Electron Temperature Measurement on QUEST Spherical Tokamak by Thomson Scattering System

Takashi YAMAGUCHI, Akira EJIRI, Junichi HIRATSUKA[1)], Makoto HASEGAWA[2)], Yoshihiko NAGASHIMA[2)], Kazumichi NARIHARA[3)], Yuichi TAKASE, Hideki ZUSHI[2)] and the QUEST group[2)]

Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa 277-8561, Japan
[1)] *Graduate School of Science, The University of Tokyo, Kashiwa 277-8561, Japan*
[2)] *Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan*
[3)] *National Institute for Fusion Science, Toki 509-5292, Japan*

(Received 30 March 2012 / Accepted 6 September 2012)

On QUEST, we are carrying out the steady state operation by RF current drive. A Thomson scattering (TS) system has been constructed to measure the plasma electron temperature. This system consists of a Nd:YAG laser of energy 1.65 J, a spherical mirror for collection of the scattering light, and a polychromator for spectroscopy. Because the Thomson scattering signal is weak for the low-density RF-sustained plasma, many scattering pulse signals were accumulated from steady-state plasmas. Electron temperature profiles were obtained for the steady-state spherical tokamak (ST) plasma for the first time. Six spatial points were measured by moving the fiber position, and the plasma electron temperature was in the range 10–500 eV.

Keywords: Thomson scattering, spherical tokamak, steady state plasma, low-density plasma

DOI: 10.1585/pfr.8.1302001

The targets of QUEST spherical tokamak (ST) research is steady state operation by RF current drive and controlled plasma wall interaction. The QUEST tokamak is an ST device with a major radius of $R = 0.68$ m and a minor radius of $a = 0.4$ m. An RF system of frequency 8.2 GHz is used for the current drive, and excitation of electron Bernstein wave is expected [1]. The typical electron density measured using a microwave interferometer is of the order 10^{17} m^{-3}.

The electron temperature measurement provided by Thomson scattering (TS) is highly reliable, and many devices are equipped with the TS system [2–8]. Temperature and density data are useful for equilibrium analysis and also for examining RF-current-driven plasmas.

Because scattering signal intensity is proportional to electron density, the measurement of electron temperature is expected to be difficult for low-density current-driven plasma. The steady-state period longer than 1 s, and the laser repetition rate is 10 Hz. Therefore, accumulation of many scattering pulse signals is possible.

The TS system is similar to that on TST-2 [9], which uses the same power Nd:YAG laser, the same polychromators and the same optical fibers. Figure 1 shows the laser path, scattering geometry, main TS components, and QUEST vacuum vessel. The TS system comprises mainly three components: (1) Nd:YAG laser of wavelength 1064 nm, energy 1.65 J, pulse width ~7 ns, repetition rate 10 Hz, output beam diameter less than 9 mm, and beam divergence 0.45 mrad, (2) a spherical mirror, and (3) polychromators. The output beam is focused near the center of the plasma by a lens of focal length 4 m.

Figure 2 shows an image of the vacuum-side of the MH14 port. This image shows a large quartz window with an effective diameter of 318 mm and a thickness of 30 mm, a two-piece shutter, and a movable target. The solid angle of the window for the scattering light generated at the center of the plasma is approximately 0.067 sr. A movable and rotatable target assembly comprising a magneto-coupling transfer rod with a stroke of 1.4 m and a stainless steel plate target was installed above the laser injection port. This target scatters green laser light, which is coaxial to the Nd:YAG laser, for alignment of the correcting optics. A two-piece stainless steel shutter, which may be opened or closed by rotating each piece, was also installed. The shutter and movement mechanism should be compact enough to fit in the port, and the intrusion toward the plasma and the degradation of the viewing sight should be avoided. The design parameters, such as the position and direction of the rotation axis of the shutter, were determined by numerical optimization. The optimized direction of the rotation axis is not parallel to the MH14 flange and horizontal plane; the resultant maximum intrusion toward the plasma from the vessel wall is 45 mm, which is shorter than the limiter height of approximately 70 mm.

