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Analysis of ArXVII spectra during sawtooth crashes in TEXTOR-94 discharges with a high-resolution x-ray polarimeter

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Introduction

Plasma polarization spectroscopy has frequently been used to measure non-thermal components in the velocity distribution of the electrons [1]. In the x-ray spectral range, the method has been utilized to interpret the spectra of the Yohkoh satellite and to study the physics of solar flares. Plasma polarization spectroscopy has, however, not yet been applied to the hot plasma core in high temperature tokamak experiments, even though some of the wave heating and current drive mechanisms as Electron Cyclotron Heating / Electron Cyclotron Current Drive (ECRH/ECCD) or Lower Hybrid Heating produce large fractions of non - thermal electrons, which need to be analyzed.
At TEXTOR-94, an x-ray polarimeter has been installed to investigate the resonance lines and their satellites of He-like impurities under well diagnosed conditions. In future the polarimeter will be used to analyze plasmas with ECRH/ECCD, where non-Maxwellian electron distributions will exist. A gyrotron system for ECRH/ECCD has recently been put into operation by the Netherlands partners in the TEC. Up to now, the experiment was utilized to study the diagnostic potential of x-ray spectroscopy at He-like ArXVII, to determine the transport properties of hot plasmas and to search for polarization effects in discharges with ohmic heating [2]. However, no polarization effects were found in ohmic discharges [3]. Non-Maxwellian electron distributions are also not expected in the quiet phase of the discharges with neutral-beam heating. In this study, it is shown that also at the sawtooth crash, no plasma polarization is observed.

Experiment

The x-ray polarimeter at TEXTOR-94 consists of two Bragg crystal spectrometers in Johann configuration. The plane of dispersion of the ‚horizontal spectrometer‘ coincides with the equatorial plane of the torus, while the dispersion plane of the second (vertical) spectrometer is oriented perpendicular to the equatorial plane. The principle of the instrument is based on the dependence of the crystal reflectivity on the polarization of the x-ray radiation. For a Bragg angle of 45°, the reflectivity is zero for radiation polarized in the dispersion plane, i. e. the π component. For the quartz crystal cut in the 110 plane and ArXVII transitions, which are observed at a Bragg angle of 54°, the ratio between the reflectivities of the σ and π components is 7, see Fig 1b. The vertical spectrometer is sensitive to radiation polarized in toroidal direction, whereas the horizontal spectrometer favours vertically polarized radiation. Both spectrometers observe approximately the same plasma volume, since the apertures were chosen to provide similar solid angles. The x-ray radiation is detected by two multi-wire proportional counters with a resolution of 0.6 mm, resulting in a spectral resolution of $\lambda/\Delta\lambda$=5300 for the horizontal spectrometer and of $\lambda/\Delta\lambda$=6000 for the vertical spectrometer. The resolution of the detectors were chosen as a compromise between spectral resolution and high count rate capability of 400 000 counts / s.

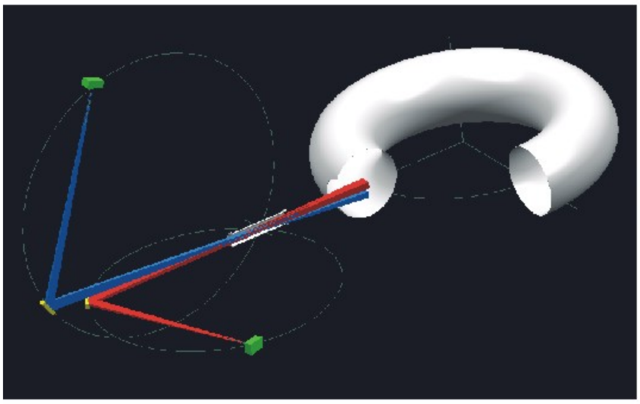

Fig 1a): *Experimental arrangement of the X-ray Johann spectrometer / polarimeter at TEXTOR-94.*

