Development of a Thomson Scattering System in the TST-2 Spherical Tokamak

Takashi YAMAGUCHI, Akira EJIRI, Junichi HIRATSUKA[1)], Yuichi TAKASE, Yoshihiko NAGASHIMA, Osamu WATANABE, Takuya SAKAMOTO, Takuya OHSAKO, Byung Il AN[1)], Hiroki KURASHINA, Hiroaki KOBAYASHI, Hiroyuki HAYASHI, Hazuki MATSUZAWA, Kotaro YAMADA, Hidetoshi KAKUDA[1)], Kentaro HANASHIMA and Takuma WAKATSUKI[1)]

Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa 277-8561, Japan
[1)]*Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan*

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The Thomson scattering system in the TST-2 has been upgraded to improve the reliability and accuracy of measurements. The signal intensity increased because of a new high-energy (1.6 J) laser. A large-numerical-aperture (N.A.) fiber was tested, and it was found that a 6-m-long fiber can be used without significant transmission loss. With the upgraded system, the typical central electron temperature and the electron density for ohmic discharges (with a plasma current of 60 kA) are 150 eV and 1.5×10^{19} m^{-3}, respectively. The temperature profile has a maximum near the center of the plasma.

Keywords: spherical tokamak, TST-2, Thomson scattering, Newtonian mirror system, fiber, polychromator, Rayleigh scattering, multi point measurement

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1. Introduction

Electron temperature is one of the most important parameters in all fusion devices, including spherical tokamaks (STs). Thomson scattering (TS) measurement is a highly reliable measurement of electron temperature, and many devices are equipped with a TS system. However, TS measurements are not easy because of the weak scattering light. The detected photon number N_f is given by

$$N_f = \frac{P}{hc/\lambda} \cdot n_e \cdot L \cdot \sigma_T \cdot \Delta\Omega \cdot C_T, \tag{1}$$

where P is the energy of the laser, c is the velocity of light, λ is the wavelength of laser , h is the Planck constant, n_{e} is the electron density, L is the length of the scattering volume along the laser, σ_T is the TS cross section, $\Delta\Omega$ is the detection solid angle, and C_T is the total transmission efficiency of the optical system. In most cases, the detection solid angle is smaller than the observation solid angle. A larger lens or a mirror is preferable to increase the observation solid angle, but it is not always easy to install a large mirror or lens. Therefore, we use a Newtonian mirror system for the collection optics. As a result, a compact and efficient system has been developed [1].

The TST-2 is an ST with a major radius $R = 0.38$ m and a minor radius $a = 0.25$ m [2]. Recently, the TS system in the TST-2 was upgraded to improve the measurement accuracy. The upgraded system is more reliable, and new results, including the temperature profile, are reported in this paper. A combination of a large-numerical-aperture (N.A.) fiber and a small-diameter mirror is necessary for a compact and efficient system. In addition, the electromagnetic and X-ray induced noises from the tokamak were reduced. We also report the testing and performance of several key components.

author's e-mail: yamaguchi@fusion.k.u-tokyo.ac.jp

2. Thomson Scattering System

The TS system consists of the incident optics, light collection optics, and spectroscopic system. Figure 1 shows an overview. We use a Nd:YAG laser with a wavelength of 1064 nm, a pulse width of 10 ns, a repetition rate of 10 Hz, and an output beam diameter of less than 10 mm. The former low-energy (0.45 J) laser has been replaced by this new high-energy (1.6 J) laser, and the typical signal-to-noise (SN) ratio was improved from 5 to 10.

We use a compact Newtonian mirror system consisting of a primary spherical mirror, 254 mm in diameter and a small secondary flat mirror (Fig. 2). The spherical mirror has a spherical radius of 442 mm; it is coated with Al + MgF_2. The system has a large solid angle (88 msr). This is larger than those achieved on other plasma devices, which are typically less than 20 msr [3–6]. The length of the scattering volume along the laser is 5.3 mm and the scattering angle is 120°. The scattered light is focused on the fiber core (2-mm diameter) through the Newtonian optics with an optical magnification of 2.3. The collected light is transferred to a polychromator through the optical

