Opportunities for Accuracy Enhancement of Core Plasma Thomson Scattering Diagnostics in Tokamak Reactors

G.S. Kurskiev[1], P.A. Sdvizhenskii[2], A.B. Kukushkin[2], E.E. Mukhin[1], M. Bassan[3]

[1]*Ioffe Physical Technical Institute, St. Petersburg, Russian Federation*
[2]*NRC "Kurchatov Institute", Moscow, 123182, Russian Federation*
[3]*ITER Organization, Route de Vinon sur Verdon, 13115 St Paul Lez Durance, France*

1. Introduction. The Thomson Scattering (TS) diagnostics of high electron temperature Te in the core plasma in tokamak reactors (ITER and DEMO) has to operate in a limited spectral range of a strongly broadened TS spectrum and allow for possible deviation of electron velocity distribution function (VDF) from a Maxwellian under condition of a strong auxiliary heating. The analysis [1] of opportunities to enhance the accuracy of the core plasma TS diagnostics suggested the use of several probing wavelengths to be able to interpret the TS data with allowance for possible deviation from a Maxwellian VDF in the range of weakly/moderate superthermal energy, with account of data for higher energy from other diagnostics (e.g., from that suggested in [2]).

Here we analyze the advantages of using two probing wavelengths for the core plasma TS diagnostics for Maxwellian and non-Maxwellian plasmas via solving an inverse problem for error assessment. This includes evaluation of the possibility to recover (i) Te up to 40 keV from visible light spectral range ~500-900 nm and (ii) moderate anisotropy of the VDF in electron pitch angles in the weakly/moderate superthermal energy range. A particular example of the ITER core plasma TS system design is considered for a test of suggested approach, and a comparative analysis of conservative and advanced approaches is given.

2. Algorithm of error assessment. The algorithm to assess the measurement error should be formulated in the frame of a synthetic diagnostics. Such a diagnostic generates "phantom" experimental data and allows direct comparison of the pristine (i.e. taken as known, "assumed") and the recovered values of diagnosed parameters. The number of photoelectrons in a given spectral channel due to Thomson scattering is as follows:

$$\left[N_{ph-el}^{(j)}\right]_{Las} = \frac{E_{Las}}{\hbar\omega_0}\Delta x_{Las}\,\Delta\Omega_{pupil}\,n_e\,r_0^2\int_{\Delta X_j}\eta_q(X)\eta_{tr}\,\eta_{fib}(X)\,\tilde{\sigma}\,dX\,, \qquad (1)$$

$$\tilde{\sigma} = \tilde{\sigma}(X, T_e, T_{e\parallel}, T_{e\perp}, \mathbf{n}, \mathbf{n_0}, \mathbf{e}, \mathbf{e_0}). \qquad (2)$$

where $X = \lambda/\lambda_0 - 1$; ΔX_j is the spectral width of the j-th channel; λ and λ_0, the wavelength of scattered and probing radiation; E_{Las}, laser pulse energy; Δx_{Las}, the length of a radiating cylinder viewed by the detector ("scattering length"); n_e, electron density; $\Delta\Omega_{pupil} = \Delta S_{pupil} / (\mathbf{r}_{emis} - \mathbf{r}_{pupil})^2$, where ΔS_{pupil} is the area of the pupil, and the vectors stand for the coordinate of the radiating cylinder and the pupil; r_0 is electron classical radius; $\mathbf{n}_0$ and $\mathbf{n}$, directions of incident and scattered light; $\mathbf{e_0}$ and $\mathbf{e}$, polarization vectors of incident and scattered light, the factors η allow for the properties of optical system. The normalized cross-section σ of the Thomson scattering is averaged over the assumed model VDF:

$$f(\mathbf{p}) = (1-\delta_{Hot}) \cdot f_{Maxw}(\mathbf{p}) + \delta_{Hot} \cdot f_{Hot}(\mathbf{p}_{\|}, \mathbf{p}_{\perp}), \tag{3}$$

$$f_{Hot}(\mathbf{p}_{\|}, \mathbf{p}_{\perp}) = C_{Hot} \exp\left[-mc^2 \left(\frac{\sqrt{1+(p/mc)^2} - 1}{p^2} \right) \left(\frac{p_{\|}^2}{T_{e,\|}} + \frac{p_{\perp}^2}{T_{e,\perp}} \right) \right], \tag{4}$$

where f_{Maxw} is relativistic Maxwellian distribution; $\mathbf{p}_{\|}$ and $\mathbf{p}_{\perp}$ are the components of momentum **p**, respectively, parallel and perpendicular to local magnetic field; C_{hot}, normalization factor (in momentum space); δ_{Hot}, total fraction of superthermal electrons. The background signal is assumed to be measured in a separate time window of similar duration. Different lasers are assumed to act in different but very close time instants. The algorithm of error assessment is as follows.

