STUDY OF PLASMA ON THE GOL-3 FACILITY BY IMAGING VUV SPECTROSCOPY

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The series of experiments on plasma heating by the electron beam of reduced diameter was carried out at the GOL-3 facility. To define the size of a high-temperature plasma region the imaging VUV spectrometer was used in these experiments. In the paper the description of the diagnostic system, the results of measurements, the comparison with simulation data of the ionization balance are presented. Estimations of transverse diffusion and macroscopic movements of the beam are discussed.

I. INTRODUCTION

Multi-mirror approach to plasma confinement for fusion is studied at the GOL-3 facility (BINP, Novosibirsk, Russia). A plasma of $10^{20}\div10^{22}$ m^{-3} density is confined in a 12-meter-long solenoid, which produces an axially periodical (corrugated) magnetic field. In the basic operation regime the solenoid consists of 55 magnetic cells with B_{max}/B_{min}= 4.8/3.2 T (mirror ratio R = 1.5). The plasma is heated by a high power relativistic electron beam up to 1-2 keV at a density of about 10^{21} m^{-3}. Energy confinement time is about 1 ms.

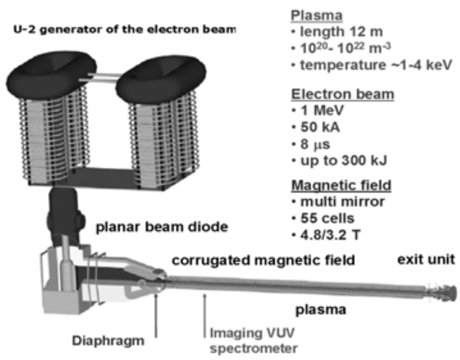

Fig. 1. Scheme of the GOL-3 multi-mirror trap

The series of experiments on plasma heating by the electron beam with reduced diameter was carried out at the GOL-3 facility [1]. To define the size of a high-temperature plasma region an imaging VUV spectrometer [2] was used in these experiments. The spectrometer allows to measure the chord distribution of the radiation power of spectral lines of plasma impurities. The comparison of spectral line profiles of ions in different charge states (exactly OII - OVI) allows to find the dimension of the beam-heated area of the plasma.

II. LAYOUT OF EXPERIMENTS

The development of experiment on the GOL-3 facility is follows. After filling the vacuum chamber with the working gas (deuterium) an electric discharge is ignited and the current flowing along the facility produces a preliminary foreplasma with temperatures of 2-10 eV. This discharge stage last about 30 μs. Then a high-power relativistic electron beam (1 MeV, 20 kA, 10 μs) is injected in to the plasma at one end of the facility. Plasma electrons in the beam cross-section rapidly heat up to 0.5-1 keV and cool down within ~1 ms after beam injection.

The experiment with reduced diameter electron beam was performed with a graphite diaphragm mounted in the beam compression unit near the entrance to main part of the trap. This diaphragm cuts central part of the beam leading to a diameter in the center of the facility (in the magnetic field 4 T) of 13 mm. The diameter of the foreplasma column is 7 cm and determined by the diaphragm at the end of the facility.

The feature of discussed experiments is the possibility to inject the beam not only into the foreplasma, but also into the neutral gas without initial ionization. Such injection doesn't provoke a destruction of in-vessel diagnostics or detectable disruption of the plasma. At the same time the well-known Kruskal-Shafranov condition is not satisfшув in that case that means that plasma should be macroscopically unstable.

The imaging VUV spectrometer [3] was used for the study of the radial plasma dimensions. In the described experiments the spectrometer was placed in a distance of

2 m from the entrance plug of the facility. The spectrometer allows to record a VUV spectrum of plasma radiation with a spatial resolution across the plasma column (see Fig. 2). The working spectral range of the spectrometer is 50–400 nm, the spatial resolution is always less than 5 mm. In the presented experiments the spectrometer operates in continues-wave mode where the recorded spectra is integrated over duration of the shot.

