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The Thomson Scattering System for DTT (Divertor Test Tokamak) edge-pedestal

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Abstract: The preliminary design of the Thomson Scattering (TS) System devoted to the measurement of the electron density and temperature in the edge-pedestal region of DTT (Divertor Tokamak Test) is described. The evaluation of the DTT pedestal width based on the presently elaborated models tested on JET and DIIID (EPED1 model) leads to a pedestal width $\Delta = 10$ mm along a radial line of sight on the equatorial plane, assuming a scenario with maximum core temperature Te = 20 keV and density ne = 5 10^{20} m^{-3}. The plasma region to be measured could be evaluated in 150 mm (15 times the pedestal width). The required spatial resolution is δr $\approx$ 3 mm to determine the pedestal profile from top to bottom with a minimum of three measurements. The number of the spatial points object of measurement is 50. The installation of the TS is in the DTT equatorial port #17: both the laser focusing optics and the collection optics are installed inside the port, thus realizing a compact design with $\theta_s = 116°$ scattering angle. The minimum laser energy per pulse is 3 J at a 100 Hz repetition rate. The evaluation of numerical aperture of the collection optics is F#/5 leading to a measurement accuracy of 10% in the electron temperature and 5% in density. These numbers are consistent with the measurements technical specifications of the ITER EDGE TS. Given the neutron flux evaluated for DTT scenarios, a collection optics made by rhodium coated molibdenum mirrors can be considered, together with collimating lenses while the collecting fibres are placed outside the port exit window.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging; Plasma diagnostics - probes; Plasma diagnostics - charged-particle spectroscopy; Plasma diagnostics - high speed photography

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1 Introduction

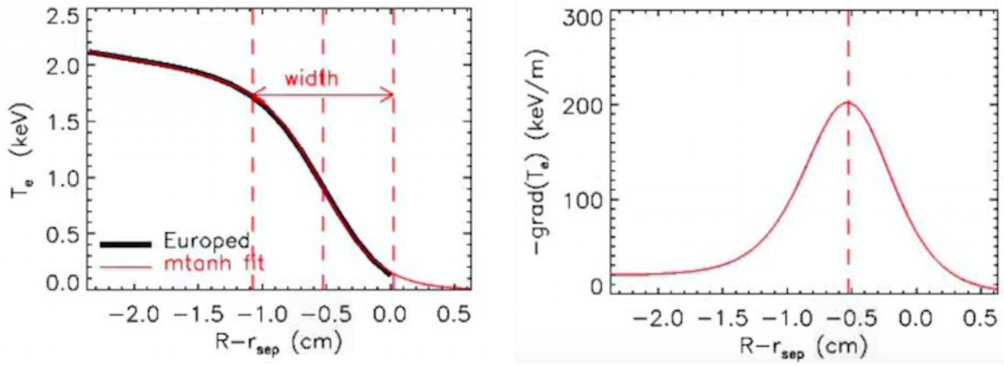
The characterization of edge plasma in tokamaks, by measuring the plasma temperature (Te) and density (ne) profiles, is an important ingredient for the knowledge of plasma confinement and MHD stability. To measure the edge plasma a Thomson Scattering System is used on tokamaks: this technique is based on the measurement of the spectrum and number of photons scattered by a plasma where a laser pulse is injected. The edge region is characterized by strong gradients, and their measurements require high spatial resolution (of the order of few millimeters). In this paper we present the *preliminary* design of a Thomson Scattering (TS) System devoted to the measurements of edge plasma temperature and density profiles resolved in time in the DTT (Divertor Tokamak Test, major radius R = 2.19 m, minor radius a = 0.7 m, toroidal magnetic field B = 6 T). The starting point is the definition of the technical specification of the measurements of temperature and density which is deduced from the edge physics (see section 2). The layout of the system can be quite compact using a quasi-backscattering geometry: for example the ITER edge TS [1, 2] uses this configuration which realizes the minimization of the space used in the port plug for the laser focusing optics and the scattered photon optical collection system. In DTT the equatorial port#17 will be dedicated to the ETS (Edge Thomson Scattering). The plan of the paper is the following: in section 2 the theoretical evaluation of the width of the edge-pedestal region is carried out and the minimum spatial resolution of the ETS is deduced; in the same section the requirements on the measurements are introduced; in section 3 the layout of the system is presented: to maximize the solid angle of the collection optics the first mirror is close to the plasma: the two options of using refractive or reflective optics in the collection optics are examined; in section 4 the evaluation of the number of scattered photons is carried out assuming an incident laser pulse energy of 3 J; in section 5 the conclusions are briefly given.

