*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.117 (2002)*

Study of Hot Plasma at the GOL-3 Multiple Mirror Trap by High Resolution Spectrometry

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Introduction

Researches on heating and confinement of dense (~10^{15} cm^{-3}) plasma in multimirror trap are carried out at the GOL-3 facility in Budker Institute of Nuclear Physics [1]. Plasma is heated by relativistic electron beam (energy content up to 200 kJ, duration up to 8 μs), which is injected in preliminary created cold deuterium plasma. The beam releases effectively its energy in the plasma due to collective interactions so that the electron temperature after the heating reaches ~2 keV. Recent experimental results from the GOL-3 facility are presented in the report [2].

Important information about basic plasma parameters such as electron and ion temperatures, density, impurities structure and dynamics may be obtained from the analysis of spectrum of plasma radiation. Therefore a diagnostics for plasma spectroscopy, which includes high-resolution spectral system and survey spectrometer, is developed at the GOL-3 facility. These diagnostics have been exploited for measurements of density and ion temperature dynamics as well as for impurities dynamics study.

Set of plasma spectroscopy diagnostics.

Scheme of the plasma spectroscopy set is shown in Fig.1. It includes two spectral devices - the high-resolution spectrometer and the spatially resolving survey spectrometer, placed at the same plasma crossection from opposite sides.

The survey spectrometer serves for obtaining of spectrum of plasma radiation in a wide range of wavelengths (35 nm) with the moderate line dispersion (3.2 nm/mm) and for chord measurements of lines emission. For recording of spectra the CCD-camera is used in integrated mode. The spectral resolution of the device is of 0.6 nm.

In the high-resolution spectral system the double grating imaging spectrograph DFS-24 used. This device consists of two successively placed grating monochromators. Total dispersion of the device is 0.45 nm/mm and spectral resolution achieved in the experiments is 0.04 nm. Plasma radiation spectrum is simultaneously recorded by two detectors. The first detector is ten channels quartz fiber assembly coupled with PMT array. Signals from PMTs are digitized with 1 MHz sampling rate. The width of each collector is 200 microns that determines the instrumental width of 0.07 nm. This detector allows to measure contours of spectral lines with good temporal and moderate spectral resolution.

For accurate record of contours of spectral lines the image converter tube (ICT) is used. The image of a spectrum amplified by ICT is recorded by the CCD-camera. ICT serves also as a shutter with programmable 1-100 μs frame duration. A spectral range of 0.01 nm corresponds to the one pixel of the CCD-camera, thus the instrumental width is determined by DFS-24 spectrometer. This detector in a frame mode allows to precisely record contours of spectral lines.

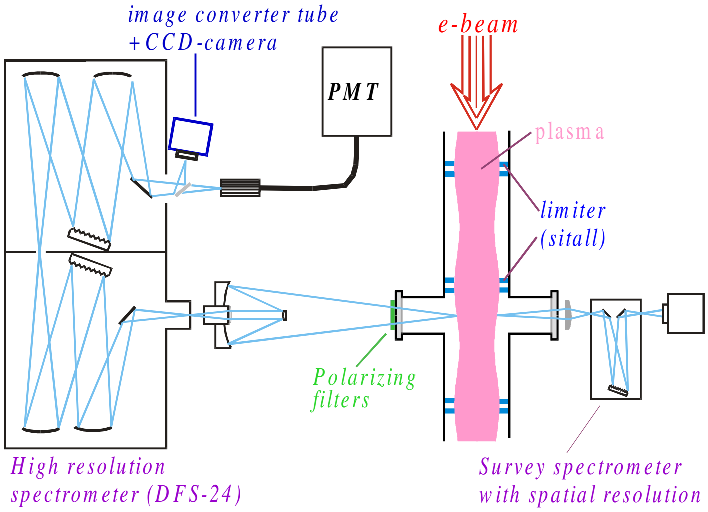

Fig.1. Scheme of spectral diagnostics.

