Development of 2-D Thomson Scattering Measurement Using Multiple Reflection and the Time-of-Flight of Laser Light

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A new two-dimensional Thomson scattering measurement (2-D TS) system has been developed using multiple reflections and time-of-flight (TOF) of laser light. Its new ideas of our 2-D TS system are (1) to reflect YAG laser light for multiple times to cover the whole $r-z$ plane of the ST (Spherical Tokamak) plasma, and (2) to reduce the number of polychromators and detectors using the time delay of the scattered light along the laser beam. We measured for the first time, Rayleigh scattering light signals with 50 ns time difference from two measurement points using a single detector, demonstrating the basic principle of the 2-D Thomson scattering system.

Keywords: Thomson scattering, two-dimensional measurement, Rayleigh scattering, Raman scattering

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1. Introduction

The Thomson scattering measurement has been widly used as the most precise and reliable plasma diagnostics for electron temperature T_e and density n_e measurements for the past 30 years [1]. Its single point measurement was upgraded to multipoint and its spatial resolution has been improved significantly using the TV Thomson system which employs spectrometers and ICCD cameras [4]. The time-of-flight of laser light was used for the first time by the LIDAR Thomson system for the purpose of realizing one-dimensional Thomson scattering measurement system through a small viewing port [5]. Recently, optical fibers were used to produce sufficient time delay for scattered light signals as a way of reducing the required numbers of detectors [6].The first 2-D TS measurement has been realized on ASDEX Upgrade [7], using five high-cost Nd:YAG laser devices. For the TS-4 device whose main mission is merging ST plasmas and their magnetic reconnection, the 2-D profile of T_e and n_e are keys to understanding the causes and mechanism for (1) the electron heating of the magnetic reconnection and (2) high-β ST formation at merging start-up. Our new approach to the 2-D Thomson scattering system is composed of (1) the multiple reflection of a laser beam to cover the 2-D ($r-z$) plane of the plasma and (2) reduction of the number of polychromators and detectors using time-of-flight of the laser light. TS measurement using multiple reflection of laser light has been already used for other purposes, to improve the time resolution of the measurement up to 10 kHz [8], and to improve the measurement accuracy of TS applying the stimuleted-Brillouin-scattering-based phase conjugate mirrors [9].

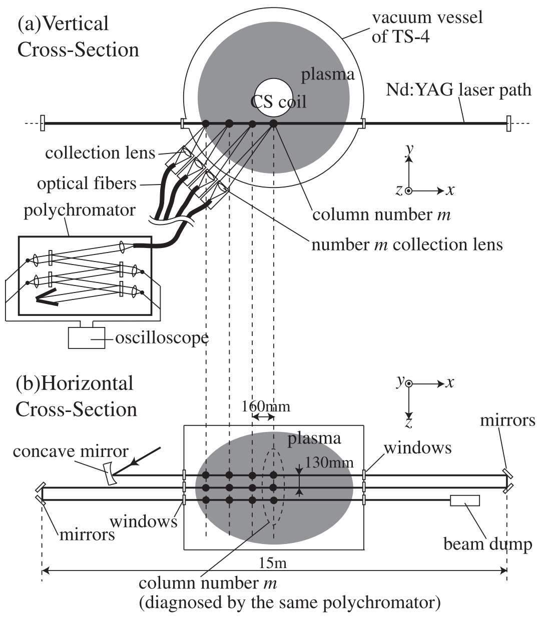

Fig. 1 (a)Vertical and (b)Horizontal Cross-Section of our 2-D Thomson scattering diagnostic system.

Figure 1 shows a schematic of vertical and horizontal cross-sections of the 2-D TS system being developed for the TS-4 device, with major/minor radii of 0.5 m/0.3 m. This system is designed to measure T_e in the range of 20-200 eV and n_e ~10^{20}/m^3 with a spatial resolution of 160 mm (four points) in the r-direction and 130 mm (three points) in the z-direction. The number of measurement

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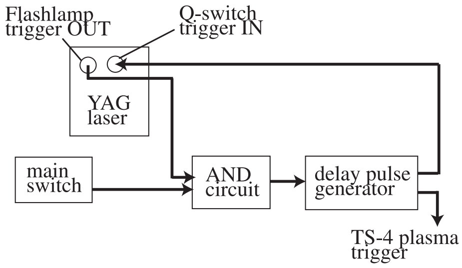

Fig. 2 Diagram of the trigger system.

points in the z-direction can be extended to five using other ports for the additional collecting lenses. The YAG laser beam is reflected multiple times by sets of mirrors located on the right-side and left-side outside of vacuum vessel. The distance between both sides of mirrors is 15 m, which can produce 50 ns of the time delay of the laser light to shuttle between both sides. The scattered lights from three measurements points (with the same column number of m circled with dashed line in Fig.1 (b)) in the z-direction are collected by three Gauss-type collection lenses and sent to a single polychromator through bundled optical fibers. We can distinguish the scattered light data from the three measurement points (the bottom width of 40 ns) using their time delay of 50 ns.