2 Evaluation of the pedestal parameters and requirements on measurements

The evaluation of the pedestal parameters is done using the code Europed [3] which implements the model EPED1 [4]. Europed Code includes the code HELENA for the evaluation of the equilibrium and the code MISHKA for the evaluation of the MHD stability. The model EPED1 assumes that the pedestal width (w) is given by the following expression:

$$w = 0.076({\beta_\theta}^{\mathrm{Ped}})^{1/2}$$

where $\beta_\theta^{\text{Ped}}$ is the poloidal beta at the top of the pedestal and the width (w) is in unit of normalized poloidal flux.The predicted temperature and density profiles are then mapped along the major radius on the outer midplane. The position and the width of the pedestal are determined by fitting the cited profiles with a modified hyperbolic tangent function (mtanh, as defined in [5]). The position of the pedestal corresponds to the maximum gradient of the fit and the width is determined from the corresponding parameter of the mtanh function. The evaluations of the pedestal width using the model EPED1 are in agreement with the measurements done on tokamak devices like DIII-D, Alcator C. mod, JET-C, JT60U [4, 6], but the agreement is not the best for JET-ILW [7]. The EPED1 model, has been used also for evaluations related to DTT pedestal in [8].The figures 1a and 1b show evaluations of the temperature profile made for a value of the beta poloidal $\beta_\theta^{\text{Ped}} = 0.55$ and the radial gradient of the temperature profile which is useful to determine the width of the pedestal. The FWHM of the gradient determines the width of the pedestal which results in 10 mm: in the figure 1a the width is depicted on the spatial temperature profile.



(a) (b)

Figure 1. (a) pedestal temperature profiles at $\beta_\theta^{\text{Ped}} = 0.55$, (b) spatial profile of the temperature gradient.

The model (EPED1) assumes the pedestal width of temperature and density equal. The pedestal density is found in general shifted externally with respect to the temperature pedestal. This means that a spatial resolution along the major radius (on the equatorial plane) of δr = 0.3 cm could be suitable for measuring at least three points from the top to the bottom of the pedestal.

As it will be noted in the next section, this spatial resolution corresponds to a linear scattering volume of $0.3/\cos(43°) = 0.41$ cm along the laser beam, since the laser beam is injected with an angle of 43°, with respect to the equatorial plane.

This requirement must be taken together the 'standard' requirement of the error bar on temperature $\Delta Te/Te \approx 10\%$ and density $\Delta ne/ne \approx 5\%$. The table 1 reports the complete set of requirements of the measurements of the DTT TS for pedestal: the measurement of density are used for the advanced plasma control while the temperature measurements are essential for the physics evaluation; the range of the Te is from 50 eV to 10 keV, while the range of density is fixed from $5\times10^{18}\text{m}^{-3}$ to 3×10^{20} m^{-3}. The minimum space range where the measurements are required, is defined as $1.075 > r/a > 0.85$ (DTT major radius R = 2.192 m, major radius at the separatrix rsep = 2.884 m, minor radius a = 0.692 m), i.e. 2.78 m $\geq$ R $\geq$ 2.93 m, ΔR = 0.15 m. The number of spatial points to be measured (Nmeas) with a spatial resolution of 0.3 cm is then Nmeas = 15/0.3 = 50 spatial points. The time resolution is defined as Δt = 10 ms. The frequency of the measurements is limited by the laser technology which presently is 100 Hz.

