An optical design and accuracy estimation for a JT-60SA edge Thomson scattering diagnostic

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Thomson scattering diagnostic in JT-60SA

Equatorial plane of JT-60SA

- port-P5 collection optics (high field side, edge)
- port-P2 collection optics (core) [H. Tojo et al., RSI 84 093506 (2013).]
- port-P1 collection optics (low field side, edge) → focused in this paper

<table>
<thead>
<tr>
<th>Target spec.</th>
<th>core</th>
<th>edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial spatial resolution</td>
<td>2 – 3 cm</td>
<td>~ 1 cm</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>0.1 – 30 keV</td>
<td>0.01 – 10 keV</td>
</tr>
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</table>
Issues of the TS system in JT-60SA

▷ Upgrade from a preliminary collection optics design (P1) is an essential task.
   Interference with port plug and fabrication difficulties of large lenses

▷ Laser polarization angle should be optimized.
   Intensity loss due to the double locations of P1(edge) and P2 (core) collection optics
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Preliminary design of edge collection optics

H. Tojo et al., RSI 81 10D539 (2010).

Used glass materials: silica, BK7, fluorite, and F2

Long distance between the entrance pupil and the first lens

Expansion of the light flux

Lens size must be large.

Fabrications of such large lenses (Fluorite and F2) are difficult; thus, an alternative design is needed.
Use of long air space in Petzval lens for flat mirrors enables installing new optical system

- **Petzval lens**
  (Original, four lenses)

- **New design**
  - Small lenses due to the STOP position
  - Flat mirrors can be used to move the second lens group

- **Side view (P1 port plug)**
  - All optical components can be installed in the slender port plug.
  - All lenses are small (D < 200 mm)
  - A pair of lenses, BK7 and F2, decreases the image size. (brighter system)
  - S-FPL51 suppresses chromatic aberration.
Total optical throughput is sustained even with small lenses and enough resolution.

**Encircled energy on fiber**

- (A): $R = 4.17$ m
- (B): $R = 4.05$ m
- (C): $R = 3.93$ m
- (D): $R = 3.82$ m
- (E): $R = 3.70$ m

Resolution on image $< 0.2$ mm

Blur on the laser $< 1.3$ mm

Radial spatial resolution $< 11$ mm

(Scattering length $\sim 10$ mm)

**Normalized optical throughput**

- Peripheral (high field)
- Preliminary design
- Optical axis
- Peripheral (low field)

This optical throughput consists of transmissivity, solid angle, and vignetting factor.
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- Laser polarization angle should be optimized.
  Intensity loss due to the double locations of P1(edge) and P2 (core) collection optics
Laser polarization angle is sensitive to measured intensity, requiring its optimization for the two collection optics.

- **Intensity profile when polarization angle (incident electric field) is vertical**
  - low intensity for P1 collection optics in this case
  - The angle should be optimized for enough accuracy in $T_e$ and $n_e$

- **Conventional scattered spectrum with fully relativistic condition**

\[
\frac{d^2P_p}{d\Omega_s d\omega_s} = r_e^2 \int \langle S_i \rangle d\vec{r} \int \left[ 1 - \frac{(1 - \vec{e}_s \cdot \vec{e}_i) \beta_i^2}{(1 - \beta_i)(1 - \beta_s)} \right]^2 \left[ \frac{1 - \beta_i}{1 - \beta_s} \right]^2 (1 - \beta^2) f(\beta) \delta(\vec{k} \cdot \vec{v} - \omega) d\vec{v}
\]

This formula assumes the incident electric field is perpendicular to the scattering plane.