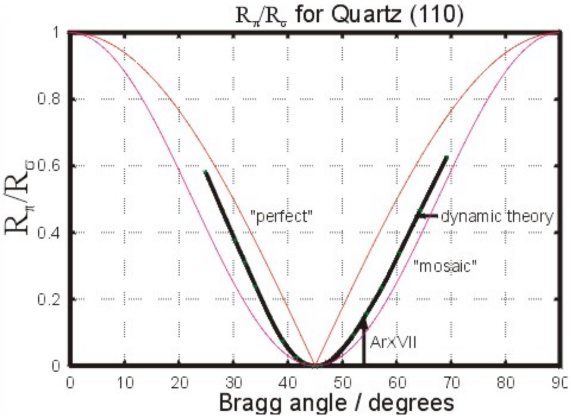

Fig 1b): *Ratio of reflectivities for π and σ polarized radiation obtained from dynamic theory [3]. Compare to frequently used approximations for perfect ($|\cos 2\theta|$) and mosaic crystals ($(\cos 2\theta)^2$).*

A series of discharges in deuterium plasmas with neutral beam heating, and with plasma currents of 390 kA and with electron densities of 3.7×10^{19} m^{-3}, was designed to provide sawtooth instabilities with regular amplitudes and periods as well as broad emission profiles, in order to minimize profile effects. During constant plasma conditions, spectra of both the horizontal spectrometer and the vertical spectrometer were taken with time resolution of 0.5 ms. The times of the sawtooth crashes were found by detecting the maximum slope of the electron temperature signals, obtained from the Electron Cyclotron Emission (ECE) diagnostic. Sawteeth, which differed by more than 5% in amplitude or period, were excluded. The x-ray spectra were then grouped with reference to the sawtooth crashes, providing for each spectrometer 50 high quality spectra relative to the sawtooth with effective time resolution of 0.6 ms.

The spectrum of the n=2 -> 1 transitions in He-like Argon is dominated by the resonance line **w**: $1s^2\ ^1S_0$ -$1s2p\ ^1P_1$, the intercombination lines **x**: $1s^2\ ^1S_0$ -$1s2p\ ^3P_2$, **y**: $1s^2\ ^1S_0$ -$1s2p\ ^3P_1$, and the forbidden line **z**: $1s^2\ ^1S_0$ -$1s2p\ ^3S_1$, and includes a large number of Li-like satellites due to the transitions $1s^2nl$ - $1s2pnl$ with $n\geq2$. Line emission is polarized due to the alignment of the ion with the colliding electron during the excitation process. the polarization vanishes in isotropic electron velocity distributions. However, if the ions are excited by a beam of electrons, a net polarization is observed. Fig 2 shows the expected polarization of the lines w, x, y, as calculated for Fe. The polarization is maximum for electrons close to the threshold for collisional excitation. The polarization vanishes for high energies. The forbidden line z is not polarized.

The natural procedure to determine polarization would be to normalize the lines w, x, and y in both spectrometers to the unpolarized line z. However, in hot plasmas the z line is populated by a large number of processes. Besides direct excitation from the ground state, the z line has contributions from cascades of higher excited levels, from cascades due to recombination of H-like ions and from inner shell ionization of Li-like ions. Additionally, the strong j satellite of Li-like Argon coincides with the z-line.

Therefore, an alternative approach was chosen. The spectra were obtained by fitting a theoretical model of the spectra to the experimental data. The model included direct excitation, and cascades, radiative recombination, dielectronic recombination and inner shell excitation. The intensity was calculated for each radial position and integrated over the line of sight for both spectrometers, the central line of sight and time averaged values for the background plasma were chosen. Atomic data for Ar were obtained by scaling the data for Ca calculated by F. Bely-Dubau et. al [6] according to Mewe and Schrijver [7]. The wavelengths of the resonance lines and the satellites were measured at the Livermore EBIT source, line components not resolved in the EBIT experiment were scaled appropriately.

