An *in-situ* Relative Calibration Method for Thomson Scattering Diagnostics Using a Double-Pass Scattering System

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A new method of *in-situ* relative calibration for Thomson scattering diagnostics using a double-pass scattering system is proposed. The ratio of scattered light signals between the first and second pass depends on electron temperature (T_e), making it possible to evaluate T_e without considering relative transmissivities. The relative transmissivities of each spectral channel can be determined at the same time. The feasibility of the method based on parameters in a JT-60SA Thomson scattering diagnostic is also examined.

Keywords: Thomson scattering, double-pass beam, calibration, YAG laser, JT-60SA

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Transmissivity losses with chromatic dependence in optical components such as lenses, mirrors and fibers, caused by intense radiation (γ-ray and neutron) from fusion plasmas, are serious concerns [1,2]. Another problem for light measurement is caused by thin films on vacuum windows that can be seen after many plasma discharges and also have chromatic dependence in their transmissivity [3]. For Thomson scattering diagnostics, the degradation in transmissivity prevent correct measurement of spectra and reduce the accuracy of measured electron temperature and density (n_e). Especially, degradation caused by radiation tends to be seen clearly in the short wavelength range (≤ 700 nm) which is necessary for determining high T_e with broad scattering spectra. Therefore, measured T_e with such losses tends to be low, as a systematic error and *in-situ* relative calibration method for the true T_e is required. The new relative calibration method proposed in this paper employs only one laser with a double-pass beam, the laser passing through the plasma twice using a reflection mirror (see Fig. 1). This is a simpler laser system in contrast with another calibration method using two different wavelength lasers [4, 5]. The authors show that the calibrated T_e is corrected and independent of unknown transmissivity degradation. It should be noted that this paper does not provide a density calibration method, which is generally performed by Raman and/or Rayleigh scattering.

In the double-pass scattering system, the scattering angles ($\theta \neq 90^\circ$) are different from each other (θ and $180^\circ - \theta$): thereby making measurement of two different spectra possible. The authors show that the spectrum ratio (signal ratio in each spectral channel) makes it possible to decide T_e without systematic error. It is assumed that the path length between the plasma and mirror is long enough for measuring the scattering signals from the first and second pass separately.

By using normalized wavelength $\varepsilon = (\lambda - \lambda_i)/\lambda_i$, where λ_i denotes input laser wavelength, measured photon counts from Thomson scattering in one spectral channel (j) measuring a range ($\varepsilon_{j-1} \leq \varepsilon \leq \varepsilon_j$), can be expressed as follows [6]:

$$N_{s,j} = C_j n_e L_s \frac{\lambda_i E_i}{hc} \Omega_s \int_{\varepsilon_{j-1}}^{\varepsilon_j} \frac{d^2\sigma_p}{d\varepsilon d\Omega} \eta(\varepsilon) T(\varepsilon) d\varepsilon \equiv C_j n_e E_i g(T_e, \theta, \lambda_i), \quad (1)$$

where L_s, λ_i, E_i, h, c, Ω_s, η, T and C_j are scattering length, laser wavelength, input laser energy, Planck constant, light velocity, solid angle, quantum efficiency in a detector, optical transmissivity and degradation factor in optical transmissivity, respectively. $d^2\sigma_p/d\varepsilon d\Omega_s$ in Eq. (1) is the differential cross section as a function of T_e and θ and includes a depolarization effect. This expression assumes that C_j is a constant value over the range of sensitive wavelengths in the spectral channel (j). The goals of this relative calibration method are to determine T_e without systematic error and to acquire C_j, which reflects unknown change and can provide information for maintenance. This calibration

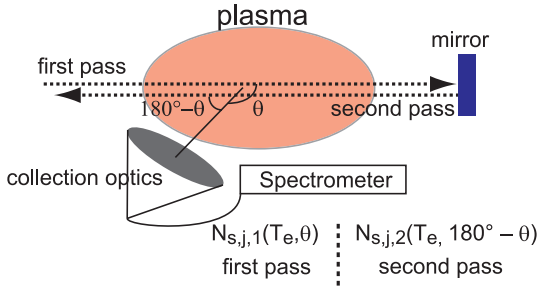

Fig. 1 Calibration method using double-pass scattering system.