More generalized expression should be used for various polarization angles.
More generalized expressions provide spectrum for various polarization angles

\[ \frac{d^2P}{d\Omega_s d\omega_s} = r_e^2 \int \langle S_i \rangle d\vec{r} \left( 1 + \frac{2\omega}{\omega_i} \right) \left| \vec{e}_s \times (\vec{e}_s \times \vec{E}) \right|^2 \exp \left[ -\left( \frac{\omega}{k\alpha} \right)^2 \right] \frac{1}{\sqrt{\pi k\alpha}} \]

polarization factor without relativistic effect = \(1 - \cos^2\theta \sin^2\phi\)

- Generalized expression (full relativistic) used for various polarization angles (\(\phi\))

\[ \frac{d^2P}{d\Omega_s d\omega_s} = r_e^2 \int \langle S_i \rangle d\vec{r} \int \left| \Pi \cdot \vec{E} \right|^2 \kappa^2 f \delta(\vec{k} \cdot \vec{v} - \omega) d\vec{v} \]

\(\Pi\): Polarization tensor

\[ \Pi \cdot \vec{E} = \left( \frac{1 - \beta^2}{\kappa^3} \right) \cdot \vec{e}_s \times \left\{ [\vec{e}_s - \vec{\beta}] \times [\vec{e}_E - (\vec{\beta} \cdot \vec{E})\vec{\beta} + (\vec{\beta} \cdot \vec{E})\vec{e}_1 - (\vec{\beta} \cdot \vec{e}_1)\vec{e}_E] \right\} \]

\(\kappa = |1 - \beta_s|\)

Both two spectra are compared to find the limit of approximated expression.
The fully relativistic expression avoids wrong measurements in high $T_e$ spectrum

- Comparison of the scattered spectrum between the full relativistic and approximated expressions

- Ratio of the two spectra
  - no clear difference in low $T_e$ (< 2keV)

For $T_e > 2$keV, the full relativistic expression was used for evaluating accuracies.
$T_e$ and $n_e$ accuracies in an assumed profiles of JT-60SA

- Assumed profiles of $T_e$ and $n_e$
  - ACCOME output (Lower single null, 5.5 MA)

- Relative errors in $T_e$ and $n_e$
  - Testing three polarization angles
  - Assumed back ground light causes significant degradation
    R~3.7 m in P2
Relative errors averaged over the ten spatial points show $\phi \sim 50^\circ$ is the best angle.

- Relative error in $T_e$ and $n_e$, averaged over the ten spatial points
  - $\phi_{P2} \sim 50^\circ$ shows the minimum errors (\sim6\%) for both $T_e$ and $n_e$.
Conclusion and future work

➢ Design of collection optics was upgraded.
   – Modified Petzval lens avoided interference with the port plug.
   – Small lenses (< 200 mm in diameter) were used to avoid difficulties in fabrications.
   – The number of lenses is reduced from the preliminary design.
     • (8 lens → 6 lens)

➢ Optimized laser polarization angle was found.
   – Fully relativistic spectrum for high $T_e$ measurements were evaluated.
   – Accuracy estimation provided an optimized polarization angle (50° away from the best for P2 collection optics) under a profile model in JT-60SA.
   – The optimized procedure can be used for various operations in experiments.

➢ Future work
   – Tolerance analysis and mechanical design of holders (lens and mirror) for the P1 collection optics
Good spatial resolution (~10 mm) over the wide wavelength range can be achieved with the modified Petzval lens.

Spot diagram on fiber for five representative spatial channels:

- (A): R = 4.17 m
- (B): R = 4.05 m
- (C): R = 3.93 m
- (D): R = 3.82 m
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Encircled energy on fiber:

Resolution on image < 0.2 mm

Blur on the laser < 1.3 mm

Radial spatial resolution < 11 mm (Scattering length ~ 10 mm)
Estimation of radial spatial resolution

(a)

ideal fiber image

scattering length ($L_s$)

YAG laser

Scale of blur ($L_b$)

blur

$\Delta R (R) = g \cdot (L_s + 2L_b) < 11 \text{mm}$

$L_s$: scattering length
$g$: transfer function from the length along the laser direction to along the radial direction

$\Delta R < 11 \text{mm}$

Scale of blur ($L_b$)

(magnification factor)

$L_b < 0.2/M$

$= 0.2/0.152$

$= 1.3 \text{ mm}$
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▷ Laser polarization angle should be optimized.
  An intensity loss due to the double locations of P1(edge) and P2 (core) collection optics

Low intensity for P1 collection optics in this case