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

Soichiro KAINAGA, Akira EJIRI[1), Yuichi TAKASE[1), Osamu WATANABE[2), Yuuki ADACHI[1), Takuya OOSAKO[1), Makoto SASAKI, Hiroshi TOJO[1), Tetsuya MASUDA[1), Junichi SUGIYAMA[1) and Takashi YAMAGUCHI[1)

Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

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

[2)*High Temperature Plasma Center, The University of Tokyo, Kashiwa 277-8568, Japan*

(Received 21 March 2008 / Accepted 28 April 2008)

A compact Nd:YAG laser Thomson scattering system was constructed and applied to the TST-2 spherical tokamak in order to measure the electron temperature and the electron density. A large solid angle (~35 msr) was achieved by use of a compact Newtonian mirror system for the collection optics. Absolute calibration was performed by Rayleigh scattering. An electron temperature increase from 140 eV to 210 eV was observed upon injection of 200 kW of RF power.

Keywords: spherical tokamak, TST-2, Thomson scattering, Newtonian mirror system

DOI: 10.1585/pfr.3.027

Thomson scattering (TS) is the most reliable diagnostic to measure the electron temperature T_e. It has been used as a basic tool in plasma experiments for about 40 years. On the TST-2 spherical tokamak [1], RF heating experiments using the high harmonic fast wave (HHFW) are being performed. HHFW is the fast wave in the frequency range of several times the ion cyclotron frequency. Because of its good accessibility to plasmas with high dielectric constants $\epsilon \equiv \omega_{pe}^2/\Omega_{ce}^2$ and strong absorption by electrons [2], HHFW is considered to be an attractive wave for electron heating and current drive in spherical tokamaks.

TST-2 is a compact spherical tokamak with major radius $R = 0.38$ m, minor radius $a = 0.25$ m, and toroidal magnetic field at the plasma center $B_t < 0.3$ T. Up to 400 kW of RF power at a frequency of 21 MHz is available. Before the application of the TS system, electron heating by HHFW was inferred by an increase in soft X-ray emission. In this indirect method, however, the electron temperature cannot be determined quantitatively. A direct measurement of T_e, such as by TS diagnostic, is required to prove the effectiveness of RF heating.

The TST-2 TS system is composed of the laser, the incident optics, the light collection optics, the signal detection electronics, and the data recording system. A 10 Hz Nd:YAG laser with an energy per pulse of 0.45 J and a pulse width of 5 ns, operating at the fundamental wavelength of 1064 nm is used. The laser beam diameter at the plasma center is less than 3 mm.

For the light collection optics, a Newtonian mirror system was adopted because it enables both compactness and high optical throughput. As shown in Fig. 1, the Newtonian mirror system consists of a primary spherical mirror of diameter 254 mm and a small secondary flat mirror. The scattered light is collected by the spherical mirror, reflected downward by the flat mirror, and reaches a 2 mm diameter optical fiber. The magnification of the collection optics is 2.3. Thus, the diameter of the scattering volume is 4.6 mm, which is larger than the laser beam diameter. The light collection optics was optimized with the help of a ray-tracing calculation. According to the calculation, a solid angle of 35 millisteradian can be realized when the center of the plasma is measured. This value is larger than those achieved on other plasma devices, which are typically about 10 millisteradian. As shown in Fig. 1, the solid angle is restricted by the outboard legs of toroidal field (TF) coils. Without the Newtonian mirror system, the fiber aperture should be located at about 250 mm away from the window to bend it. As a result, a spherical mirror with a di-

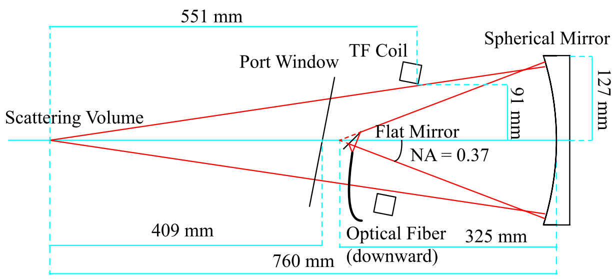

Fig. 1 Configuration of the collection optics.

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

ameter of 450 mm is required to obtain the same collection efficiency.

The scattered light is resolved in wavelength by an interference filter polychromator and detected by avalanche photodiodes (APDs). These are on loan from the National Institute for Fusion Science. In order to reject stray light with the same wavelength as the incident laser light, filters have a high rejection ratio ($< 10^{-5}$) at the laser wavelength. Outputs of the APDs are recorded by a 4-channel high speed oscilloscope with a bandwidth of 500 MHz. One channel is used to monitor the incident laser power.

