

Multichannel SPD system for radiated power study on the Globus-M tokamak

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Understanding of physics of plasma-wall interactions, behaviour of intrinsic or injected plasma impurities always has been important for fusion research. Distribution of impurities emission in the tokamak plasma can be effectively studied using multichannel radiation losses measurements. In the paper the reconstruction technique of plasma emissivity relied on chord measurements of radiated power is considered. Radiation losses were obtained by the 16x16 SPD (Silicon Precision Detector) system [1]. The diagnostics is a compact, relatively simple set of linear arrays based on high sensitive absolutely calibrated silicon photodiodes with p-n junction [2,3]. Experiments were performed on the spherical tokamak Globus-M with $B_T=0.4$ T, $I_p<0.25$ MA, $R/a=1.5$ [4].

Profile reconstruction technique

For the reconstruction procedure measurements of radiated power from the linear array of photodiodes in the midplane of the tokamak were used. The SPD array had tangential to the plasma column field of view. The tangency radii of each chord of view are presented in Fig. 1. The uniformity of radiation along plasma magnetic surfaces was assumed. The magnetic reconstruction data was retrieved from the EFIT code. Plasma column was divided into the circular zones with constant emissivity. Thus the discrete form of the problem is the following: $\mathbf{K}\boldsymbol{\varepsilon}=\mathbf{B}$, where \mathbf{K} – is the coefficient matrix, with each element corresponding to the chord length in the particular emission zone, m , \mathbf{B} – vector of chord brightness, measured by each photodiode, W/m^2 , and $\boldsymbol{\varepsilon}$ – is the emissivity vector in each radiating zone, W/m^3 .

Owing to the near singularity of \mathbf{K} matrix the stated problem is ill-posed. Using only mean-square method in such cases gives the solution that is strongly oscillating and far from real. One of the ways to retrieve the appropriate solution is to introduce the additional condition for the stated problem. In the present work emissivity smoothness on the magnetic flux surfaces was used as such condition. The method is known as Tikhonov regularization technique [5]. The degree of smoothness is determined by regularization

parameter. The minimizing functional is the following: $\|\mathbf{K}\boldsymbol{\varepsilon} - \mathbf{B}\|^2 + \lambda \|\mathbf{C}\boldsymbol{\varepsilon}\|^2 \rightarrow \min$, that is equivalent to the solution in the form of: $\boldsymbol{\varepsilon}_\lambda = \mathbf{K}^T (\mathbf{K} \times \mathbf{K}^T + \lambda \mathbf{C} \times \mathbf{C}^T)^{-1} \mathbf{B}$, $(*)$, λ – regularization parameter, \mathbf{C} – finite difference equivalent of the second degree derivative. Generalized singular value decomposition technique of matrix pair \mathbf{K}, \mathbf{C} was used to retrieve the pseudoinverse matrix in $(*)$.

The choice of the regularisation parameter was carried out using discrepancy principle. With the rise of λ the residual norm also increases and the reconstructed profile changes significantly. Too low λ could lead to highly oscillative emissivities with negative values, making the solution unphysical. At the same time oversmoothed solutions should be avoided. In Fig. 2 the result of the profile reconstructions is presented for different regularization parameters and corresponding relative residual norms. Although the distributions are rather distinct at the boundary region, the values of total radiated power are sufficiently close, being 51 kW for the case $\lambda=0.05$, 45 kW for the case $\lambda=0.28$.

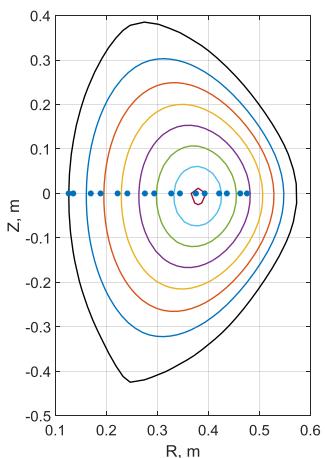


Fig. 1. Poloidal magnetic flux surfaces of Globus-M; dots - values of tangency radii (perpendiculars from tokamak centre to the each chord of view).

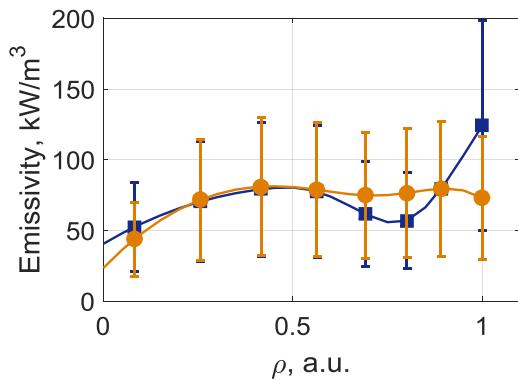


Fig. 2. #35537. OH discharge, $I_p=200$ kA, $\langle n_e \rangle = 4 \cdot 10^{19} \text{ m}^{-3}$, $t=167$ ms. Emissivity profiles for different regularization parameters and corresponded relative errors: $\lambda=0.052$, $\|\delta B/B\|=2\%$ (blue squares), and $\lambda=0.277$, $\|\delta B/B\|=6\%$ (orange circles).

Time evolution of the plasma emissivity in poloidal flux coordinates in typical ohmic discharge in deuterium during steady state phase is presented in Fig. 3. One can see that the radiated power profile was highly peaked at the periphery up to 164 ms. That period corresponded to the limiter configuration of plasma, thus impurities from central column easily penetrated to the plasma periphery. After that so called ‘natural’ divertor configuration had formed, radiation from the edge reduced. Further rise of the emissivity in the plasma core is due to density increase effect.

