Near-infrared plasma spectroscopy in support of divertor Thomson scattering diagnostics development for ITER

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Abstract. One of the main challenges of the implementation of divertor Thomson scattering system on ITER is weak laser scattering signal to be detected against intense background plasma radiation. The paper review briefly the line and continuum radiation data from present magnetic fusion devices in the spectral range of interest to TS diagnostics. The results will form the basis of design and development of the TS diagnostics for the ITER divertor.

1. Introduction

The operation of divertor Thomson scattering (TS) system on ITER will be under adverse conditions: the measurement will have to be made with the high radiation loads acted on optical elements which operates in a harsh environment and exposed to particles and dust. Additional challenges include a limited diagnostic access to the plasma and a weak laser scattering signal to be detected against intense background radiation. Here we review briefly the line and continuum radiation data from present magnetic fusion devices and calculation results of ITER divertor radiation in the spectral range of interest to TS diagnostics – the near infrared (NIR) region in the vicinity of 1000 nm. As it is seen from Figure 1 there are 21 viewing chords crossing the outer divertor leg and the divertor area under the dome.

A spectral survey of divertor plasma emission in the NIR range has been undertaken in the Globus-M Spherical Tokamak (St.Petersburg, RF), JET (Culham, UK) and NSTX (Princeton, USA) devices. The survey provided initial estimates of the impact of line and continuum emission on the ITER TS measurements accuracy. Based on the measurements it was possible to shape spectral characteristics of TS polychromator channels to minimize contributions from background plasma line radiation to the
TS signal. Based on estimates of the continuum and black body radiation intensities (from divertor plasma and divertor plates, respectively), the calculations of $T_e$ accuracy were performed. The results will form the basis of design and development of the TS diagnostics for the ITER divertor.

2. Continuum background radiation within TS spectra

The background radiation in spectral channels of divertor TS in ITER is the continuous plasma radiation, thermal radiation of viewing surfaces, line radiation and stray light from laser radiation scattered on the dust and close walls. The specially developed grating spectrometer based on principle of subtractive dispersion [1] should manage the problem of the expected high intensive stray light. The continuous radiation of divertor plasma has two inputs: blackbody radiation of heated walls that is substantially target plates / dome surfaces and the strong bremsstrahlung radiation ($\sim n_e^2$) of high dense plasma $n_e \sim 10^{20}-10^{21} m^{-3}$ of ITER divertor. The background radiation is temporally constant within laser pulse scale and will be measured before laser pulse and subtracted. Nevertheless, accuracy of the measurements will drop as square root from sum of TS and background signal. Both types of background radiation are important for 11 spatial channels under the dome due to: (1) the upper viewing covers the heated surface attackable by plasma flows and (2) observation chords penetrates over the more extended plasma regions. Moreover, here the detected TS spectrum (and background) is wider in accordance with the higher temperatures under the dome.

The most intensive black body radiation is expected for the upper chords viewing the dome surface, the estimated temperature here is 600 K (see Figure 2). As it is seen from Figure 3, the ratio of TS signal to surface radiation is $\sim 2$ for this temperature and is not crucial for noise consideration. The measurement limitations will arise at temperatures more than 1500 K. But care should be taken to the surface color temperature that can strongly differ from predicted bulk temperature. The matter is that carbon films on the divertor surface can have a rather high temperature [2]. Actually, JET experiments show the black body emission from the divertor with temperature reaching 2000 K [3]. It is worth to note that the detailed calculation of surface radiation intensity for ITER divertor plates is complicated now, but it is necessary to keep in mind the possible additional noise source.

The bremsstrahlung input estimation is carried out from calculated plasma parameters distribution along viewing chords. The distribution was extrapolated from 2D matrix of plasma parameters simulated with the SOLPS4.3 code [4] for the main operational mode with 5MW loading on divertor targets.

The bremsstrahlung input is mainly pronounced for six spatial channels on the top where the viewing chords directed under the dome and the path through divertor plasma is several times longer than for other chords (see Figure 2). As it is seen from comparison of TS signal and bremsstrahlung signal in spectral channels of grating spectrometer (see Figure 4), the estimated level of

![Figure 2. The temperature estimation along target plates.](image)

N corresponds to the squared points in Figure 1.

![Figure 3. Ratio of heated surface radiation to TS signal for different temperatures of the surface](image)

![Figure 4. Signals within 4-th channel – TS and bremsstrahlung for observation chords.](image)
bremsstrahlung can strongly exceed TS signal for the upper spatial points of probing chord and can markedly limit the diagnostics sensitivity.

