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Thomson scattering diagnostics for ITER divertor

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Abstract. The ITER design has highlighted the fundamental need to monitor the machine operation in more detail. The mission of the Thomson scattering diagnostics in the ITER divertor research/operation is discussed with due attention paid to challenges and capabilities of the existing diagnostic design.

1. Introduction

Detailed measurements of electron parameters in ITER divertor will be an important part of the experimental programme. The measurements will be used in studies of the divertor ability to adequately control plasma position during disturbances with adequate screening of impurities released as a result of intense plasma-surface interaction. The Thomson scattering (TS) system for the ITER divertor [1] is well suited for this purpose. The diagnostic will provide the measurements in the outer divertor leg with the provisional target requirements according to Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range or coverage</th>
<th>Spatial resolution</th>
<th>Time resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>1 – 100 eV</td>
<td>5cm along leg</td>
<td>15 ms (60 Hz)</td>
</tr>
<tr>
<td>$n_e$</td>
<td>$10^{19}$ - $10^{21}$ m³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* the upper limit of measured electron temperature is discussed in [2]

Table 1. Provisional target requirements for the TS diagnostics in the outer divertor leg

The difficulty for Thomson scattering in the divertor is associated generally with limited access to the plasma and with survivability of optical components that have to be placed close to this region. Here we review briefly the measurement requirements and the role of the divertor TS with special attention to challenges and capabilities of the approach, omitting the technological problems of the in-vessel diagnostics design as well as dedicated R&D on survivability of in-vessel diagnostic components.

2. Potential Role of Thomson Scattering System in ITER Divertor

Measurements of electron parameters in the divertor pursue two basic aims: monitoring inter-mode transitions (e.g., attached/detached conditions of the divertor plasma) and measuring the divertor impurity concentrations and flows. The requirements to the range and accuracy of the electron temperature and density measurements in the ITER divertor are based on the results of modeling of operational conditions and follow from the main objectives of the measurements. Simulated with the
SOLPS4.3 code [3], 2D distributions of electron temperature and density (see Figure 1) show the range of plasma parameters in the divertor region to be expected in different operational modes.

The operational range of the divertor corresponds to long time operation with a power loading on the divertor plates of 6.5 to 10 MW/m$^2$ (see Figure 1-b,c,d). The lowest load (Figure 1-e) corresponds to excessively high plasma density in the divertor region and then, deterioration of the main plasma confinement and potential discharge disruption can be expected. The highest load is beyond the design limits, and the operation mode shown in Figure 1-a can be allowed for several seconds only. Figure 2 shows the distribution of electron parameters along the given probing chord in the outer divertor leg. As seen from the SOLPS simulations, the expected range of the divertor plasma parameters varies strongly along the probing chord, especially near the ionization front, and is rather restricted in each spatial point under the inter-mode transitions. The maximum power flux on the divertor targets is to be controlled within 20% around 8 MW/m$^2$. The corresponding variation of the plasma parameters distribution along the probing chord can be used to diagnose a shift of the ionization front position. As shown in Figure 3, the most pronounced effect is expected in the downstream region of the outer leg. One can see that the parameter variations corresponding to a 10% change of the power loading of the target can be detected.

Figure 1. 2D distribution of electron temperature (left) and density (right) for discharges with loads on divertor plates: (a) 15 MW/m$^2$ (run 1537), (b) 10 MW/m$^2$ (1511), (c) 8 MW/m$^2$ (1514), (d) 6.5 MW/m$^2$ (1540), (e) 0.5 MW/m$^2$ (1538). Dots along the probing chord (arrow) mark the provisional spatial channels of the diagnostics.

Figure 2. $T_e$ and $n_e$ distribution along the probing chord of the TS system in the outer leg of the ITER divertor for three modes within the operational window. The central one is shown with red crosses, and the two others marked by blue and black lines are the limiting cases appropriate for the long time operation.

