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Improvements of data quality of the LHD Thomson scattering diagnostics in high-temperature plasma experiments

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In Large Helical Device (LHD) experiments, an electron temperature \( T_e \) more than 15 keV has been observed by the yttrium-aluminum-garnet (YAG) laser Thomson scattering diagnostic. Since the LHD Thomson scattering system has been optimized for the temperature region, 50 eV \( \leq T_e \leq 10 \) keV, the data quality becomes worse in the higher \( T_e \) region exceeding 10 keV. In order to accurately determine \( T_e \) in the LHD high-\( T_e \) experiments, we tried to increase the laser pulse energy by simultaneously firing three lasers. The technique enables us to decrease the uncertainties in the measured \( T_e \). Another signal accumulation method was also tested. In addition, we estimated the influence of high-energy electrons on \( T_e \) obtained by the LHD Thomson scattering system.

I. INTRODUCTION

The Thomson scattering system is one of the most reliable diagnostics for measuring the electron temperature \( T_e \) and density \( n_e \) profiles of fusion plasmas. We constructed a Thomson scattering system and installed on the Large Helical Device (LHD) in 1989.\(^{1,2}\) The measured \( T_e \) range has been optimized for \( T_e=50 \) eV–10 keV. Currently, high-temperature plasmas whose \( T_e \) exceeds 10 keV have been generated by the strong electron cyclotron resonance heating (ECRH).\(^{3,4}\) In such a high-temperature region, the data quality of measured \( T_e \) becomes worse. In addition, the electron density is low, \( n_e \sim 10^{18} \) m\(^{-3}\), in usual high-\( T_e \) ECRH experiments. This makes data quality further degraded. To accurately determine \( T_e \) in the LHD high-\( T_e \) low-\( n_e \) experiments is one of the key issues. We tried to improve the \( T_e \) data quality by two methods. Both of them are based on an attempt to increase the signal intensity and decrease the statistical uncertainties. In this paper, we describe the methods for improving \( T_e \) data quality. In addition, we estimated the influence of high-energy electrons produced by strong ECRH on \( T_e \) obtained by the LHD Thomson scattering system.

II. LHD THOMSON SCATTERING SYSTEM

The LHD Thomson scattering system measures the \( T_e \) and \( n_e \) profiles of LHD plasmas along the LHD major radius at a horizontally elongated section, as shown in Fig. 1. Typical specifications are listed in Table I. Since the LHD Thomson scattering system has several yttrium-aluminum-garnet (YAG) lasers, flexible multilaser operations are possible. Thomson scattered light is collected with a large \( (1.5 \times 1.8 \) m) spherical mirror and analyzed by polychromators that have five wavelength channels. The five filter transmissions are optimized for the \( T_e \) range, \( T_e=50 \) eV–10 keV.

III. IMPROVEMENT OF \( T_e \) DATA QUALITY

A. Near simultaneous laser firing

The LHD Thomson scattering system has three 2.3 J/10 Hz high-energy YAG lasers (Thales SAGA 230-10). By using more lasers, flexible multilaser operations are possible. For example, three 2.3 J/10 Hz lasers can be used as a 6.9 J/10 Hz laser by firing the lasers simultaneously. Increasing the laser pulse energy is expected to be useful for the measurements in low density plasma experiments in which both signal intensity and signal-to-noise ratio are low. Figure 2 shows an example of the raw signal waveform detected by a wavelength channel in a polychromator, and a gate pulse applied to the analog-to-digital converter. In order to cause...
no damages to optics such as beam guiding mirrors and laser windows, we shifted the peak positions to control the maximum intensity. Figure 3 shows a comparison of $T_e$ profiles obtained by 1 laser and 3 lasers. The plasma performances of the two discharges were almost the same, and the line densities were $n_e/H_11011 > 10^{19}$ m$^{-2}$. As shown in the left figure, the $T_e$ error is large in the temperature above $T_e/H_11011 > 8$ keV, whereas $T_e$ errors are small below $T_e/H_11011 > 8$ keV. By using three lasers, the $T_e$ error bars have been successfully decreased by 50% around the plasma center. When two lasers are used, $T_e$ error bars were decreased by 45%. The degree of improvement of $T_e$ data quality is more significant around the plasma center, $T_e/H_11011 > 10$ keV. In the previous paper, we discussed on data quality improvement using four YAG lasers. The central temperature and density were 2.5 keV and 0.6 $n_e/H_11011 > 10^{19}$ m$^{-3}$, respectively. The experimental uncertainty was decreased by 65% in the experiment. The degree of improvement in the previous experiment is somewhat better than that in this experiment, but the difference is not large.

