# DEVIATIONS FROM MAXWELLIAN ELECTRON DISTRIBUTION IN THE RECONNECTION REGION OF MAGNETIC ISLANDS IN THE TEXTOR TOKAMAK

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## Introduction

An experimental study of magnetic islands requires local measurements of island structures with high spatial and time resolutions. Such a tool has become available with a Thomson scattering (TS) diagnostic developed in the TEXTOR tokamak [1]. The diagnostic combines a high measurement accuracy (1-2%), high spatial resolution (<1 cm) and fast sampling rate (5 kHz). It is capable to measure a fine structure of electron temperature, density and pressure in and around rotating magnetic islands [2] in TEXTOR (Fig 1-3). The measured structures in the islands reveal the following essential features:

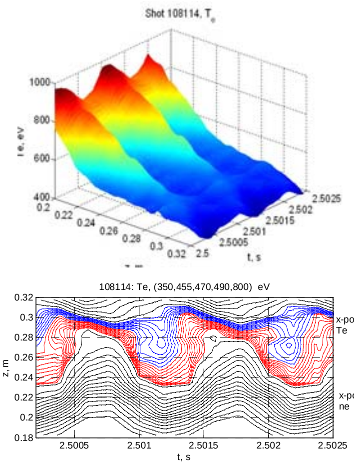


*Fig.1*
*Surface and contour plot of Te*

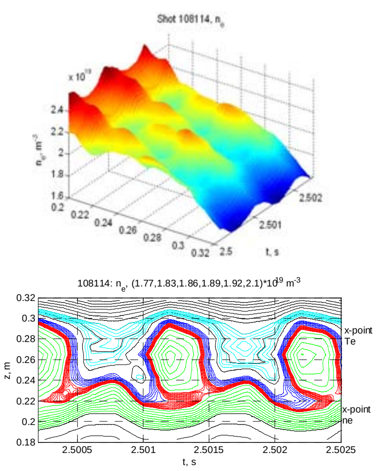


*Fig.2*
*Surface and contour plot of ne*

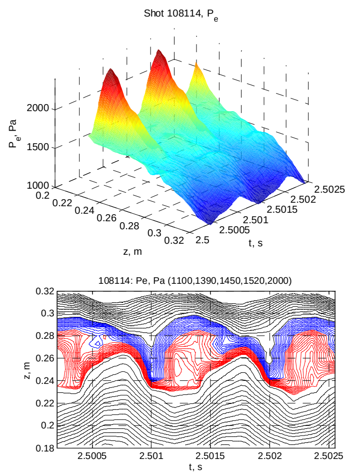


*Fig.3*
*Surface and contour plot of pe*

- X-points of the structures are strongly poloidaly stretched and look like x-lines
- X-points of Te and ne are split radially and both shifted from the island centre
- ne is peaked in the o-point, whereas pe is well flat there.

Asymmetric island structures and splitting x-points can hardly be accounted for diffusion phenomena. The perturbed plasma current density and magnetic structure of the island and they should play an essential role in formation of the island structures. Estimation of the perturbed plasma current from the measured TS spectra is presented in the paper.

## Possibilities of current density measurements by TS diagnostic in TEXTOR

Generally, TS diagnostic can measure electron drift velocity together with routine measurements of Te and ne. For that the drift velocity must have a component along the difference wave vector $\boldsymbol{k_s}$-$\boldsymbol{k_i}$, where $\boldsymbol{k_i}$ is the incident and $\boldsymbol{k_s}$ is the scattering wave vectors of photons. But usually, the sensitivity of TS diagnostics is too low for these measurements.

The TS diagnostic on TEXTOR has a very high sensitivity due to a multipass intracavity laser utilized in the system [3]. Possibilities of plasma current measurements in TEXTOR are mostly determined by the geometry of laser probing and scattered light collection shown in Fig. 4.