Plasma radiation is focused on the entrance slit of the device by an objective with main parabolic mirror of 230 mm diameter. Window of vacuum chamber is covered with polarizers in order to select required component of a line. A part of shots was done with one half-frame set to a σ-component and other half-frame – to a π-component relative to confining magnetic field. Simultaneous separate measurement of both components gives additional confidence in the case of complex spectral lines. An example of Na I lines in magnetic field 4.4 T is shown in Fig.2. The optical fiber detector is exposed only by π–polarized light.

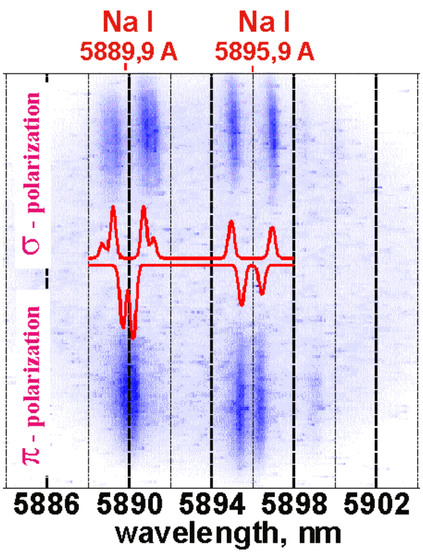

Fig.2 Frame of CCD-camera

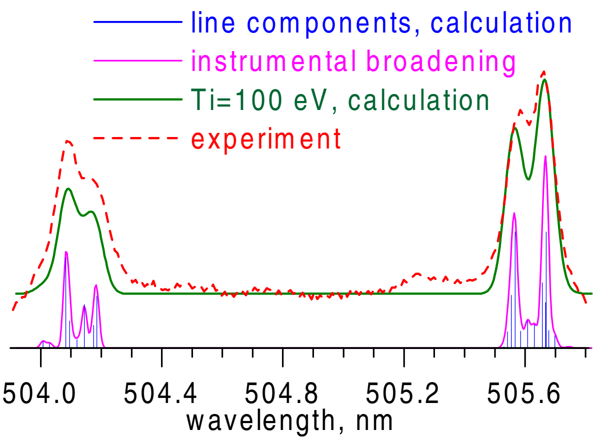

Fig.3 Zeeman splitting and Doppler broadening of σ-component of Si II line.

Ion temperature measurement by broadening of impurity ions spectral lines.

The appearing, dynamics and spatial distribution of impurity lines were observed by the spectral diagnostics. Brightest impurity lines belong to atoms and single-charged ions of elements which origin from limiters - to lithium, silicon, sodium, carbon and titanium. Maximal radiation power is emitted from the relatively cold plasma edge. Thus, measurements of temperature by broadening of brightest spectral lines gets under estimation of ion temperature of edge plasma. In Fig.3 the contour of σ-component of doublet of Si II ion (504.10 nm, 505.60 nm) is given. The bottom diagram shows components of Zeeman splitting in magnetic field 4.4 (position of lines corresponds to wavelength, and height - to relative intensities). Above of it the calculation only of instrumental broadened line contour is shown. Instrumental function corresponds to ion temperature 30 eV. On the top diagram measured contour of the line and calculated contour for temperature 130 eV are shown. Thus, ion temperature is 100±30 eV for this measurement.

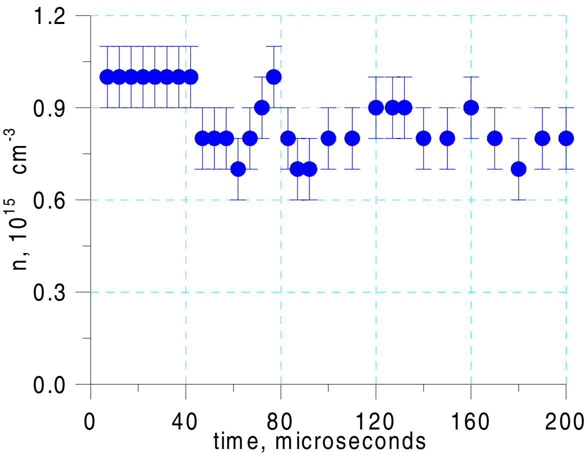

Fig.4.Electron density obtained from Stark broadening of H_β line.

