplification system multiple times. This new MP system uses the laser amplification system several times after the sixth pass, instead of using mirror 2 for confining. Figure 3 shows the MP signal (red line) corresponding to a new MP system with multiple amplifications and the gate pulses of the two Pockels cells (blue and brown lines) with an initial 3 W laser in the gas scattering experiment. The pass numbers are presented as well. A delay of ~150 ns occurred between the gate pulses of the PCs and MP signals, owing to the traveling times of the laser and scattered light. The timing of the PCs is indicated by the dotted line in Fig. 3. The gate pulse durations of PC 1 and PC 2 were 700 ns and 550 ns, respectively. The difference in trigger time between PC 1 and PC 2 was 150 ns. PC 1 produces the third pass and beyond after the second pass. After the sixth pass, the laser entered the laser amplification system, and the double-passed laser passed through the laser amplification system again. The intensity of the ninth pass signal was increased by the laser amplification system. Moreover, the intensity of the eleventh pass signal was the same as that of the ninth pass signal. After the 13th pass, the amplification rate decreased because the stored energy of the amplifier decreased. We successfully obtained continuous large MP signals with the lower laser power using the developed MP system comprising the laser amplification system. The total integrated signal intensity obtained with the laser amplification system was ~20 times larger than that of the single pass signal in the single-pass configuration. The new MPTS system, which directs the laser to the amplification system multiple times, can improve the MP signal intensity and maintain it as high as the initial laser output intensity. This lower laser power condition allows us to investigate higher-electron-density plasmas, such as those entailed in pellet injection experiments, which have electron densities of the order of $10^{19}$ $m^{-3}$.

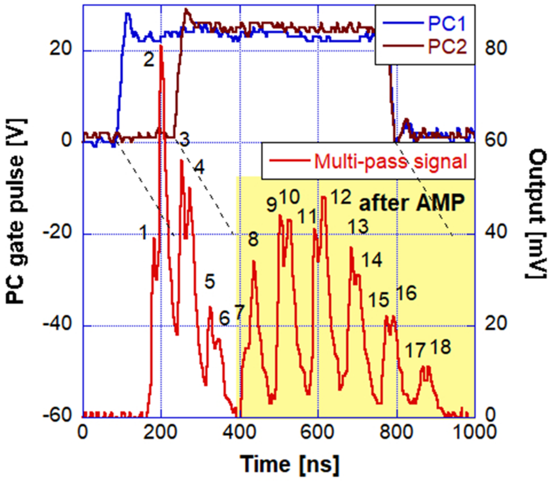

**FIG. 3.** Multipass signal and gate pulses of PCs. Timings of two gate pulses for the multipass system indicated as dotted lines. Pass numbers are shown.

## V. SUMMARY

We constructed a new MPTS system that comprised a laser amplification system, laser beam profile adjuster, and polarization control system to obtain more MP signals. The laser amplification system improved the degraded laser power after multiple signal passes in the MPTS system. For the first time, we successfully obtained continuous substantially amplified MP signals in the lower initial laser power condition by recurrently injecting the MP laser to the laser amplification system using the developed MP system comprising a laser amplification system.

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## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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