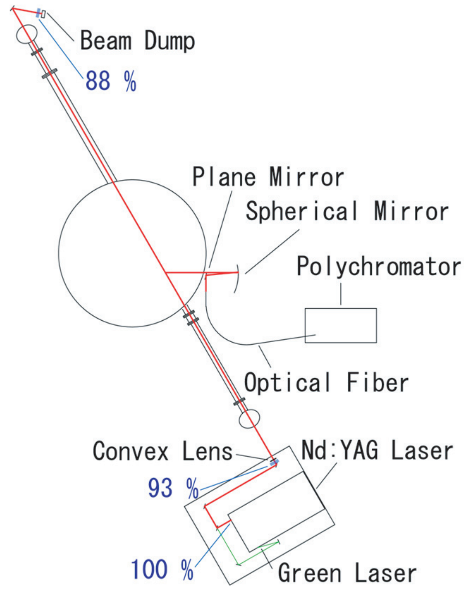

Fig. 1 Overview of the Thomson scattering system in TST-2. Blue percentages indicate the ratio of energy at that location to energy at the laser exit.

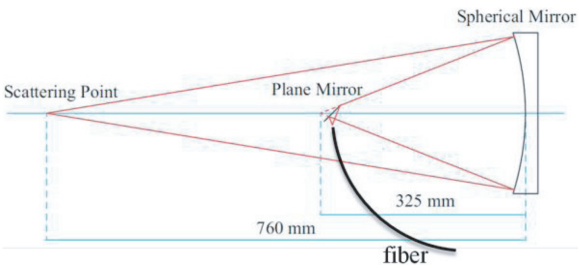

Fig. 2 Diagram of the optics of the Newtonian mirror system.

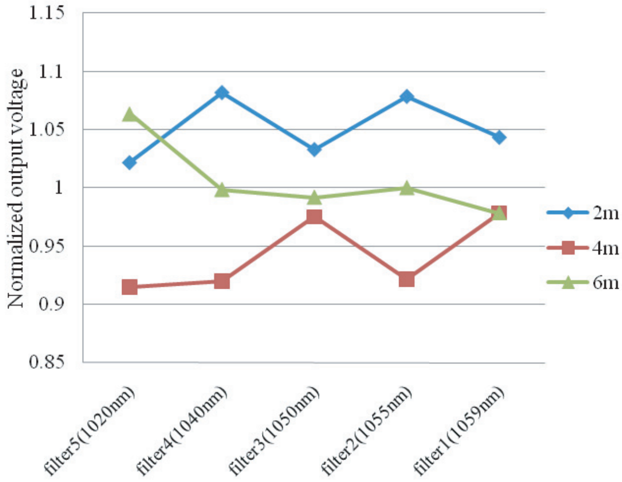

Fig. 3 Normalized output voltages of five wavelength channels in the polychromator. Three fibers with different lengths are measured.

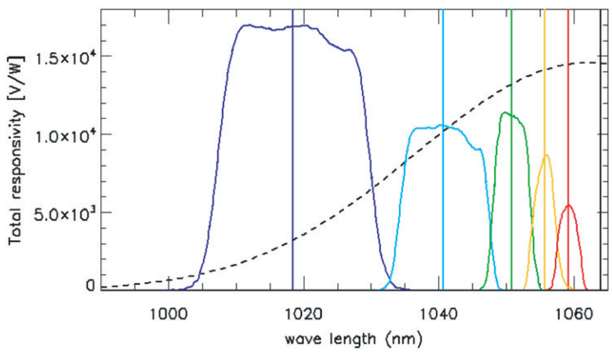

Fig. 4 Total spectral response of each channel.

fiber. We use a large-N.A. (= 0.37) optical fiber (Fiberguide, APC2000/2150N) to collect the scattered light from the spherical mirror with a large observation solid angle of 88 msr. The N.A. of the fiber we used is guaranteed only for lengths less than 2 m and decreases with increasing length when it is longer than 2 m [7]. This feature is typical of large-N.A. fibers. Since we locate the polychromator far from the tokamak to reduce the electromagnetic and X-ray induced noises, a long fiber (6 m in the present system) is required. Figure 3 compares the transmission for different fiber lengths. No systematic dependence on either the length or the wavelength appears, and the variation seems to be caused by measurement error.

The polychromator has five wavelength channels, and it consists of five avalanche photodiodes, five interference filters, a collimating lens, and five relay and collection lenses. The polychromator is on loan from the National Institute for Fusion Science [5]. The polychromator must be calibrated to calculate the spectral response of each channel. The light from a standard light source is resolved in wavelength by a monochromator and injected onto the fiber with an incident angle similar to that of the Thomson scattered light. The spectral sensitivity of each channel was measured (Fig. 4). In addition to this wavelength-resolved sensitivity, light from the standard light source was directly injected onto the fiber to cross-check the wavelength-integrated signal for each channel.