In order to calibrate the TS system, the TST-2 vacuum vessel was filled with nitrogen gas up to 300 Torr and the Rayleigh scattering (RS) signal was measured. The measured RS signal was proportional to the nitrogen density. The stray light was determined as the signal measured at zero pressure, and corresponds to the RS signal at 141 Torr.

With the calibrated TS system, the electron temperature and density of TST-2 plasma were measured at R = 380 mm. In this case, the scattering angle was $2\pi/3$ radian. A typical discharge with HHFW heating (SN51628) is shown in Fig. 2. In Fig. 2 (b), data after t = 25.6 ms are not shown because they are inaccurate due to fringe jumps. Signals of channels 3, 4, and 1 of the polychromator are shown in Figs. 3 (a)∼(c). At t = 24.3678 ms, a peak appears in each channel. When the plasma is not produced, these peaks do not appear, indicating that the stray light is negligible.

A procedure to calculate T_e and electron density n_e from these raw data is as follows. First, the area under the TS pulse is calculated by integrating the pulse over a time interval Δt = 60 ns. The value of Δt is determined so as to cover only the TS pulse. In order to estimate the background plasma radiation included in the TS signal, the same time integration is performed at several time points slightly after the TS pulse. The error of the TS signal is estimated by the standard deviation of these reference integrals.

Secondly, a fitting function is prepared. For given T_e and n_e, the output signal of each channel S_i^{cal} is calculated as

$$S_i^{\mathrm{cal}} = C_0 \int \sigma_{\mathrm{T}}(C_1, \lambda) f_i(\lambda) \mathrm{d}\lambda, \qquad (1)$$

where C_0 and C_1 are fitting parameters, σ_{T} is the Thomson scattering cross section, and f_i is the spectral responsivity of each channel.

Finally, a fitting is performed. A result is shown in Fig. 3 (d). The calculated T_e and n_e are T_e = 210 ± 15 eV and n_e = (2.14 ± 0.05) × 10^{19} m^{-3}, respectively. The errors of T_e and n_e were determined from both the errors of the raw TS signals and the accuracy of fitting. However, in addition to this, there can be an error of n_e due to the temperature drift of APD, which is around 10∼20 %. If we assume the density profile is parabolic, the line-integrated electron density data shown in Fig. 2 (b), indicates n_e = (1.7 ± 0.3) × 10^{19} m^{-3}, which is consistent with the TS result within the error.

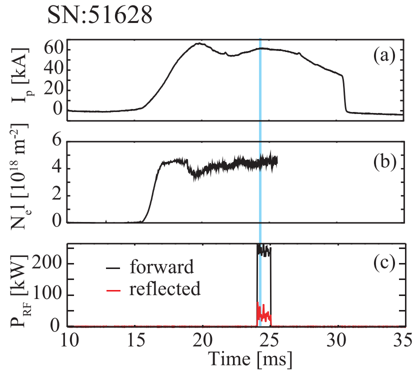

Fig. 2 Typical RF heated discharge. (a) plasma current, (b) line-integrated density, (c) RF power. The blue vertical line shows the laser injection timing (t = 24.37 ms).

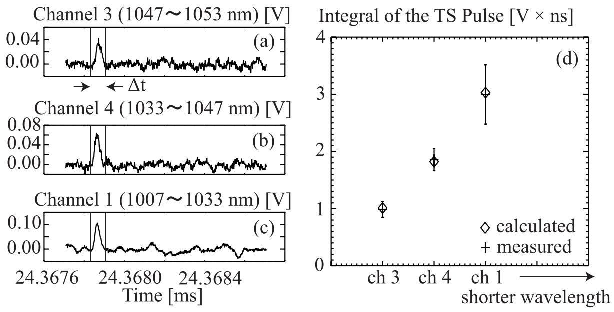

Fig. 3 (a)∼(c) Output signals of three channels of the polychromator measured at R = 380 mm (SN51628). Black vertical lines show the integration interval Δt = 60 ns. (d) Measured and calculated signals of each polychromator channel. T_e = 210 eV and n_e = 2.14 × 10^{19} m^{-3} were used for the calculation (diamonds in Fig. (d)).

When RF power is injected, electron heating was observed under some conditions. Generally, during or after RF power injection, the plasma current starts to decrease and the discharge is terminated earlier compared to that without RF injection. When the decrease of the plasma current was large, electron heating was not observed. On the other hand, when the decrease of the plasma current was small, a T_e increase from 140 ± 9 eV to 210 ± 15 eV was observed.

In summary, a compact TS system, in which a Newtonian mirror system was adopted for the collection optics, was constructed and applied to TST-2. For the density calibration, RS measurements were used. The density measured by the TS system was consistent with that measured by the interferometer. When heated by HHFW, T_e increased from 140 eV to 210 eV under some conditions.

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