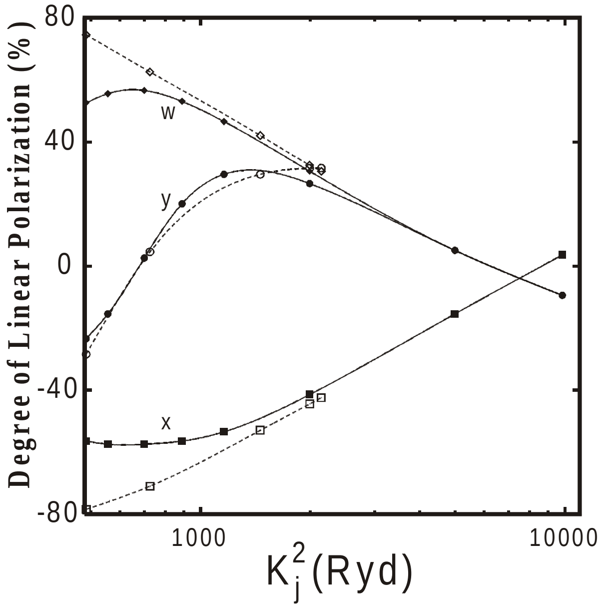

Fig. 2: Polarization degree for the lines **w**, **x**, and **y** for heliumlike iron as calculated by Inal and Dubau [5]

The fit provides measurements of the ion temperature, the electron temperature and the relative concentration of Li-like and H-like to He-like ions. The experimental spectra are well approximated by the model spectrum over the full range, except for the x and y intercombination lines, where scaling factors are required. The scaling factor is around 1 for the x line and about 0.75 for the y line. These scaling factors are independent of temperature and reflect the inaccuracies of the atomic data.

Results and discussion.

The results for both spectrometers are shown in Fig 3. The fits show the amplitudes of the w line, the electron temperature as well as the scaling factors for the x and y lines both for the vertical and the horizontal spectrometer. Polarization at the sawtooth crash should show up in a sudden change of the scaling factor during or just after the sawtooth crash. Within the resolution of the measurement, no change in the relative intensities was detected. Even though the average values of the scaling factors and hence the intensities are higher for the vertical spectrometer than for the horizontal spectrometer, this cannot be attributed to polarization due to directed electrons. In discharges with neutral beam heating and hence low loop voltage, there is no mechanism to accelerate the electron permanently to high energies. Only during the sawtooth crash, there could be fields caused by rearrangements of the internal poloidal magnetic field, inducing temporary current sheets. Since sudden changes of the scaling factors ar not observed at the time of a sawtooth crash, we conclude that non-thermal electrons are either absent or that they cannot be detected by the x-ray polarimeter.

The remaining slow variations of the scaling factors are most probably due to the radial variation of the line emission which is not measured yet. This will be taken into account by using an imaging Bragg spectrometer for the horizontal system.

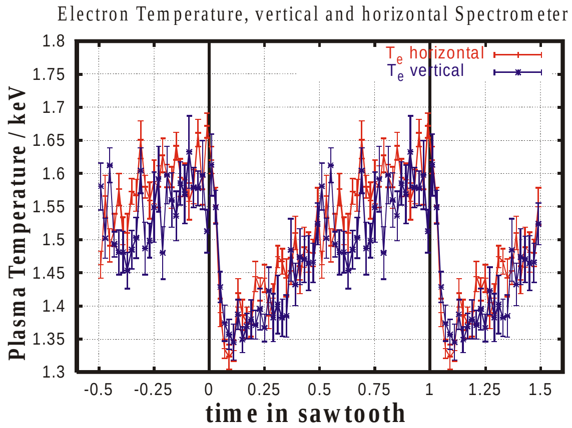

Fig 3a) Electron temperature $T_e(0)$ during the sawtooth derived from the horizontal (red) and the vertical (blue) spectrometer