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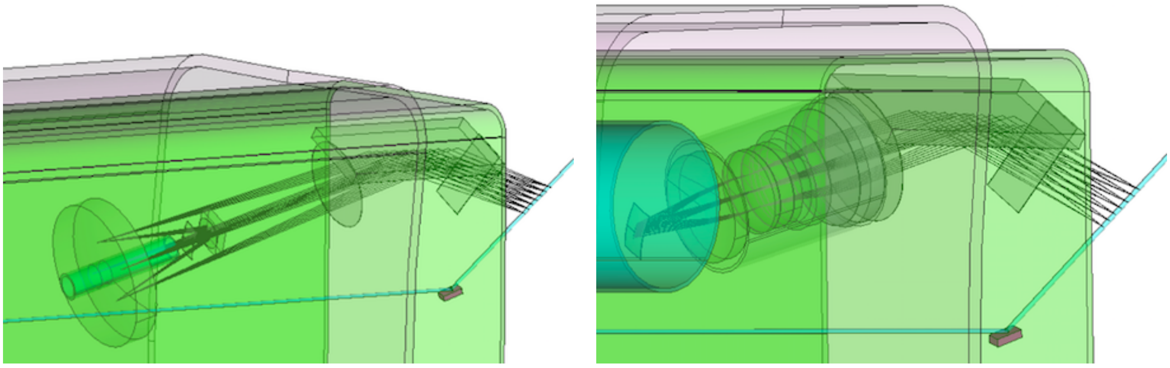
Table 1. Requirements on the measurements of the Thomson Scattering system for the edge-pedestal.

Parameter	Role	Condition	Te and ne range	Time resol	Space resol	Accuracy
Pedestal Te(r)	Physics evaluation	1.075 > r/a > 0.85	0.05–10 keV	10 ms	3 mm	10%
Pedestal ne(r)	Advanced Control	1.075 > r/a > 0.85	$5 10^{18} m^{-3}$–$3 10^{20} m^{-3}$	10 ms	3 mm	5%

3 Layout of the ETS (Edge Thomson Scattering) System

The possibility of using a compact design of the system is always preferable because it saves space and costs. In the case of the DTT ETS, a part of the equatorial port #17 is dedicated to both laser beam injection and the optical system for the scattered light collection, in quasi-backscattering geometry. The figure 2a and 2b show a first design of the ETS layouts.



(a) (b)

Figure 2. (a) and (b): possible layouts of Edge Thomson scattering in DTT: (b), with refractive optics; (a), with reflective elements only. In light transparent green is represented the port plug, in light purple the port duct. The cyan volumes define the vacuum light pipes containing the optical relay system.

The Edge TS system in DTT will be placed in one of the equatorial ports in DTT toroidal sector #17: this sector is shared with other diagnostic systems, and the space for the collection optics well be limited to the upper right part of the port. A direct radial laser path is not feasible; the laser cannot be dumped in the inner first wall and is directed in a less problematic region, in this case in the proximity of the upper divertor region: in order to do so, a grazing incidence, redirecting mirror is placed at the level of external equator. The collection optics for this system address a number of issues, namely withstanding plasma heat and radiation flux while granting sufficient aperture and resolving power. The first mirror candidate could be a Molibdenum mono-crystal coated with a layer of few microns of Rodium, with average (on the scattered spectrum) reflectivity close to 75–80%. These mirrors can withstand the high neutron flux produced by DTT plasma, estimated as 1.3 10^{17}neutron/s [8], corresponding to 1.49 10^{15}neutron/(m^2 s), which is the neutron flux estimated for the scenario at max power. The estimated neutron flux in ITER (blanket or divertor) is 10^{16}–10^{18}n/(m^2s) [9]: in this reference an induced loss of transmission of the fiber optics measured at a wavelength $\lambda = 1.55$ µm is of the order of 0.4–0.75 dB/m at a neutron fluence 3.5 10^{21}n/m^2. This means that on DTT the fiber optics will reach this loss of thansmission after 2.35 10^6 s = 27 days of operation. The need of installing the fiber optics behind

