Backward and forward scattering configurations in LHD Thomson scattering system

I. Yamada[1], R. Yasuhara[1], H. Funaba[1], K. Narihara[1], H. Hayashi[1],
E. Yatsuka[2], T. Hatae[2], H. Tojo[2], M. Yoshikawa[3], and T. Minami[4]
[1]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[2]*Japan Atomic Energy Agency, Naka 311-0193, Japan*
[3]*Plasma Research Center, University of Tsukuba, Tsukuba, 305-8577, Japan*
[4]*Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan*

Introduction

The large helical device (LHD) Thomson scattering system measures electron temperature and density profiles of LHD plasmas. The original LHD Thomson scattering system has a backward scattering configuration with a scattering angle of 167º. [1][2] In the original design, laser pulses are absorbed by a beam dump after traveling through plasma. Recently we removed the beam dump and added a beam-returning mirror and an optical delay path of 30 m. The laser beam is reflected by the mirror and runs through the LHD plasma again. Owing to this, the Thomson scattering light can be observed twice for each pulse. In the second observation, we measure the Thomson scatting signals from a forward scattering configuration with a scattering angle of 13º (=180º–167º). As the optical delay path has been installed, the two signals can be separately observed.

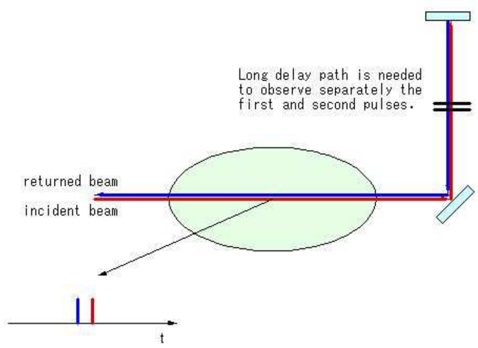

Fig. 1. Schematic diagram of the backward and forward scattering configurations.

Thomson scattering at small scattering angle

The Thomson scattering spectra from the forward and backward scatterings differ significantly, because the Thomson scattering spectrum depends on the scattering angle. By utilizing the feature, we can extend the measurable electron temperature range without any modification of polychromators. The original LHD Thomson scattering system has been optimized for a temperature range of 50 eV–10 keV. In the forward scattering configuration, the LHD Thomson scattering system is expected to be able to measure electron temperatures from 1 keV to more than 50 keV. [3]

The Thomson scattering spectrum is a function of electron temperature and scattering angle. The Thomson scattering spectrum is insensitive to the scattering angle when the scattering angle is large; however, it depends strongly on the scattering angle in forward scattering. Most of the approximation formulae for the Thomson scattering spectrum have been developed and verified for right-angle and backward scattering configurations. Therefore, we developed an approximation formula for forward scattering based on the Selden's formula, which is used by many Thomson scattering diagnostic teams worldwide. [4] The shape of the Thomson scattering spectrum calculated using Selden's formula is also good for forward scattering; however, the amplitude should be corrected. We have determined a simple analytical density correction term as follows.

$$q = \sum_{i=0}^{3} a_i T_e^i\,,\ a_i = \sum_{j=0}^{4} b_{ij}\theta^j\ , \quad (1)$$

$$M(\lambda; T_e, \theta) = q^{-1} S(\lambda; T_e, \theta)\ , \quad (2)$$

where M is the modified Thomson scattering spectrum, S is the original Selden's formula, θ is the scattering angle in degrees, T_e is the electron temperature in keV, and the fit parameters b_{ij} are given in Table I.

Table I. Fit parameter to calculate the density correction term for Selden's formula.

b_{ij}		i = 0	1	2	3
	0	0.99999944	−0.0038412296	1.1005860e−05	−2.6573392e−09
	1	−1.9508837e−07	−1.5727947e−05	1.7910866e−07	1.3532714e−11
j	2	1.2109893e−08	2.4178156e−06	−1.6857518e−08	1.0908465e−11
	3	−3.5048572e−10	−8.6331969e−09	2.4414603e−10	1.7614165e−13
	4	1.3072304e−12	−1.3256505e−12	−7.7736911e−13	−9.2587770e−16

Figure 2 shows a plot of the indefinite integral of the modified Selden's formula, $\int M(\lambda; T_e, \theta) d\lambda$. When the correction term is used, the integral is in the range of 1.0 ± 0.005 for wide temperature and angle ranges of 1 eV–100 keV and 1^o–180^o respectively. In addition to the correction, we studied a distortion of the Thomson spectrum shape due to the finite dimensions of the observation window. For example, the scattering angle has a finite spread of 10.0^o–16.7^o for the LHD plasma center. The scattering angle spread does not cause any major problems for backward scattering measurements, because the Thomson scattering spectrum is insensitive to scattering angle when the scattering angle is large; however, it is sensitive at small scattering angles. Figure 3 shows Thomson scattering spectra coming from a scattering point (plasma center) through the observation window. They differ significantly for the forward scattering configuration. Therefore, we estimated the Thomson scattering spectrum by averaging the forward scattering spectra at each observation point.

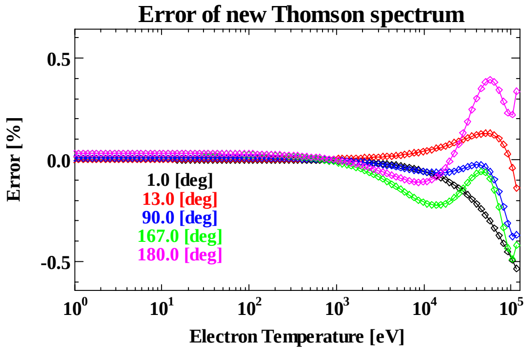

Fig. 2. Estimated error of the modified Selden's formula.