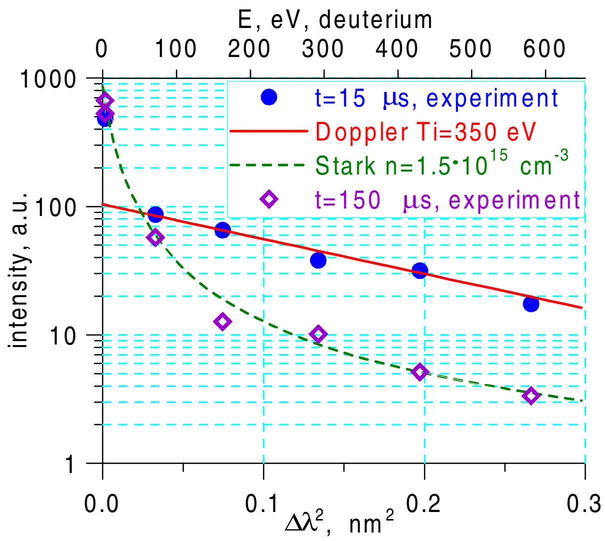

Fig.5 Contours of D_α line measured at 15 μs and 150 μs after REB injection in one shot with calculation of Doppler and Stark contours.

Measurement of plasma density and ion temperature dynamics.

The theory predicts [3] that shape of hydrogen line H_β is more sensitive to plasma density changes in comparison with H_α line. As we used deuterium work gas, we used the analysis of D_β contour for electron density measurements (see Fig.4). Obtained data agree with measurements of density by interferometer and Thomson scattering. It is important to notice, that a density during operating time of facility does not exceed of 1.5×10^{15} cm^{-3}. At the

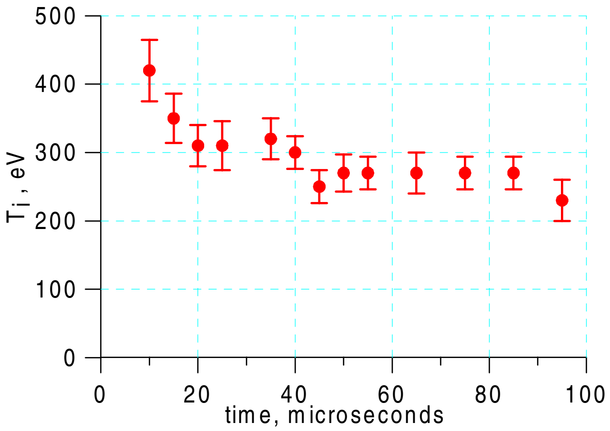

Fig.6. Dynamics of ion temperature.

same time D_α line contour essentially differs from calculated for such density. Fig.5 shows the contours of D_α spectral line measured at 15 µs and 150 µs after beginning of beam injection in depending on kinetic energy of radiating atom. Points and boxes show the measured contour, the straight line is Gauss curve corresponding to radiation of deuterium atoms with temperature 350 eV, dotted line - Stark profile of line for density 1.5×10^{15} cm^{-3} calculated as described in [4]. The line contour at 15 µs is better fitted by Gauss curve, therefore we receive radiation of neutrals from hot plasma and able to find ion temperature. Dynamics of ion temperature measured by broadening of D_α spectral line is shown in Fig.6. Maximum temperature is close to 500 eV just after the beam injection ends and exceeds 200 eV for at least 100 µs. After 100 µs temperature measurements become impossible due to domination of Stark broadening.

Conclusion.

The set of diagnostics for plasma spectroscopy is created at the GOL-3 facility. Measurements of plasma density dynamics by D_β line are carried out. Ion temperature measured by deuterium lines broadening is up to 500 eV. Confinement time of hot plasma is more than 100 µs.

Plasma edge is investigated by impurities lines. The temperature achieves 100 eV. Chord measurements of intensity of impurities lines shows that radiation power is mainly emitted from plasma edge and spectral lines belong to elements, which are containing in limiters.

References

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