Plasma effective charge diagnostics at the Globus-M2 tokamak

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Abstract. The conventional method for determining the effective ion charge $Z_{\text{eff}}$ is based on measurements of the bremsstrahlung intensity in the spectral regions free from line radiation. This paper describes the design of the $Z_{\text{eff}}$ diagnostics at the Globus-M tokamak as well as the results of the first measurements. With allowance for the emission intensity estimates, the geometry of the experiment was chosen; the filter monochromators for recording bremsstrahlung were designed and manufactured. Using the Thomson scattering data on $T_e(R)$ and $n_e(R)$ profiles, time dependences $Z_{\text{eff}}(t)$ were obtained in several shots of the Globus-M tokamak. The results of simulations $Z_{\text{eff}}$ performed using the ASTRA transport code are consistent with these measurements.

1. Introduction

In the plasma fuel of the tokamak, there are atom/ion impurities, such as carbon, oxygen, nitrogen, iron, and helium. As a rule, the impurities come into the plasma from the tokamak walls due to the chemical and physical sputtering of the surface of the plasma-facing components. The degree of plasma contamination by impurities can be characterized by the effective ion charge $Z_{\text{eff}}$, which is defined as follows [1]:

$$Z_{\text{eff}} = \frac{\sum_i n_i Z_i^2}{\sum_i n_i Z_i}.$$  \hspace{1cm} (1)

where $n_i$ is the concentration of the $i$-th impurity, $Z_i$ is the nuclear charge of atom of the $i$-th impurity, and summation is performed over $i$ impurity species.

Currently, the method of $Z_{\text{eff}}$ determination based on measurements of the bremsstrahlung continuum intensity in the visible and near-infrared (NIR) spectral regions is conventional and it is used on many facilities [2–4]. This paper describes the diagnostics which has been employed to determine $Z_{\text{eff}}$ from measurements of the bremsstrahlung intensity in the NIR spectral range, and presents the first results of the effective charge measurements performed at the Globus-M spherical tokamak.

2. The method for measuring $Z_{\text{eff}}$ based on the bremsstrahlung measurements

The bremsstrahlung spectral power density per unit solid angle $\frac{dP_{\text{ff}}}{d\omega d\lambda}$ depends on the effective ion charge $Z_{\text{eff}}$ and is given by the formula (2) [1]:

$$\frac{dP_{\text{ff}}}{d\omega d\lambda}.$$
The recombination radiation is negligible, are used to calculate in accordance with [6], the solid angle (line-of-sight) $P$ by a photodetector. The bremsstrahlung power $P_{br}$ is determined as $P_{br} = \frac{U_{exp}}{A}$, where $U_{exp}$ is the measured photodetector output voltage and $A$ is the calibration factor.

The ion effective charge $<\text{Z}_{eff}>$, which is averaged over the considered volume, is calculated using the Thomson scattering (TS) formula (2), and the known electron temperature $T_e(R)$ and electron density $n_e(R)$ distributions over the major radius $R$ in the volume under consideration:

$$<\text{Z}_{eff}> = \frac{N_{br}}{1.5 \cdot 10^{-29} \cdot \langle g_{ff} \rangle \int V \int \Omega(l) \cdot K(\lambda) \cdot \frac{n_e^2(R)}{\lambda^2 \sqrt{T_e(R)}} \exp \left(-\frac{hc}{\lambda T_e(R)}\right) dVd\lambda}$$

Integration is performed over wavelengths within the range corresponding to the spectral characteristics of the interference filter $K(\lambda)$, and also over the volume $V$ of the bremsstrahlung registration. The solid angle $\Omega$, from which the radiation is collected, depends on the distance $l$ from the radiating region to the monochromator.

3. Experimental setup
Diagnostics was designed to perform measurements at the Globus-M and later at the upgraded Globus-M2 tokamaks. The Globus-M tokamak [7] has the following parameters: the major radius is $R = 0.36$ cm, the minor radius is $a = 0.24$ cm, the aspect ratio is $A = 1.5$, the toroidal magnetic field is $B_{tor} \leq 0.4$ T, and the plasma current is $I_p = 150$–250 kA.

An optical system collects radiation from a quasi-parallel volume with a diameter of $d = 2$ cm. The sight line in the equatorial plane of the Globus-M tokamak is plotted as 3 in Figure 1a. The spatial distributions $T_e(R)$ and $n_e(R)$ used to evaluate $\text{Z}_{eff}$ are obtained using the Thomson scattering (TS) diagnostics [8].