2. Experimental Setups

The 2-D TS system under development is composed of (1) a Nd:YAG laser, (2) a laser beam optics, (3) a light collecting optics, (4) polychromators, and (5) a data acquisition system. Their details are described in the following sections.

2.1 Laser

A Nd:YAG pulse laser: QUANTEL Model YG982E has an energy of ~2.4 J, FWHM of 10 ns, bottom width of 40 ns and a beam divergence of 0.5 mrad. The repetition (10 Hz) rate is indifferent to our TS system because the duration time of the plasma produced by the TS-4 is a few milli-second, which is much shorter than the interval time of laser light emission. A fundamental wavelength of Nd:YAG laser, 1064 nm, is used avoiding the spectrum lines of H_β (486 nm) and H_γ (436 nm) close to the wavelength of the second harmonic (532 nm). The polarization of the laser light is linear, utilizing for combining YAG Continuous Wave guide laser, which will be described at next section. Figure 2 shows the diagram of the trigger system of the laser and the capacitor banks for the coils of the TS-4 device. Only when the main trigger pulse are superposed, a start trigger is generated by the delay pulse generator, DG535 manufactured by Tokyo Instruments Inc., then the pulse generator delivers the trigger pulse for Q-switch of the Nd:YAG laser and the condenser banks.

2.2 Laser beam optics

Fig. 1 shows mirrors and a concave mirror which are used for making the laser beam path. Those mirrors are required to have not only high tolerance for the high energy laser beam but also high reflectance ratio, because loss of the light by the reflectance cannot be neglected due to a number of the laser beam reflections. To meet the requirement, dielectric multilayer mirrors with high energy tolerance (>3.75 J/cm^2) and high reflectance ratio (> 99 %) are used.

A concave mirror ($f = 30$ m) is located at the laser beam entrance to suppress the beam divergence (< 0.5 mrad) of the Nd:YAG pulse laser because the laser beam path tends to be long in our 2-D TS system. In the present setup, the mirrors in both sides of TS-4 device are not concaved due to small diameter of laser beam.

Instead of the conventional helium-neon laser, a YAG CW laser is used together with the IR (Infrared) scope for the beam alighnment of the system, because the dielectric multilayer mirrors do not have reflectance near the wavelength of He-Ne's (632.8 nm).

2.3 Light collecting optics

The main components of the light collecting optics are composed of (1) objective lenses, which collect scattering light and (2) bundled fibers, which transfer the scattering light from the objective lenses to the polychromators.

As seen in Fig. 1, the scattering lights from the measurement points with same column number m (three measurement points in same r) are collected by a single objective lens system. Therefore, four sets of collecting lens systems are used to cover whole 3×4 measurement points in Fig. 1. The preliminary collecting lens system has been already installed for the measurement points of r = 205 mm, now new collecting lens for points of r = 529 mm is under construction. The former lens system has three individual lenses for three measurement points, covering the solid angle as small as ~ 2.07×10^{-4} sr. On the other hand, the latter lens system for three measurement points covers the solid angle of 1.94×10^{-2} sr, which is 93.7 times as large as that of the former system. The shorter focal length of the new lens also contributes to the great increase of the solid angle.

Each of the bundled fibers on the collecting lenses side is composed of nineteen single silica optical fibers of 600 µm in core diameter. The diameter of the bundled fibers is about 3 mm at the edge as shown in Figure 3. As described previously, those three bundled fibers are combined to one with diameter of ϕ6.6 mm.

2.4 Polychromators

The polychromators are composed of four interference filters and four light-detecting components. Figure 4 shows the schematic of the polychromator. Wavelength ranges of the filters transmit are 1056-1052, 1052-1045,

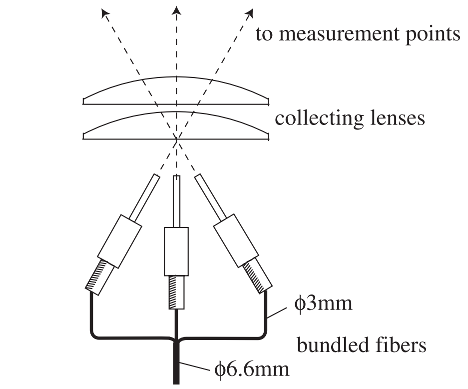

Fig. 3 Dchematic of new collecting lens.

