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High-resolution Thomson scattering system on the COMPASS tokamak: Evaluation of plasma parameters and error analysis[a)]

M. Aftanas,[1,2,b)] P. Bohm,[1] P. Bilkova,[1] V. Weinzettl,[1] J. Zajac,[1] F. Zacek,[1] J. Stockel,[1] M. Hron,[1] R. Panek,[1] R. Scannell,[3] and M. J. Walsh[4]
[1]*Institute of Plasma Physics AS CR, v.v.i., Za Slovankou 3, 182 00 Prague 8, Czech Republic*
[2]*Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague 2, Czech Republic*
[3]*Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom*
[4]*ITER Organization, CS 90 046, St Paul lez Durance Cedex 13067, France*

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The electron density and temperature profiles measured by the Thomson scattering diagnostic on the COMPASS tokamak are used for estimation of electron kinetic energy, energy confinement time, and effective charge number Z_{eff}. Data are compared with the line-integrated electron density measured by a microwave interferometer in an ohmically heated plasma with a circular cross section. An error analysis of both electron temperature and density are performed by two methods–a constant chi-square boundaries method and a Monte Carlo simulation, determining asymmetrical error bars for the electron temperature. [http://dx.doi.org/10.1063/1.4743956]

I. INTRODUCTION

The Thomson scattering (TS) system for the core plasma on the COMPASS tokamak[1] has been commissioned and is routinely used for measurement of profiles of both electron density n_e and electron temperature T_e.[2] In this paper we present profiles of T_e and n_e for ohmically heated plasmas with a circular cross sections including error bars. We compare the TS data with the data obtained by a single-chord line-integrated electron as density measured by a microwave interferometer. We also compare measured electron temperature with plasma parameters obtained by magnetic diagnostics to estimate effective charge number using formula for Spitzer resistivity. Moreover, we determine electron kinetic energy and the electron energy confinement time. In the second part of the contribution, an error analysis of both electron temperature and density is performed by the constant chi-square boundaries method. Besides this, Monte Carlo simulation, as a way to determine the error of the electron temperature, is introduced with the aim to increase precision and provide asymmetrical error bars for the electron temperature measurements.

II. SETUP OF THE DIAGNOSTICS

Thomson scattering diagnostic for COMPASS[3] facilitates two Nd:YAG lasers of 30 Hz repetition rate and 1.5 J pulse energy each as a source of intense radiation for scattering.[4] The scattering region inside the plasma is divided into two parts: edge at 200 mm to 300 mm above the mid-plane with spatial resolution of up to 3 mm and core at −30 mm to 210 mm above the midplane with spatial resolution of 10 mm. The scattered light from both regions is collected by custom designed objectives and relayed by fibre bundles out of the tokamak area into 29 polychromators.[5] Each of these polychromators divide the light into five spectral channels (using a set of filters), and light from each of these channels is then imaged onto an avalanche photodiode, where it is converted to an electrical signal. From each polychromator four of the five spectral channels are digitized; channels are chosen according to expected electron temperature range at corresponding spatial point. Signals from all 29 polychromators are digitized using a 120 channel 1 GS/s analog-to-digital converters system.

III. PLASMA PARAMETERS

A. Calculation of electron energy confinement time

The energy confinement time τ_E can be estimated from TS data. Confinement time is defined by the global energy confinement $dW(t)/dt = P_{OH} - W(t)/\tau_E$, where $W(t)$ is total energy of the plasma (both electrons and ions) and P_{OH} is plasma heating power. Total energy of the plasma particles $W(t)$ is given by kinetic energy of all particles $(3/2)k(n_eT_e + n_iT_i)$ integrated over plasma volume V. Only electron density n_e and temperature T_e is measured by TS, ion density n_i and temperature T_i are estimated to contribute to the total energy by 1/3 of the electron energy (as usual case for purely ohmically heated tokamak plasma due to higher mobility of the electron component[6]). The plasma is circular in cross section, vertical coordinate z corresponds to r. Resulting plasma energy $W(t)$ is shown in Fig. 1(b).

The ohmic heating power P_{OH} (Fig. 1(b)) is given by product of plasma current I_{plasma} (which is measured by magnetic diagnostics, Fig. 1(a)) and resistive part of loop voltage on the plasma torus U_{res}. This voltage is not measured

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[b)]Author to whom correspondence should be addressed. Electronic mail: aftanas@ipp.cas.cz.

