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Advances of Thomson scattering diagnostic on the TEXTOR tokamak

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Abstract. A Thomson scattering (TS) diagnostic based on the laser multi-pass intra-cavity plasma probing has been developed and successfully implemented in the TEXTOR tokamak [1, 2]. The laser system operates in a burst mode delivering up to 45 laser pulses 50 J of probing energy each at 5 kHz frequency. The diagnostic has provided the measurements of fast evolution of electron temperature and density at accuracy of 2% and 1% correspondingly at a spatial resolution <1 cm along the whole plasma diameter during a 9 ms time interval. The developed TS diagnostic combines unique features: large amount of collected photons, a high repetition rate of the measurements, a high spatial resolution along the whole plasma diameter and a high spectral resolution with hundred spectral points. Some of new advances of the TS diagnostics and its possible applications on the TEXTOR tokamak are briefly discussed in the report.

1. Introduction

Thomson scattering diagnostic on the TEXTOR tokamak has achieved unique capabilities in measurements of fast evolution of electron temperature (T_e) and density (n_e) profiles due to laser intracavity multipass probing [1, 2]. In this report some new developments of the TS diagnostic are proposed and briefly discussed. The realization of these plans will allow getting new essential physical data in plasma experiments.

2. Electron distribution and plasma current density

TS diagnostics deal with light spectra scattered by free electrons in plasma from a laser beam, but usually only two parameters are extracted from the TS spectra: the width and amplitude corresponding to local T_e and n_e. In principle, TS diagnostic could provide other parameters like the shift of the spectrum, distortions of the spectral wings and etc which relate to important physical quantities, but collected scattered photon fluxes are too low for these measurements.

The new TS system in TEXTOR can open a possibility to study TS spectra and electron distribution, but not only T_e and n_e quantities. Figure 1 shows TS spectra measured in TEXTOR with the double- (blue) and 12-pass (red) probing systems from a $8*12*2$ mm^3 plasma volume at the line electron density $\sim 2*10^{19}$ m^{-2} in a single laser pulse. The 12-pass system allows a significant reduction of the statistical errors and expansion of the spectral range of the measurements from 2.5 keV to 6 keV in terms of electron energies. When averaging the scattered signals over all pulses in the laser train results the measurement accuracy of scattered spectra achieves 1-2% in the plasma centre. It is illustrated by black points with error bars in the figure. These capabilities are quite essential for study of ECR heating and current drive when EC waves can disturb the distribution of high energy electrons.

Another possibility relates to the measurements of plasma current density in TEXTOR. The line of sight of the TS collection optics is turned to the toroidal axis by ~81° in the horizontal plane. Therefore the electron current drift velocity $\underline{v_D = j/en}$ has a small projection on the differential wave vectors $\Delta k_{1,2}$ $= k_s - k_{i1,2}$ resulting in a distortion of the TS spectra [3]. Here k_s is the wave vector of radiation scattered to the TS collection optics and $k_{i1,2}$ are wave vectors of the direct and return laser beams
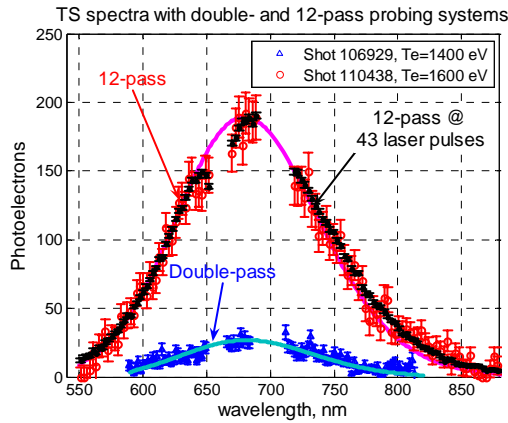

Figure 1. TS spectra measured with double- and 12-pass laser probing systems

The relative change of the scattered spectra at the thermal velocity v_{Te} is $\sim 2 * v_D / v_{Te} * Cos\eta$ [3], where η is the angle between the plasma current and the differential wave vector. For the TEXTOR geometry ($Cos\eta$ ~0.16) the expected changes of scattered spectra deviations range from ~0.4% to 1% in a 300 kA plasma discharge.

The accuracy of the measurements with the 12-pass system in individual spectral points (Figure 1) ranges from ~6% in the spectral core to ~15% in the spectral wings. Enlargement of the observation volume and averaging the scattered signals over 40 pulses of a laser train allow the reduction of the accuracy by a factor of 10 and direct measurements of electron current density in a single plasma discharge. Note, such measurements have been proofed in the RTP tokamak by collecting data from 20-40 plasma discharges [4].