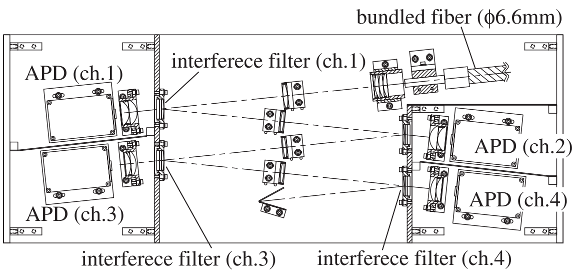

Fig. 4 Schematic of polychromator.

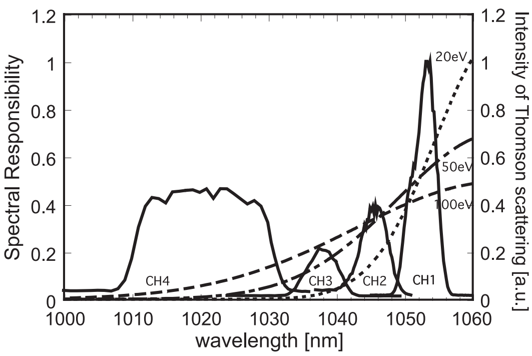

Fig. 5 Transmission characteristics of interference filters.

1045-1035,and 1035-1005 nm as shown in Figure 5. Each filter has high blocking power ($> 10^5$) at 1064 nm, wavelength of Nd:YAG laser, to cut the stray light.

2.5 Detectors

The detector used in our TS system is avalanche photodiode (APD) with pre-amplifiers manufactured by Hamamatsu Photonics Inc. It has sensitive area of ϕ3 mm, sensitivity of $2{\times}10^3$ A/W, higher cutoff frequency of 100 MHz, and C5331-SPL of model number. Key points to choose APD for our 2-D TS system are (1) radius of sensitive area and (2) response speed. Though the smaller sensitive area is required for the better response time of APD, ϕ3 mm in the sensitive area is lower limit for our TS system for collecting the scattering light from the thick (ϕ6.6 mm) bundled fibers of 0.37 in NA to the small sensitive area of APD. The response speed faster than 100 MHz (high cut-off frequency), is needed for our TS system to detect the scattered signal whose FWHM is 10 ns and to distinguish the signals which appeare at 50 ns intervals.

2.6 Data acquisition system

The data of APD detectors are digitized by the high-speed oscilloscope (DS-8814) manufactured by IWATSU. Its maximum sampling rate of 400 MHz and the higher cut-off frequency of 100 MHz are faster than the detector's response speed.

3. Evaluation of Light Intensity

Intensity of Thomson scattering light and output signal value was evaluated, as shown in the following formula:

$$W = P \cdot n_e \cdot l \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \cdot \mathrm{d}\Omega, \tag{1}$$

where W is intensity of scattering light inside of the solid angle, $P = 2.4\,[\mathrm{J}]/10\,[\mathrm{ns}] = 2.4 \times 10^8\,[\mathrm{J/s}]$ is the power of the Nd:YAG pulse laser, $n_e \sim 10^{20}\,[\mathrm{m^{-3}}]$ is the electron density, $l = 0.015\,[\mathrm{m}]$ is length of the Thomson scattering area along the path of the Nd:YAG laser beam, $d\sigma/d\Omega \sim 7.95 \times 10^{-30}\,[\mathrm{m^2}]$ is Thomson scattering cross section and $\mathrm{d}\Omega \sim 1.94 \times 10^{-2}\,[\mathrm{sr}]$ is solid angle of the collecting lens. Substituting those values, W is calculated to be 55 [μW]. Output signal value of APD with the interference filter (here, ch.1 1056-1052 [nm]) is estimated as follows:

$$V_{APD} = W \cdot A \cdot \int (T(\lambda) \cdot f_k(\lambda))\mathrm{d}l \cdot B, \tag{2}$$

where $A \sim 0.7$ is a transmitting efficiency through collecting lens and bundled fiber, $T(\lambda)$ is a Thomson scattering output ratio of wavelength l to all wavelength ($T_e = 50$ eV), $f_k(\lambda)$ is the transmission rate of the filter (here, ch.1 1056-1052 [nm]), and $B \sim 6.8 \times 10^4$ [V/W] is a photoelectric conversion sensitivity of the APD including pre-amplifier. The value for $\int (T(\lambda) \cdot f_k(\lambda))\mathrm{d}\lambda$ is estimated to be 0.05 and V_{APD} is calculated to be 0.104 [V] which is large enough to be easily measured by the oscilloscope.