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method is based on the spectrum ratio between the first and second pass in a spectral channel. The ratio can be written as follows using Eq. (1):

$$\frac{N_{s,j,2}}{N_{s,j,1}} = \frac{E_2}{E_1}\frac{g_j(T_e, 180^\circ - \theta, \lambda_i)}{g_j(T_e, \theta, \lambda_i)}. \quad (2)$$

Here, the subscripts "1" and "2" denote the first and second laser passes. Since θ and λ_i are known values, this indicates that T_e can be decided without knowing the degradation factor (C_j).

In order to determine T_e in measurements, Eq. (2) should be used in multiple spectral channels because shot noises from total measured photon counts cause deterioration in pure scattered spectra. The main photon counts except for Thomson scattered light are generated from bremsstrahlung, impurity radiation and wall refraction. The unknown T_e is therefore decided by minimizing the following value as a least square method:

$$\chi^2_{T_e} = \sum_j \left(\frac{N_{m,j,2}}{N_{m,j,1}} - \frac{E_2 g_j(T_e, 180^\circ - \theta, \lambda_i)}{E_1 g_j(T_e, \theta, \lambda_i)} \right)^2 \Big/ \sigma^2_{R,j}, \quad (3)$$

$$\sigma^2_{R,j} = \frac{N^2_{m,j,2}}{N^2_{m,j,1}} \left(\frac{\sigma_{j,1}}{N_{m,j,1}} + \frac{\sigma_{j,2}}{N_{m,j,2}} \right)^2, \quad (4)$$

$$\sigma^2_{j,k} = N_0 + F_n(N_{s,j,k} + 2N_{b,j}), \quad (5)$$

where $N_{m,j,k}$ and $N_{b,j}$ are the measured and background photon counts in a spectral channel j, respectively. The subscript k stands for the first ($k = 1$) and second ($k = 2$) passes. The deviation in measured photons ($\sigma_{j,k}$) is expressed in terms of photon counts generated by dark current noise N_0 and noise enhancement factor F_n [7]. Meanwhile, the deviation in ratios ($\sigma_{R,j}$) is decided by error propagations when taking ratios. Once T_e is determined, the spectral waveform of scattered light is fixed and then the degradation factor for each channel can be evaluated. In practice, $C_j n_e$ (calibration factor) is acquired because no density calibrations are considered. The unknown calibration factors can therefore be obtained by minimizing the following value:

$$\chi^2_R = \sum_j \sum_{k=1}^{2} \frac{(N_{m,j,k} - C_j n_e E_k g_j(T_e, \theta_k, \lambda_i))^2}{\sigma^2_{j,k}}. \quad (6)$$

The simulated annealing method [8, 9], which is effective for problems including many local minimum values, is suitable for this minimization with multiple variables ($C_j n_e$).

To demonstrate the validity of this method, i.e. its system and statistical errors, the parameters and specifications of a JT-60SA Thomson scattering system [10] for core measurement ($\theta = 140.2^\circ$) and transmissivity spectrum of optical fibers in JT-60U were used. The diagnostic laser was a YAG laser (3 J, typically) and the use of a five-channel polychromator with APD (Avalanche photo diode) detector was assumed. In this estimation, $n_e = 2.5 \times 10^{19}\,\mathrm{m}^{-3}$, $\Omega_s = 4\,\mathrm{msr}$, $\lambda_i = 1064\,\mathrm{nm}$, $L_s = 0.03\,\mathrm{m}$, $N_0 = 225$, $F_n = 3$ and $E_2 = 0.774E_1$ were used. Figure 2 (a) provides differential cross sections, i.e. scattered spectra at $T_e = 10\,\mathrm{keV}$, showing differences between the first and second pass; it also shows the filter configuration in the polychromator. The different waveforms suggest that accuracies strongly depend on T_e and θ. The transmissivity of the collection optics and quantum efficiency of APD in the polychromator are shown in Fig. 2 (b). While the transmissivity of a 100-meter fiber (non-irradiated) is provided by the black line in Fig. 2 (c), the red line represents irradiated fibers measured after 18 years of DD plasma operation in JT-60U. The absorbed doses of neutron and γ-ray were estimated to be 1.5×10^4 Gy (4.0×10^{18} n/m^2 in fluence) and 4.0×10^2 Gy, respectively, by three-dimensional neutronics calculation [11] at the port position where the