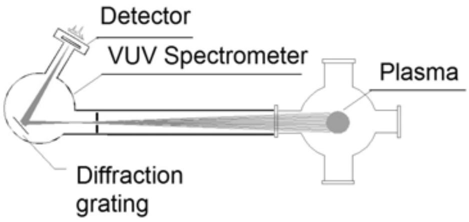

Fig. 2. Scheme of the VUV imaging spectrometer and Seya–Namioka optical scheme

III. RADIAL PROFILES OF SPECTRAL LINES

Three different regimes with thin electron beam are investigated by VUV imaging diagnostic. These are the injection of the electron beam into the neutral gas (A) and preliminary plasma with initial density of $2\cdot10^{14}$ cm^{-3} (B), and beam injection to plasma with increased (up to 10^{15} cm^{-3}) initial density (C). Further those regimes will be denoted as A, B, and C.

The spectral region 55-100 nm was chosen for the measurements. Two dominating spectral lines in this region are OV 62.9 nm and OV 76.0 nm. Typical images obtained with the diagnostics for those three regimes are presented in the Fig. 3. In the regime B the specific dimensions of radiated area (measured by OV line radial distribution) exceeds 6 cm and is comparable with the dimensions of the preliminary plasma column. The images of spectra in the shots with beam injection and with preliminary plasma are practically identical.

For the regime A (beam injection to neutral gas) the dimension of radiated area is sufficiently smaller and lies in the range 1.5-2 cm. The dimension and position of radiating area for a sequence of shots in this regime is shown in the Fig. 4. by a gray scale together with the calculated dimension of electron beam at the registration point. In most shots the dimension of the radiating area is close to the size of the beam. At the same time there are several shots with sufficiently increased size of the plasma that may be caused by unstable passing of the beam.

On the images taken in the regime C two areas of plasma are clearly seen. These are a cold periphery detectable by spectral lines of low-ionized ions and a hot core with intensive OV spectral lines. The size of this hot core is close to the plasma dimensions in the regime A, whereas the size of periphery is identical with the plasma in the regime B.

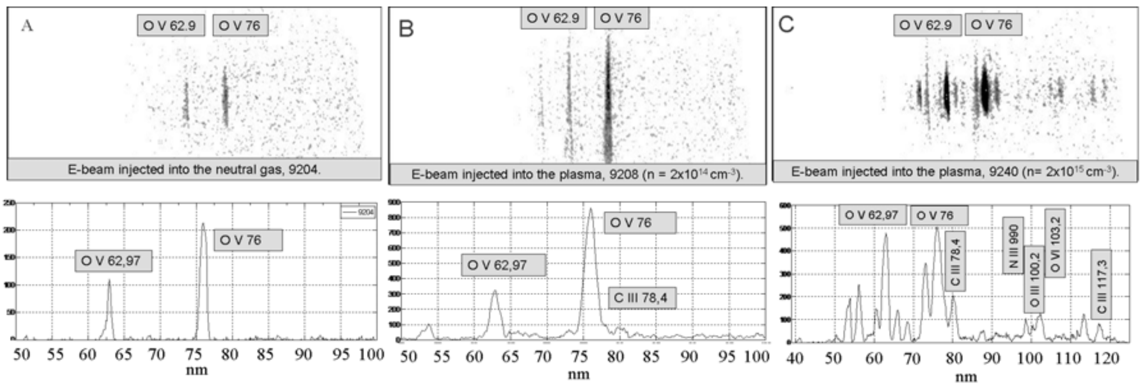

Fig. 3. Top row: spectral images Y-axis spatial distribution, x-axis wavelength; lower row: radially integrated line intensity scan vs wavelength

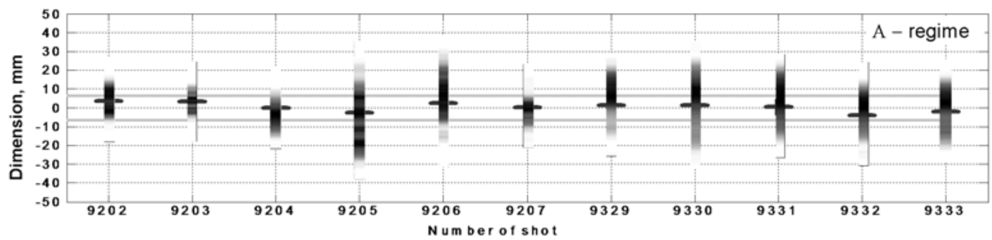

Fig. 4. Dimension and position of radiating area

IV. DISCUSSION

Calculations of ionization balance for oxygen ions were performed to explain of the experimental results. In the calculation defined a linear grow of temperature up to a maximum value within 10 μs was assumed that stays constant for additional 500 μs. Calculations were produced for maximal temperatures of 8, 10, 15, 25 eV. Such definition of a temperature dynamics allows a rough estimation of the oxygen ionization balance in preliminary plasma and initial phase of beam heating of the gas or the plasma.

