An in-situ spectral calibration method of Thomson scattering diagnostics for severe radiation circumstances

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Data validations and analysis are essential for diagnostic developments

So far

Experimental data are correct with enough calibrations.

accessible!

In near future

Experimental data become incorrect.

inaccessible!

Use of some special techniques (data acquisition and/or analysis) enables validating data.

This talk focuses on a novel calibration method (data validation) for Thomson scattering diagnostics
Contents

- Thomson scattering diagnostic and significance of calibrations
- Techniques of calibration method
- Experimental demonstrations in TST-2 and LHD
- Expected performance for JT-60SA, ITER, and DEMO
- Summary
Measurements of board spectra are required in Thomson scattering (TS) diagnostic

- Thomson scattering system providing electron temperature ($T_e$) and density ($n_e$) profile

- Scattered spectra at various $T_e$

One of fundamental diagnostic for plasma control and study about plasma instabilities
Degradations in optical components have been reported in various tests and experiments

- Change in fiber transmissivity (neutron irradiation test)
  

- Change due to thin films on the vacuum window surface
  
  [H. Yoshida et al., RSI 68, 256 (1997)]

\[ T = T_0 \exp[-\alpha(\lambda)t] \]

Decay constant \( \alpha \)
Transmissivity losses cause underestimation in $T_e$

- Scattered spectra generated from YAG laser

Degraded spectrum at 6 keV is close to 5 keV

Unknown degraded transmissivity causes underestimations of $T_e$

Developments of calibration methods are necessary for such severe conditions
Contents

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To correct unexpected transmissivity loss, measurements using a standard light source is a good way

- Standard light source in the measured position generates known spectrum

![Diagram showing light source, polychromator, and transmittance calculation](image)

The known spectrum from wavelength channels are measured.

Output signals \[ V_1, V_2, V_3, \ldots, V_5 \]

**Polychromator**

\[
V_j = \int I(\lambda) \eta_j d\lambda
\]

Transmissivities

Adjustments of sensitivities between the wavelength channels are possible.

However, this method cannot be used under severe radiation condition, requiring some techniques.
Principle of a double-pass scattering system

- Measurement using a double-pass scattering system

- Two scattered spectra from the both scatterings

Scatterings must be measured separately.

Two spectra at the same $T_e$ can be evaluated.
Data analysis: Signal ratios provide correct $T_e$ without knowing transmissivities

- Measured photon counts at a spectral channel $j$

  Transmissivity (assumed as a constant) Laser energy

  $N_{m,j} = n_e \eta_j \Delta \lambda_j E L_s G(T_e, \theta, \lambda_i)$

  bandpass width scattering length

  Contribution from the spectrum

  Measured photon counts at a spectral channel $j$

  $\frac{N_{m,j}}{N_{m,j}}$ between $\theta = \theta_1$ (first pass) and $\theta = \theta_2$ (second pass),

  the ratio of $E L_s G(T_e, \theta, \lambda_i)$ remains.

  (No transmissivities !)

  Unknown parameters

  Measured ratio $\left( \frac{R_{m,j}}{R_{th,j}(T_e, \frac{E_2 L_s,2}{E_1 L_s,1})} \right)^2$ to be minimized

  $\chi^2 = \sum_j \frac{\left( R_{m,j} - R_{th,j}(T_e, \frac{E_2 L_s,2}{E_1 L_s,1}) \right)^2}{\sigma_{R,j}^2}$

  $T_e$ and $\frac{E_2 L_s,2}{E_1 L_s,1}$ are obtained without calibrations.
Data analysis: Relative transmissivities can be derived using the obtained $T_e$

- Chi-squared to infer relative transmissivities ($n_e \eta_j \Delta \lambda_j$)

$$
\chi^2_j = \sum_k \left( \frac{N_{m,j,k} - n_e \eta_{c,j} \Delta \lambda_j E_k L_{s,k} G(\theta_k, T_e, c)}{\sigma_{j,k}^2} \right)^2
$$

$k=1$ (first scattering)  
2 (second scattering)

Photon counts from a single pass showing relative transmissivity between the wavelength channels ($j=1,2,3...$)

$C_j$ can be written by a simple expression:

$$
C_j = \frac{\sigma^2 N_{m,j,1} G'_{j,1}(T_e) + \sigma^2 N_{m,j,2} G'_{j,2}(T_e)}{\sigma^2 G'_{j,1}(T_e)^2 + \sigma^2 G'_{j,2}(T_e)^2}.
$$

$G'_{j,k} \equiv E_k L_{s,k} G(T_e, \theta_k, \lambda_i)$
Previous work: Multiple laser method provides $T_e$ without knowing transmissivities

- **Measurement using two lasers**
  
  [O.R.P. Smith et al., RSI 68, 725 (1996).]