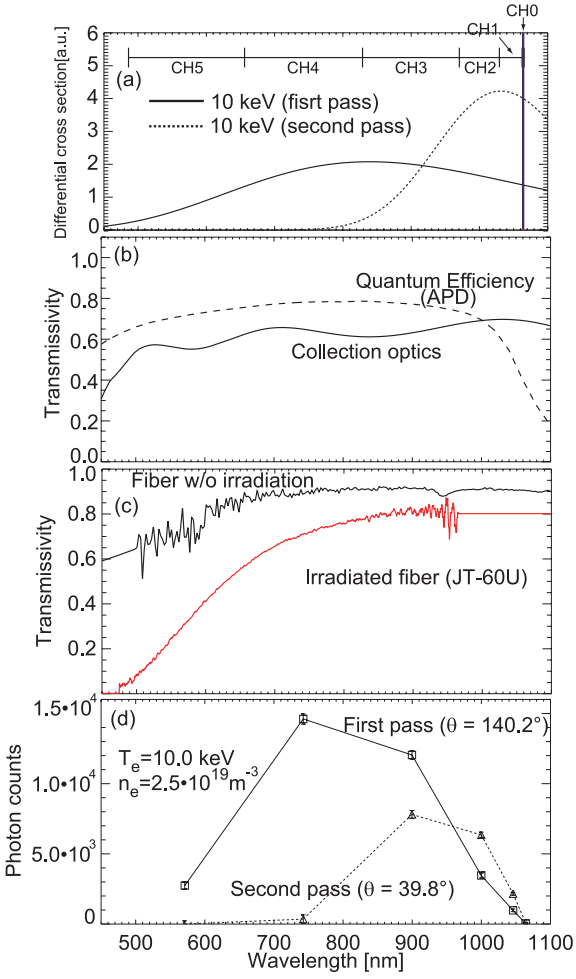

Fig. 2 (a) Differential cross section of Thomson scattered light at $T_e = 10\,\mathrm{keV}$ together with a configuration band-pass filters in polychromators. (b) Transmissivities of collection optics (solid line) and quantum efficiency of APD (broken line). (c) Transmissivities of fiber without irradiations and irradiated fiber in JT-60U. (d) Expected photon counts of each spectral channel at first and second pass.

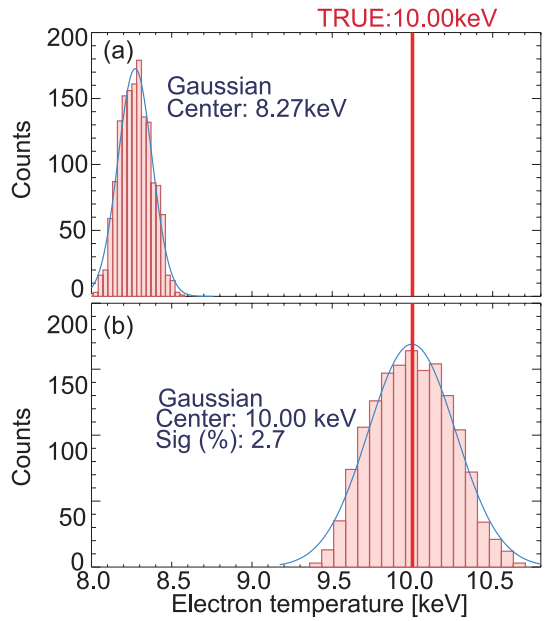

Fig. 3 Histogram densities of T_e (a) without calibration and (b) with calibration in using irradiation fiber of JT-60U.

