Progress in Development of the ITER Edge Thomson Scattering System

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*The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*
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Requirements for ITER edge plasma diagnostics

Steep $T_e$ and $n_e$ gradients are expected at the edge.

<table>
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<tr>
<th>Parameter</th>
<th>Area</th>
<th>Range</th>
<th>Resolution</th>
<th>Accuracy</th>
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<tr>
<td>$T_e$</td>
<td>$r/a &gt; 0.85$</td>
<td>0.05-10 keV</td>
<td>Spatial: 5 mm (0.25% of $a$)</td>
<td>10 %</td>
</tr>
<tr>
<td>$n_e$</td>
<td>$r/a &gt; 0.85$</td>
<td>$5 \times 10^{18}$ – $3 \times 10^{20}$ m$^{-3}$</td>
<td>Temporal: 10 ms (100 Hz)</td>
<td>5 %</td>
</tr>
</tbody>
</table>
Outline of ITER ETS

*Yatsuka, RSI, to be published (2013).

**Hatae, RSI, 83, 10E344 (2012).
Due to the harsh radiation environment, the ITER ETS must have complicated geometry, and balance of specifications is crucial.

Objectives and solutions of collection optics design

1. Neutron shielding
2. High signal intensity
3. Reliability against harsh radiation environment, thermal and electromagnetic loads
4. Fine spatial resolution (evaluated as the next topics)
   A) Backscattering configuration → Scattering angle close to 90 deg.
   B) Aberrations of collection optics → Small angle of incidence to concave mirror

Neutron flux (Suarez, ITER_D_DXM45Z)
Two factors for degrading the spatial resolution were evaluated.

1. Backscattering ($\theta > 90$ deg.)

- Laser beam
- Scattering length $L$
- Diameter $D \approx 3.2$ mm ($1/e^2$)
- Scattering angle $\theta$
- Viewing chord

Degradation by backscattering is up to 10% in the ETS.

2. Aberrations

Spot diagram from the laser beam to fiber end plate

- Wavelengths: 550 nm, 650 nm, 750 nm, 850 nm, 950 nm, 1050 nm
- Typical values:
  - RMS spot diameter: 0.72 mm
  - Magnification from the laser beam to the fiber: 0.3

Degradation of spatial resolution by aberration: $\Delta L_{opt} = 0.72/0.3 = 2.4$ mm
Spatial resolution of 5 mm is achievable for the ETS including geometric and optical degradations.

Effective spatial resolution \( \sqrt{L_{geo}^2 + \Delta L_{opt}^2} \)

- Instrument function due to backscattering \( L_{geo} \)
  - Dominant factor: Aberrations
  - Impact of backscattering is relatively minor.

ETS can measure edge \( T_e \) and \( n_e \) profiles with the spatial resolution of \(~5\) mm and the scattering length of \(~4\) mm in ITER.
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   B) Accuracy
      I. Gate duration
      II. Fast sampling

3. Summary
Intense background light increases statistical error.

- Bremsstrahlung emission from divertor plasma strays into collection optics via diffusive reflection on the Be first wall.

\[ \text{1 keV, } 1 \times 10^{19} \, \text{m}^{-3}, 800-960 \, \text{nm} \]

\[ \theta=120 \, \text{deg.}, 1 \, \text{keV} \]

\[ \text{Spectral Density} \]

\[ \text{Wavelength [nm]} \]

Background level

\[ \text{Signal level (peak)} \]

Background light drastically degrades S/N.

Candidate methods to improve S/N

1. Reduce laser pulse duration with same pulse energy
2. Increase number of data points by fast sampling
Laser pulse duration is one of the most important specifications.

Gate for subtracting background light

- $T_e$ and $n_e$ measurements were simulated by a code that produces APD current data with error for every spectral channels.

Statistical error reduces dramatically with decreasing the laser pulse duration.

Limitations

- To be consistent with optical design (detector size), the laser pulse duration (FWHM) should be longer than approximately 2 ns.
- To avoid the beam damp damage, long laser pulse duration is desirable.
Fast sampling improves statistical error but

- $T_e$ and $n_e$ measurements were simulated by a code.
- Waveform of several temporal points is directly used (not integrated with respect to time).

- Statistical error is slightly reduced by fast sampling because the weight of data point can be taken into account.

Errors at 1 keV

**Error [%]**

- Te, Integration
- Te, 1.25 GS/s
- Te, 2.5 GS/s
- ne, Integration
- ne, 1.25 GS/s
- ne, 2.5 GS/s
Summary

- ETS is being designed for edge plasma diagnostics in ITER.
- Spatial resolution and accuracy are crucial specifications.

- Designed collection optics supports optical performances and compatibility in ITER environments at the same time.
  - 
    - Large solid angle of collecting with neutron shielding
    - Withstand harsh environments (neutron/gamma flux, thermal and electromagnetic loads) in the port plug
    - Spatial resolution of 5 mm to investigate the edge pedestal

- Intense background light from divertor plasma increases error in measurements while ETS does not directly view the divertor.
  - Laser pulse duration should be short (\(~4\) ns FWHM) to improve S/N
Backup Slides
Measurement using Upper Port is available for only $r/a > 0.9$

- 20 mm along laser is equivalent with 5 mm across midplane.

