On-Demand Density Correction Using Steady-State Plasmas in the LHD Thomson Scattering

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In order to measure reliable electron densities of fusion plasmas by using Thomson scattering system, both accurate absolute calibration and long-term stability in the system are required. Even if slight misalignment of some optics occurs, it may cause large errors in measured densities. We propose a new method to obtain correction factors to the errors originated from misalignment by using steady-state plasma discharges. In addition to the data correction, realignment of the laser beam can be applied also.

Keywords: Thomson scattering, density calibration, on-demand density correction, beam alignment, steady-state plasma, LHD

1. Introduction

Thomson scattering is one of the most reliable plasma diagnostics for measuring electron temperature and density profiles. The LHD YAG Thomson scattering has routinely measured electron temperature and density profiles of LHD plasmas[1, 2]. For absolute electron density measurements, the Thomson scattering system should be absolutely calibrated, whereas electron temperatures are obtained from relative measurements of Thomson scattered spectrum. To obtain absolute electron densities, we have tried Raman and Rayleigh scattering calibrations using gaseous nitrogen and/or dry air[3, 4]. The calibration factors obtained in the gas calibration are valid as far as all components are completely stable after the calibration. Even if slight misalignment of some optics occurs, it may cause huge errors in measured densities. Accurate and stable alignment of laser beam and light collection optics is one of the key issues in the development of Thomson scattering devices, and some alignment methods have been proposed[5-7]. However, it will be difficult to fix whole conditions completely for a long-term, especially in large devices such as LHD. Then, the calibration is recommended to be carried out at some intervals. However it is difficult in LHD for some reasons. For example, filling the LHD vacuum vessel with gas frequently may make the wall condition worse, resulting in degrade of plasma performance. Therefore, we propose a new method to obtain correction factors to the errors originated from misalignment without filling the vacuum vessel with gas. In the method, LHD steady-state plasma discharges are used as targets. Therefore, it can be carried out frequently without any bad influence on plasma performance. In the method, the best alignment condition and correction factors are determined by scanning laser beam during a steady-state plasma discharge. In this paper, we describe the experimental set-up and procedures.

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2. Experimentals

In the LHD Thomson scattering, Thomson scattered light is collected with a large, 1.5 m x 1.8 m spherical mirror onto bundled optical fibers whose diameters are 2 mm. Laser beam diameter inside LHD plasmas is 2-3 mm, and the width of the laser image on the fibers is about 1 mm. Before carrying out absolute gas calibration, the laser beam path and the geometrical settings of the light collection optics are optimized as to get maximum signal intensity. Under the best alignment condition, the laser beam image is located at the center of fibers, and comes into focus on the fiber entrance plane as shown in Fig.1 (a). If the image position deviates horizontally from the fiber center, such horizontal misalignment decreases light collection efficiency as shown in Fig.1 (b). In addition, if

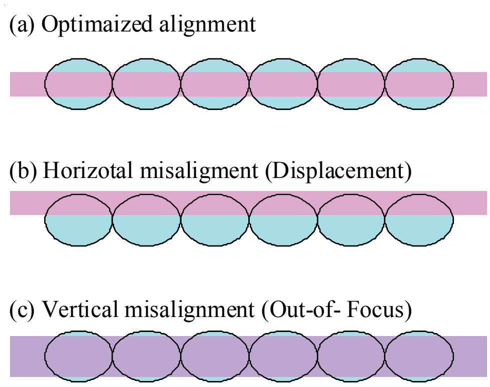

Fig.1 Optimized laser image on the fibers, (a). Both horizontal and vertical misalignments increase the collection efficiency loss, shown as (b) and (c).