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the bioshield emerges from these evaluations.A purely refractive optics cannot survive given the heat load either on the first lens or on a vacuum window, which cannot be efficiently cooled; in any case the first element must be an actively cooled metallic mirror, which absorbs most of short wavelength radiation. By bending the optical systems, the subsequent elements are also better covered by the water-cooled first wall and so less exposed to neutron damage. In figure 2a and 2b two alternative layouts are displayed; the tables 2 and 3 give the technical specifications of the optical systems. While being preliminary designs, these ensure a 0.1 NA, or F# = 5, and they grant 0.15 mm blur circle (circle of minimum confusion) for the refractive system, and 0.25 mm blur circle for the reflective system on the image plane. Tha evaluated magnification of the optics is $M \approx 2.9$ for both (reflective as well as refractive systems). This means that on the object space the spatial resolution for the refractive system is 0.45 mm and for the mirror system 0.75 mm. The scattering angle (θ_s) in both layouts is $\theta_s = 116°$; the angle of the laser beam with respect to the radial direction is 43°. The minimum spatial resolution required on the measurements is $\delta r = 3$ mm on the radial line of sight which consists in a $3/\cos(43) = 4.10$ mm on the laser beam: the image dimension of the scattering volume has a linear dimension $4.10/2.9 = 1.41$ mm on the focal plane where the optical fibres are located. Summing up the blur circle, the linear dimension of the image of the scattering volume is $1.41 + 0.15 = 1.56$ mm for the refractive system and $1.41 + 0.25 = 1.66$ mm. As for the refractive system, a 5 elements group featuring Fused Silica (figure 2b and table 2). BK7 and MgF2 elements has been considered, in order to employ radiation hard materials, and has been optimized for chromatic correction in the 750–1050 nm. The optics are supposed to be mounted in a gas cooled, vacuum sealed metal barrel. The possibility of mounting all the optical components on a common mechanical support can make easier the alignment between them. The reflective systems (figure 2a and table 3) is a bent Cassegrain layout; a purely spherical mirror ensures sufficient resolution and, while the latter improves by elliptization (the conic constant of the mirror $k = -0.5$). On the other hand, a toroidal aspherical secondary is required.

Table 2. Geometrical characteristic of collection optics, refractive model. Angle of scattering 116°, NA = 0.11, object distance = 395 mm.

Element	Material	Aperture	Curv. rad. surf1	Curv. rad. Surf2	Thickness	Distance to next el.
mirror1	Copper alloy	120×320 mm	Inf. (AOI = 75°)	na	20 mm	305 mm
lens1	Fused silica	r = 75 mm	300 mm	600 mm	30 mm	24 mm
lens2	MgF2	r = 62 mm	136 mm	−135 mm	25 mm	26 mm
lens3	BK7	r = 55 mm	236 mm	798 mm	20 mm	25 mm
lens4	MgF2	r = 55 mm	−118 mm	143 mm	24 mm	30 mm
lens5	Fused silica	r = 62 mm	113 mm	−958 mm	20 mm	125 mm

Table 3. Geometrical characteristic of collection optics, reflective model. Angle of scattering 116°, NA = 0.11, object distance = 395 mm.

Element	Material	Aperture	Curv. rad. surf1	Curv. rad. Surf2	Thickness	Distance to next el.
mirror1	Copper alloy	120×320 mm	Inf. (AOI = 75°)	na	20 mm	600 mm
mirror2	TBD	R = 120 mm	−405 mm	na	TBD	200 mm
mirror3	TBD	40×50 mm	y = 571, x = 461 mm	na	TBD	70 mm

In relation to the redirecting mirror for the laser beam, it is a metal mirror, copper coated with gold or rodium, the dimensions are 60×60 mm^2. The laser beam diameter on the mirror is determined by the damage threshold of the coating: for the Rhodium coated mirror the damage threshold [10] at a laser wavelength 1064 nm is in the range of 0.3–0.5 J/cm2 at 5 ns pulses, resulting in a safe operation of the mirror when a grazing incidence is realized for 3 J laser energy per pulse. and the beam diameter on the mirror is of the order of 40 mm.

The NA of the collection optics is 0.11 on the object side and 0.3 on the image side: this means that a fine tuning of the magnification to match the actual fiber NA will be required after the fiber choice.

4 Evaluation of the scattered power

The evaluation of the scattered power is perfomed using the formula [11]:

$$Ps = {r_0}^2 L\ ne\ d\Omega\ Pi \tag{4.1}$$

where $r_0^2 = 7.95\ 10^{-30}\ m^2$ is the electron classical radius squared, dΩ (= 31.4 10^{-3} sterad) the collection solid angle, ne the plasma electron density (ne ≥ 5 $10^{18}\ m^{-3}$), L the linear dimension of the scattering volume (L = 0.004 m), *Pi* is the incident laser power:

$$\frac{Ps}{Pi} = 4.99\ 10^{-15} \tag{4.2}$$

In these conditions, taking into account also the Bremsstrahlung radiation (P_B), the possibility of having a ratio $Ps/P_B \geq 10$ can be realized for a laser energy of 3 J in 10 ns (0.3 10^9 W).

