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Design of Thomson scattering diagnostics for the Divertor Tokamak Test (DTT) facility

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Abstract: In the Divertor Tokamak Test (DTT) facility two Thomson scattering (TS) systems are under design for the measurements of T_e and n_e in the core plasma region and in the divertor respectively. The divertor TS system under study is a conventional TS system based on a Nd:YAG laser source, a fiber optic based light collection system and a set of filter polychromators equipped with Si APD detectors. The laser beam and the collection optics share an aperture between adjacent cassettes of the lower divertor and the scattering signal is collected from a set of scattering volumes close to one of the divertor legs by a collection optics system located under the divertor dome and is carried to the polychromators by fiber optic bundles. The filter polychromators are designed to measure T_e as low as 1 eV. Measurements with a spatial resolution of 10 mm are possible, with accuracy limited by the plasma n_e and the background light. For the core TS system, two options are under consideration: a conventional system, similar to that designed for the ITER core TS, in which T_e and n_e are measured along a large fraction of a laser beam crossing the plasma near the equatorial plane and the detection system is again based on fiber optic coupled filter polychromators. The spatial resolution is 5 cm in the central region and 1 cm at the plasma edge. Alternatively a TS system based on the LIDAR concept, previously implemented in JET, is under consideration. Recent advancements in laser and detector technology allow achieving a spatial resolution similar to that of a conventional system, but with a simpler and reliable experimental set-up and possibly at a lower cost.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging; Nuclear instruments and methods for hot plasma diagnostics

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Contents

1 Introduction

The Divertor Tokamak Test (DTT) facility is a new fusion experiment presently in the advanced phase of design, that will be built and operated in Frascati, Italy [1, 2]. The purpose of DTT is to investigate various alternatives for power exhaust in a fusion experiment with plasma conditions sufficiently close to those foreseen for DEMO. This will include the study of alternative divertor magnetic configurations, such as the SFD (snowflake divertor), the XD (X divertor), the DN (double null divertor) and the SXD (super-X divertor) [2], and the use of liquid metal targets for critical plasma facing components. To carry out its scientific program, the DTT experiment will be equipped with full set of diagnostics, that include two Thomson scattering (TS) systems for the measurements of T_e and n_e profiles in the divertor and in the core plasma respectively [3]. In this paper we describe the preliminary design of these two systems, we discuss the solutions adopted for optimizing the access to the plasma, and the detection system, and present the results of a preliminary performance analysis. Figure 1 shows a picture of the DTT device and of a poloidal cross-section of the machine, showing the layout of the vacuum vessel and of the diagnostic ports. The system requirements we assumed in this design are a spatial resolution of 5 cm in the center of the plasma and 1 cm in the plasma edge and in the divertor, with a time resolution of 10 ms everywhere.

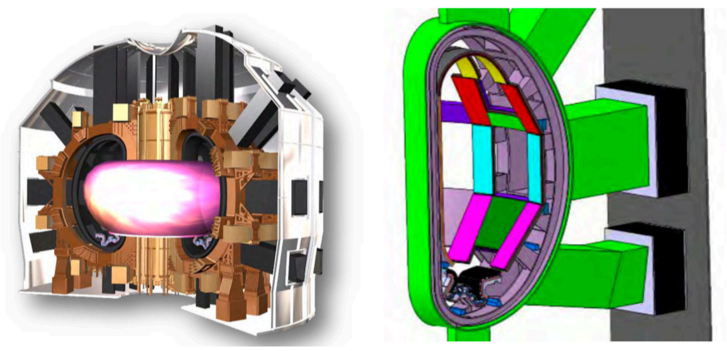

Figure 1. Left: a general view of the DTT device. Right: 20° sector of DTT, showing the vacuum vessel, the diagnostic ports and the first wall.

2 The DTT divertor Thomson scattering system.

Of the two TS systems of DTT, the divertor system is the one whose development poses higher challenges. This is due to several reasons: 1) the divertor region is considerably recessed with respect to the machine diagnostic ports and the physical constraints of the divertor mechanical components makes difficult to have an efficient optical access; 2) in the divertor region there is a considerable level of background light, due to the high level of plasma radiation (continuum and impurity lines) and also to blackbody radiation from heated divertor components; both produce a background light pedestal superimposed to TS signals whose fluctuations may considerably limit the accuracy of TS measurements; 3) as shown in other experiments, in some cases the T_e and n_e values in the divertor plasma are such that the conditions of incoherent TS are not fulfilled. This makes difficult both to reliably measure and interpret the TS spectra [4].