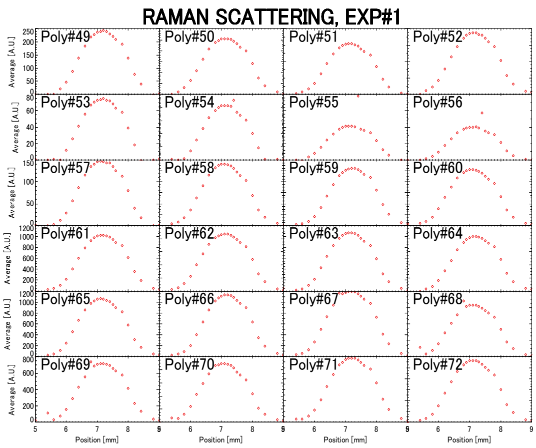

Fig.2 Examples of scattering signal intensity distribution by the horizontal fiber scan.

the image is out of focus, the vertical misalignment also decreases light collection efficiency as shown in Fig.1 (c). Of the two misalignment effects, the former is more sensitive than the latter in the LHD Thomson scattering. For optimizing the relative position between the center of the laser image and fiber array, we developed a laser scanning system and fiber scanning system. In the laser scanning system, a steering mirror is controlled with a high-precision piezo motor driven mirror mount and LabVIEW based control system. It allows the laser beam

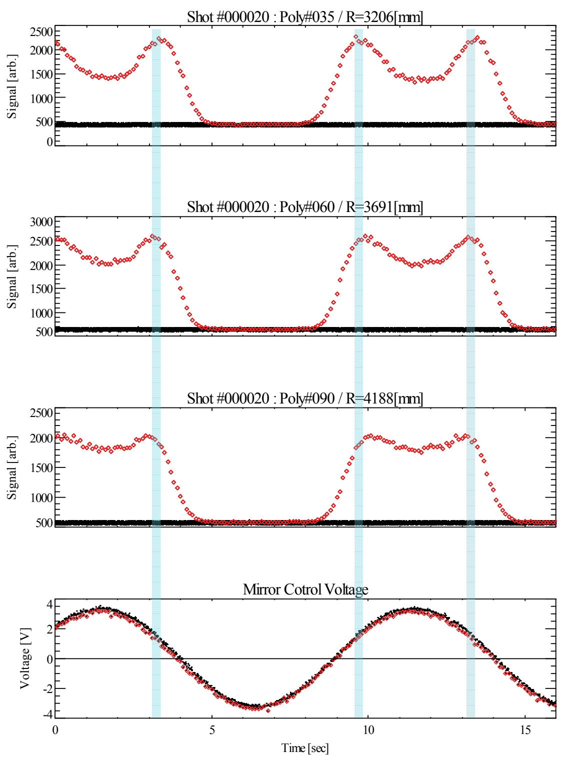

Fig.3 Examples of scattering signal intensity in the horizontal laser beam scan. The upper three figures show signal intensity detected by three polychromators. The bottom sine waveform is the steering mirror control voltage.

to scan both horizontally and vertically, whereas the fiber array is driven only horizontally by a remote controlled AC motor. As a preliminary check, we examined the two scanning systems by using Raman scattering in gaseous nitrogen. Figure 2 shows an example of Raman scattering signal intensities measured by scanning the fiber array horizontally. They were detected by some polychromators that see around the plasma center. The best fiber array position was determined to be 7.05 mm in the case. Next, an example of the horizontal laser beam scan is shown in Fig.3. The laser beam was scanned horizontally by using a steering mirror. The bottom waveform in Fig.3 shows the steering mirror control voltage. The upper three figures show scattering signal intensities detected by three polychromators that see R_{ax}=3.21, 3.69 and 4.19 m respectively. The light-blue lines indicate the position where the signals reach maximum values. Both the scanning systems have been verified to work well. We can optimize the alignment of the laser beam and fiber array by either scanning methods. Just after the optimization, we carried out usual Raman and/or Rayleigh calibration to obtain absolute calibration factors. The calibration factors obtained are valid, as far as all components are completely stable and whole conditions are fixed after the calibration. However, it will be difficult to fix whole conditions completely for a long-term, especially in large devices such as LHD. Even slight misalignment of some optics occurs, it may cause huge errors in measured densities, as expected from Figs.2 and 3. There is a possibility that the errors exceed 10 % within one month. Therefore, frequent gas calibration (roughly speaking, weakly calibration) will be recommended for obtaining reliable electron density profiles, but it is difficult from a point of view of wall conditioning and experimental schedule in LHD. Therefore, we have tried a new optimization method using the LHD steady-state plasma discharges instead of that using gas scattering.