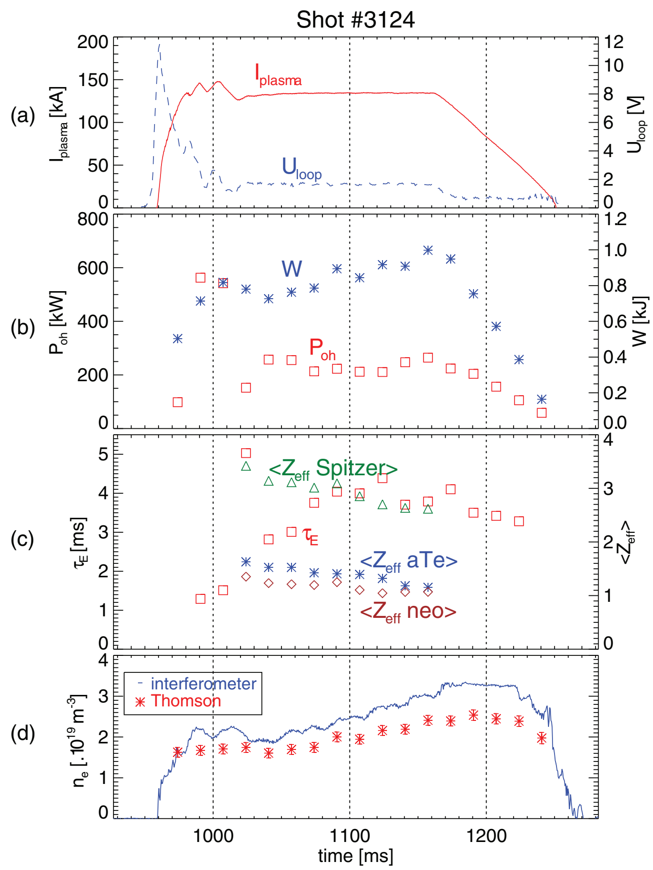

FIG. 1. Plasma parameters evolution (described in the text).

directly, but can be determined from $U_{res} = U_{loop} - L \times dI_{plasma}/dt$, where loop voltage U_{loop} is measured by a flux loop surrounding the tokamak vessel (Fig. 1(a)), inductance L is approximately 1 μH. The time derivative in the energy confinement equation is estimated from comparison of $W(t)$ from two subsequent TS measurements.

Resulting evolution of confinement time τ_E is shown in Fig. 1(c). In the quasi-stationary phase of the discharge it varies between 3 ms and 4 ms.

B. Estimate of Z_{eff} using Spitzer resistivity

Plasma resistivity depends upon temperature. For high collisionality plasmas, plasma resistivity is equal to Spitzer resistivity[7–9] $\eta_S = 2.8 \times 10^{-8} Z_{eff} T_e^{3/2}$, where Z_{eff} is effective charge number and electron temperature T_e is in keV. When the collisionality is low, neoclassical correction η_N can be used to deal with existence of banana particles trapped in magnetic field. These particles do not contribute to the plasma current.[9] Neoclassical resistivity can be calculated as:[8] $\eta_N = \eta_S/(1-\sqrt{\mathrm{r/R}})^2$. Unknown effective charge number Z_{eff} can be estimated from comparison with fundamental equations for mean resistivity, $\eta = (U_{loop}\pi a^2)/(2\pi R I_{plasma})$, where $R = 0.56$ m is major radius and $a = 0.20$ m is minor radius of COMPASS tokamak, U_{loop} is loop voltage, and I_{plasma} is plasma current.

Now, from T_e profiles measured by TS, U_{loop}, and I_{plasma}, Z_{eff} averaged over plasma cross section can be estimated (Fig. 1(c)). Calculating Spitzer resistivity for each TS spatial point, integrating over circles and subsequently comparing with I_{plasma} gives $\langle Z_{eff}\ Spitzer\rangle$, including the neoclassical correction gives $\langle Z_{eff}\ neo\rangle$. Another approach, averaging T_e over the plasma cross section first and then calculating Spitzer resistivity gives $\langle Z_{eff}\ aTe\rangle$.

C. Comparison of TS and interferometer

Electron density measured with TS is compared with line averaged electron density determined by interferometer diagnostic.[10] The TS n_e profile is averaged over a plasma semi-diameter; plasma center vertical position is estimated from TS T_e profiles. As can be seen in Fig. 1(d), absolute magnitude of density measured by TS is slightly underestimated compared to the interferometer however time evolution from both diagnostics are well correlated. This can be explained by a radial plasma displacement – contrary to interferometer, TS is probably missing plasma center. The radial plasma displacement will be determined as soon as EFIT magnetic reconstruction is available (expected still in 2012).

D. Prospects-dynamics of plasma parameters

The two independent Nd:YAG lasers at 30 Hz used in the TS system of COMPASS bring an advantageous possibility to investigate plasma parameters dynamics by changing a mutual timing of the laser beams from several hundred nanoseconds up to several milliseconds. Namely, electron density and temperature profiles evolution during transition phases, e.g., during strong MHD activity or between modes with different confinement time (L-H and H-L transitions), will be used for studies of energy and particle transport. A shorter delay between the laser pulses was used to confirm expected profile behavior in the shots with an artificial plasma column shift provided by a new feedback positioning system. Currently, dynamics of vertical displacement events (VDE) and their stabilization is going to be investigated using TS on the COMPASS tokamak.