B. Raw signal accumulation methods

Next, we tried the raw data accumulation method on fixed plasma discharges to decrease statistical uncertainties. A total of 29 fixed plasma discharges were carried out. The line electron density was $n_e/H_11011 > 0.3$ $10^{19}$ m$^{-2}$, and the reproducibility of the 29 plasma discharges was within ±10%. In this case, each $T_e$ profile was measured with 1 laser pulse. Figure 4 shows the $T_e$ profiles obtained by a raw data accumulation of fixed 1, 2, 5, and 29 plasma discharges. Relative errors around the plasma center, $dT_e(0)/T_e(0)$, are 26%, 18%, 11%, and 5.5%, respectively. The data quality, i.e., smallness of error bars, becomes better as the number of accumulated shots increases, as expected. Further, we tried the other data accumulation method. In this method, raw signals in a few time frames during the period when the plasma is almost stationary are summed up. By using this method, the data quality has been improved by 54% and 39% when 3 and 5 temporal frames were added, respectively. As the case of the simultaneous laser firing, the degree of improvement of $T_e$ data quality is more significant around the plasma center, $T_e/H_11011 > 10$ keV.

Figure 5 shows the summary of the degree of improvement of $T_e$ data quality. Horizontal axis stands for the number of laser pulses or accumulated raw data, and vertical axis shows the uncertainty of $T_e/H_11011 > 0$ normalized to unity at $n=1$. Roughly speaking, normalized $T_e$ errors in the three different methods show a similar behavior, as $1/\sqrt{n}$. This suggests that the $T_e$ data quality is mainly determined by the statistical uncertainty in low-$n_e$, high-$T_e$ plasma experiments. Since above the methods are not exclusive, then they can be applied jointly. The normalized $T_e$ error has been successfully decreased down to 10% by combing the shot accumulation and frame accumulation methods.
IV. ON THE INFLUENCE FROM HIGH-ENERGY ELECTRONS

During strong ECRH plasma discharges, the electron distribution function may consist of two components, the lower energy bulk component and high-energy component. The LHD Thomson scattering system mainly observes the Thomson scattered light by bulk electrons, and that by high-energy electrons (HEEs), is hardly detected. However, the $T_e$ obtained by the Thomson scattering diagnostics is affected by them when a considerable amount of HEEs is generated. Since the wavelength resolution of the polychromators is poor for accurately observing the two components, it is difficult to obtain the information on HEEs by the Thomson scattering diagnostics. However, considering the influence of HEEs on $T_e$ measured by Thomson scattering diagnostics is useful for the check of accuracy and reliability. Therefore, we estimate $T_e$ under an assumption that the temperature of high-energy component is 69 keV and the population range is 0%–50%. An example is shown in Fig. 6. The upper figure shows $T_e$ profiles as a function of HEE population of 0%, 20%, and 50%. As expected, $T_e$ obtained by the Thomson scattering system decreases as the population of HEEs increases. In other words, bulk temperatures obtained by the Thomson scattering system under the assumption that no HEEs exist are overestimates. However, the error caused from ignoring HEE effect is not large in this work. Even when the population of HEEs is assumed to be 50%, the error has been estimated to be 14%. If accurate and reliable information on HEEs is provided from another diagnostics and/or theoretical calculation, more practical data analysis taking the effect of HEE into account will be possible.

V. SUMMARY

In order to accurately measure $T_e$ and $n_e$ profiles of low-$n_e$, high-$T_e$ LHD plasmas by the LHD Thomson scattering diagnostics, we tried two methods: near simultaneous laser firing method and data accumulation method. Experimental uncertainty has been successfully reduced by both methods. The results suggest that experimental error is mainly determined by the statistical uncertainty. We also considered the influence of HEEs generated in ECRH experiments on Thomson scattering diagnostics. It has been estimated to be small. More accurate estimation of that needs the help of another diagnostics and/or theoretical works.

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