Impurity transport studies on the Globus-M tokamak

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Introduction

Accumulation of impurities in the plasma core of magnetic-confinement fusion device can lead to substantial fuel dilution and plasma cooling through radiation that ultimately results in deterioration of plasma confinement. Exploration of impurity transport is essential to understand mechanisms of impurity behaviour in the plasma. Such investigations in a spherical tokamak can broaden the existing knowledge for conventional tokamaks to low aspect ratio and high beta regimes.

Experimental setup

The paper presents analysis of radial transport properties of intrinsic carbon in ohmic discharges in the spherical tokamak Globus-M with major radius R=0.36 m and aspect ratio A=1.5. Plasma parameters for the discussed discharges were: 200 kA plasma current (I_p), 0.4 T toroidal magnetic field (B_T) and I_p=250 kA, B_T=0.5 T, safety factor at the 95% magnetic flux surface q_{95}=4.6. Plasma had configuration with 1.9 elongation, 0.35 average triangularity. For spatial measurements of radiation losses in a poloidal cross-section the 24-channel linear array based on SPDs (Silicon Precision Detectors [1,2]) was constructed and installed in the equatorial port of the tokamak. The 1×24 SPD array has 3,5×55 mm^2 and 55×22×3,5 mm^3 dimensions of the front end and amplifier board respectively. The linear array and the 16×16 tangential SPD matrix array [3] were used for the plasma emissivity profile reconstruction.

2D plasma emissivity profile reconstruction

One can see the lines of view projections on the poloidal cross-section for the 16×16 tangential camera and lines of view of 1×24 poloidal linear array in figure 1a. Measured brightnesses for each chord are also presented in the figure for the shot #37060 (I_p=200 kA, B_T=0.4 T). The projections were used to calculate coefficient matrix for the 2D plasma emissivity profile reconstruction with the square pixels as local basis functions (mesh with 3.2 cm side in figure 1a, b). For the regularization Tikhonov method with the discrepancy principle was used. The solutions that were not smooth on the poloidal magnetic fluxes were penalized using anisotropic diffusion model [4]. The model helps properly estimate the radiated power from the main plasma volume as high radiation levels, for example in the divertor area or near the limiter, can be reconstructed even with the restricted number of lines of view. Resulted reconstructed 2D plasma emissivity profile using developed method is shown in figure 1b. It should be taken into account that artefacts always present in the reconstructed image, so a trade-off should be made between low residuals and physical reliability of the solution.

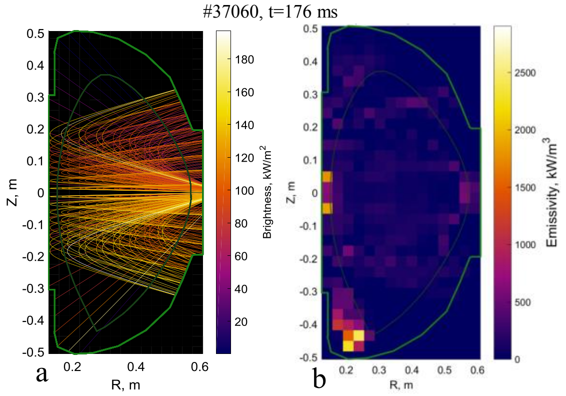

Fig.1. Shot #37060, I_p=200 kA, B_T=0.4 T. a) projections on the poloidal cross-section for the 16×16 tangential array and lines of view for the 1×24 array with the corresponding measured brightness's and b) reconstructed 2D emissivity profile.

Experimental and modelling results

Plasma radiation losses and other parameters were investigated during plasma current and toroidal magnetic field scan at constant q_{95} in the discharges for deuterium plasma species in the H-mode confinement regime. Electron density and temperature profiles were measured by Thomson scattering (TS) diagnostics. Density profile was the same in the discharges with average value along central chord $\langle n_e \rangle_{ch}=4.2\cdot10^{19}m^{-3}$. Core electron temperature increased by ~50% in I_p=250 kA, B_T=0.5 T shots relatively to shots with I_p=200 kA, B_T=0.4 T mainly due to I_p rise. The TS profiles for two discharges are shown in figure 2. The ion temperature was measured by neutral particle analyser; core value was ~ 220 eV and was not changed significantly. The experimental radiation losses profiles averaged over poloidal magnetic surfaces are presented in figure 3. For high field side (HFS) and low field side (LFS) averages were made separately. One can see that in the shots with higher I_p, B_T the plasma core radiates less than for the low I_p, B_T cases. Also modest poloidal asymmetry in radiation is seen – higher emissivity at HFS of the plasma. One of the reasons is that impurities can more easily penetrate from central column

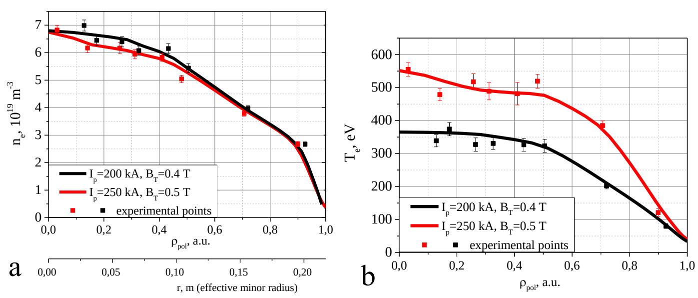

Fig.2. Profiles of a) electron density and b) electron temperature for shots #37060 (black) and #37046 (red); squares –measurements, lines – ASTRA modelling.

of the tokamak due to shorter distance to it and plasma-column periodic contact. Stronger plasma interaction with the central column results in by an order higher radiated power in that region outside LCFS than in the main plasma (fig. 1b). Deuterium gas-puffing from the valve mounted on the central column in the equatorial plane can also lead to higher radiated power at HFS of plasma due to higher neutral density of the main gas.

