Effective ion charge of plasma Zeff determination by its X-ray radiation spectrum

© V.Yu. Goryainov, A.V. Voronin, V.A. Kornev, I.V. Miroshnikov, D.N. Tkachenko, V.V. Zabrodsky, M.Yu. Kantor

Ioffe Institute, St. Petersburg, Russia
E-mail: vgoryainov@mail.ioffe.ru

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A method for determining the effective plasma charge is proposed by measuring bremsstrahlung. For this purpose, a high-temporal-resolution X-ray detector is installed on the TUMAN-3M tokamak. First values of the effective plasma charge Z_{eff} for an ohmic discharge, averaged over volume of the detector's field of view, are obtained as a function of time.

Keywords: effective ion plasma charge Zeff, bremsstrahlung, SPD detector, tokamak, beryllium foils.

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The effective charge of plasma ions is one of the crucial parameters characterizing a discharge and its course. Most importantly, the effective charge value indicates the presence of impurities that exert a negative influence on plasma confinement. However, its precise determination still often proves difficult. In the present study, a method for determining effective charge based on X-ray data is detailed.

X-ray radiation detectors are used successfully to measure tokamak plasma parameters (electron temperature, radiation losses) and allow one to detect plasma disturbances [1–4], and specifically determine the effective charge of plasma. Since bremsstrahlung radiation dominates over recombination and cyclotron radiation in tokamak plasma at electron temperatures greater than 10 eV, the following formula may be used to calculate effective charge Z_{eff} in hydrogen plasma [5,6]:

$$Z_{eff} = \frac{\sum_i n_i Z_i^2}{\sum_i n_i Z_i}, \qquad Z_{eff} = \frac{AU}{CP},$$

$$P = \iint \Omega \frac{gn^2}{\lambda^2\sqrt{T}} \exp\left(-\frac{hc}{\lambda T}\right) d\lambda dV, \tag{1}$$

where CP is the total bremsstrahlung radiation power collected by the detector [W], n_i is the impurity density [cm^{-3}], Z_i is the impurity ions charge, $C = 1.9 \cdot 10^{-28}$ is the bremsstrahlung power spectral density constant associated with the quasi-classical approximation for hydrogen [6] (dimensionless), U is the detector signal [V], λ is the wavelength [Å], T is the electron temperature [eV], $g \approx 1$ is the Gaunt factor for free-free transitions in the energy region of 0.5−10 keV, n is the electron density [cm^{-3}], Ω is the solid angle of plasma radiation reaching the sensor [sr], h is the Planck constant [eV · s], and c is the speed of light in vacuum [Å/s]. Coefficient A [W/V] was calculated by calibrating the detector against a reference X-ray source with an energy of 12 keV.

The installation diagram of the device on the TUMAN-3M tokamak (minor radius $a = 0.25$ m, major radius $R = 0.55$ m, toroidal magnetic field $B_T = 1.0$ T) and its design are presented in Figs. 1, *a* and *b*. A sensitive element in a flanged housing was connected via a ceramic junction to one of the tokamak ducts. The diagnostic setup was positioned at an angle of 45° below the equator and directed toward the center of chamber in the poloidal section without tangential inclination. Diaphragm *3* (Fig. 1, *a*) with a diameter of 2.3 mm positioned at a distance of 110 mm from the sensitive region was used to reduce the detector viewing angle of detector to $\alpha = 2.6°$, which make it possible to collect radiation from a small area of plasma and use the radial profiles of density and temperature to calculate integral (1). The smallness of the radiation collection angle allows to present the solid angle as constant $\Omega = 2\pi\big(1 - \cos(\alpha/2)\big) \approx 1.67 \cdot 10^{-3}$ sr. The Z_{eff} value from formula (1) is then obtained by averaging over the collection area.

Beryllium foil with a thickness of 15 μm (*1* in Fig. 1, *b*) [7] is mounted in front of the sensitive element (*2* in Fig. 1, *b*) to cut off radiation with an energy lower than 0.5 keV. The sensitive element was a silicon photodiode (SPD) [8] with an active region diameter of 3.2 mm and a time resolution finer than 0.1 μs.

Electron density measurements were carried out in ten channels using a microwave interferometer. The electron temperature at the center of the plasma column was determined using a foil X-ray spectrometer by calculating ratio of signals from channels with different beryllium foil thicknesses (50 and 100 μm) [1]. The foil method allowed us to determine the maximum electron temperature within the field of view (in present case, center of the column). Electron temperature and density at periphery of the column were measured by Langmuir probes to establish a continuous radial profile. The accuracy of effective charge measurements was $\sim 30\%$. The measurement error is attributable primarily to the low level of useful signal relative to noise.

