Progress in Development of the Advanced Thomson Scattering Diagnostics

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Abstract. We have been studied the advanced Thomson scattering diagnostics from viewpoints of new concepts, laser technology and spectrum analysis. This paper summarizes results of development on technologies for advanced Thomson scattering diagnostics.

1. Introduction

Incoherent Thomson scattering [1] is one of the essential diagnostics for measurement of local electron temperature (Tₐ) and density (nₑ), and is widely used in fusion plasma experiment. Thomson scattering is established diagnostic technique; nevertheless, further improvement on the measurement capability has been required for physical understanding of the fusion plasma. For example, a low temperature measurement (< 100 eV) is needed to study a divertor plasma, while a high temperature measurement (~30 keV) is also needed to study a reactor-class core plasma. On the other hand, high repetitive measurement is necessary to observe transient phenomena such as formation/collapse of a transport barrier. And a necessity of profile measurement with high spatial resolution has risen. To realize such requirements effectively, development of new technology is crucial. We have been studied the advanced Thomson scattering diagnostics to meet such requirements from viewpoints of new concepts, laser technology and spectrum analysis. This paper summarizes results of development on technologies for advanced Thomson scattering diagnostics.

2. New concepts for Thomson scattering

2.1. Polarization interferometer based on Fourier transform spectroscopy

In the Thomson scattering diagnostics, grating spectrometers or filter polychromators have been utilized to analyze the scattered spectrum thus far. Although these are widely used, there are some disadvantages: the throughput is relatively small in the case of grating spectrometer, the transmissivity of rear placed spectral channels decreases when the interference-filter-type polychromator has many wavelength channels. The main advantage over polarization interferometers based on the Fourier
transform spectroscopy is amenability to imaging, simplicity of design and cost. There may be some transmission advantages because of the use of a small number of high transparency components. Furthermore, this is suitable for measurements with restricted plasma background light. Polarization interferometers for the Thomson scattering diagnostics have developed to evaluate the validity.

A method based on measurement of the optical coherence of scattered radiation at a fixed optical delay has been proposed for Thomson scattering [2]. A dual channel polarization interferometer utilizing a fixed-thickness birefringent plate has been developed [3]. The polarization interferometer is composed of a birefringent plate of fixed optical delay sandwiched between polarizers as shown in Figure 1. By suitably choosing the optical delay, these independent outputs provide sufficient information to determine both the electron temperature and density. The scattered signals at the complementary output ports are

$$S_{\pm}=0.5I_0\{1\pm\zeta_T(\phi_0)\}$$

where $I_0$ is the spectrally integrated light intensity, $\zeta_T(\phi_0)$ is the Thomson spectrum fringe visibility at monochromatic birefringent phase delay $\phi_0$. The value of $I_0$ is in proportion to $n_e$, and value of $\zeta_T(\phi_0)$ is function of $T_e$.

Since proof-of-principle tests is carried out in TPE-RX reversed-filed-pinch (RFP) machine using the existing YAG laser Thomson scattering system, parameters for design of a dual channel polarization interferometer are fixed as follows: $T_e \leq 1 \text{ keV}$, $n_e \geq 1 \times 10^{19} \text{ m}^{-3}$, scattering angle 90°, YAG laser wavelength 1064 nm. A YAG laser Thomson scattering system has been already installed in TPE-RX, and this system has a conventional filter polychromator (4 spectral channels). The electron temperature of one spatial point at the plasma center was measured using the filter polychromator and the polarization interferometer alternately. To compare at different temperature ranges, data during PPCD (high temperature data) and before PPCD phase (low temperature) are measured. As a result, similar $T_e$ values within data variation and error bar ranges were successfully measured by both interferometer and polychromator [4].