4. Rayleigh Scattering Measurement

The electron density n_e can be measured by absolute value of all scattered photons. Therefore, it is necessary to know the efficiency of the whole optical system and calibrate the number of photons. In convensional TS systems, the calibration is executed by measuring the pressure dependency of Rayleigh scattering light intensity from the gas whose Rayleigh scattering cross section is already known. Since we do not have the extra APD channel for wavelength of Rayleigh scattering light, we are planning to use Raman scattering for the density calibration. Rayleigh scattering is used (1) to check how large the stray light is

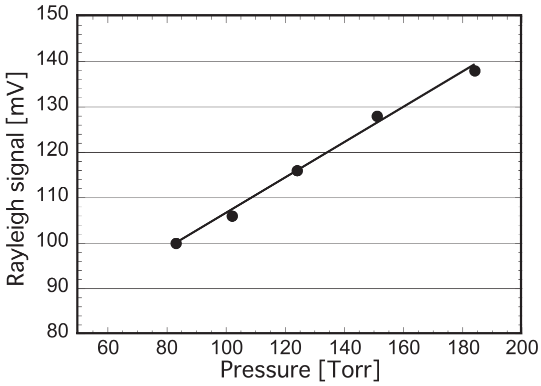

Fig. 6 Pressure dependency of Rayleigh scattering light.

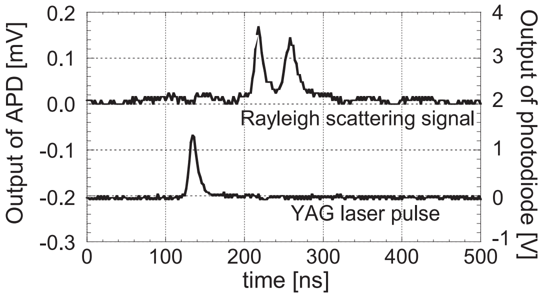

Fig. 7 Rayleigh scattering light from two adjacent measurement points.

and (2) to demonstrate the basic idea of utilization of laser light's time-delay. In our preliminary TS system, the pressure dependency of Rayleigh scattering light intensity is measured at the single measure point as shown in Figure 6. The measured signal was observed to increase with the gas pressure, indicating that we measured Rayleigh scattering light.

We have already detected the multiple Rayleigh scattering lights from the two adjacent points. As shown in Figure 7, the two Rayleigh scattering signals were measured by the APD detectors. These data indicate that four sets of the preliminary results will be a new 2-D (2×4 points) measurements of the Rayleigh scattering and suggests that the basic ideas of 2-D Thomson scattering system works reasonably well. We are now planning to complete full 2-D measurement of Thomson scattering light for 2-D T_e and n_e profiles.

5. Calibration by Raman Scattering

In the present setup, it is difficult to use Rayleigh scattering for density calibration because its wavelength is same as that of stray light. In our TS system, the amount of stray light tends to be larger than the conventional TS system due to the multiple reflection of the laser light. In Raman scattering measurement, an interference filter, which has high blocking power at the wavelength of stray light, can be used because the wavelength of the scattering light

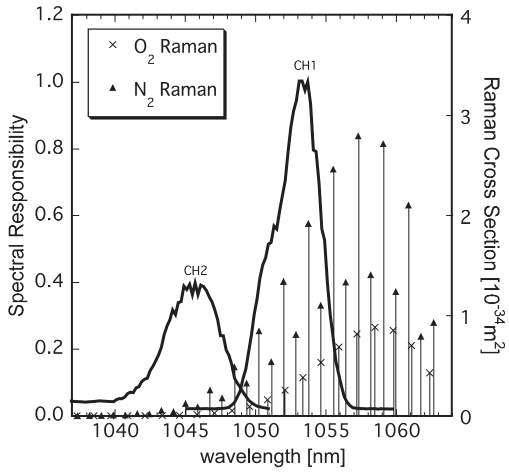

Fig. 8 Cross sections of Raman scattering light.

is shifted from that of laser light [10]. Figure 8 shows the cross sections of Raman scattering light from nitrogen and oxygen and the transparent characteristics of four interference filters.

6. Conclusions

A new 2-D TS system has been developed using multiple reflections and TOF of YAG laser light. The Rayleigh scattering light from adjacent two points have been detected successfully by one detector, indicating that the basic idea of 2-D TS system by TOF of laser light, works reasonably well. Raman scattering measurement is suited to absolute calibration of the TS system on TS-4, avoiding the large amount of stray light at the wavelength of 1064 nm. We are now planning to complete the full 2-D measurement of TS light for 2-D T_e and n_e profiles.

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