Te dynamics of the oxygen OV 76.0 nm spectral line for the defined temperature dynamics with maximal temperatures 8, 10, 15, 25 eV are presented in the Fig. 5. As seen from this picture the emission of this spectral line appears in the plasma after 100 μs for Te=8 eV and after 10 μs for Te=25 eV. So, if the preliminary plasma temperature exceeds 8 eV it will radiate the interested OV line.

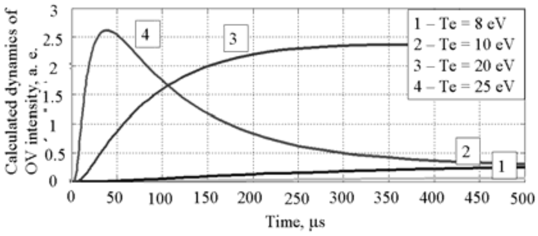

Fig. 5. Dynamics of the oxygen OV spectral line

The density dependence of the electron temperature of preliminary plasma was measured previously by nitrogen spectral lines intensity ratio (NIII/NII) and by laser scattering system (Fig. 6). As follows from this figure, for regime A the temperature of preliminary plasma exceeds 10 eV, as a consequence the OV lines are excited in the column of preliminary plasma. Beam-heated zone is shouldn't identified at the image in this regime out of a preliminary plasma background.

For shots with a density $10^{15}cm^{-3}$ (regime C) the preliminary plasma temperature is insufficient for ionization of oxygen into an OV ion and the studied lines excited only in beam-heated zone. The same situation is valid for beam injection into neutral gas (regime A), where there is no plasma outside of the beam transport zone.

Thus for regimes A and C intensity profiles of OV lines correspond to dimensions of the beam-heated area of the plasma. There even weak heating of the plasma periphery (20 eV only) should cause a broadening of the profiles; that means the profile of studied line is very sensitive to transverse energy transport of the particles.

In the stable shots observed the dimensions of the hot core are close to the calculated diameter of the beam, hence there is no sufficient transverse transport in this case. Using the data of the hot core dimensions (1.5 cm) and the characteristic lifetime of plasma (100 μs – from optical emission observations) it is possible to derive an upper estimation for the diffusion coefficient in plasma of 2 m^2/s.

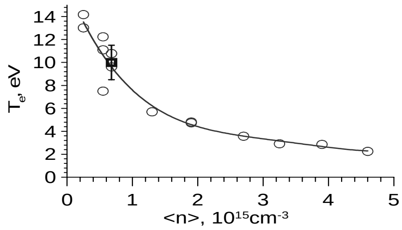

Fig. 6. Density dependence of electron temperature in the preliminary plasma measured by nitrogen spectral lines intensities ratio (NIII/NII) (circles) and by laser scattering (square).

V. SUMMARY

The series of experiments on plasma heating by the electron beam with reduced diameter was carried out at the GOL-3 multi-mirror trap. The results of the measured plasma spectrum from an imaging VUV spectrometer in different regimes of the GOL-3 operation and comparison these results with simulation data of the ionization balance are presented. The size of a high-temperature plasma region is studied and the dimension and position of the reduced electron beam are defined. In the stable shots observed dimensions of the hot core are close to the calculated diameter of the beam, hence there is no sufficient transverse transport in this case. The upper estimation of transverse diffusion coefficient is derived to 2 m^2/s.

Regular measurements of line profile position indicate shot-to-shot transverse movement of the beam at the measuring location. The characteristic scale of such movements is about half of the beam diameter. Such shifts indicate a lack of global stability of the beam. At the same time beam movements are slow enough so that they don't cause an increase of hot core dimensions.

ACKNOWLEDGMENTS

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REFERENCES

1. V.POSTUPAEV et al. This conf.
2. A.BURDAKOV et al. Instruments and Experimental Techniques 47, p.234 (2004).
3. I.IVANOV et al. Proc. of OS-2004 Conf., Novosibirsk, Russia, 5-9 July 2004, (2004).