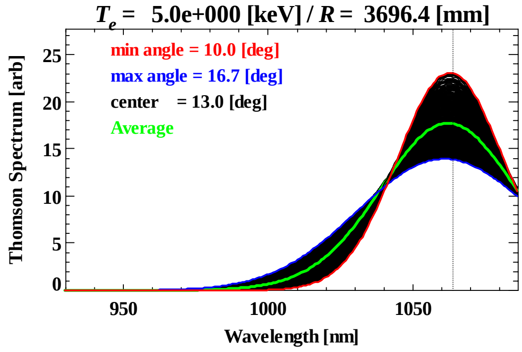

Fig. 3. Thomson scattering spectra at $T_e = 5$ keV. The shape depends on the path of the scattering light through the window.

Experimental results

In the 16th LHD experiment campaign in 2012, we tried to measure electron temperature and density using the forward scattering system as well as the original backward scattering system. First, we clearly observed the forward Thomson scattering signals, as shown in Fig. 4. The leading and following pulses are backward and forward scattering signals, respectively, and the square waveform is a gate pulse sent to analog-to-digital converters. As the 30-m optical delay path has been installed, the 2 signals are observed separately, and the temporal delay of the forward scattering signal is 100 ns. Figures 5 (a) and (b) show comparisons of electron temperatures and densities, respectively, measured by the forward and backward scattering configuration systems in a plasma discharge; these values are found to be in good agreements. Figures 6 (a) and (b) show summaries of the comparisons of electron temperatures and densities, respectively, obtained by the forward and backward scattering systems in the experiment campaign. Results from the forward scattering measurements show good agreement with those from the backward scattering measurements. The discrepancy between the two results was within 16% and 11% for electron temperature and density, respectively.

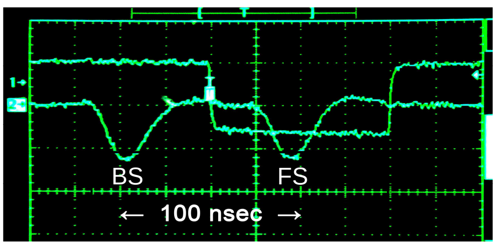

Fig. 4. Observed backward and forward Thomson scattering signals.

We finally note that the backward and forward scattering systems measure the components of electron temperature that are nearly parallel and perpendicular, respectively, to the incident laser beam direction respectively as shown in Fig. 7. Therefore, they observe

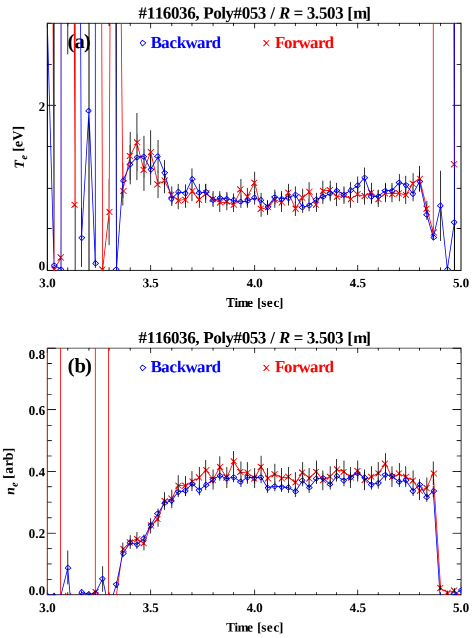

Fig.5. Comparison of (a) T_e and (b) n_e measured by the backward and forward scattering configurations.

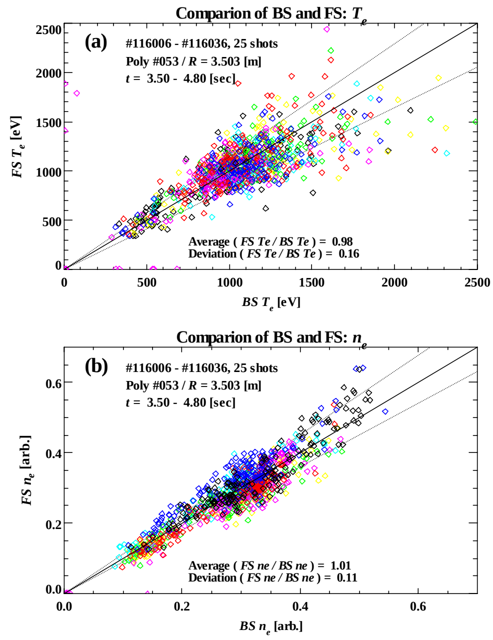

Fig.6. Summary of comparison of (a) T_e and (b) n_e measured by the backward and forward scattering configurations.

intrinsically different temperature components. If a temperature anisotropy exists, it may be possible to verify it by comparing the two components. A hybrid backward and forward Thomson scattering system will be a useful tool to search for this anisotropy

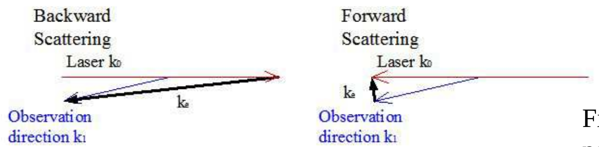

Fig. 7. The temperature component parallel to $\boldsymbol{k_e} = \boldsymbol{k_1} - \boldsymbol{k_0}$ is observed.

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