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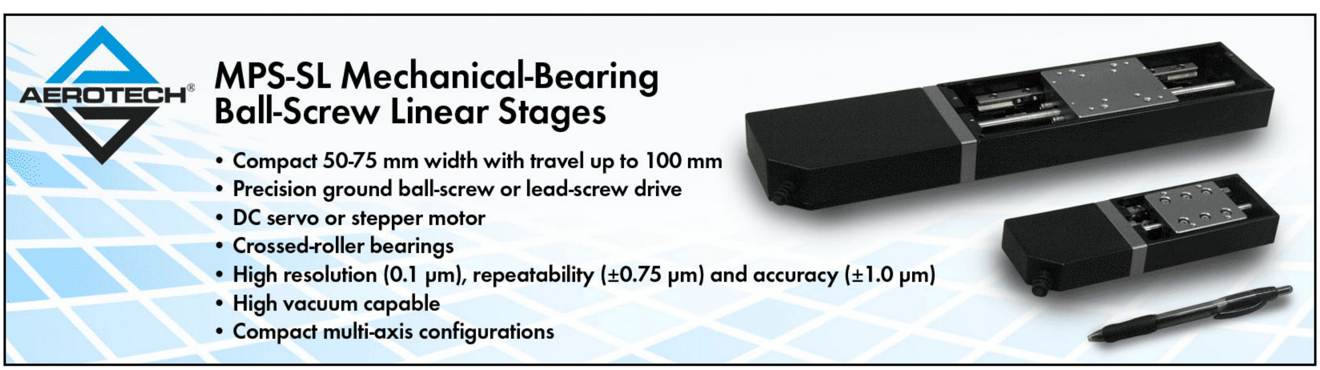

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Improvements of data quality of the LHD Thomson scattering diagnostics in high-temperature plasma experiments[a)]

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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. © *2010 American Institute of Physics.* [doi:10.1063/1.3483189]

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 m $\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

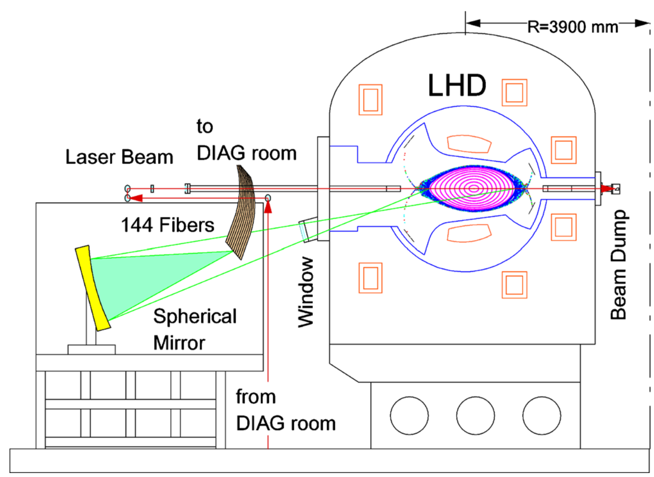

FIG. 1. (Color online) Schematic of the LHD Thomson scattering system.

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TABLE I. Typical specification of the LHD TS system.

	Outside-inside
Scattering angle	161°–171°
Solid angle	39.0–9.4 msr
Spatial resolution	11.6–25.4 mm
Number of observable spatial points	Up to 200
Temporal sampling frequency	10–100 Hz
Measurable T_e range	5 eV–20 keV
Optimized T_e range	50 eV–10 keV
Measurable n_e range	$\geq 10^{18}$ m^{-3}

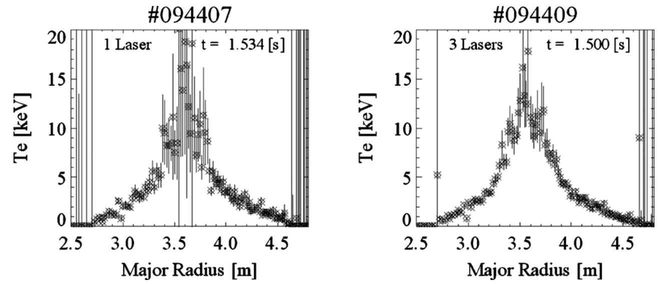

FIG. 3. T_e profiles measured by single laser pulse and three laser pulses.

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 $\sim 0.3 \times 10^{19}$ m^{-2}. As shown in the left figure, the T_e error is large in the temperature above ~ 10 keV, whereas T_e errors are small below $T_e \sim 8$ 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, $T_e \geq 10$ keV. In the previous paper, we discussed on data quality improvement using four YAG lasers.[5] The central temperature and density were 2.5 keV and 0.6×10^{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 $\sim 0.3 \times 10^{19}$ m^{-2}, and the reproducibility of the 29 plasma discharges was within $\pm 10\%$. 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, $T_e \geq 10$ 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 $T_e(0)$ normalized to unity at $n=1$. The results in the near simultaneous laser firing mode are plotted as diamonds. A series of circles and triangles are obtained by the shot accumulation method and the frame accumulation method, respectively. The solid curve shows $1/\sqrt{n}$. 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.