This study, certainly, requires a perfect calibration of the TS system which should provide the instrumental errors less than the achieved statistical errors. A development of special fitting procedures is also required.

3. TS measurement at a low plasma density

A study of plasma-wall interaction on the TEXTOR tokamak [5] utilizes low temperature plasmas at the electron densities 10^{16}-10^{17} m^{-3}. The achieved laser probing energy is already high enough to deliver a significant number of scattered photons from this plasma, while the TS spectrometer [6] was not designed for low temperature measurements. As the result, most of the collected photons are lost

Figure 2.

a. Line electron density (HCN) and plasma current along with laser probing energy.

b. Averaged T_e and n_e (TS) and D_α emission.

in a spectral blocking region around the laser wavelength formed by a notch filter and a gap in a two part mirror [6].

Nevertheless, the TS system allows an assessment of the diagnostic capabilities for these studies from TS measurements at the very start of TEXTOR plasma discharge when the electron density develops from the zero level to ~10^{18} m^{-3}. Laser pulse probing energy, developing line integrated electron density and plasma current are shown in figure 2. Developing electron temperature and density measured by TS diagnostic and averaged along their spatial profiles as well as D_α line emission are shown in section b) of the figure.

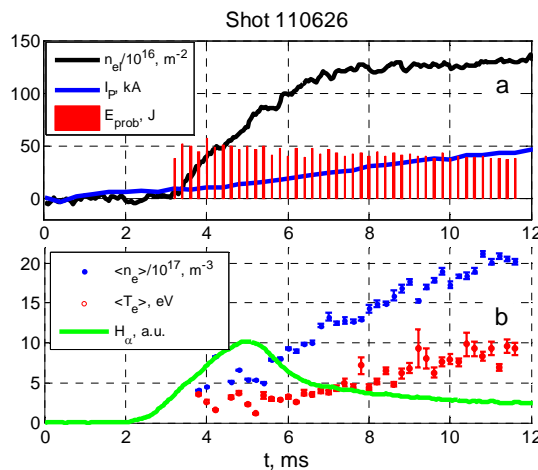Figure 3 presents two contour plots of measured TS spectra at 3.2 and 4 ms. The TS images are transformed so that the ruby wavelength is straight (red line). White curves are the borders of the blocking region.

While $T_e < 3$ eV the collected spectra are completely blocked in the spectral gap. The measurements become possible after 4th ms as soon as the blue wing of a TS spectrum comes out from the gap at $T_e > 3$ eV. The wing at $T_e = 3$ eV contains only ~10% of the total collected photons, but the density

measurement accuracy is rather good ~15% which corresponds to a hundred registered photoelectrons in the spectral wing.

Some measured profiles are shown in figure 4. One can see that hot plasma starts from the central region (blue circles) expanding to the edges during first few ms.
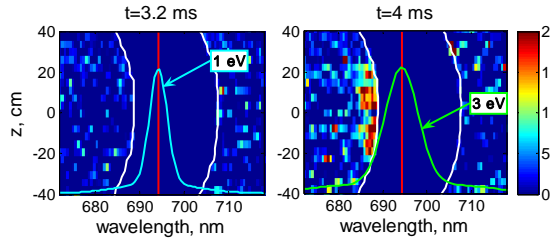

Figure 3. TS signals at 3.2 ms and 4 ms ($n_e \sim 3*10^{17}$ cm^{-3}).
Red line is the ruby laser wavelength;
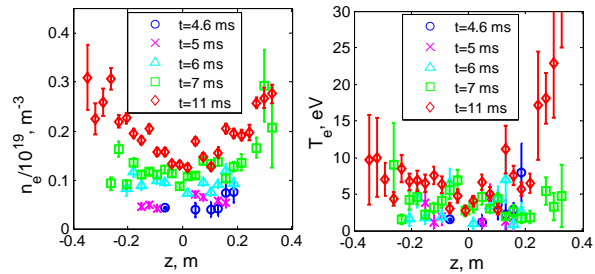White curves are the blocking region borders

Figure 4. Electron density and temperature profiles measured by TS at the start of plasma discharge.

In a steady state, the measurement accuracy can be improved by 4-6 times by summing up scattered photons along the whole laser train enabling TS measurements at ne~10^{16} m^{-3} if Te>3 eV. TS measurements of lower T_e require:

1. a higher dispersion grating;

2. a more narrow central blocking region well matched to the laser wavelength shape in the intermediate image plane of the spectrometer. This could be achieved by shifting the scattered spectra from the entrance slit and dumping the laser wavelength in a curved mask;

3. a more narrow band notch filter, e.g. highly doped ruby [7, 8];

4. development of a fitting procedure for low T_e measurements.