Thomson scattering measurements in the divertor plasma have been performed in various experiments [5–8] and others are in the advanced design or construction phase [9, 10]. From the analysis of these experiments and the analysis of the mechanical structure of the machine and its diagnostics accesses, we have chosen for the divertor TS system the layout shown in figure 2. The laser beam is inserted in the divertor region from below, through the bottom vertical port. It enters the plasma divertor region through a gap between two adjacent divertor cassettes and the same gap is also used by the collection optics. The laser beam is focused in a thin pencil whose path goes through the plasma close to the X point (for a standard single null configuration), following one of the two divertor legs. The laser beam hits the vacuum chamber sufficiently defocused that no beam dump is necessary to avoid wall damage. The scattering signal is collected from a scattering

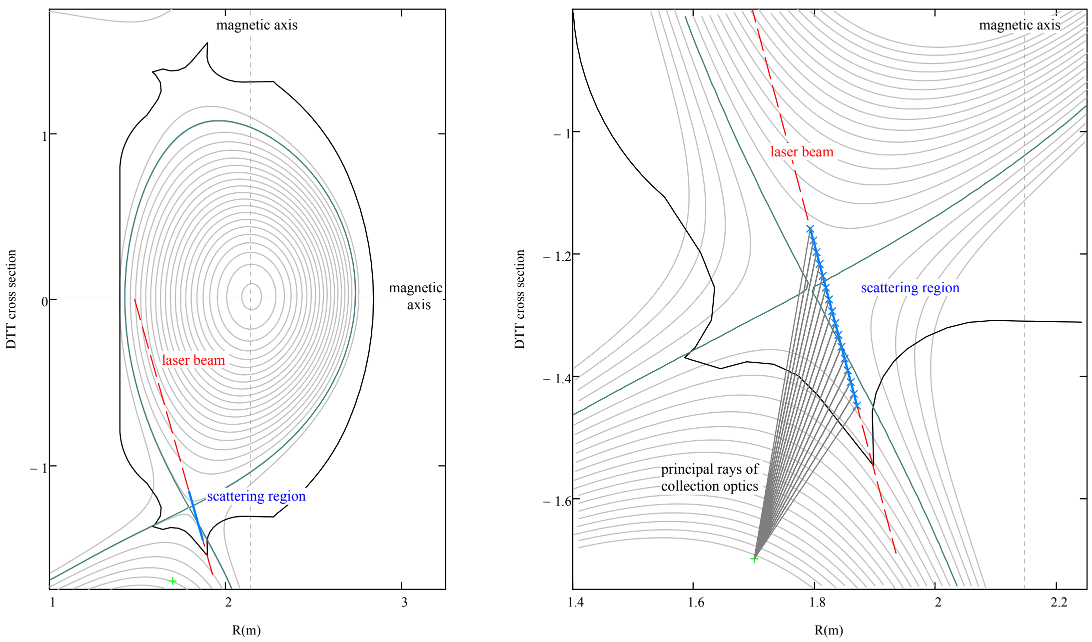

Figure 2. The laser path, the position of the measurement points and the principal rays of the collection optic lens system.

region of 30 cm of total length, extending into the plasma beyond the separatrix, by a collection optic system located under the divertor dome. In this way the heated surfaces of the divertor target tiles are out of the field of view.

The collection optics is constituted by a lens system located behind a vacuum window and the scattering region is observed through the gap between two adjacent dome tiles. The scattering region is imaged onto a set of fiber optic bundles that carry the light signal to a set of filter polychromators, where the TS spectrum is recorded and analyzed by using the well known scheme of a set of cascaded bandpass interference filters and Si APDs. The spatial resolution and the number of measurement points are determined by the configuration of the fiber optic bundles. Up to 30 measurement positions along the scattering region are possible, with a spatial resolution of 1 cm. Figure 3 shows the collection optics solid angle and the scattering angle for this arrangement, confirming that relatively high apertures (up to $F/8$) are feasible.