1. The assumed number of laser-produced photoelectrons (1) is calculated for each spectral channel and each laser for a set of assumed values of unknown parameters, $\xi_{assum} = \left\{ T_e^{assum},\ T_{e\|}^{assum},\ T_{e\perp}^{assum},\ n_e^{assum},\ \delta_{Hot}^{assum} \right\}$ for the VDF (3),(4), or for a set of values of $\xi_{assum} = \left\{ T_e^{assum},\ n_e^{assum} \right\}$ for a Maxwellian VDF.

2. The phantom experimental spectrum is generated many times to allow for the quantum noise of detector and amplifier in the both measurements, with and without laser scattering. The residual of total, $\left[N_{ph-el}^{(j)} \right]_{Total}$, and background, $\left[N_{ph-el}^{(j)} \right]_{Backgr}$, signal in each spectral channel is calculated with a proper randomization. For $\left[N_{ph-el}^{(j)} \right]_{Laser} \gg 1$, one can take a Gaussian with the average $\left[N_{ph-el}^{(j)} \right]_{Laser}$ and the mean square deviation $\sigma_j = \sqrt{\left[N_{ph-el}^{(j)} \right]_{Las} + 2\left[N_{ph-el}^{(j)} \right]_{Backgr} + 2\left[\sigma_j^2 \right]_{Ampl}}$, where $\left[\sigma_j \right]_{Ampl}$ describes the noise of amplifier.

3. To recover the parameters under search, $\xi = \left\{ T_e, T_{e\|}, T_{e\perp}, n_e, \delta_{Hot} \right\}$, and evaluate the error of their recovery, one has to solve many times the following inverse problem, a minimization of

the difference between the "phantom" experimental laser-scattering signal and the respective variable calculated signal:

$$\sum_{\lambda_0}\sum_{j}\left|\left\{\left[N_{ph-el}^{(j)}(\xi_{assum})\right]_{Total}-\left[N_{ph-el}^{(j)}\right]_{Backgr}\right\}_{Random}-\left[N_{ph-el}^{(j)}(\xi)\right]_{Las}\right|\xrightarrow[\xi]{}\min, \quad (5)$$

where summation goes over various lasers and spectral channels. The accuracy of recovery of the value of parameter B is defined as an average of the normalized mean square deviation from the assumed value of B over statistical distribution of the recovered values of B:

$$Acc(B^{(assumed)})\equiv 2.5\left[\left\langle\left(B/B^{(assumed)}-1\right)^2\right\rangle\right]^{1/2}. \quad (6)$$

The factor 2.5 in (6) corresponds to 98% probability to find the value of B in the range $\left\{B^{(assumed)}-2.5\,\delta B,\ B^{(assumed)}+2.5\,\delta B\right\}$, $\delta B=[\langle(B-B^{(assumed)})^2\rangle]^{1/2}$.