The laser beam passes through the plasma and is

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

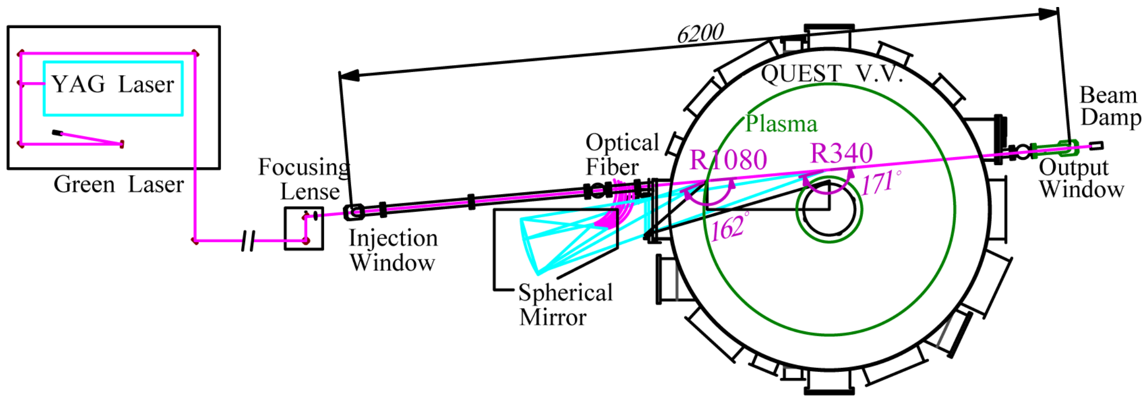

Fig. 1 Arrangement of the QUEST device and the TS system.

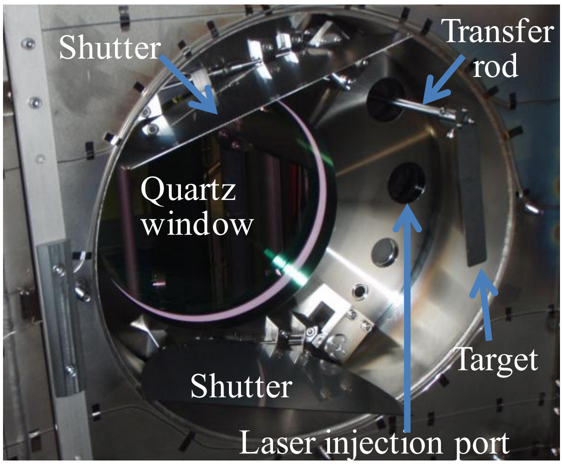

Fig. 2 Vacuum-side photograph of the laser injection and correcting window port (MH14).

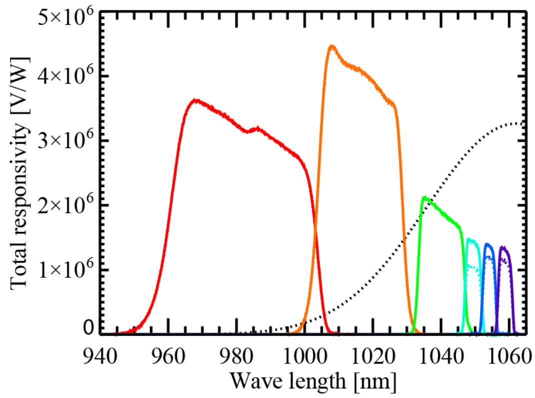

Fig. 3 Spectral sensitivity of each wavelength channel of the polychromator. The black dotted curve shows a Maxwell distribution of 80 eV.

damped by a beam damper located outside the output window. The transmitted power at the beam damper is approximately 90 % of the laser output power. For the collection of scattering light, a gold-coated spherical mirror of radius 0.5 m and curvature radius 1 m is used. The TS system was designed to measure six spatial points in the plasma (major radius: 340–1080 mm). The scattering angle is 162–171°. The system has a backward scattering configuration [2–4] in which the scattering length and scattering intensity increase. The scattering length is 17–51 mm, and the solid angle is 0.03–0.05 sr. We used a large numerical aperture (= 0.37) optical fiber (core diameter of 2 mm) [9] to collect the light reflected from the spherical mirror.