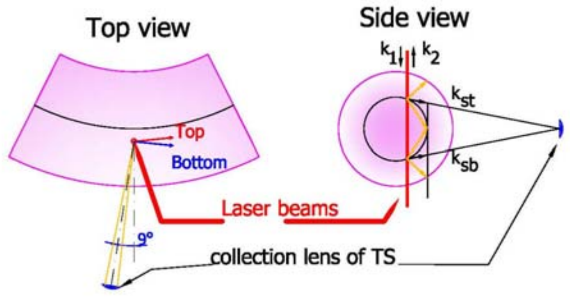


*Fig. 4*
*Geometry of laser probing and light collection of TS on TEXTOR*

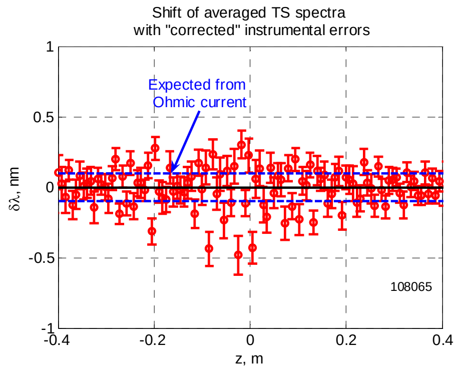


*Fig. 5*
*Statistical deviations of TS spectral shift.*

TEXTOR plasma is probed by laser beams along the vertical axis close to the plasma centre. The laser beam crosses the plasma volume 12 times until it returns back to the laser body. Scattered light is collected by a lens from the whole plasma chord of 0.9 m height nearly perpendicularly to the tokamak toroidal axis. A small tilt of the line of sight from the normal to the toroidal axis makes it possible to measure the electron current drift velocity by the TS diagnostic. In the region of magnetic islands (r~0.2 m) the projection of the current drift significantly changes because of helicity of magnetic field lines.

We assume that the electron current results in the displacement of the TS spectra from the Mattioli shape [4] to simplify the further analysis and catch the effect of plasma current perturbations in the magnetic island. Actually, the electrons in longitudinal electric field are distributed in Spitzer-Harm [5] and the TS spectra should be treated in a different way [6].

The spectral shifts of TS spectra are different for the back and force laser beams:

$$\Delta\omega_i = (\vec{k}_s - \vec{k}_i) * \vec{v}_d \quad i = 1,2; \qquad (\Delta\omega_1 + \Delta\omega_2)/2 = \vec{k}_s * \vec{v}_d = \alpha v_r + \beta v_p + \gamma v_j \qquad (1)$$

Here $\boldsymbol{v}_d$ is the drift velocity projected to the directions of the difference wave vectors of two beams coming up and down $\boldsymbol{k}_i$ and the scattering vector $\boldsymbol{k}_s$. We assume that the resulting spectral shift is the average of those from the two laser beams: $\Delta\omega=(\Delta\omega_1+\Delta\omega_2)/2$. So, the TS diagnostic is measuring the projection of the drift velocity to the scattering direction. A fitting procedure has been developed for measuring the TS spectral shift. The procedure is based on the least square fit of experimental data to the Mattioli spectra in the space of Te, ne and the spectral shift $\Delta\lambda$.

| | α | β | γ |
|---|---|---|---|
| Upper island | 0.1 | -0.7 | 0.14 |
| Lower island | 0.1 | 0.7 | 0.02 |

The projections of the radial, intrinsic poloidal and helical electron drifts to the scattering direction are given in the table for the regions of upper and lower magnetic islands assuming the normal directions of the toroidal current and magnetic field in TEXTOR.

The contribution of the plasma current to the TS spectral shift is 0.14 in the upper island and it is negligible in the lower island. The expected TS spectral shifts for typical Ohmic plasma at the current density 1 MA/$m^2$ and electron density $2*10^{19}$ $m^{-3}$ are ~ 0.1 nm.

Measurements of so small shifts require perfect calibrations of the diagnostic system. It turns out that instrumental errors of the system are about 1 nm in terms of spectral shift and they must be corrected. The correction was done in software. First run of the fitting procedure with an averaged TS spectrum returned the ‘instrumental’ spectral shift. The wavelength base was corrected for the instrumental shifts in each spatial point and then the fitting procedure was run again for individual laser shots with the new wavelengths.

Spectral shifts measured in this way in Ohmic island-free plasma is shown in fig. 5. Each point in the plot was obtained after averaging ~40 pulses in the laser burst. The error bars of these measurements are calculated from the spread of spectral shifts measured in individual pulses of the burst. The statistical errors of spectral shift measurements are estimated to be ~0.1 nm for the full laser burst and 0.6 nm for a single laser pulse.

**Measurements of TS spectral shifts in the island region**

A wide rotating m/n=2/1 islands were created in plasma by AC currents in the DED helical coils of TEXTOR. The rotation period of the island was 1 ms. The TS diagnostic was able to measure during ~nine periods and provided 5 measurements in each period.

Conditional averaging of TS spectra in accordance with their island phases was used for measurements of TS spectral shifts in rotating islands. As the result, the statistical errors of the shift measurements were reduced down to ~0.3 nm. This accuracy makes it possible to discriminate peaks of the spectral shifts located at the inner edge of the m/n=2/1 island. The peaks synchronized with the island o-points are shown in Fig. 6 for the upper and lower islands.