In fact the plasma light can be evaluated by the following formula [11]:

$$P_B\,(W) = 2.0910^{-36} g\, Z^2 \left[\frac{ne\ ni}{\lambda s T e^{1/2}}\right] Vp \frac{d\Omega}{4\pi} \exp\left(-\frac{1.2410^{-4}}{\lambda s T e}\right) W \tag{4.3}$$

where all the quantities are in CGS units, g is the Gaunt factor (g ≈ 1–5), Z is the plasma zeta effective (Z = 2), ne and ni are the electron and ion densities (ne = ni = 5 $10^{12}\ cm^{-3}$), Vp is the total plasma volume (in cm^3) seen by the collection optics (Vp = 120 · 0.5 · 1 = 60 cm^3), the scattered wavelength λs (≈ 10^{-4} cm), the electron temperature Te = 10^4 eV, the solid angle is dΩ = 4 10^{-2} sterad. The total plasma background power entering the collection optics is evaluated: $P_B = 2.09\ 10^{-36} \cdot 20 \cdot [25\ 10^{24}/(10^{-2})] \cdot 60 \cdot (4\ 10^{-2}/12.57) \cdot \exp(-1.24\ 10^{-4}) = 2010^{-9}$ W.

With the aim of evaluating the ratio of the scattered power to the bremsstrahlung it is useful introducing the integration time of the electronics which is evaluated in 25 ns.

This means that the ratio (Ps · laser pulsewidth)/(P_B · electronics integration time) = 30.

The total scattered power can be deduced from (4.1): Ps = 0.00499 10^{-12}·0.3 10^9 = 1.497 10^{-6} W.

The total number of scattered photons can be evaluated supposing: laser time pulsewidth of 10 ns and a reference wavelength if 1micron (hν = 20 10^{-20} J): this leads to a total number of scattered photons Nph = 1.487 $10^{-6} \cdot 10^{-8}/(2\ 10^{-19})$ = 7.485 10^4. Assuming a total transmission of the optical system T = 0.5, the total number of photons on the optical fibres is Nph(OF) = 3.74 10^4.

The table 4 shows a comparison of the ETS/DTT with JET HRTS [12], MAST-U TS [13], FTU TS [14–16] (the number of photons has been evaluated at ne = 5 $10^{18}\ m^{-3}$).

Table 4. Comparison of DTT ETS figures with those of JET-HRTS, MAST-U and FTU-TS.

	DTT ETS	JET HRTS	MAST-U TS	FTU-TS
collection optics F/#	5	25	6	2,7
solid angle (msr)	31,4	1,26	21,82	108
scattering length (mm)	4	15	10	20
laser energy (J)	3	5	1,6	1
Transmission of Collection Optics	0,5	0,6	0,8	0,4
Nr Photons into Optical Fibre	37425	24166	118143	$1{,}4\ 10^6$

5 Conclusions

The preliminary design of the Thomson Scattering (TS) System for the DTT edge-pedestal plasma region is presented in this paper. A compact design of the layout includes the collection optics mounted on the equatorial port #17 together with the laser focusing optics. A scattering angle $\theta_s = 116°$ can be realized, with a collection solid angle $\Omega = 31.4\ 10^{-3}$ sterad, corresponding to F# = 5. A spatial resolution of 3 mm on a line of sight on the equatorial plane is required following the evaluation of the pedestal width in the high power DTT scenario. The first collecting mirror is a metal mirror made by molibdenum monocrystal coated with rhodium. The scattered light is then collected by a telescope which makes the image of the laser beam on optical fibres. Two options are considered for the telescope made by lenses or mirrors. A Nd:YAG laser of 3 J at 100 Hz repetition rate is planned as light source. The number of the scattered photons is in reasonable agreement with similar TS systems in operation on various machines, which are on line with the technical specifications of a high resolution TS.

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