collection optics and fibers were installed. When C_j is treated as unity for the non-irradiated fiber, the degradation factors can be expressed as $[C_0, C_1, C_2, C_3, C_4, C_5]$ = [0.884, 0.881, 0.879, 0.882, 0.780, 0.417] for the irradiated fiber. In this calculation, the transmissivity change in the fiber only was assumed, while changes in other optical components were ignored. The resultant measured photon numbers in Fig. 2 (d) for each pass provide a spectrum ratio without significant error, except for CH0 (1063.5-1065.5 nm) and CH5 (486.0-656 nm) due to insufficient photon numbers. For an evaluation of calibration accuracies, measured photon numbers, $N_{m,j,1}$ and $N_{m,j,2}$ in Eq. (3) were simulated by adding randomly changed photon numbers within the range of the deviation $\sigma_{j,k}$. Here, the same estimation of background light ($N_{b,j}$) as in [8] was used but parameters such as Z_{eff} (effective ionic charge) = 3.0 and Δt (data acquisition time) = 100 ns were also used in this calculation. The fitting was repeated many times (1,500) to determine the accuracy of the calibration. Figure 3 provides the effectiveness of the relative calibration method, with systematic and statistical errors evaluated by fitting to Gaussian waveforms. When T_e was determined without relative calibration (in other words, when $C_j = 1$ was assumed to calculate T_e), the resultant T_e tended to be 1.73 keV lower than the true value (10 keV) decided by the center of the fitted waveform. Contrastingly, the calibration produced almost the true T_e value within less than 0.01 keV (Fig. 3 (b)). However, the variances of the fitted waveforms treated as statistical errors became large ($\sigma \sim 2.7\%$). The main reason for this was that the number of data set to be fitted in the calibration became smaller than in the case of normal measurement. Other parameters ($C_j n_e$) were then acquired by minimizing of Eq. (6).

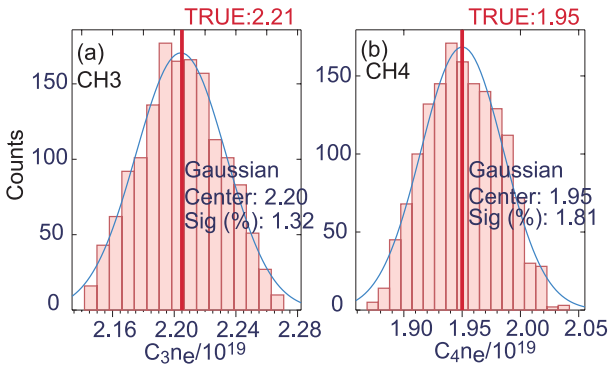

Fig. 4 Histogram densities of calibration factors for CH3 $C_3 n_e/10^{19}$ (a) and CH4 $C_4 n_e/10^{19}$ (b) in using irradiation fiber of JT-60U.

Figure 4 provides histogram densities for $C_3 n_e$ (CH3) and $C_4 n_e$ (CH4) as a typical result. No clear systematic errors were given (less than 1%) and their variances (statistical error) were less than 2%. For other channels, variances of 17.33% (CH0), 3.1% (CH1), 1.85% (CH2) and 7.67% (CH5) were found. The large statistical error in $C_0 n_e$(CH0) reflects small photon counts due to high T_e (=10 keV) and a narrow band-pass width (3 nm) on the wavelength space. This should be improved for low T_e measurement.

In conclusion, measuring two different scattered spectra in a double-pass scattering system make it possible to decide T_e without considering the degradation factor (relative transmissivity losses). $C_j n_e$ (calibration factor reflecting unknown relative transmissivity losses) can then be assigned using the spectrum at decided T_e without systematic errors. This therefore indicates that *in-situ* relative calibration is possible using this method. The feasibility of use in a JT-60SA Thomson scattering system was also discussed. It was found that this technique eliminates systematic error (−1.73 keV) in T_e due to transmissivity loss in fibers. The calibration factors ($C_j n_e$) do not have clear systematic errors and their statistical errors are less than 8%, with the exception of one spectral channel for Rayleigh calibration. In future, error dependencies on θ and T_e and comparison with another method in [4, 5] will be discussed.

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