A fast-response polychromator was developed for QUEST and TST-2 in study [10]. The polychromator comprises six avalanche photodiodes (APD) and interference filters. The spectral sensitivity of each channel is shown in Fig. 3. The sensitivities are normalized by the input power to the polychromator, which is measured at the exit of the optical fiber, as shown in the figure. In addition, light from a standard light source is directly injected into the fiber to crosscheck the wavelength-integrated sensitivity for each channel.

The plasma current sustained by an RF (8.2 GHz) power supply of 40 kW was 15 kA, and the discharge duration was approximately 8 s (see Fig. 4). The discharge duration was significantly longer than the time constant of the magnetic field penetrating through the vacuum vessel [1], and the external field was kept constant. The plasma current, which was driven by the RF power supply, remained constant during the discharge. The plasma exhibited an inboard poloidal field null configuration and was characterized by a high value of β_p [11]. We assumed that the plasma parameters remain constant during the period t = 3.3–8.2 s, and accumulated the signals to reduce the statistical error. We were unable to plot a trend for the temperature and density evolutions when the period was divided into several shorter periods and the temperatures and densities for these periods were compared.

Because the signal-to-noise (S/N) ratio of one pulse signal is low, signals from 3.3 to 8.2 s between 2 and 5 similar discharges (between 100 and 250 laser pulses) were accumulated. To reproduce similar discharges, the device

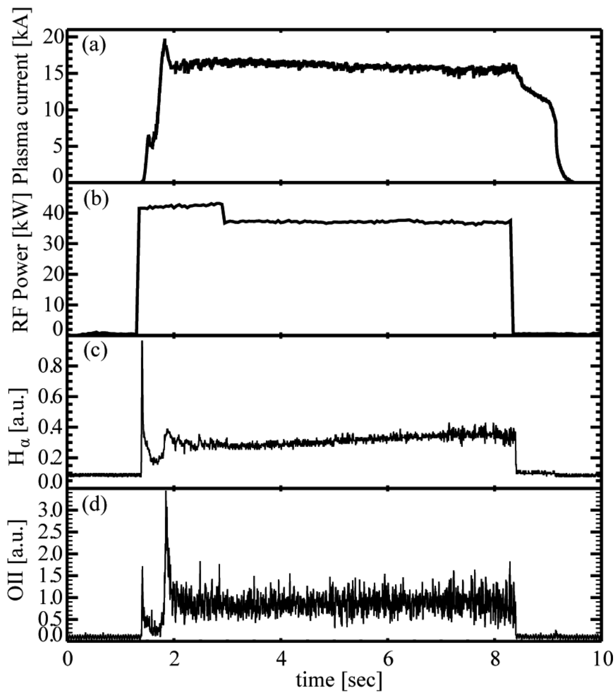

Fig. 4 Time evolution of (a) plasma current, (b) net RF power, (c) Hα emission, and (d) OII emission (Shot No.19102).

was operated under the same operating conditions. Data on the same experimental day were used, and the similarity of plasma parameters, such as plasma current and radiation, was checked. Note that the plasma current is solely driven by the RF power supply, the similarity of the plasma current implies that the RF wave propagation, wave absorption, slowing down and confinement of electrons are similar. Figure 5 shows the averaged signals for each wavelength channel and the signal of a laser monitor PIN diode. In this case, the scattering point was located at the major radius of 636 mm. Because the stray light level at a given spatial point is similar to the scattering signal intensity, the stray light signal was subtracted. The averaged signals were integrated from 0 ns to 80 ns to extract the scattering component. The noise was estimated from the scatter of time-integrated signals during the periods before and after the scattering light was emitted. The maximum S/N ratio is approximately 10 for this experiment. Maxwell distribution function, which has two free parameters Temperature and intensity, was integrated with the wavelength sensitivity for each channel and compared to the corresponding wavelength channel. Figure 6 shows the comparison of these integrated values. The values on the vertical axis are divided by the wavelength width for each interference filter to illustrate the shape of the spectrum. The parameters were optimized to yield the best fit. The electron temperature is 21 ± 4 eV for this case.

