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journal or publication title	Review of Scientific Instruments
volume	Vol. 75
number	No. 10
page range	pp.3912-3914
year	2004-10-01
URL	http://hdl.handle.net/10655/9005

doi: 10.1063/1.1789605

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Citation: *Rev. Sci. Instrum.* **75**, 3912 (2004); doi: 10.1063/1.1789605

View online: <http://dx.doi.org/10.1063/1.1789605>

View Table of Contents: <http://rsi.aip.org/resource/1/RSINAK/v75/i10>

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Design and development of the large helical device TV Thomson scattering

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(Presented on 20 April 2004; published 12 October 2004)

We have developed a television (TV) Thomson scattering and installed it on the large helical device (LHD). The LHD TV Thomson scattering consists of a yttrium–aluminum–garnet (YAG) laser, beam transport system, scattered light collection optics, spectrometer, intensified charge coupled device camera, and data acquisition system. The spatial and temporal resolutions are about 7 mm and a few seconds, respectively. The temporal resolution of the LHD TV Thomson scattering is not good, but will be enough for long-time, steady-state discharge experiments in LHD. In the initial experiments, we measured electron temperature profiles of LHD plasmas at five spatial points. It has been found that the electron temperatures measured by the LHD TV Thomson scattering reasonably agree with those obtained by the LHD YAG Thomson scattering. We will report the details of the LHD TV Thomson scattering system with some experimental data. © 2004 American Institute of Physics. [DOI: 10.1063/1.1789605]

I. INTRODUCTION

We have installed a yttrium–aluminum–garnet (YAG) Thomson scattering system on the large helical device (LHD) and it has worked well for the measurements of electron temperature and density profiles of LHD plasmas.^{1–3} In addition to the LHD YAG Thomson scattering, we have been developing a TV Thomson scattering system.^{4–6} The LHD TV Thomson scattering measures electron temperature profiles along with the LHD major radius at a vertically elongated plasma cross section whereas the YAG Thomson scattering observes them at a horizontally elongated plasma cross section. By comparison of electron temperature profiles obtained with the two Thomson scatterings, more useful information such as three-dimensional, helical magnetic surface structures is expected to be obtained. In this article, we describe the LHD TV Thomson scattering system in detail.

II. LHD TV THOMSON SCATTERING SYSTEM

The LHD TV Thomson scattering consists of a YAG laser, beam transport system, scattered light collection optics, spectrometer, intensified charge coupled device (ICCD) camera, and data acquisition system. The schematic diagram is shown in Fig. 1. In contrast to the YAG Thomson scattering that uses two hundred polychromators and a thousand analog to digital converters, the TV Thomson scattering system is simple and the calibration can be made easily because only one spectrometer and ICCD camera are used for the analysis of scattered light spectrum. In the initial operation, we observe electron temperatures at five spatial points along with the LHD major radius. The number of observation points will be increased up to more than 100 by adding optical fibers that transmit Thomson scattered light from the light collection optics to the spectrometer, and an imaging optics that connects the fibers and spectrometer.

A. Laser system

In the LHD TV Thomson scattering, green, second harmonics from a YAG laser (Continuum, NY-81) is used as the light source. The wavelength, pulse energy, and repetition rate are 532 nm, 0.2 J, and 50 Hz, respectively. The transport length from the laboratory where the YAG laser is located to LHD is about 50 m. The laser beam is guided with eight mirrors. The final mirror is installed inside the LHD vacuum vessel and is molybdenum-coated copper mirror. The other seven mirrors outside the vacuum vessel are usual dielectric mirrors. As shown in Fig. 2, the final mirror is protected by a stainless-steel cover and movable shutter to reduce the damage due to the impact of high energy particles from plasmas and the adsorption of boron and titanium for wall conditioning. The diameter of the laser beam inside plasmas is 1–3 mm.