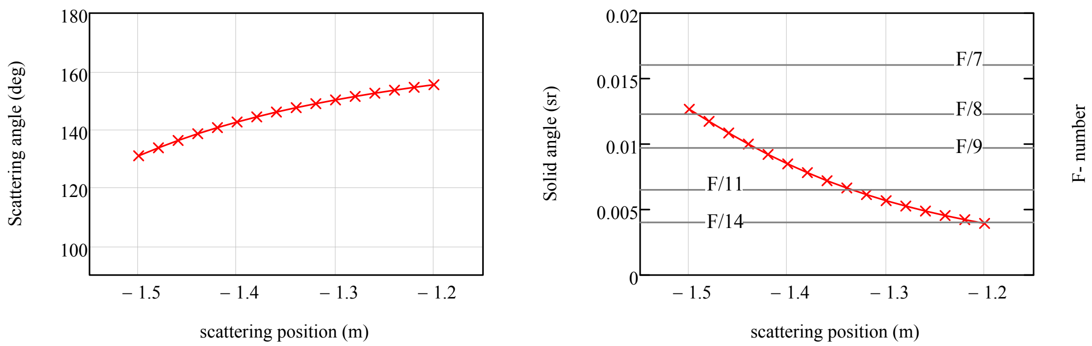

Figure 3. The scattering angle and the solid angle of the collection optics. The scattering position is the distance of each scattering volume from the impact point of the laser beam on the first wall.

The high level of plasma light background expected in the divertor region suggests the following design choices:

1. A Nd:YAG laser with a pulse energy $E \geq 3$ J, with 100 Hz repetition rate and pulse duration of $\sim$ 5 ns FWHM will be used. The short laser pulse will mitigate the effect of the background light allowing a short integration time.

2. The well known method of optically multiplexing the scattering signals by using fiber bundles of two or three different lengths, although very effective in reducing the number of polychromators and data acquisition modules, is not appropriate in this system because it multiplies by two or three times the background light seen by each spectral channels. For this reason it is desirable to use fiber bundles of the same length and as many polychromators as the measurement points.

The use of such a short laser pulse has an impact also on other aspects of the system. First it will restrict the choice of the APDs to those with a sufficiently fast response time.[1] In addition it may help to mitigate the measurement noise due to the laser stray light. In fact most of the stray

[1] A suitable APD for the TS divertor system is the Hamamatsu S11519-30 APD, with 3 mm diameter active area, 1.25 ns rise time and good sensitivity in the visible and near-infrared.

light will be generated by the impact of the laser beam with the first wall. However, the laser beam can be directed to impact on a point out of the direct view of the collection optics so that the laser stray light will be collected only via diffuse reflections from the first wall on the opposite side of the vacuum vessel. But in this way the distance travelled by the stray light from the laser impact point to the collection optics will be of the order of ~ 3 m, long enough to appear sufficiently separated in time from the scattering pulses in the APD output signals.

Finally the requirement of extending the measurable T_e range down to 1 eV is particularly challenging for the design of the polychromators, because it requires to include in the spectral channel set some filters with a transmission band as narrow as 1 nm or less [5]. Interference filters with a sufficiently narrow transmission band are commercially available [7], nevertheless larger transmission bands allow better performances in terms of in-band transmission and out-of-band reflection, together with a very high rejection ratio of the laser line near the transmission edge. Although we expect that a large part of the stray light generated in the system can be suppressed by exploiting its delay in the arrival time, we cannot exclude the presence of a residual stray light noise in the scattering pulses. For this reason a good rejection ratio of the laser line in the filter polychromators is mandatory for good stray light suppression. It has been demonstrated that about the same accuracy in low T_e measurements provided by a pair of very narrow filters can be obtained by using a pair of filters with larger transmission bands located on the two sides of the input laser line, and whose transmission edges are set at different distances from the laser line [7]. This solution is made possible by the fact that for low T_e, the TS spectrum covers a limited spectral region on the two sides of the laser line, where the quantum efficiency (QE) of the Si APDs does not change remarkably. In figure 4 we compare the performances of two different spectral channel sets, one that uses a conventional set of filters, with a very narrow one, only in the blue side of the laser line and the second that uses a set of larger filters on both sides of the laser line, implementing the above scheme.