Measurement of one point on the interferogram using the dual channel polarization interferometer is insufficient to evaluate the electron temperature with the wider range. We considered that measurement of the whole or the main part of interferogram is essential for the wider electron temperature range. When the whole or the main part of interferogram is measured, it is possible to reconstruct the Thomson scattered spectrum accurately. We have been developing a prototype multichannel polarization interferometer using the Wollaston prism to evaluate the availability for the Thomson scattering diagnostics as shown in Figure 2 [4]. The light from the optical fiber bundles is collimated by a lens, and is introduced to an interferometer part. The interferometer part is simple structure that the Wollaston prism is sandwiched between two polarizers. An interferogram which is localized at a plane inside the Wallaston prism is imaged onto a photo cathode of an image intensified CCD camera by an imaging lens. Interferograms of various monochromatic light sources were measured by the multichannel polarization interferometer. In this test, a green He-Ne laser ($\lambda = 543.5 \text{ nm}$), a red He-Ne laser ($\lambda = 632.8 \text{ nm}$) and a near-infrared LED ($\lambda = 850 \text{ nm}$) were used as light sources. These spectra were reconstructed from interferograms by FFT. Since 15-periods of the fringe can be observed for 632.8 nm He-Ne laser, effective wavelength resolution becomes $\sim 60 \text{ nm}$ in this
system. It is possible to measure the electron temperature of more than 100 eV (scattering angle 90°) in this system. To measure low temperature of less than 100 eV, it is necessary to increase the fringe frequency.

Polarization interferometers based on the Fourier transform spectroscopy for the Thomson scattering diagnostics have been examined to evaluate the validity. The validity of dual channel polarization interferometer has been proved by the plasma measurement. It seems that both dual channel and multichannel interferometers are useful instruments to observe the Thomson scattering spectrum. Based on these results, we have investigated imaging interferometers for analysis of Thomson scattering spectra [5]. We have also considered an application of Solc filter to Thomson scattering [5]. A Solc filter is a multiwaveplate polarization interferometer whose passband can be tailored according to the number of plates and their respective thicknesses and orientations. It is possible that this method realize the multichannel polychromator by the simple optics.

2.2. Multipass Thomson scattering using SBS phase conjugate mirror

In the conventional Thomson scattering system, a focused laser beam is injected into the plasma in order to generate scattered light, and the beam is then dumped by a beam dumper after passing through the plasma. Since the beam transmission loss in the plasma is negligible, the energy of the dumped beam is almost the same as that of the input beam. The large laser energy which passed through the plasma is abandoned without recycling. It is natural to consider that the beam that has passed through the plasma can be utilized again for measurement. In the case of using a flat mirror to turn the beam, since the beam has a positive divergence angle, the returned beam spreads after the beam is reflected by the mirror. The significant stray light will be generated when the spread beam touches the vacuum vessel and laser port, leading to the difficulty in Thomson scattering measurement. In the case of using a concave mirror, although it is possible to decrease the generation of stray light, precise beam alignment is required. We have focused on a phase conjugate mirror based on stimulated Brillouin scattering (SBS) [6] to address a multipass Thomson scattering. The SBS is one of the most common nonlinear optical processes for achieving a phase conjugate wave with the inclusion of a small Brillouin frequency shift. The part of the nonlinear optical medium that causes phase conjugation is called a “phase conjugate mirror (SBS-PCM)” in order to distinguish it from a conventional mirror. We confirmed 95% of the reflectivity at 145 W (2.9 J × 50Hz) of average power using JT-60U Thomson scattering laser [7,8]. In the high average-power operation, the SBS-PCM worked stably without laser breakdown of the SBS medium.

A double-pass Thomson scattering measurement using SBS-PCM was carried out in JT-60U [7,8]. A laser beam passing through the plasma is reflected by the SBS-PCM in place of a beam dumper, and the reflected beam is automatically returned along the same path as the incident one by the phase conjugate effect, and passed through the plasma again. If a conventional mirror is used for this purpose, very precise beam alignment is frequently required to reduce the amount of stray light. However, such alignment is completely unnecessary in the case of the SBS-PCM. After an initial simple positioning of the SBS-PCM, alignment-free operation can be realized by the phase conjugate effect. Two ohmic plasma discharges with similar electron densities and temperatures were performed, and the electron temperature and density were measured with and without the double-pass scattering method. As a result, the intensity of the scattered light became 1.6 times larger and the relative errors of electron
temperature and density were reduced to 2/3 in comparison with single-pass scattering.