We present the results for 200 runs of solving the inverse problem for the following input parameters which are considered in the ongoing analysis of the core plasma TS system in ITER: various combinations of two lasers with $\lambda_{01}=1064$ nm and $\lambda_{02}=1320$ nm; E_{Las} = 4 J (the same for all lasers), $\eta_{tr}=0.3\cdot 0.7\cdot 0.8=0.168$ is the total transmission factor of optical system (a flat efficiency of 30% for the collection optics, a 70% packing efficiency for the fiber bundles, a 80% optical efficiency of the spectrometers); the quantum detector sensitivity, η_q, is taken to have the APDs spectral sensitivity like the Excelitas C30956EH in the range above 650 nm and like the Hamamatsu S8664 in the range below 650 nm; the fibers transmission factor, η_{fib}, is taken as that of typical anhydro silica-silica fiber, 30 m long; $\left[\sigma_j\right]_{Ampl}=50$, $\Delta x_{Las}=0.07$ m, $\Delta\Omega_{pupil}=1.38\times10^{-3}$ sr. The angle between $\mathbf{n_0}$ and $\mathbf{n}$ is taken $159.5°$ that corresponds to observation of the plasma column center; linear polarization vectors $\mathbf{e_0}$ and $\mathbf{e}$ coincide and are perpendicular to scattering plane. The background signal is formed by the direct signal from plasma Bremsstrahlung along the line of sight and the reflected-from-the-wall light which is determined by the line radiation emitted in divertor (the background signal data are provided in [3]). We use the notations: $\bar{B}=\langle B\rangle$, $\Delta B=\left[\left\langle(B_i-\bar{B})^2\right\rangle\right]^{1/2}$, $T_{eff}=2<E_{kin}>/3$, $E_{kin}=mc^2\left(\sqrt{(p/mc)^2+1}-1\right)$.

The measurement of a high temperature, ~40 keV, under conventional assumption of a Maxwellian VDF appears to be not sensitive to diversification of wavelength whereas for the reconstruction of a more complicated VDF, with a 10% fraction of an anisotropic quasi-

Maxwellian VDF of moderate superthermal energy, one has an increase of accuracy of measuring the effective temperature (mean energy) (cf. Table 1).

Table 1. Measurement error for parameters *B*, evaluated under assumption of the VDF in the form (3), (4).

	B	$B^{(assumed)}$	2 Lasers, 1064 nm				2 Lasers, 1064 nm, 1320 nm				2 Lasers, 1320 nm			
			$\bar{B}$	ΔB	*Acc* (*B*), %	δB	$\bar{B}$	ΔB	*Acc* (*B*), %	δB	$\bar{B}$	ΔB	*Acc* (*B*), %	δB
10 keV	T_e, keV	10	9.9	0.2	**6**	0.3	9.9	0.3	**7**	0.3	9.9	0.3	**7**	0.3
	$T_{e\parallel}$, keV	15	17	8	**140**	8	18	9	**150**	9	18	10	**170**	10
	$T_{e\perp}$, keV	12.5	13	4	**73**	4	12	3	**65**	3	12	3	**51**	3
	n_e, 10^{19} m^{-3}	3.00	3.01	0.02	**2**	0.02	3.01	0.03	**3**	0.03	3.01	0.04	**3**	0.04
	δ_{Hot}	0.05	0.07	0.05	**280**	0.06	0.07	0.07	**400**	0.08	0.07	0.06	**330**	0.07
	T_{eff}, keV	10.4	10.5	0.3	**7**	0.3	10.6	0.5	**11**	0.5	10.6	0.4	**10**	0.4
40 keV	T_e, keV	40	38	3	**19**	3	39	2	**12**	2	39.3	1.7	**11**	1.8
	$T_{e\parallel}$, keV	60	58	11	**46**	11	58	10	**43**	10	58	10	**41**	10
	$T_{e\perp}$, keV	50	53	15	**77**	15	52	12	**63**	12	52	10	**53**	11
	n_e, 10^{19} m^{-3}	3.00	3.02	0.05	**5**	0.06	3.01	0.04	**4**	0.05	3.01	0.04	**4**	0.04
	δ_{Hot}	0.10	0.21	0.19	**550**	0.22	0.15	0.13	**340**	0.14	0.14	0.09	**240**	0.10
	T_{eff}, keV	45	47	3	**16**	3	46.0	1.6	**10**	1.9	45.7	1.2	**8**	1.4

Note that the high error of recovering the parameters, which describe particular type of the deviation from a Maxwellian (especially, parameter δ_{Hot}), does not influence the accuracy of recovering the mean energy of the non-Maxwellian VDF. Thus, the inverse problem solution is stable with respect to recovery of the mean energy regardless of particular form of the deviation from a Maxwellian in the thermal and weakly superthermal range of electron energy.

3. Conclusions. The opportunity to enhance the accuracy of the core plasma Thomson Scattering diagnostics in tokamak reactors via using the lasers with two different wavelengths, against conventional use of one wavelength, is tested on the example close to the planning ITER diagnostics. The results illustrate the trend towards increasing the accuracy with increasing range of Te measurements.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

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