By moving the fiber position, we were able to obtain the electron temperature and density profiles (see Fig. 7). Evaluation of absolute density has not been possible; thus,

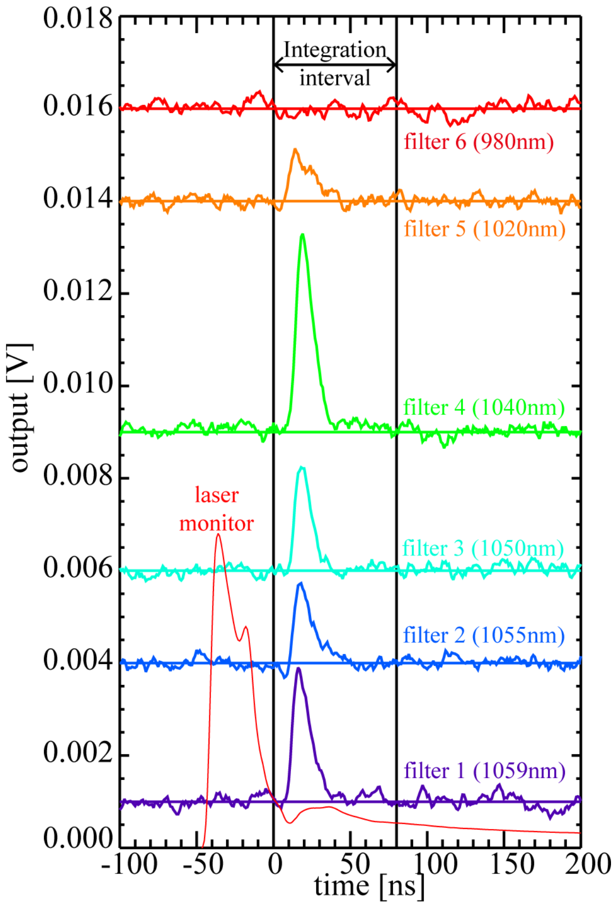

Fig. 5 Averaged scattering signals from 33rd to 82nd laser injections (at 3.3–8.2 s) and three discharges.

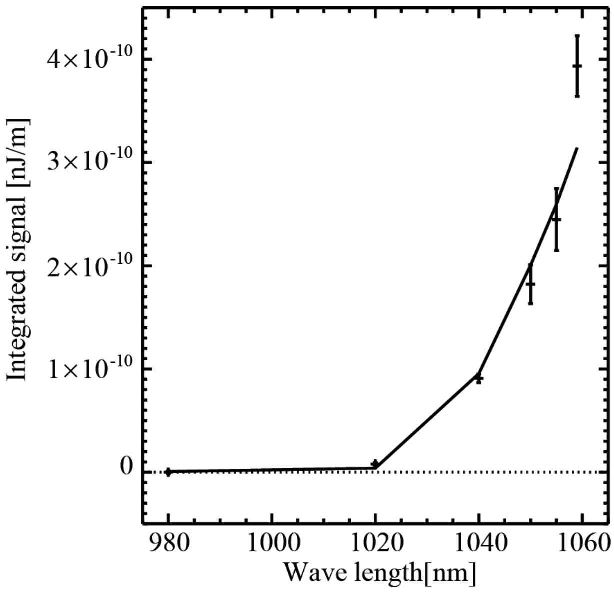

Fig. 6 Fitting to a Maxwell distribution function. The cross points with error bars show the integrated scattering signal. The polygonal line shows fitted values (21 ± 4 eV).