These data are calculated assuming $n_e = 3 \times 10^{19}\,\mathrm{m}^{-3}$, input laser energy $E = 3$ J (in the plasma), scattering length $L = 1$ cm, collection optics solid angle $\Delta\Omega = 6.7 \times 10^{-3}$ sr $(F/10)$, scattering angle $\theta = 147°$, collection optics transmission $T = 0.3$ (from plasma to detectors), APD Hamamatsu S11519-30, excess noise factor $k = 3.6$ and no plasma light. The values of θ and $\Delta\Omega$ are those of the central point in the scattering region of figure 2. In figure 4 the spectral sensitivity in the two upper plots is the ratio between the number of photons scattered into the solid angle of the collection optics and the number of primary charges (photoelectrons) produced in each APD, before the avalanche amplification. Its spectral dependence is substantially determined by the wavelength dependence of the APD QE.

The lower plots shows that the scattering signals detected in each channel are considerably higher (and for this reason less noisy) for the channel set with large filters on both sides of the laser line. Nevertheless, their impact on the accuracy of T_e and n_e measurements is lower than for the conventional configuration with narrow filters on the blue side only. In fact the two effects compensate each other and eventually the accuracy of the T_e measurement is about the same.

In conclusion our calculations confirm that the proposed set-up provides sufficient scattering signals and T_e and n_e measurements with sufficient accuracy in the DTT divertor. However, ultimately the accuracy of the measurement will be dominated by the plasma light background that, so far, has not been taken into account. Simulations of the plasma radiation in the DTT divertor

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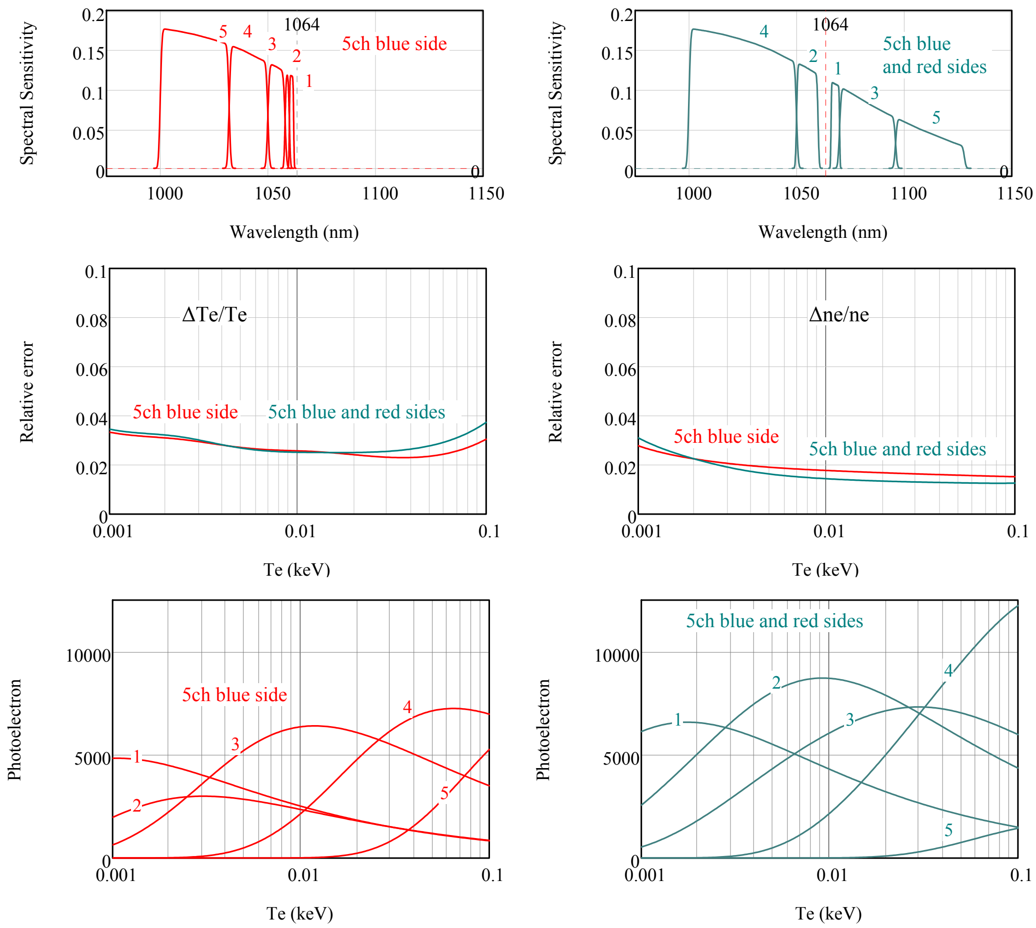

Figure 4. Upper: the two spectral configurations with filters on the blue and on both sides of the laser line; numbers indicate the spectral channels. Middle: expected relative errors on T_e and n_e as a function of T_e. Lower: the scattering signals in the 5 measurement channels (numbered) as a function of T_e.

region are under way and the performance of this system will be further investigated when these data will be available.