B. Light collection optics

In the LHD TV Thomson scattering, right angle scattering configuration and reflecting telescope type light collecting system are adopted as shown in Fig. 1. The observation solid angle is about 0.2 msr and spatial resolution is 7 mm. Thomson scattered light is collected by a rectangle 65 cm × 30 cm spherical mirror onto optical fibers whose core diameter is 0.6 mm. The reflecting telescope type light collection system is chromatic aberration free, then convenient for observing accurate spectral distribution of Thomson scattered light, whereas spherical aberration that reduces spatial resolution still remains when a spherical mirror is used. We use a pair of fiber arrays; the first array is set along with the laser beam image and observes both Thomson scattered light and plasma light. The second one sees only plasma light from the neighboring region. The plasma lights observed by the first and second arrays are almost equal and then Thomson scattering signals can be deduced successfully by subtracting the plasma light signals observed by the second array from the signals collected with the first array.

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FIG. 1. Schematic diagram of the LHD TV Thomson scattering system. The scattering angle is 96° at the plasma center. The laser beam transport length is about 50 m and the final steering mirror is located inside the vacuum vessel. Thomson scattered light is collected with a spherical mirror onto the optical fiber array, transmitted to the spectrometer through the fibers, and recorded by the ICCD camera.

C. Spectral analysis and data acquisition

In order to determine the spectral distribution of Thomson scattered light, we use a traditional grating spectrometer with the focal length of 275 mm (Acton Research, Model 275). We observe the blueshifted Thomson scattered light to avoid the strong $H\alpha$ (656 nm) and $He I$ (668 nm) radiations located at the red side. In order to eliminate stray light, a notch filter with the optical density >6 at 532 nm, which is designed for Raman spectroscopy (CVI, RNF-532.0), is inserted into the spectrometer. Even though the TV Thomson scattering system has no view dumper and sophisticated beam dumper in the vacuum vessel, stray light is suppressed successfully by the filter. The lower and upper limits of the measurable temperature are 50 eV and 10 keV, respectively. They are currently limited by the specification of the Raman filter and the observation wavelength range of the spectrometer and ICCD system, respectively. The upper limit will be easily extended by substituting the grating in the spectrometer.

The wavelength-analyzed light is recorded with an ICCD camera (Princeton Instruments, 576E) whose pixel format 384×576 and quantum efficiency of $\sim 10\%$. We have

FIG. 2. (a) Mo-coated Cu mirror installed inside the LHD vacuum vessel and (b) covered view. The incident laser beam comes from a lower port and is turned toward the LHD inner center by the mirror.

FIG. 3. An example of the Thomson scattering spectrum observed at five different points. Electron temperatures are determined from the fit curves.

carefully calibrated the spectrometer and ICCD camera system by using a standard lamp, deuterium lamp and mercury emission tube. The ICCD camera is gated with the pulse sequence synchronized with the laser fire pulses. The gating pulse width is set to be 50 ns. Due to the low laser pulse energy, small observation solid angle, and low detection efficiency, observed Thomson scattered light is so weak that electron temperature cannot be determined with single laser pulse. Therefore, we stored signals for 50–500 pulses, corresponding to the data acquisition time of 1–10 s. Then, the LHD TV Thomson scattering cannot see fast phenomena, but the temporal resolution will be enough for the long-time, steady-state plasma discharge experiments in LHD.

III. RESULTS AND DISCUSSION

In Fig. 3, an example of relative Thomson scattering spectrum measured at different five points is shown. Nonrelativistic Gaussian fit curves are also plotted in the figure. From the fit curves, we estimate the electron temperatures. For high temperature plasmas, relativistic effects should be taken into account in order to determine temperatures

FIG. 4. Comparison between electron temperature profiles measured by the LHD TV Thomson scattering, circles, and YAG Thomson scattering, solid line.

accurately.⁷ In the initial experiments, since the typical electron temperatures were below 1.5 keV, nonrelativistic spectrum is a good approximation as well. The extra error due to neglecting relativistic effects is estimated to be less than 10%.

Figure 4 shows an example of electron temperature profiles measured by the TV Thomson scattering (circles) and the YAG Thomson scattering (solid line). The two profiles are found to show a good agreement, showing reliability of the two Thomson scattering systems in LHD. We note that the experimental uncertainties are estimated to be 15%-25%, mainly depending on the plasma density and radiation. We are planning to make further improvements of the TV Thomson scattering.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of the LHD experimental group. This research was partially supported by the Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Research (B), No. 14380221, 2002–2003.

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