Previously, a four-channel oscilloscope was used to measure three wavelength channels simultaneously. The accuracy was inadequate when the discharge reproducibility was poor. We introduced a new eight-channel high-speed oscilloscope with which all five wavelength channels can be recorded simultaneously. Consequently, fitting to a Maxwell distribution is improved.

Rayleigh scattering is measured to calibrate the total absolute sensitivity, which is needed to derive the electron density. Nitrogen gas was used, and the pressure in the TST-2 device was raised to 300 Torr (Fig. 5). The linear component indicates scattered light, and the offset indicates stray light. In Fig. 5, the primary mirror was adjusted to measure $R = 380$ mm, which is the location of the plasma center. Since the present system has one polychromator unit, we must adjust the primary mirror to measure the other positions. The results are summarized in Table 1.

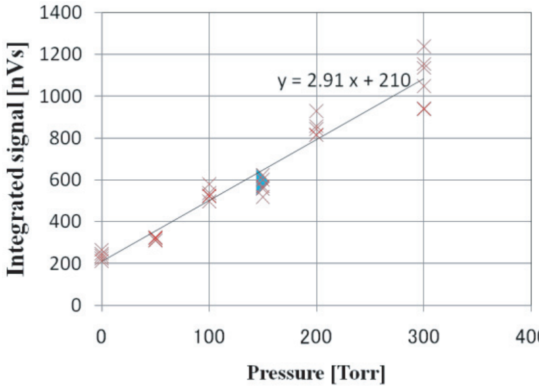

Fig. 5 Rayleigh scattering signal measured at $R = 380$ mm.

Table 1 Results of multi point Rayleigh scattering.

Major radius [mm]	Scattering power (slope) [nVs/Torr]	Stray light (offset) [nVs]
295	3.16	1090
330	2.93	691
380	2.91	210
430	2.35	571
480	2.58	1460

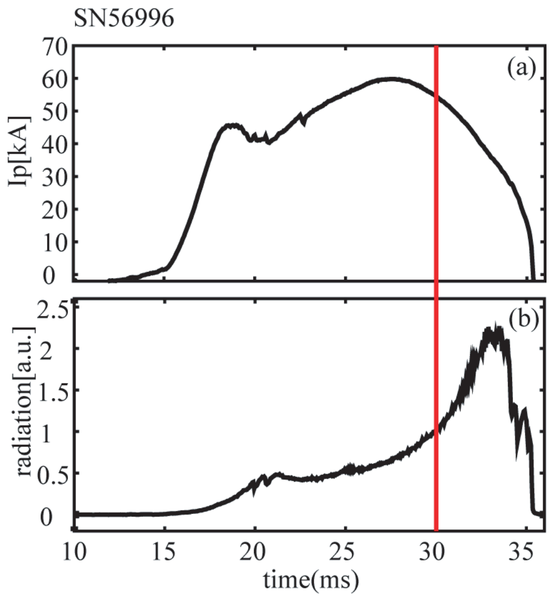

Fig. 6 Typical discharge. Plasma current (a) and radiation measured by an absolute extreme ultraviolet (IRD, AXUV) photodiode (b) are shown. Vertical red line indicates the measurement time ($t = 30$ ms).

3. Measurement Results

The electron temperature and density were measured by this upgraded system. Typical discharge waveforms of the TST-2 are shown in Fig. 6. In this case, we injected

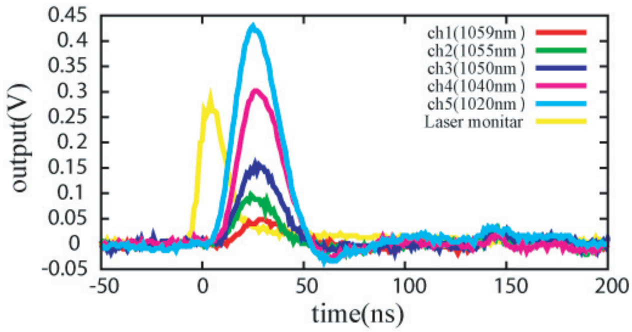

Fig. 7 Scattering signals and laser monitor signal. Scattering signals are integrated from 0 to 60 ns.