  Scattered light must be separately measured.

- **Two scattered spectra from YAG and RUBY**

  $T_e = 5$ keV, $\theta = 140^\circ$

  Two spectra at the same $T_e$ can be measured.
The double-pass scattering system provide overlapped spectra at any $T_e$

- **Double pass scattering**
- **Multiple (two) lasers**

Two spectra can be overlapped at any $T_e$

Two spectra are far from each other.
$\Rightarrow T_e$ range is limited.
Thomson scattering diagnostic and significance of calibrations

Techniques of calibration method

Experimental demonstrations in TST-2 and LHD

Expected performance for JT-60SA, ITER, and DEMO

Summary
TST-2 and Thomson scattering system

<Typical plasma parameters>
R (major radius): < 0.38 m, a (minor radius): 0.25 m, B_t (toroidal field) < 0.2 T,

- Plasma current: \( I_p \sim 100 \text{ kA} \)
- Discharge duration: \( \Delta t \sim 40 \text{ ms} \)
- \( n_e \sim 10^{19} \text{ m}^{-3} \)
- \( T_e < 400 \text{ eV} \)

Laser system: YAG laser, 1064 nm, 1.6J
Spectrometer: polychromator with 6 wavelength channels
Measured signal ratio provides correct $T_e$

- Signal ratio between the two passes

### SN89151, $R = 389$ mm

**Graph:**
- **X-axis:** Wavelength [nm] from 960 to 1060
- **Y-axis:** Ratio of integrated signals
- **Inset:** CH5, signal

**Data:**
- **CH1, CH2, CH3, CH4, CH5, CH6**
- **Fitted line:** $T_{e,c} = 196 \pm 16$ eV
- **CH4 and CH5 dominate $T_e$ determination**

**Table:**
- **Conventional method**
  - $T_e = 205 \pm 13$ eV

The fundamental principle of this method was demonstrated.
LHD experiments already developed a double-pass scattering system to measure high $T_e$ and anisotropy in $T_e$.

- Path length ~ 30 m
- Temporal delay ~ 100 ns

$T_e$ range < 2keV

Purpose of these experiments
Confirm the validity of this method for a higher $T_e$ range
Typical signals from the double-pass scatterings in LHD

- **Typical signals**
  - CH1 (1055.8 - 1060.1 nm)
  - CH3 (1046.5 - 1052.9 nm)
  - CH4 (1032.6 - 1045.8 nm)
  - CH5 (943.6 - 1010.3 nm)

- **Integrated area for $T_e$ calculations**

- **Measured ratios and fitting results**
  - $T_e = 746 \pm 0.061$ keV

No signal in the second pass (forward scattering) $\rightarrow$ not used
$T_e$ and the relative transmissivity measurements for a wide $T_e$ range have been demonstrated at LHD and TST-2

- $T_e$ measurements
- Relative transmissivity measurements (LHD)

Good agreements between the two method for a wide $T_e$ range (two orders)

Thomson scattering diagnostic and significance of calibrations

Techniques of calibration method

Experimental demonstrations in TST-2 and LHD

Expected performance for JT-60SA, ITER, and DEMO

Summary
JT-60SA utilizes super conducting toroidal / poloidal coils, new vacuum vessel and new cryostat.

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Plasma Current $I_p$</td>
<td>5.5MA</td>
</tr>
<tr>
<td>Toroidal Field $B_t$</td>
<td>2.25T</td>
</tr>
<tr>
<td>Major Radius $R_p$</td>
<td>2.97m</td>
</tr>
<tr>
<td>Minor Radius $a_p$</td>
<td>1.18m</td>
</tr>
<tr>
<td>Elongation $\kappa_x$</td>
<td>1.93</td>
</tr>
<tr>
<td>Triangularity $\delta_x$</td>
<td>0.5</td>
</tr>
<tr>
<td>Safety Factor $q_{95}$</td>
<td>3</td>
</tr>
<tr>
<td>Plasma Volume $V_p$</td>
<td>133m³</td>
</tr>
<tr>
<td>Flat Top</td>
<td>100 s</td>
</tr>
</tbody>
</table>

Total heating power (NB+ECH): 41MW
The double-pass scattering diagnostic will be utilized in JT-60SA.

Spatial channel at the core ($\theta = 125^\circ$) was used to evaluate accuracy.
Systematic errors in $T_e$ can be negligible with this new method.