IV. ERROR ANALYSIS ON TS DATA

Data processing part of the COMPASS TS system is done in IDL environment. The signal as a function of the time is recorded for each polychromator (13 polychromators for the core TS system) and four wavelength channels, then it is fitted (as Gaussian) and integral $S_{high\_pass\_filter}$ is calculated.[11] The error σ_S of the integral is calculated as a composite of Poisson, plasma light, and amplifier noise error.[12] The Poisson contribution can be determined from Raman scattering calibration[5] and it is given by $\sigma_{Poisson}{}^2 = F_{Raman} \times S_{high\_pass\_filter}$. Plasma light contribution can be estimated in the similar way from the $S_{low\_pass\_filter}$ integral over time of the laser pulse (let us say $\pm 2\sigma$ of the pulse width) or it can be determined together with amplifier noise as a signal oscillations variance σ_{noise} outside of the scattered pulse region (when no scattered signal is present). Following the previous statements the $\sigma_S{}^2$ is taken for COMPASS as $F_{Raman}{}^2 \times S_{high\_pass\_filter}{}^2 + \sigma_{noise}{}^2$.

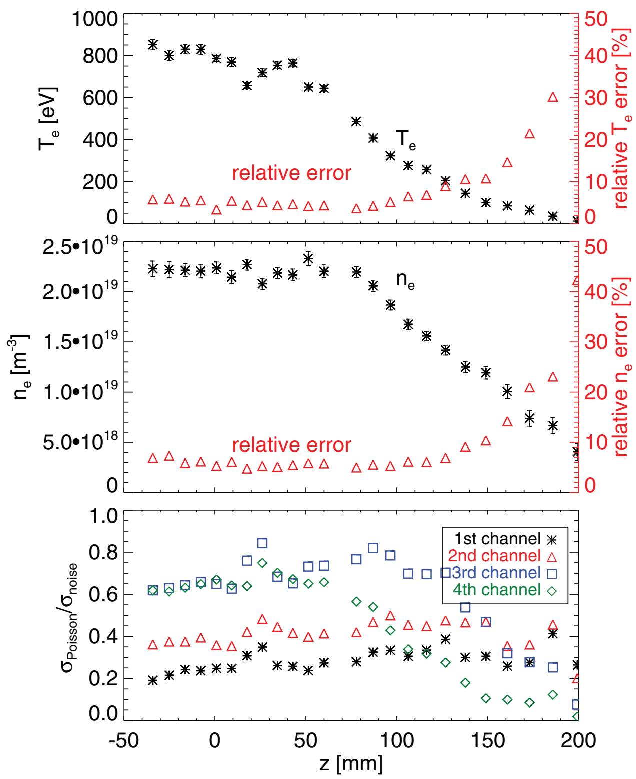

FIG. 2. Errors of T_e and n_e calculated by constant chi-square boundaries method for one standard shot.

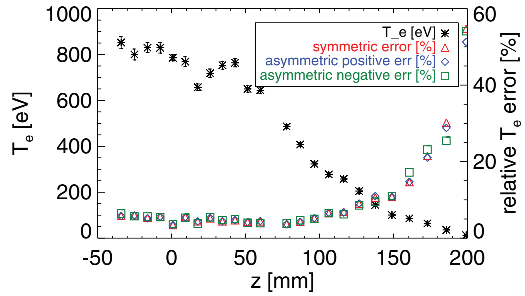

FIG. 3. Comparison of the T_e errors determined by the chi-square boundaries method and the bootstrap method.

Electron temperature T_e is calculated from the fitted integral $S_{high\_pass\_filter}$ and the error σ_S by the means of chi-square minimization. Up to now the error of the electron temperature σ_{T_e} was estimated by the constant chi-square boundaries method (Fig. 2). Bootstrap method,[13] as a new way to estimate the error of the electron temperature has been implemented. This method is based on Monte Carlo simulation and the basic idea behind it is that the actual data set is in most cases the best (or the only) available estimator of the underlying probability distribution. Bootstrap method can often be used when you do not know enough about the underlying process to do a pure Monte Carlo simulation. Artificial data are generated from the measured values and error of the measured data is taken as a standard deviation of the generated random ones. In principle we should simulate additional raw signals (time evolution of the voltage measured on each photodiode). This would cause additional fitting of $S_{high\_pass\_filter}$ for each simulated signal. We are generating directly Poisson distributed $S_{high\_pass\_filter}$ instead. According to the previous description we are moreover able to calculate asymmetrical T_e errors. It is based on dividing the artificial T_e to the ones which are greater and to the ones which are smaller than measured electron temperature.

Both methods were compared for several plasma shots and time segments (example shown in Fig. 3.). As it can be seen that the bootstrap method shows minor asymmetry of the temperature errors, but the difference was not significant (~10% difference). The disadvantage is the time of the calculation – with bootstrap method the calculations takes at least 100-times more computation time (for our case couple of minutes for all profile) than the constant chi-square boundaries method.

V. CONCLUSION

High spatial resolution of Thomson scattering diagnostics is a powerful tool not only for delivery of T_e and n_e profiles but also for computing other quantities as stored energy, confinement time and estimate of Z_{eff}. The routinely operating core TS system is currently being complemented with another TS system focused on the plasma edge.

Errors of TS profiles were calculated with two different methods. Additionally to the constant chi square method, Monte Carlo simulation method allows also determination of asymmetrical error of T_e. However, analysis of the results does not show a significant difference between them. The faster chi-square method is therefore sufficient for routine data processing.

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