4. Local measurements of deuterium atom density

Local measurements of hydrogen or deuterium atom density in plasma with Laser Induced Ionization (LII) are based on laser ionization of excited atoms and quenching their line emission [9]. One of the advantages of the LII over widely applied Laser Induced Fluorescence [10] technique is a possibility to use a ruby laser for the measurements.
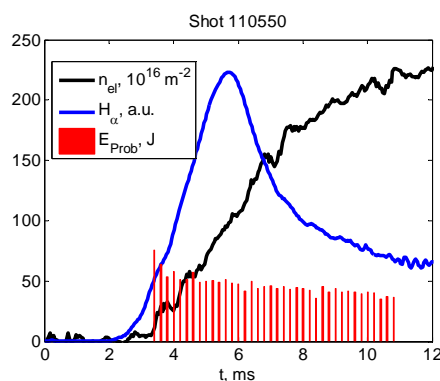

Figure 5. Line electron density (HCN) and D_α emission at the start of plasma discharge along with laser probing energy
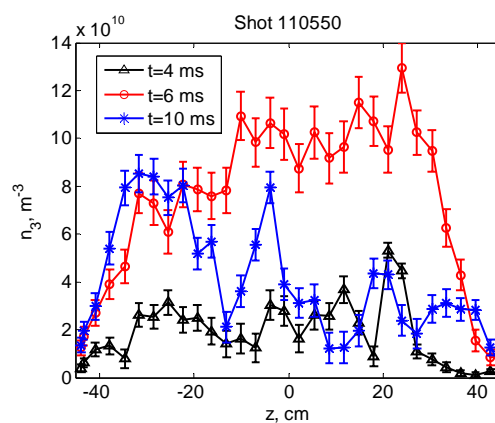
Figure 6. Local density of deuterium atoms at the 3rd level

The multipass intracavity probing provides a high laser probing energy, long laser pulse duration and an extension of the radiated plasma volume along the line of sight. These factors are very important for the LII diagnostic, increase considerably its sensitivity and made possible the LII measurements at the plasma start in TEXTOR.

The evolution of line electron density and D_α emission at the start are shown in figure 5. A 100 MW/cm^2 laser probing intensity (50 J during 1.5 µs through ~0.3 cm^2 laser cross section in plasma) is

quite enough to ionize nearly all hydrogen and deuterium atoms from the 3rd excited level on the laser beam path in plasma [9]. The ionization results in partial quenching D-alpha emission collected by the TS diagnostic from plasma. The quenching signals were determined as the difference between the signals taken with and without laser pulses. The local density of the excited atoms on the laser beam path can be found directly from the measured signals [9, 11]:

$$n_3 = \frac{\Delta N}{V_{Las}\,\Omega\,\eta\,A_{32}\,\tau}$$

Here ΔN is the quenching signals in photoelectrons, $V_{Las}\sim1.5$ cm^3 is the volume on the laser beam path from which the signals are collected, $\Omega\sim0.005$ sr is the solid angle of light collection, $\eta\sim0.03$ is the ratio of the registered photoelectrons to the photons collected from plasma, $A_{32}= 0.44*10^8$ 1/s is the probability of spontaneous radiation decay from the 3th to 2nd atomic level, $\tau\sim1.5$ μs is the duration of laser pulses.

The local densities of the excited atoms measured in different times at the spatial resolution ~3 cm are shown in figure 6. The statistical errors are in the range from 10% to 30% and the diagnostic sensitivity is ~10^{10} m^{-3}. The density of the ground state atoms can be calculated from a collisional-radiative model (see e.g. [12]) using local T_e and n_e data. The sensitivity of the LII diagnostics in respect to the ground state atom density is expected to be ~10^{13} m^{-3} in TEXTOR. These estimations can be even improved by several times at the steady state by summing up the quenching signals from several laser pulses.

The excited atom density is significantly reduced in a hot plasma core and the quenching signal is much worse distinguished against intense D_α emission from the plasma edge. A ~10-fold enhanced sensitivity of the LII diagnostic for the plasma core measurements can be achieved by a ~2-3-fold enlargement of the laser beam diameter in plasma with a special multipass system [11]. In this case the sensitivity of the LII diagnostic in TEXTOR is estimated to be ~10^9 for excited and 10^{12} for ground state deuterium atoms in a cubic meter. In a steady state conditions the sensitivity can be additionally improved by about the order of magnitude after averaging quenching signals along a laser pulse train.

5. Conclusion

TS diagnostics equipped with a multipass intracavity laser probing system provides not only perfect TS measurements, but opens new applications of the diagnostic for studies of tokamak plasmas from measurements of the electron energy distribution, plasma current density, electron density and temperature fluctuations, TS measurements at very low plasma density and local measurements of neutral hydrogen atom density.

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