In the case of double-pass scattering, scattered light can be increased by up to a factor of 2, as mentioned above. However, most of the input energy remains in the double-passed beam. We have proposed the multi-pass Thomson scattering method that utilizes the input beam energy more effectively and that generates over twice the amount of scattered light [7,8]. Since the multi-pass scattering method is an extension of the double-pass method, the components of the multi-pass scattering system are similar to those used in the double-pass system, except that another SBS-PCM with a lens, a thin film polarizer, and a large aperture Pockels cell are added. Multi-pass scattering generates over twice the amount of scattered light by confining the laser beam between a pair of SBS-PCMs. The laser beam can be confined between a pair of SBS-PCMs by control of the laser beam’s polarization. As mentioned, alignment-free operation can be realized by the SBS-PCM after an initial adjustment. In the case that the optical loss is under 10%, the scattering light is amplified up to about 5 times larger than that of single pass when the laser beam passes the plasma after 10 times. When an appropriate optical delay is installed between a pair of SBS-PCMs, temporal separation of each pulse is possible. Consequently, very high repetitive measurement is available by burst laser pulses. Advantage of this method is that one laser system is enough to produce burst pulses. We have been preparing the multipass Thomson scattering system for the proof-of-principle tests in LHD.

3. Laser technology for Thomson scattering

The laser system is a key component of Thomson scattering diagnostics. To improve the spatial resolution, an increase of laser energy is necessary. Producing shorter laser pulses is crucial for improvement of spatial resolution in the case of the LIDAR. To observe the transient phenomena by Thomson scattering, high repetition laser is required.

In the solid-state laser, development of high output energy and high repetition laser system is not easy, and the performance is limited by the thermal effects of laser rod in the high power amplifier (thermal lens effect, birefringence) and parasitic oscillation. To solve these issues, the SBS-PCM was applied to a conventional YAG laser system in JT-60U [7-10]. Before introducing the SBS-PCM, the laser system is composed of an oscillator and a series of four amplifiers. This system produced a Gaussian-like beam with an energy of 1.5 J, a pulse length of ~30 ns, and a divergence of < 0.5 cm·mrad (half angle) at a 30 Hz repetition rate (average power is 45 W).

The average power is limited by issues above. The optical configuration was changed from single-pass single amplifier stage to double-pass twin amplifier stages employing SBS-PCMs. The optical layout of the high average power laser system is shown in Figure 4. The performance of the laser was drastically enhanced by the improvements and finally achieved 373 W (= 173 W + 200 W) of average power (7.46 J × 50 Hz). The average power exceeded eight times that of the original laser system. This laser system was in routine operation for Thomson scattering diagnostics in the JT-60U.

As another application of SBS-PCM, we have studied SBS pulse compressor (SBS-PC). To obtain pico-second pulses, the mode-locking scheme which requires complicate optical configuration has been used so far. We focus on SBS-PC for application to the LIDAR. The SBS-PC is similar to the SBS-PCM, and uses a very long SBS cell (or plural long SBS cells). The optical layout is simple compared to the mode-locking, and the reflected pulse is compressed automatically by the long SBS cell. In core LIDAR system in ITER, YAG laser of the 1064-nm wavelength is considered to improve the measurement error very high $T_e$ up to 40 keV. Required pulse width for the core LIDAR in ITER is 300 ps, we set the target at less than 300 ps. Since a compression ratio corresponds to a phonon
lifetime, a FC-40 liquid having a short phonon life time of 240 ps was selected to obtain the target pulse width. We fabricated two long SBS cells as SBS-PC. The cell had 1.5 m in a length, 4 cm in a diameter and AR-coated windows at both ends, and the FC-40 was filled. One cell was used as an SBS generator, another cell was used as an SBS amplifier. As a result, a 13-ns YAG laser pulse was temporally compressed to a 160 ps phase conjugated pulse at 1064-nm wavelength as shown in Figure 5 [11]. The maximum reflectivity was over 80% without any damage. It seems that this technique is applicable to the LIDAR.