Calculation of profile of carbon radiation power

For considered temperature range the main source of radiated power in the experiments is impurity emission. Carbon was assumed the main impurity in Globus-M plasma because of the graphite tiles used as plasma facing components of the tokamak. The carbon radiated power is defined as $P_C = n_C n_e L_C(T_e)$, W/m^3 , where n_C – carbon density, m^{-3} , n_e – electron density, m^{-3} , $L_C(T_e)$ – carbon cooling curve, $\text{W} \cdot \text{m}^3$. The $L_C(T_e)$ curve was retrieved using ADAS [6] in assumption of coronal equilibrium. In present calculations flat carbon concentration profiles were used with absolute values estimated using ASTRA code [7]. Input parameters for the modelling in ASTRA were the following: electron temperature and density profiles retrieved from Thomson scattering diagnostics, plasma current, toroidal magnetic field, plasma shape characteristics, carbon density. Carbon concentration was set to provide agreement of the estimated loop voltage and the experimental one. For the calculation neoclassical conductivity provided by NCLASS code was used.

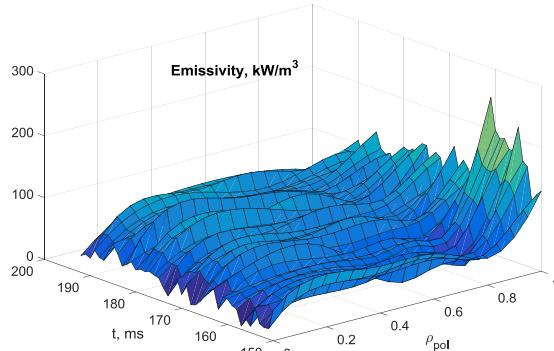


Fig. 3. #35537. OH discharge, $I_p=200$ kA, $\langle n_e \rangle = 4 \cdot 10^{19} \text{ m}^{-3}$. Time evolution of plasma emissivity.

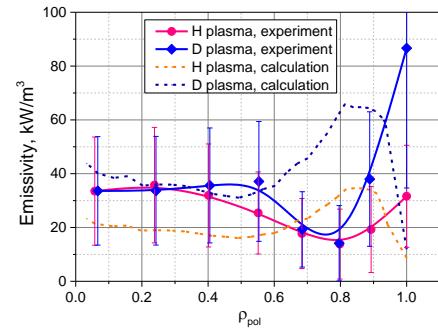


Fig. 4. #35710 – H plasma, #35783 – D plasma. OH discharge, $I_p=170$ kA, $\langle n_e \rangle = 3 \cdot 10^{19} \text{ m}^{-3}$. Reconstructed profiles of radiated power, measured in the experiments and calculated using ADAS.

Neutral density profile was estimated by means of DOUBLE code, using charge exchange (CX) spectra measured by NPA. The ratio of the average density of neutral hydrogen and deuterium atoms to the average electron density for considered discharges was $\langle n_H \rangle_R / \langle n_e \rangle_R \sim 10^{-4}$.

The resulted profiles of carbon radiated power for hydrogen and deuterium ohmic heated plasmas with plasma current 170 kA, line average densities $\sim 1.8 \cdot 10^{19} \text{ m}^{-3}$ are given in Fig. 4. In both cases calculated emissivity was peaked at the plasma boundary. The maxima values of calculated profiles are in the plasma edge where densities of neutral hydrogen isotopes are still high and the electron temperature values are enough to CX processes play significant role in the ionization balance of carbon. The plasma radiation

mostly comprises of C⁵⁺ ion emission, which radiates most intensely at the corresponded temperatures and neutral density levels.

Experimental profiles reconstructed for hydrogen and deuterium plasmas are also presented in Fig. 4. For deuterium plasma emissivity reaches its maximum value at the boundary, although it shifted to the periphery as compared to the calculated profile. It could be explained by limitations in chords of view, resulting in reconstruction inaccuracies. Carbon and neutral density profiles as well as non-coronal effects could also influence the consistency of the measured and calculated profiles.

Experimental emissivities in hydrogen plasma were lower than in deuterium. In contrast to deuterium plasma the core emissivities in hydrogen are the same order as boundary. It is known that physical and chemical sputtering of light target material (such as carbon) increase with the rise of atomic mass of the projectile. Hence impurity concentration in deuterium plasma could be higher, than in hydrogen. Higher energy and particle confinement time in deuterium plasma in comparison with hydrogen in Globus-M [8], could also lead to higher impurity radiation. Calculated corresponded effective charge values – 2.5 for hydrogen and 4 for deuterium plasmas – confirm larger content of impurities in deuterium discharges.

Conclusions

Emissivity profiles of the Globus-M tokamak plasma were reconstructed using Tikhonov regularization technique from chord measurements by multichannel SPD diagnostics. For deuterium plasma experimental radiation profile was peaked at the boundary and emissivity was larger than in hydrogen discharges. Higher sputtering yield of graphite tiles in deuterium plasmas, as well as the reduced sensitivity of the silicon photodiodes low energy region could explain the difference. Calculated emissivity profiles and effective charge values also demonstrated lower impurity radiation in hydrogen plasma as compared with deuterium.

Acknowledgments

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