By using the method, we estimate errors due to misalignment, and determine the correction factors to them. When the laser beam is scanned during a steady-state plasma discharge, Thomson scattering signal intensity varies according to the beam position. We can know the laser position where signal intensity reaches maximum value and the maximum intensity for each spatial channel. From the information, we determine light collection efficiency, i.e. the ratio of signal intensity at the previously adjusted position and maximum intensity at the point. Once the light collection efficiencies are obtained, we can make corrections to apparent measured electron densities. Figure 4 shows an example, which was obtained in a LHD steady-state plasma experiment. During the plasma discharge, main plasma conditions such as electron temperature profile, line electron density, and stored energy were kept almost constant. The upper

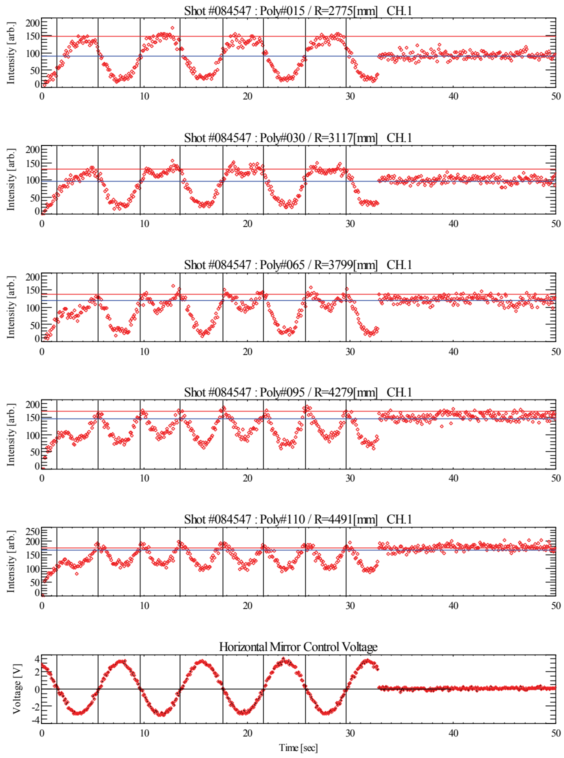

Fig.4 Examples of Thomson scattering signal intensity during a steady-state plasma discharge. The laser beam was scanned with the bottom waveform.

five figures show Thomson scattering signal intensities detected by five polychromators that see R_{ax}=2.78, 3.12, 3.80, 4.28 and 4.49 m respectively, and the bottom waveform is the mirror control voltage. Similar to Fig.3 obtained in gas target experiments, Thomson scattering signals were modulated with the laser position as expected. In the Fig.4, the red and blue lines indicate maximum signal intensity, I_{max}, and signal intensity at the datum position, I_0. Light collection efficiency is determined from $\eta = I_0/I_{max}$. In the case of the Fig.4, the collection efficiency is almost 1 in the outer region, and it decreases with the major radius. About 30-40 % light loss has been observed at the inner region in the case. This means that misalignment of either laser beam or fiber array, or both occurs in the inner region. The light collection efficiencies are plotted in Fig.5. Since our

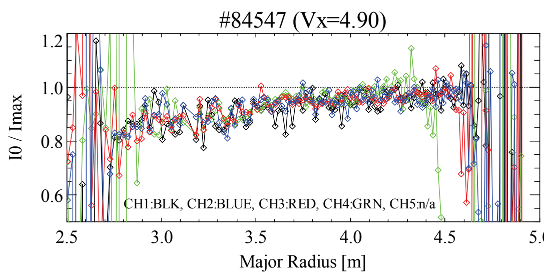

Fig.5 Light collection efficiencies determined from the wavelength channels 1-4, black, blue, red and green, respectively.