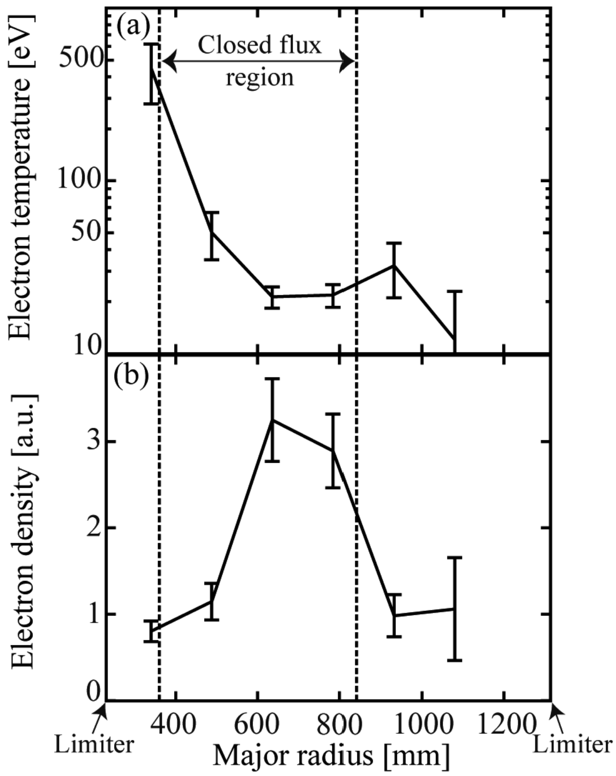

Fig. 7 (a) Electron temperature profile and (b) electron density profile for the inboard null configuration plasma. The dashed lines show the last closed flux surface calculated by RTFIT.

the relative density profile was obtained, as shown in Fig. 7. At each spatial point, scattering signals were accumulated between 2 to 5 discharges. The closed flux region was represented by R = 350–840 mm, which is obtained from RTFIT (the plasma was represented by a filamentary current, which is consistent with the magnetic measurements). The resultant electron density profile has a peak at ~700 mm, and according to RTFIT magnetic calculation, a magnetic axis is also located around this position. The electron temperature profile is rather flat at R = 600–1000 mm. The temperature near the inboard limiter is approximately an order of magnitude higher than that in the region R = 500–1000 mm. This result indicates the possible presence of a high-temperature region around the inboard null point. Plasmas with inboard poloidal field null configurations are being extensively studied [11]; detailed studies in this regard are required.

Thus, we developed a Thomson scattering system for QUEST and obtained Thomson scattering signals with a maximum S/N ratio of approximately 10. The electron temperature was in the range 10–500 eV in steady-state operation with the inboard null configuration. Unlike typical ohmic plasma, The temperature profile has no peak at the core plasma. The electron temperature profile was obtained by Thomson scattering on the RF-sustained steady-state spherical tokamak plasma for the first time.

Acknowledgments

This study was supported by Grants-in-Aid for Scientific Research (No. 21246137, 21226021) from Japan Society for the Promotion of Science (JSPS) and National Institute for Fusion Science (NIFS) Collaborative Research Program No. NIFS09KUTR039.

[1] K. Hanada *et al.*, Plasma Sci. Technol. **13**, 307 (2011).
[2] K. Narihara *et al.*, Rev. Sci. Instrum. **66**, 4607 (1995).
[3] K. Narihara *et al.*, Rev. Sci. Instrum. **72**, 1122 (2001).
[4] B.P. LeBlanc *et al.*, Rev. Sci. Instrum. **74**, 1659 (2003).
[5] H. Murmann *et al.*, Rev. Sci. Instrum. **63**, 4941 (1992).
[6] T. Hatae *et al.*, Fusion Eng. Des. **34–35**, 621 (1997).
[7] R. Scannell *et al.*, Rev. Sci. Instrum. **79**, 10E730 (2008).
[8] D.M. Ponce-Marquez *et al.*, Rev. Sci. Instrum. **79**, 10E730 (2010).
[9] T. Yamaguchi *et al.*, Plasma Fusion Res. **5**, S2092 (2010).
[10] A. Ejiri *et al.*, Plasma Fusion Res. **5**, S2082 (2010).
[11] H. Zushi *et al.*, 24th IAEA Fusion Energy Conference, EX/P2-14 (2012).