3. Line emission within TS spectra

The ranges of measured electron parameters in ITER are determined by the technical requirements to ITER diagnostics [7]. One of the disputed electron parameters in ITER divertor is maximal $T_e$ which is declared in [7] as 200 eV. At the same time the upper limit of $T_e$ guaranteed by technical specification of divertor TS (see [6]) is 100 eV. The complexity of the TS measurements in the range from 100 eV to 200 eV is the strong line radiation in the range from 1004 nm to 1012 nm that interfere with TS spectra. The only neatly study of the spectral gap can help to fit the diagnostic specifications to the technical requirements. To calculate the intensity of plasma radiation within TS spectral range it was used the divertor plasma parameters simulated with the code SOLPS4.3 [5]. The intensity of hydrogen line emission and bremsstrahlung was calculated by the code CRETIN [4] along two observation chords directed under the dome and in the outer leg (see Figure 1). Results of these calculations are presented in Figure 5. As is seen, the line intensity strongly exceeds (up to ~2 orders in the line peak) the continuous radiation and the reduction of TS signal/noise ratio can be prohibitive. The use of filters blocking the spectral lines will limit the polychromator spectral range and as a result $T_e$ range. Therefore, the spectral shaping should be a compromise between a minimal line income and a maximal covering of TS spectra which means that the line broadening is one of the main critical points for TS spectrometer spectral channel shaping. The thorough simulation (see Figure 6) of the broadening of the P7 line integrated along two considered chords (see marked by blue chords in Figure 1) involves a number broadening mechanism - Zeeman splitting, ion static/dynamic and electron impact Stark broadening, Doppler broadening. It was shown, the basic mechanisms of the broadening are Zeeman splitting and ion static Stark broadening. As is seen from Figure 6 the resulting FWHM of the lines does not exceed 1 nm. But the acceptable radiation level for the most background lighted chords directed under the dome is one order more than bremsstrahlung level and corresponds to the line width of ~4 nm.

In support to the calculations the experimental study of the NIR plasma emission was performed in tokamaks NSTX, JET and Globus-M. The measurements were made in the divertor region where the thermal loading on the divertor targets are similar one to the ITER (~several MW/m²). The coincidence of absolute signals integrated along the viewing chords can be explained by equivalent properties of the SOL plasma that is conventionally the main source of radiation. In this case the results of the experiments can be extrapolated on ITER and can be considered as a starting point to estimate background condition in ITER divertor. As is seen from the spectra (Figure 7) the main obstacle lines are the lines of H/D from Pashen series and He-II superimposed.
with carbon line. The spectral intensities of the lines measured in the divertor of NSTX and Globus-M are nearly equal and two order more than expected intensity of bremsstrahlung in ITER divertor. The performed spectroscopic calculations and measurements help to shape the spectral characteristics of TS polychromators. The spectral channel of designed grating polychromator are presented in Figure 8. The first three narrow channels are intended to measure the low temperatures \( \geq 1 \text{eV} \). Next six channels serve temperature range up to 200 eV. The channel characteristics was optimized to provide the even \( T_e \) measurement accuracy within full range of TS temperature range [5]. At the same time according to previous consideration the He/C and broadened hydrogen lines became the limiting factor to measure temperatures \( \sim 200 \text{eV} \). To manage this complications the characteristic of 9-th channel is corrected by filter (Figure 7) notching the line emission.

4. Conclusions
The spectroscopic measurements and calculations were used as the basis for TS polychromator design to provide minimal income of plasma radiation into the TS measurements accuracy. The density and temperature ranges of TS diagnostics following from [4] are limited within \( n_e=10^{19}-10^{21} \text{m}^{-3} \) and \( T_e=1-200 \text{eV} \) under accuracy \( \leq 5 \% \) and \( \leq 10 \% \) respectively. The predicted accuracies of \( n_e \) and \( T_e \) along the probing chord (21 points) for Principal operation mode 8 MW/m\(^2\) (run #1514 [5]) are presented in Figure 9. The intensity of bremsstrahlung background light was taken multiplied by 10 that is conventional for TS accuracy simulation [DDD5.5]. As is seen from Figure 8 the needed accuracy of 5\% for density and 10\% for temperature does not exceeded in this simulation for the main ITER operation regime.

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