In our design we have assumed that TS in the divertor fulfils the conditions of incoherent TS, i.e. with $\alpha = (k\lambda_D)^{-1} \ll 1$ where α is the scattering parameter, k is the module of the scattering vector and $\lambda_D$is the Debye length of the plasma in the scattering volume [11]. The scattering parameter can be written as $\alpha = 1.5 \times 10^{-11} \lambda_i\,[\mu\mathrm{m}] \sqrt{n_e\,[\mathrm{m}^{-3}]\,/(T_e\,[\mathrm{eV}]\,(1-\cos\theta))}$ where λ_i is the incident laser wavelength and θ is the scattering angle. This expression indicates that in the divertor plasma there may be regions with low T_e and high n_e where the assumption of incoherent scattering is no longer valid. In this case the interpretation of the scattering spectrum in terms of T_e and n_e is more complicated [4]. This scattering regime is not considered here and the validity of the above condition should be verified as soon as detailed information on the expected values of T_e and n_e in the divertor region will be available.

Finally we point out that, given the high variety of the divertor magnetic configurations that will be studied in DTT, TS measurements along more than a single laser chord would be

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recommended [4]. To this purpose we observe that in the proposed set-up, the collection optic system can be built to occupy a long and narrow slice extending in the radial direction under the divertor. Therefore it seems possible to build a second independent collection optics system, side by side with the previous one, and observe a different laser chord slightly displaced in the toroidal direction, using the same aperture in the divertor dome.

3 The DTT core Thomson scattering system

A second TS system is under study for DTT whose main purpose is to measure the T_e and n_e profiles in the central region of the plasma and, as in many other fusion experiments, provide also the information necessary to resolve the edge pedestal. For this system we have again followed a conventional approach, as for the divertor TS system, and have chosen to use the equatorial diagnostic port both for the input laser and for the collection optics, in a set-up similar to that foreseen for the ITER core TS system [12]. This set-up provides good accessibility to the edge region, where the highest resolution is required and the plasma conditions make the measurement more critical. In our design, the laser beam path crosses the centre of the plasma with an inclination of $\sim 15°$ on the horizontal. Here, contrary to the divertor TS, the input laser beam must be kept focalised in very thin pencil across most of plasma diameter and therefore a beam dump will be necessary to avoid laser damage of the first wall and to reduce the laser stray light diffused in the vacuum vessel. The scattering signals from a $-0.4 \leq r/a \leq 0.95$ plasma region along the laser beam are collected by a lens system located in the same equatorial diagnostic port, in a backward-like geometry, similar to that of the divertor system. Figure 5 shows the scattering region along the laser beam, and the scattering and the solid angles provided by this set-up. The spatial resolution is defined by the geometry of the fiber optic bundles and has been chosen to be 5 cm in the central region and ~1 cm at the outer edge.