- **Assumption:** unknown degradation occurs

- **Procedure to evaluate calibration accuracy**

  \[
  N_{m,1} = N_{s,1} + \text{Random No. } (-\sigma_{j,k} - +\sigma_{j,k})
  \]

  \[
  N_{m,2} = N_{s,2} + \text{Random No. } (-\sigma_{j,k} - +\sigma_{j,k})
  \]

  Calculation of $T_e$ and $C_j$ for 1000 times

- **Histograms of calculated**

  [Graph showing histograms for Conventional method and Double-pass (Signal ratio)]

  Data validity is confirmed.
Relative transmissivity losses can be determined with enough accuracy.

- Distribution of relative transmissivity

In JT-60SA, we are now planning to use this method for not only correct $T_e$ determination but also monitoring transmissivity change.

![Graph showing relative error in $C_4/10^{19}$ with wavelength channels 500–660 nm and 1062.5–1065.5 nm.](image)
Use of one port is a realistic design of Thomson scattering diagnostics in ITER and DEMO

- Geometry of TS system using one port

![Diagram showing TS system with one port, wide scattering angle, high $T_e$ plasma, measured point, laser, and collection optics.]

Reflection mirror is necessary but need various analysis. (EMF, heat load, and oscillations)

Calibrations using a double-pass scattering system in such wide scattering angle and high $T_e$ have not been considered.
Optimization of wavelength channels are essential to measure both spectra.

- **Scattered spectra at wide scattering angle** ($\theta_1 = 160°$ and $\theta_2 = 40°$)

  - Configuration of wavelength channels must be carefully selected.

- **Accuracy evaluations are performed by the following two steps**
  1. Optimize wavelength channels considering both scatterings
     - The number of wavelength channels
     - Measured wavelength range
     to find the best configuration for good accuracy
  2. Estimate $T_e$ and $C_j$ accuracies using the optimized conditions
Calibration methods of ITER Thomson scattering system and parameters used in this study

● Core measurements

θ < 160°
< 40 keV

Scattering angle

T_e range

Two or three lasers

Calibration method


T_e cannot be evaluated in some T_e range (2 lasers)

Accuracy

Low T_e cannot be evaluated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering length (L_s)</td>
<td>63 mm</td>
</tr>
<tr>
<td>Scattering angle (θ)</td>
<td>160°</td>
</tr>
<tr>
<td>Solid angle (Ω_s)</td>
<td>2.72 msr</td>
</tr>
<tr>
<td>Transmissivity except for polychromator (T_opt)</td>
<td>35%</td>
</tr>
<tr>
<td>Target normalized radius ((R-R_0)/a)</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

In this study, parameters for the core measurements are used to evaluate accuracies.
Use of border enable finding good segments of wavelength channels

Locations of the wavelength channels

# of channels ($N_{ch}$): 5

Error calculation

$$Err. (\lambda_1, \lambda_2, \lambda_3) = \langle \frac{\sigma_{Te}}{T_e} \rangle$$

The minimizations were performed by the simulated annealing method [2].


Optimized wavelength channels provide good accuracy (<10%) for $T_e = 0.5 – 40$ keV, same level as three laser method.

- Scan over the No. of wavelength channels
  - Average relative error
    - $\theta = 160^\circ$
    - Minimum error at $N_{ch} = 7$
    - No clear change for $N_{ch} > 5$ is attributed to internal transmissivity losses in polychromators

- Averaged relative errors in $T_e$ at $N_{ch} = 7$
  - $[\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5] = [921, 995, 1034, 1049, 1057 \text{ nm}]$
  - $\left\langle \frac{\sigma_{T_e}}{T_e} \right\rangle = 5.3\%$

- ITER core TS
  - Two lasers
  - Three lasers
Relative transmissivities (calibration factors) can be measured

- C_j with expected error bars at T_e = 1 keV

- Relative errors of C_j at T_e = 0.1, 1, 40 keV

All wavelength channels can be measured in T_e = 1 keV measurements. → possible to monitor degradation even during experiments.
Contents

- Thomson scattering diagnostic and significance of calibrations
- Techniques to overcome radiation conditions
- Experimental demonstrations in TST-2 and LHD
- Applicability in JT-60SA
- Expected performance for ITER and DEMO
- Summary
Summary

- An in-situ calibration method using a double-pass scattering system has been developed as a data validation technique.
  - Measurements of two overlapped spectra enable providing $T_e$ without knowing the transmissivities.

- $T_e$ and relative transmissivities have been successfully measured in TST-2 and LHD (0.1 – 2 keV).

- JT-60SA will utilize a double-pass scattering system
  - The data validation is confirmed by numerical analysis showing the method suppresses a systematic error in $T_e$.

- This method can be used in new type of Thomson scattering diagnostic with a wide scattering angle and high $T_e$.
  - Wavelength channels considering the forward and backward scattering are optimized to provide high accuracy in $T_e$.
  - Good accuracies (<10%) for a wide $T_e$ range are expected.