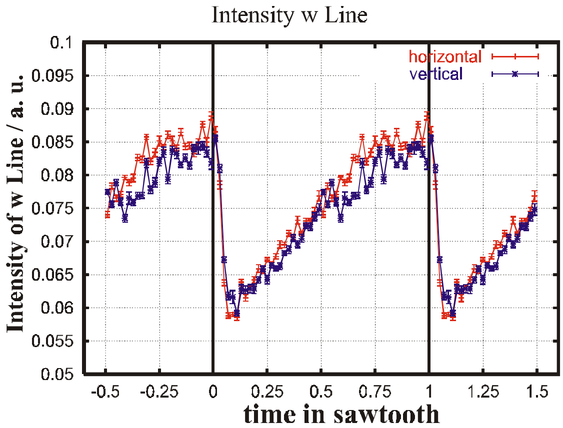

Fig 3b) Intensity of the w line in the horizontal (red) and the vertical (blue) spectrometer

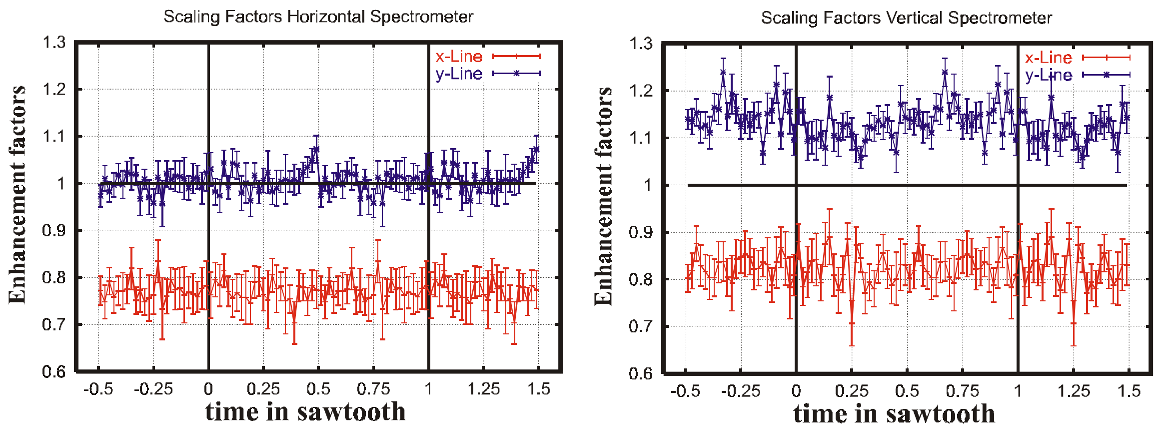

Fig 3c) Scaling factors for the x-line (red) and the y line (blue) for the horizontal (left) and the horizontal spectrometer (right)

References :

1. T. Fujimoto and S. Kazantsev, Plasma Phys. Control. Fusion **39**, 1267 (1997)
2. G. Bertschinger, W. Biel, Textor-94 Team, O. Herzog, J. Weinheimer H.-J. Kunze and M. Bitter, Physica Scripta Vol. **T83** 132-144, 1999
3. J. Weinheimer, O. Herzog, G. Bertschinger, M. Bitter and H.J. Kunze, 25th Eur. Phys. Soc. Conf. Controlled Fusion and Plasma Physics Prague, p 1522, (1998)
4. S. A. Stepanov, http://sergey.bio.aps.anl.gov/xoh.html
5. M. K. Inal and J. Dubau, J Phys. B: At. Mol. Phys. **20**, 4221 (1987)
6. F. Bely-Dubau, J. Dubau, P. Faucher, A. H. Gabriel, M. Loulergue, L. Steenman-Clark,, S. Volonte, E. Antonucci and C. G. Rapley, Mon. Not. R. Astron. Soc. **201**, 1155 (1982)
7. R. Mewe, J. Schrijver, and J. Sylvester, Astron. Astrophys. Suppl. Ser. **40**, 323 (1980)