To increase the laser gain, development of new laser materials is a solution. Recently, ceramic material which is equivalent to the laser performance of the conventional laser crystal has been developed. Furthermore, it became that ions which was difficult to dope in the conventional laser crystals was possible to dope in the ceramics. We studied an application of Cr$^{3+}$ and Nd$^{3+}$ co-doped YAG (Cr, Nd:YAG) ceramics [12] to high power laser. In the Cr, Nd:YAG ceramics, absorbed energy by Cr$^{3+}$ is transferred to Nd$^{3+}$, the laser efficiency is improved as a result. We produced a Cr, Nd:YAG ceramics rod that the length and the diameter are 100mm and 8mm, Cr and Nd concentrations are 0.05% and 0.8%, respectively. The amplification test was carried out to compare the performance between the conventional Nd:YAG crystal (Nd concentration is 1.0%) and Cr, Nd:YAG ceramics using JT-60U laser system. When pumping energy and repetition rate were 93 J and 50 Hz, respectively, the extracted energy of the ceramic rod was 1.08 J which corresponded to 1.5 times larger extracted energy of the crystal (0.71 J). Therefore, the Cr, Nd:YAG ceramics is promising material to improve the laser efficiency easily.

4. Spectrum analysis
To evaluate high $T_e$, consideration of relativistic effect is indispensable. Fully relativistic formulae for Thomson scattering diagnostics have been developed. A compact analytic formula for fully relativistic Thomson scattering spectrum including depolarization has been presented [13]. By rational approximation, an analytic formula with high accuracy (relative error < 0.1% at 100 keV) is obtained, which is applicable to a wide range of plasmas. The applicability of Thomson scattering measurement is expanded to a class of non-Maxwellian plasmas which can be described by generalized Lorentzian (kappa) distributions. A fully relativistic scattering spectrum has been presented in an analytic form which allows the possibility of a more robust estimation of the bulk electron temperature in the existence of high energy component [14]. A simple formula for reconstructing fully relativistic electron momentum distribution functions from Thomson scattering data has been also presented [15]. Although the formula assumes the isotropy in momentum space, it may be useful for obtaining detailed information on the electron distribution function in fusion plasmas. The first formula has been used to evaluate the electron temperature in JT-60U. It seems that these formulae are useful for Thomson scattering diagnostics in various plasma experiments.

To observe the Thomson scattering spectrum in the wide $T_e$ range, investigation for the necessary number of wavelength channels and optimum band width of these channels in a spectrometer is significant to evaluate $T_e$ with high accuracy. This examination also contributes to the minimization of the development cost for the spectrometer. The necessary number of wavelength channels for a spectrometer has been investigated in Thomson scattering diagnostics [16]. The measurement errors ($\sigma$) are evaluated for a realistic case and their lower limits ($\overline{\sigma}$) are given in explicit forms. For a given number of wavelength channels, optimal channel allocation in wavelength space is sought by minimizing the average relative errors. As a scale of the goodness of measurement, the ratio $\overline{\sigma}/\sigma$
averaged over the electron temperature of interest is introduced. This quantity ranges from 0 to 1 and tends to 1 as the lowest achievable error is approached. If \( \langle \sigma / \alpha \rangle \approx 0.9 \) is sufficient, then for a typical ruby laser system measuring 400-700 nm, seven channels is adequate number for covering the electron temperature of 0.01-10 keV and five channel for 0.1-10 keV. Designs for polychromators of the ITER edge Thomson scattering system have been investigated utilizing this scheme \[17,18\].

5. Conclusions

We have developed new technologies for an advanced Thomson scattering diagnostics to meet various requirements for understanding physical phenomena in fusion plasmas. These technologies for the advanced Thomson scattering diagnostics may contribute future Thomson scattering diagnostics. For example, a polarization interferometer is applicable for \( T_e \) measurement with wide range and imaging measurement. A multipass Thomson scattering and high average power laser employing SBS-PCM may improve the S/N ratio and repetition rate for the measurement, and allows measurement with high spatial resolution. An SBS-PC is a promising technology for LIDAR to generate short laser pulse. A Cr,Nd:YAG will be used for high-efficiency and high average power laser system. Fully relativistic formulae will contribute to the spectrum analysis with wide \( T_e \) range. A guideline to optimize wavelength channels will be useful for a design of spectrometer.

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