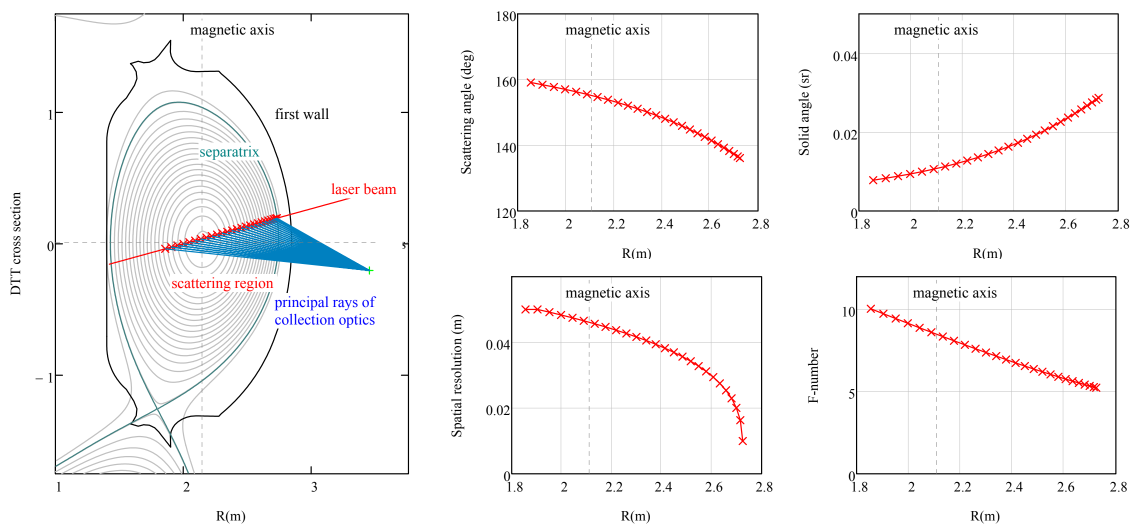

Figure 5. Layout of the core TS, showing the scattering position in the plasma along the laser beam, the solid angle, the scattering angle and the spatial resolution provided by this set-up.

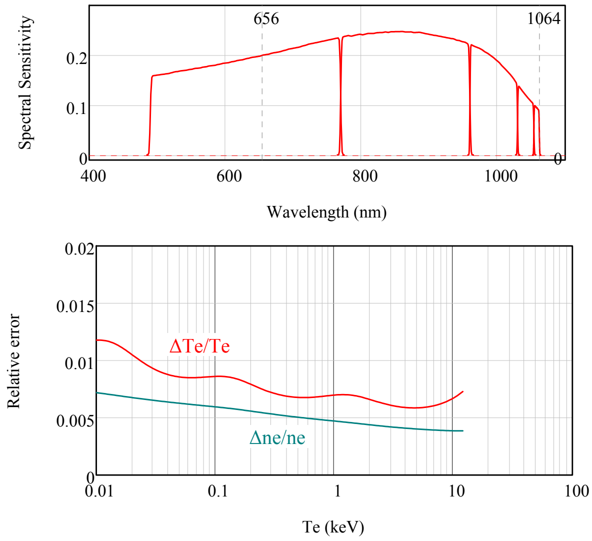

Figure 6. The expected performances with a set of 5 spectral channels. The error calculations correspond to TS measurements at $R = 2.25\,\mathrm{m}$. Laser energy $E = 3\,\mathrm{J}$, scattering angle $\theta = 151°$, scattering length $L = 4\,\mathrm{cm}$, solid angle $\Delta\Omega = 2.87 \times 10^{-2}\,\mathrm{sr}$, $n_e = 3 \times 10^{19}\,\mathrm{m}^{-3}$, transmission $T = 0.3$ (plasma to detectors), APD Excelitas C30956EH, excess noise factor $k = 4$ and no plasma light.

In figure 6 we show the spectral transmission functions provided by the filter set in the polychromator and the QE of the APDs. This has been designed for measurements in the range $10\,\mathrm{eV} \leq T_e \leq 12\,\mathrm{keV}$. Figure 6 shows also the expected measurement errors as a function of T_e for a measurement position in the center of the scattering region.

A more detailed analysis of the system performances has been carried out considering a specific T_e and n_e spatial profile, as expected in a single null, 5.5 MA, H-mode, plasma scenario [13], and taking into account the effect of the plasma light background noise. To this purpose a map of T_e and n_e in the entire plasma volume seen by the collection optics has been calculated from the 2D maps of the poloidal flux on the plasma cross section, available from equilibrium codes in the G EQDSK format and from 1D-profiles of T_e, n_e and Z_{eff} as a function of the normalized toroidal flux, from the magnetic axis to the plasma boundary, available from transport codes.

To calculate the plasma light background we followed the same method as used for ITER [14]. First we have generated 2D T_e and n_e maps in the plasma poloidal cross section, associating to each (R, Z) point of the flux computational grid the T_e and n_e values determined by interpolating the 1D T_e and n_e profiles in correspondence of the local value of the poloidal flux. Then we have calculated the values of T_e and n_e along each line of sight by a bilinear interpolation of the 2D T_e and n_e surfaces. Finally the plasma light has been calculated by spatially integrating the plasma bremsstrahlung emissivity along each viewing chord. We have also included an enhancement factor $\xi = 2$ for a preliminary estimate of the contribution of line emission [12]. Then the error on each measured TS signal has been determined including the signal shot noise, the plasma light background and the detector dark current and excess noise. The results of this calculation are shown in figure 7.