*[Kajita, FED]*
From VV to port-cell
Degradation due to roughness

Roughness and reflectivity

$R_0$ and $d/\lambda$ are key parameters of reflectivity.

$$R = R_0 \exp\left[-\frac{(4\pi d)^2}{\lambda^2}\right]$$

$R_0$: Reflectivity of the ideally smooth surface
$d$: average roughness
$\lambda$: wavelength

$d/\lambda=0.025$ -> 10% reflectivity degradation
$d/\lambda=0.038$ -> 20% reflectivity degradation

Main causes of reflectivity degradation

Ion bombardment causes erosion -> Increase roughness
Deposition of particles (Be, Diverter material, SS) -> Increase roughness, Change surface material
Transmutation (e.g. Ag to Cd) -> Change surface material (and roughness?)
Degradation due to neutron/gamma irradiation

Spectral channel

- Wavelength of YAG laser:
  - 50 eV
  - 2 keV
  - 10 keV

Graphs showing
- Throughput vs. Wavelength [nm]
- Photoelectrons vs. Electron temperature [keV]
Details of geometric degradation of spatial resolution

![Graph showing the relationship between scattering angle, beam diameter, and scattering length.](image-url)
Performance of collection optics

Fiber endplate

Interspace-side (7x12 fibers)

Polychromator-side

2.5 mm

1.24 mm

2.2 mm

Laser propagation

Solid angle of collection [msr]
Scattering angle [degrees]

Major radius [m]
Details of aberration

Coverage area

Entrance pupil

Vac. windows

Image

M1

M2

M3

M4

M5

M6

M7

M8

M9

L1

L2

L3

L4

L5

L6

L7

L8

L9

Wavelength

- 550 nm
- 650 nm
- 750 nm
- 850 nm
- 950 nm
- 1050 nm

24 September 2013, LAPD16 O(16)
22/12
JADA XXXXXX / ITER_D_XXXXXX
Radiation resistant glasses

- Most of lenses are fused-silica.
- 2 lenses are LF5G15 (Cerium doped glass, $n=1.58$, $v_d=41$) to compensate chromatic aberration

* Schott catalogue
Prototype YAG laser

✓ Quick replacement
  ➢ Water is not filled in laser cavity
  ➢ Flashlamp assemblies are easily removed

✓ Rigid alignment
  ➢ Re-alignment is not necessary at flashlamp replacement
  ➢ SBS-PCM (Stimulated Brillouin Scattering Phase Conjugate Mirror) enables to keep parallel propagation of two beams
Beam dump design

- Laser injection
- Attenuated gently
- Absorbed effectively

Beam energy

New design

Existing beam dump

Absorptance vs. Incident Angle [degree]

- W, Ppol.
- Mo, Ppol.
- W, Spol.
- Mo, Spol.
Beam dump design

Beam dump is inclined to slot of blanket
9.6 kW/m²
Alignment of field of view by balancing signal intensity
<table>
<thead>
<tr>
<th>Method</th>
<th>Intensity or spectral</th>
<th>Configuration</th>
<th>Period</th>
<th>Issues</th>
</tr>
</thead>
</table>
| Rayleigh scattering           | Intensity             | Same as TS     | ~once/2y years   | • Filling neutral gas   
• Stray light                                                          |
| Raman scattering              | Intensity             | Same as TS     | ~once/2y years   | • Filling neutral gas   
• Depolarization at collection optics                                      |
| In-vessel light source        | Spectral              | Similar to TS  | ~once/2y years   | • Installing light source in vacuum vessel (Remote handling)          |
| Reflector on shutter rear-plate| Both                  | Dedicated path | ~once/day        | • Degradation of reflectivity on shutter                                 |
| Dual laser                    | Spectral              | Same as TS     | During discharge | • Alignment of two beams   
• Course spectral resolution   
• Accuracy depends on $T_e$ and $n_e$ during calibration.               |
Minimize merit function with weight

\[ \chi^2 = \sum_{i=1,N} w_i [U_i - n_e F_i(T_e)]^2 \]

\[ n_e = \frac{\sum_i w_i F_i U_i}{\sum_i w_i F_i^2} \]

\[ U_i = \sum_{j=1,M} S_{i,j} \]

\[ S_{i,j} = I_{TS}(t_j) M \]

\[ w_i = \frac{1}{\sigma(U_i)^2} \]

Uncertainty of \( U_i \)

Details of APD noise was taken into account

\[ \sigma(U_i)^2 = \sum_j \left[ 2q(I_{TS} + I_{BG} + I_{dg})BM^2 F + \frac{4kTB}{R_L} \right] \]

Thomson scattering

Background

Dark current

\[ q: \text{elemental charge} \]

\[ B: \text{Band width} \]

\[ M: \text{Current magnification factor at APD} \]

\[ F: \text{Excess noise} \]

\[ kT: \text{Temperature} \]

\[ R_L: \text{Resistance of circuit} \]