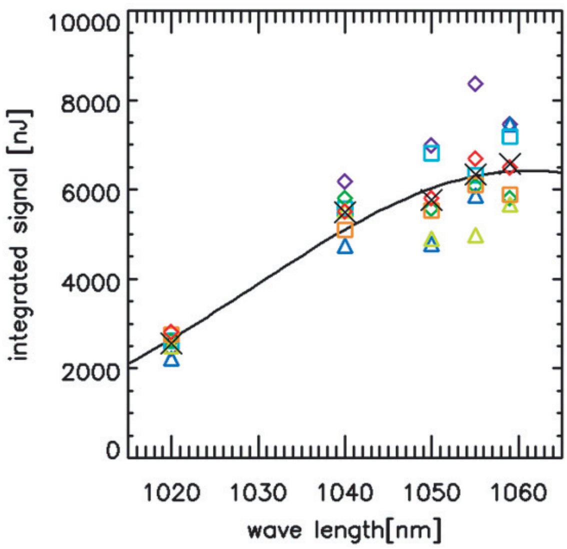

Fig. 8 Fitting to a Maxwell distribution. Different colors (except crosses) represent measurements for different but similar discharges. Crosses represent shot-averaged values.

the laser at $t = 30$ ms and measured at $R = 380$ mm. All the scattering signals and the laser monitor signal are shown in Fig. 7. In this case, the maximum SN ratio was 10 on channel 5. The scattering signals are integrated from 0 to 60 ns, and the results of our analysis are shown below. Figure 8 shows the data and a fitted curve representing a Maxwell distribution with relativistic effects. Each channel's signal is divided by the product of the sensitivity and bandwidth of the filter to show the fitting to a Maxwell distribution. In practice, we use the wavelength-integrated sensitivity in the fitting. The shot-by-shot scatter of the signal intensities is calculated, and the standard deviation is used to calculate the temperature and density errors. In this case, the central electron temperature and the electron density were 150 eV and 1.5×10^{19} m^{-3}, respectively. Because the laser and recording scheme were upgraded, the relative error of the temperature improved from 19 % to 12 % when we analyzed a similar discharge.

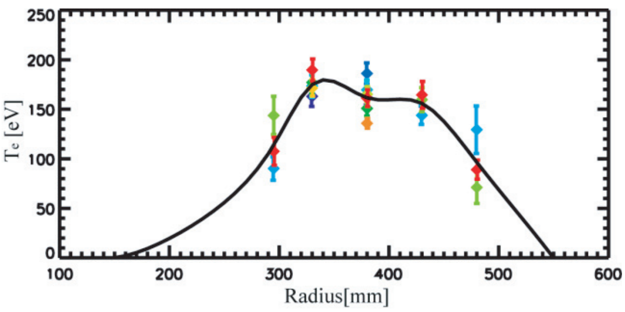

Fig. 9 Electron temperature profile. Different colors represent data from different discharges.

We estimate the number of photons incident on the fiber by summing up the photons on each channel. We multiplied by two to include longer-wavelength components; the resulting total photon number N_p is estimated as 1.2×10^5. The incident photon number calculated by Eq. (1) is $N_f = 4.8 \times 10^5$. Comparing these photon numbers yields a total transmission efficiency of the optical system of about 1/4. This efficiency is not large, partly because of the reduction in the detection solid angle due to the secondary plane mirror and toroidal field coils.

We measured the spatial profile using many similar discharges. The result measured at 25 ms is shown in Fig. 9. A spline curve was drawn using the measured temperatures assuming that the temperature is zero at the inboard and outboard boundaries. The electron temperature profile is flat around the center. The profile is similar to that measured in START [8], which is a spherical tokamak similar in size to the TST-2.

4. Summary

The Thomson scattering system in the TST-2 was upgraded to improve its accuracy. Installation of a new high-energy laser with energy 1.6 J increased the SN ratio. Large-N.A. fibers with different lengths were tested, and no significant transmission loss was found up to 6 m. The scattering power and stray light in Rayleigh scattering were measured.

A typical ohmic plasma was measured. The electron temperature and electron density were 150 eV and 1.5×10^{19} m^{-3}, respectively. The temperature profile was obtained; its shape was rather flat and had a maximum near the center of the plasma.

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