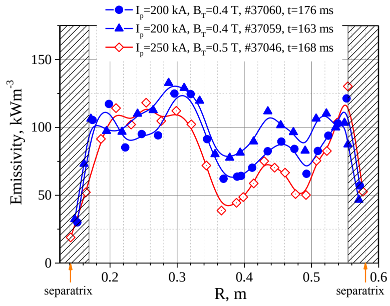

Fig.3. Magnetic surface averaged emissivity profiles inside LCFS in the discharges with I_p=200 kA, B_T=0.4 T and I_p=250 kA, B_T=0.5 T.

To investigate impurity transport behavior and radiation properties in the discussed discharges modelling was performed. Carbon from wall graphite tiles was assumed to be the main intrinsic impurity in the plasma and thus responsible for the measured radiation losses. Although in the considered discharges tungsten plates were installed in the lower divertor plates of the tokamak, comparison of the radiation losses measured by wide-angle single SPD in the shots with all carbon wall and with carbon wall and tungsten plates showed no significant difference in the radiated power of the plasmas (fig. 4). One can suppose that heat and particle fluxes of the plasma were insufficient to cause substantial erosion of tungsten plates and dilution of plasma in the considered discharges. However, W transport from divertor to the main plasma volume and radiation strength of W lines in the tokamak require additional investigation.

Investigation of carbon transport properties during steady state of the discharges was performed using coupled ASTRA [5] and STRAHL [6] codes. STRAHL uses excitation, ionization, recombination rates and radiation characteristics from ADAS database and thus calculates impurity radiated power using collisional-radiative model. It solves 1D transport equation for impurity concentration for each charge state inside LCFS and has simple 2D model for impurity transport in the plasma scrape-off-layer (SOL). Parallel impurity fluxes in the SOL are described by parallel loss time that was determined from connection length and ion flow velocity. Mach number, electron temperature in the SOL were measured using Langmuir probes. The range for carbon influx was calculated through expected radial

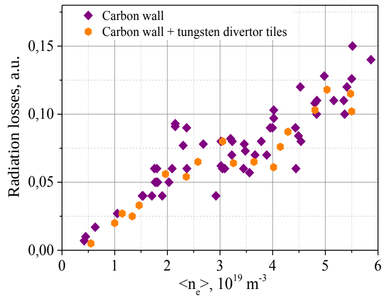

Fig.4. I_p=200 kA, B_T=0.4 T. Radiation losses in ohmic discharges with full carbon wall and with carbon wall with tungsten divertor plates.

flux of main plasma ions (deuterium) on the plasma wall and sputtering yield of graphite about several percents. Exact impurity influx was adjusted to achieve best match between modelled radiation losses profile and loop voltage with the experimental ones. Carbon transport coefficients were assumed neoclassical and calculated using NCLASS module [7]. The modelling revealed that carbon concentrations (about 5% of n_e) required to match measured and calculated plasma loop voltages through conductivity calculation by NCLASS are enough to reproduce the experimental radiation losses, that is another confirmation of negligible tungsten content in the main plasma volume. In the considered regimes carbon ions were mainly in a Pfirsch-Schluter regime. In this regime diffusion coefficient depends on plasma parameters as $D_C^{PS} \sim q^2 m_C n_i T_i^{-0.5} B_T^{-2}$. One can see carbon neoclassical diffusivity in the range of 0.3-1.1 m^2/s for both low I_p, B_T and high I_p, B_T cases in figure 5a. A fall of carbon diffusivity at $\rho_{pol} > 0.9$ toward the plasma boundary reflects the presence of the edge transport barrier, which is seen on the measured electron density profiles. Neoclassical convective velocity of carbon was mainly negative. That inward pinch and low diffusivity are responsible for peaked carbon concentrations. Peaking factors V_c/D_c well coincided with the carbon inverse scale lengths $(L_{nc})^{-1}$ for $\rho_{pol} < 0.95$ as outside that radius neutral carbon source is not negligible. Simulated radiation losses profiles were also hollow (as seen on figure 5b for the shot #37046). Deviations in the profile of modelled radiation losses from measured values can arise due to diagnostics restrictions (nonlinear sensitivity, spatial resolution), reconstruction errors, poloidal asymmetries in the radiated power, as well as uncertainties in the modelling.

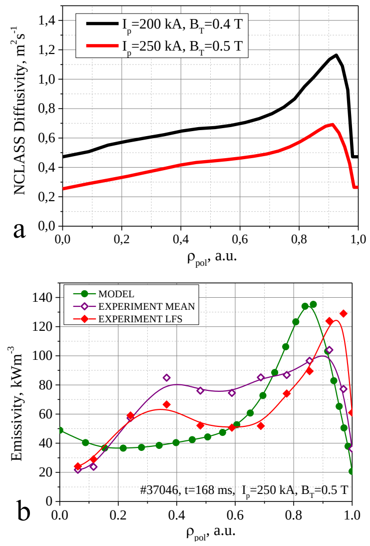

Fig.5. a) NCLASS carbon diffusivity; b) Experimental (for LFS and mean) and modelled radiation losses profile for shot #37046.

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