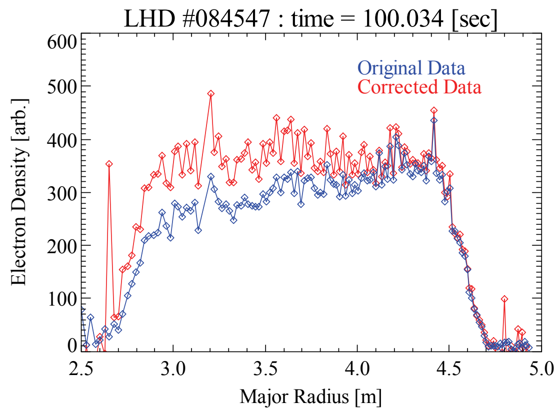

Fig.6 Comparison of the apparent electron density profile (blue) and corrected one (red).

polychromators have five wavelength channels, then we can estimate light collection efficiencies with them as far as enough scattering signal is detected by the channels. In the Fig.5, four collection efficiencies are plotted. They were determined with the wavelength channel 1 to 4 (black, blue, red and green, respectively). They show a good agreement as expected. Once the light collection efficiencies are determined, we can make corrections to apparent measured electron densities. Figure 6 shows a comparison of raw and corrected density profiles. The corrected profile shows symmetrical profile as expected whereas the raw profile is asymmetrical as the light collection efficiency. The apparent asymmetrical density profile is thought to be originated from scattering light loss at the inner region. Necessary discharge time for the laser scanning experiments is not long, about 3-5 sec. Since such steady-state plasmas are easily generated in LHD, the on-demand density correction method can be easily and frequently carried out.

In addition to the data correction, we can also make the realignment by using the data of Fig.4. They include the information on the degree of misalignment and how realignment should be made. We easily know the best mirror driving voltage at which scattering signal intensities

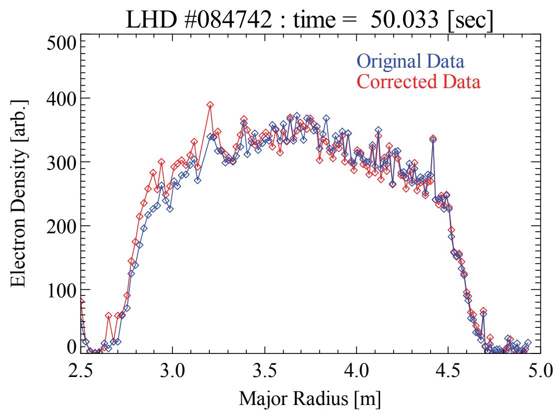

Fig.7 Apparent electron density profile (blue) and corrected one (red) after realignment of the laser beam path.

reach maximum vales. After the realignment, the optimized alignment condition has been restored again. In Fig.7, an example is shown. Raw and corrected density profiles show a good agreement, showing that the realignment has been successfully applied.

Finally, we mention a disadvantage of the data correction method. In this method, since plasma discharges are used as scattering targets, it can be applied to only the polychromators that observe the region where plasma exists, whereas all polychromators are calibrated in gas scattering experiments, because gas fills the vacuum vessel entirely. The light collection efficiencies can be determined accurately for the polychromators by which enough scattering signal intensities are detected. However, the accuracy decreases at the plasma edge region due to low signal intensity as shown in Fig. 5. A few strange corrected densities at the plasma edge region seen in Fig. 6 originate from the inaccuracy in the determined correction efficiency. The realignment can be carried out in any cases. By combining the data correction and realignment methods from the on-demand beam scanning experiments, the data reliability and quality are improved significantly.

3. Summary

We have installed on the laser scanning system on the LHD Thomson scattering to carry out on-demand density data correction and laser beam realignment using steady-state plasma discharges. Since plasmas are used as targets in the method instead of gas, it can be carried out frequently. With the method, realignment of the laser beam path can be easily made also. The on-demand data correction and realignment methods will increase data reliability and quality significantly.

Acknowledgements

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