These calculations are to be considered preliminary and may be refined in future, once the design of the system will be completed and more information on the plasma light background will

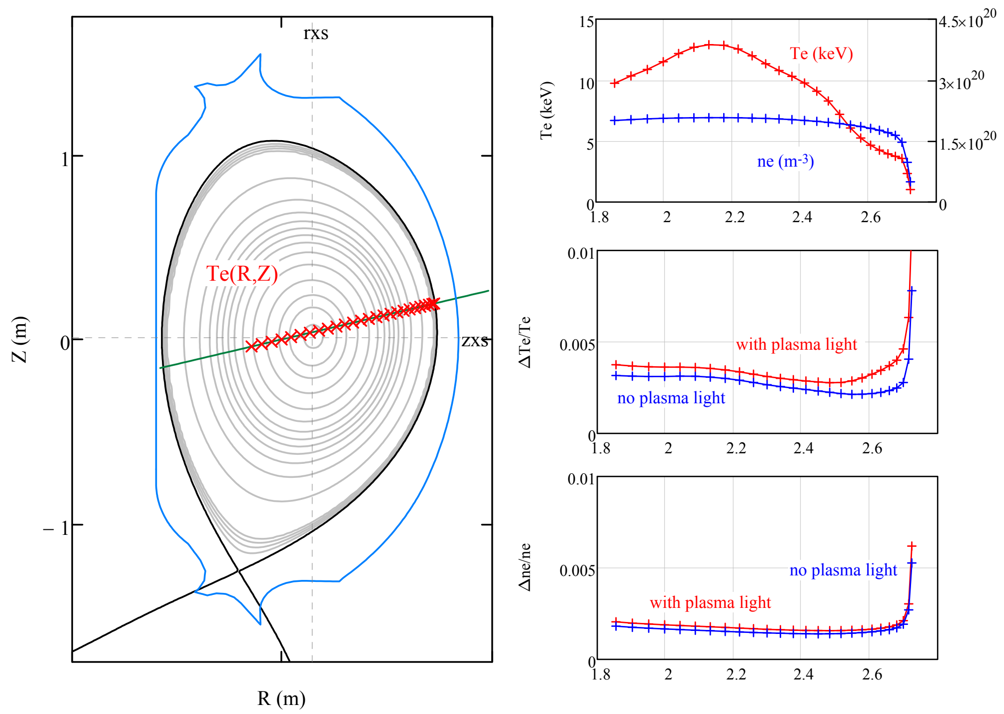

Figure 7. Left: the 2D map of the plasma T_e and the measurement positions in the plasma along the laser beam. Right: the T_e and n_e profiles along the laser beam and the expected T_e and n_e measurement errors calculated with and without the plasma light.

be available. However they indicate that to a first approximation the accuracy of the core TS system is consistent with the system requirements assumed.

4 The LIDAR option for the DTT core TS system

In alternative to the previous design, a different TS system, based on the LIDAR approach is under consideration. In fact, the LIDAR TS concept, implemented in JET in the mid 80s, and subsequently upgraded [15], has never been adopted again. The reason is that the JET system, which was based on a 300 ps ruby laser and a set of MCP PMTs (microchannel plate photomultipliers) with 320 ps pulse response time, only allowed a 6.5 cm spatial resolution and 4 Hz measurement frequency. This was not considered sufficient for other, subsequent plasma experiments. Nevertheless, recent advances of laser and fast detector technology make possible LIDAR TS measurements with better spatial and time resolution. A LIDAR TS scheme, entirely based on commercially available equipment has been proposed for DTT, with spatial and time resolution comparable with those provided by a conventional TS system [16]. These performances may be further improved by using state-of-the art detectors and laser equipment available on a custom basis from various manufacturers. A LIDAR TS system for measurements in the core plasma would have many advantages for DTT, such as a simpler, fiberless collection optics with a reduced impact on the machine, easier alignment and calibrations, the need of a single polychromator and a limited set of data acquisition channels, possibly resulting in a TS system with performances similar to those of a conventional system and a lower cost.

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