![Figure 1a](image1.png)

![Figure 1b](image2.png)

3.1. Spectral regions
The spectral regions free of spectral lines were determined in the course of designing the plasma effective charge diagnostics based on measuring the bremsstrahlung intensity. The radiation spectra of
the Globus-M tokamak plasma were investigated to choose suitable intervals. The spectra were measured using the spectrometric system consisting of the MDR-23 monochromator and the OMA-V infrared camera (Figure 2). For the effective charge measurements at the Globus-M tokamak, the interference filter (6 in Fig. 1b) with a central wavelength of \( \lambda = 1029 \text{ nm} \) and a width of \( \Delta \lambda = 21 \text{ nm} \) was used. The spectral characteristic of the filter is shown in Figure 2; the filter was used to select the spectral region during the \( P_{br} \) power recording.

![Figure 2. The plasma emission spectrum in the Globus-M tokamak, obtained using the MDR-23 monochromator-based system and the OMA-V IR camera, and the transmission band of the interference filter.](image)

3.2. Arrangement of the diagnostics
The bremsstrahlung emission is registered by the filter monochromator (see Figure 1b). It consists of the filter (6 in Figure 1b) used to separate the spectral interval, the lens (5 in Figure 1b), which collects the radiation onto the detector FPU-100-2 semiconductor photodiode (2 in Figure 1b) with a transimpedance amplifier (4 in Figure 1b). The evaluation of the expected bremsstrahlung power (\( 10^{-6} \text{ mW} \)) in the electron temperature and density ranges, which are standard for the Globus-M tokamak, was used to set the detector characteristics. The conversion coefficient of the amplifier was \( R_s = 10^7 \text{ V/A} \).

3.3. System calibration
The absolute calibration of the filter monochromator has been carried out with the USLR-V12F-NMNN Labsphere integrating sphere, as a light source with constant emissivity and the radiance. The known spectral characteristics of the light source (its radiation power density \( I(\lambda) \)) allow calculating the ratio \( A \) between the output photodiode voltage \( U \) and the radiation power falling onto the integrating sphere \( P: A = \frac{U}{P} \). The determined calibration coefficient turned to be \( A = 3.80 \text{ V/W} \).

During calibration, the detection system included all the optical components used in the experiment.

4. First experimental results
The temporal evolution of \( Z_{eff} \) and some other plasma parameters for shots with NBI heating and the plasma current \( I_p \cong 180 \text{ kA} \) (#37068 and #37069) are demonstrated in Figure 3a. The measurement error consists mainly of the Thomson Scattering diagnostics errors and the uncertainty of the contribution of bremsstrahlung reflected from the graphite plasma-facing components. Taking into account possible sources of measurement errors, the maximum error of the \( Z_{eff} \) measurements was calculated to be 26%.

The results of the ASTRA transport code simulations [9] are compared with measured \( Z_{eff} \). When solving the transport equations, the \( T_e(R) \) and \( n_e(R) \) profiles were taken from the TS diagnostics data, the ion temperature profile \( T_i(R) \) was measured by the CXRS diagnostics [10], and the plasma current \( I_p \) was set as the boundary condition. We consider carbon as the basic impurity in the ASTRA model the calculations since the material of the wall in the Globus-M is graphite.

The temperatures of H/D ions and impurities are assumed to be equal, since, under the conditions of neoclassical transport, the frequency of collisions of impurity ions with H/D ions is much higher
than the frequency of ion-electron collisions [11]; therefore the temperatures of different ions are fast equalized.

The plasma effective charge $Z_{\text{eff}}$ was selected so that the calculated loop voltage coincided with the experimentally measured one. The simulation results and the measured $Z_{\text{eff}}(t)$ values in shot #37069 are shown in Figure 3b. The simulation results are in good agreement with the experimental $Z_{\text{eff}}$ values.

5. Conclusions
The NIR line-integrate bremsstrahlung measurement system has been developed in the Globus-M tokamak. The first $Z_{\text{eff}}$ measurement results with this diagnostic system in various regimes of the tokamak shots are obtained, and they are in good agreement with the results of ASTRA transport code simulations.

The plasma effective charge diagnostic system has been installed and tested at the Globus-M2 tokamak, which successfully started operating in 2018 [12, 13]; the bremsstrahlung power was measured in test shots. We plan to perform simultaneous spectral measurements in IR and visible spectral ranges during the same shot in order to obtain independent results.

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