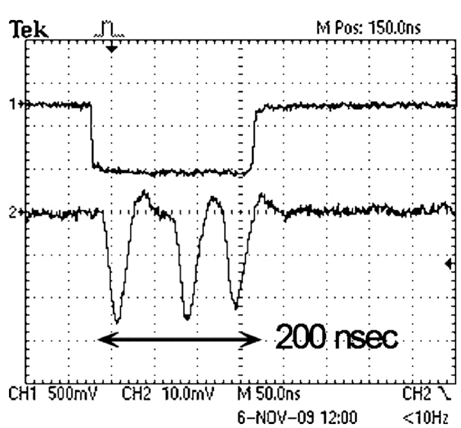

FIG. 2. Thomson scattered signal from three laser pulses (lower waveform). Upper waveform is the ADC gate pulse.

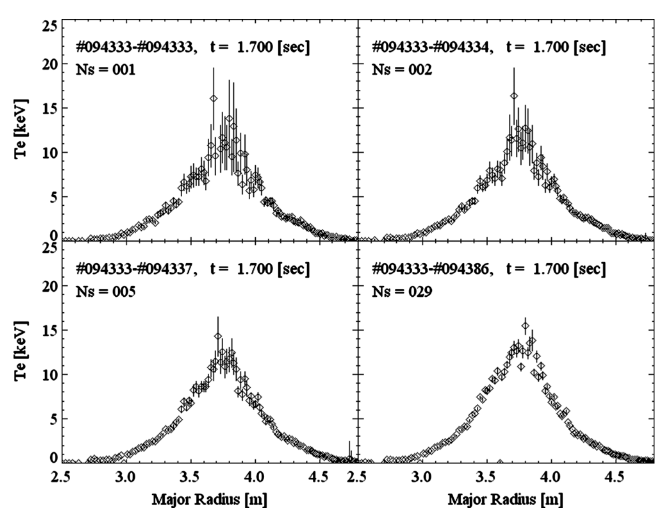

FIG. 4. Comparison of T_e profiles obtained by raw data accumulation of 1, 2, 5, and 29 fixed plasma discharges.

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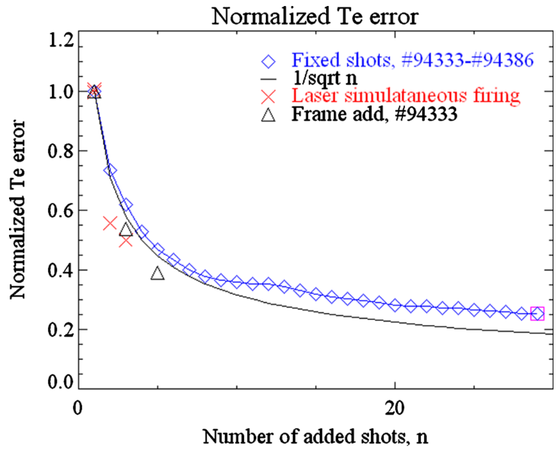

FIG. 5. (Color online) Normalized experimental error of T_e as a function of the number of laser pulses or accumulated plasma shots.

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.[6] 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 at the 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

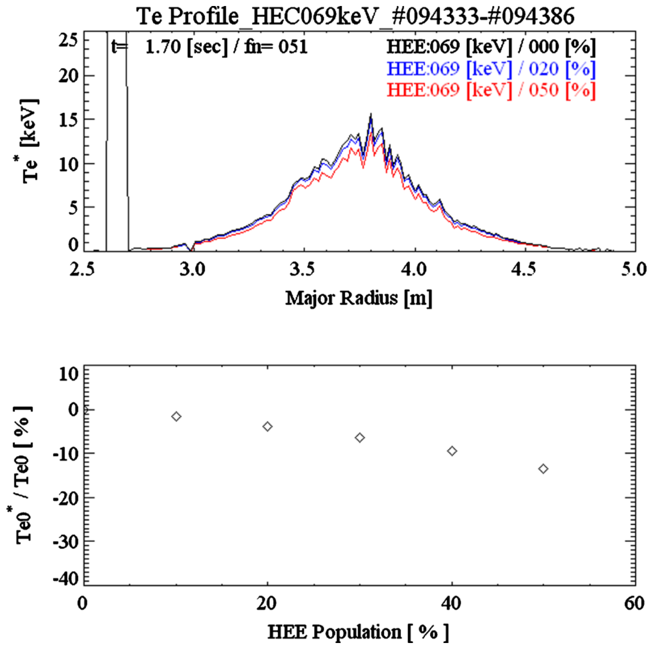

FIG. 6. (Color online) Comparison between electron temperature profiles that takes HEE effects into account T_e^* and the difference between $T_e(0)^*$ and $T_e(0)$.

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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