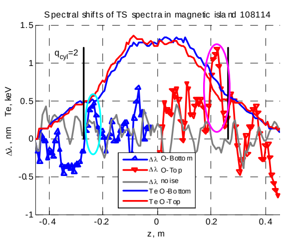

*Fig. 6*
*TS spectral shifts in the o-phase of the islands*

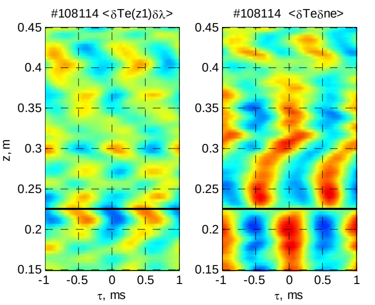


*Fig. 7*
*Te correlations with TS spectral shift (left) and Te*ne correlation (right) in the upper plasma region*

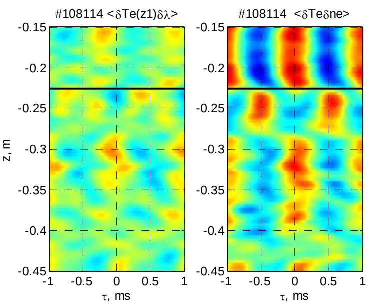


*Fig. 8*
*Te correlations with TS spectral shift (left) and Te*ne correlation (right) in the lower plasma region*

Periodical variations of the spectral shift in the island become clear from their normalized correlations with variations of $T_e$ in the upper and lower islands shown in fig. 7 and 8.

The strongest correlations are located in the layers of ~1 cm wide at z= ±0.23 m. More distinct correlations in the upper region indicate that the periodical spectral shift relates to the helical electron drift or local perturbations of the plasma current density. The blue spectral shift in the island o-point indicates the parallel directions of the perturbed and unperturbed currents.

Weak spectral shift correlations in the lower island (fig. 8) indicate that possible poloidal electron drift in the island are much less than the helical electron drift. This conclusion is in the accordance with the force balance in the island [7] estimated from the experimental data.

Therefore we assume further that the TS spectral shift variations relate to the perturbation of plasma current density induced by a high longitudinal electric field generated in the reconnection regions of the island.

The difference of spectral shifts between the o- and x-points averaged over several discharges is ~0.5 nm. The electron distribution in the electric field is not only shifted but also disturbed to the Spitzer-Harm shape [5]. The perturbation of helical current estimated with taking into account the Spitzer-Harm distortion is in the range $j_i$~0.5-1 MA/m$^2$ which is above the local unperturbed current density 0.5 MA/m$^2$. The island width calculated from this perturbed current ($4r_s\sqrt{\pi\, j_i\, d/(I_s q')}$) well corresponds to the measurements.

The highest current perturbations are located close the inner border of the m/n=2/1 island. In this region, the phase jump of correlations between Te and ne take place as shown in the right plots in fig. 7 and 8. There are two weaker perturbations in the island visible in the correlation plot of fig. 8. But their amplitude can hardly be measured because of noises. A few weaker current perturbations are visible also in the neighboring upper island m/n/=3/1.

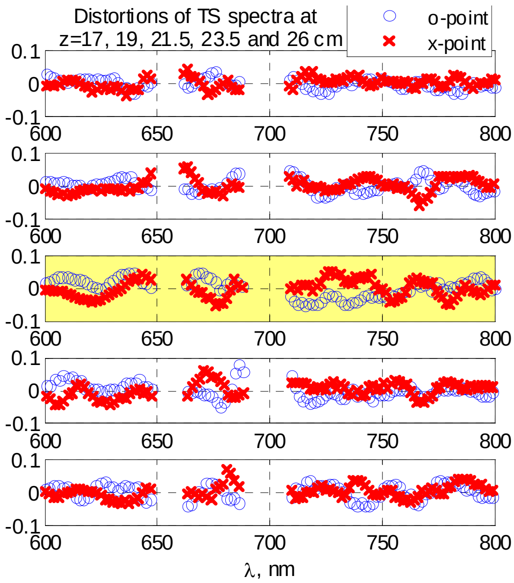


*Fig. 9*
*Deviations of TS spectra from the Mattioli shape*

Deviations of the averaged spectra from the Mattioli shape around the current perturbation in the upper m/n=2/1 island are shown in fig. 9. The spectra marked by the red crosses are measured in the x-phases and other spectra marked by the blue circles are measured in the o-phases of the island. The deviations of four spectra around z=0.215 m are at the statistical level. The TS spectra measured in the region of the current perturbations (z=0.215 m) show visible deviations from the Mattioli shape which indicate violated Maxwellian electron distribution in the region.

## Acknowledgments

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## References

1. M.Yu.Kantor et al. Plasma Phys. Control. Fusion 51 (2009) 055002
2. M.Yu.Kantor et al. Proc. of the 37th EPS and Plasma. Phys. Dublin, Ireland, P4.134 (2010)
3. M.Yu.Kantor and D.V.Kouprienko. Rev. Sci. Instr. 70, 780, (1999)
4. M.Mattioli. EUR-CEA-FC-752 (1975)
5. L.Spitzer and R.Harm. Phys. Review, 89, 977, (1953)
6. S.E.Serge. Plasma Physics, 20, 287, (1978).
7. G.Bateman. MHD instabilities. Cambridge, Mass., MIT Press, 1978.