Figure 3. Variation of $T_e$ and $n_e$ along the probing chord. The bold blue line corresponds to deviation of the maximum power flux density on divertor plates from 8 to 10 MW/m$^2$ and the black one from 8 to 6.5 MW/m$^2$. The thin lines correspond to a 10% variation of the power loading. The red lines mark the expected limits of the measurement accuracy.
The information from the upper part of the leg cannot be used for the detection of the simulated transition (although it can help with interpretation of spectroscopic data). However, the position of ionization front characterized by strong gradients of $T_e$ and $n_e$ can move due to the expected delay of the plasma position control response to transients [4]. In addition, the planned divertor exchange strategy implies that operational experience gained on CFC targets will be required for tungsten. In the new divertor design the extended tungsten baffle will allow magnetic configurations in which the separatrix strike points are placed on the upper, tungsten part of the target. Therefore the uncertainty of the ionization front position and, hence, the position of the strong gradients of the electron temperature and density necessitates a uniform distribution of the spatial diagnostic channels along the probing chord.

3. The Challenge for the Thomson Scattering System in the ITER Divertor

Plasma characteristics vary strongly along the probing chord, where actually two areas can be identified (see Figure 2), each demanding a specific instrumental approach. The upper part of the probing chord has rather normal plasma parameters for an edge plasma in fusion experiments: $n_e \sim 10^{19} - 10^{20} \text{ m}^{-3}$ and $T_e \sim 20 - 50 \text{ eV}$ and the lower part is characterized by strong gradients of the electron parameters $n_e \sim 10^{19} - 10^{21} \text{ m}^{-3}$ and $T_e \sim 1 - 50 \text{ eV}$. The extra-low $T_e$ and resulting requirement to measure extra-narrow Thomson spectra will be aggravated by extremely high stray light expected just in the area due to possible dustiness and proximity to the walls. We suggest using different spectral equipment for these two parts of the probing chord. One of them, based on the filter spectrometers, is a conventional and reliable approach for modern Thomson diagnostics, and it is logical to use it for analysis of the upper part of the probing chord. A grating spectrometer with extremely high rejection of stray light and fine resolution is a good solution for the TS spectrum measurements in the bottom of the outer leg. Figure 4 shows the error calculations as a function of temperature for the expected experimental conditions with $n_e$ of $10^{19} \text{ m}^{-3}$. The working range of a grating spectrometer is from 1 eV to 100 eV, if an accuracy of better than 10% for $T_e$ and 5% for $n_e$ measurements is required. The low temperature limit of the filter spectrometer is several eV. The uncertainty of the ionization front position requires a flexible strategy for the spectral device distribution to keep the diagnostic operational during the temporal displacement (see above) of the ionization front. One of the solutions is to interleave the more reliable filter spectrometers with the more expensive but more powerful grating spectrometers in the upper part of the probing chord.

One of the most challenging requirements is the measurement of extremely low $T_e$ (~1eV range) near the ionization front. In the cool and dense plasma the laser wavelength approaches the Debye length and the deviation of the shape of the scattered spectra from Gaussian becomes very pronounced. The Salpeter parameter (defined as the inverse product of the change in the scattered wave vector times the plasma Debye length) shows the degree of collective behaviour in the scattering: higher values correspond to the collective scattering and lower to the individual particle scattering. Usually classical analysis of scattered spectra with assumption of Gaussian shape of the scattered spectra is considered valid when the Salpeter parameter does not exceed 0.25, whereas the expected maximum of the Salpeter parameter in the proposed TS geometry can reach 0.43 at the highest $n_e$ considered for the ITER divertor operation, Fig.5. The calculated spectra for the classic case (electron density $\sim 10^{19} \text{ m}^{-3}$) and for the maximal Salpeter parameter 0.43 (which can be expected under deterioration of plasma confinement) are shown in the Figure.6 along with transmission of the first spectral channels of
4. Conclusions

Measurements along the divertor leg can provide useful information to support the proper divertor operation. In particular, they can provide the data on the location of the ionization front for the interpretation of spectroscopic data and validation of models of divertor performance. Due to strong plasma non-uniformity near the ionization front and uncertainty of the ionization front position, a uniform spatial resolution is needed along the whole probing chord. Two different kinds of spectral instrumentation are suggested for assessment of the top and bottom parts of the probing chord to cope with the extreme conditions in the bottom part (measurements of extra-narrow Thomson spectra aggravated by expected intensive stray light). One of the most challenging requirements is diagnosing the cool, dense plasma near the ionization front, where the collective behavior in the scattering can be important. For the most problematic case of high density and extremely low temperature, it is shown that the expected distortion of Gauss-like Thomson spectra is not insurmountable and can be avoided by excluding the signal of the first spectral channel from consideration.

Acknowledgments

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References