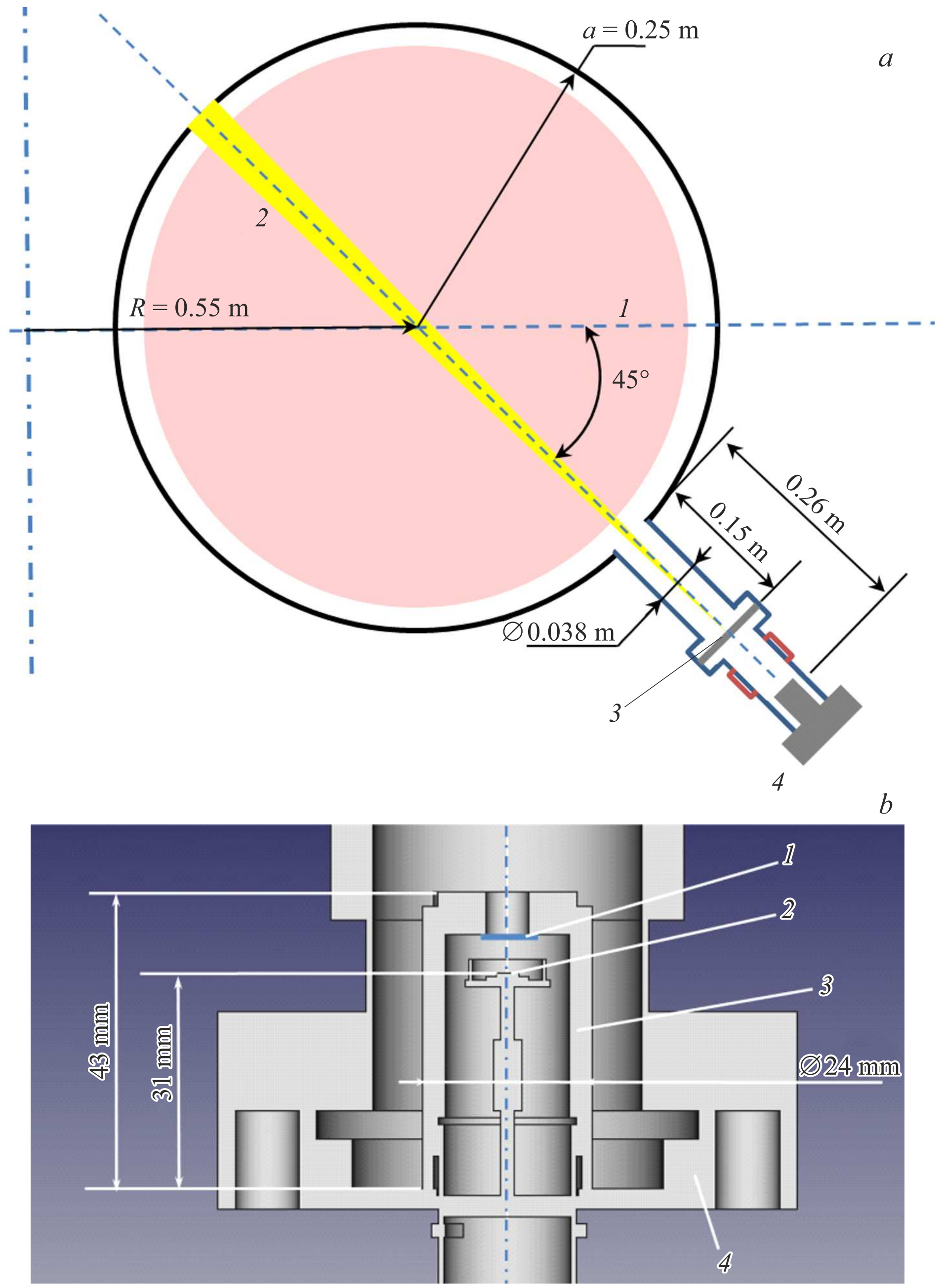

Figure 1. *a* — Diagram of detector installation at a TUMAN-3M tokamak, poloidal section. *1* — Plasma column, *2* — detector field of view, *3* — diaphragm, and *4* — detector. *b* — Internal structure of the detector. *1* — Beryllium foil, *2* — sensitive element, *3* — cap, and *4* — flange.

Figure 2, *a* shows the radial profiles of density $n(r)$ and temperature $T(r)$ plotted on the basis of measured points and interpolated within several time intervals. The formulae for interpolation were as follows:

$$n(r) = n_a + (n_0 - n_a)\left(1 - \left(\frac{r}{a}\right)^{\alpha}\right)^{\beta},$$

$$T(r) = T_a + (T_0 - T_a)\left(1 - \left(\frac{r}{a}\right)^{\alpha}\right)^{\beta}, \qquad (2)$$

where a is the minor radius of a tokamak; r is a variable coordinate; n_a and T_a are the boundary values of electron density and temperature respectively; and n_0 and T_0 are density and temperature of electrons in center of plasma column. Parameters α and β were adjusted to bring profiles (2) closer to the experimental points. The obtained values of Z_{eff} for an ohmic hydrogen discharge are shown in Fig. 2, *b*. It is evident that Z_{eff} varies little with time (is about 2.2–2.8); it is slightly lower at 80–90 ms than at the onset of the discharge (at 40–50 ms).

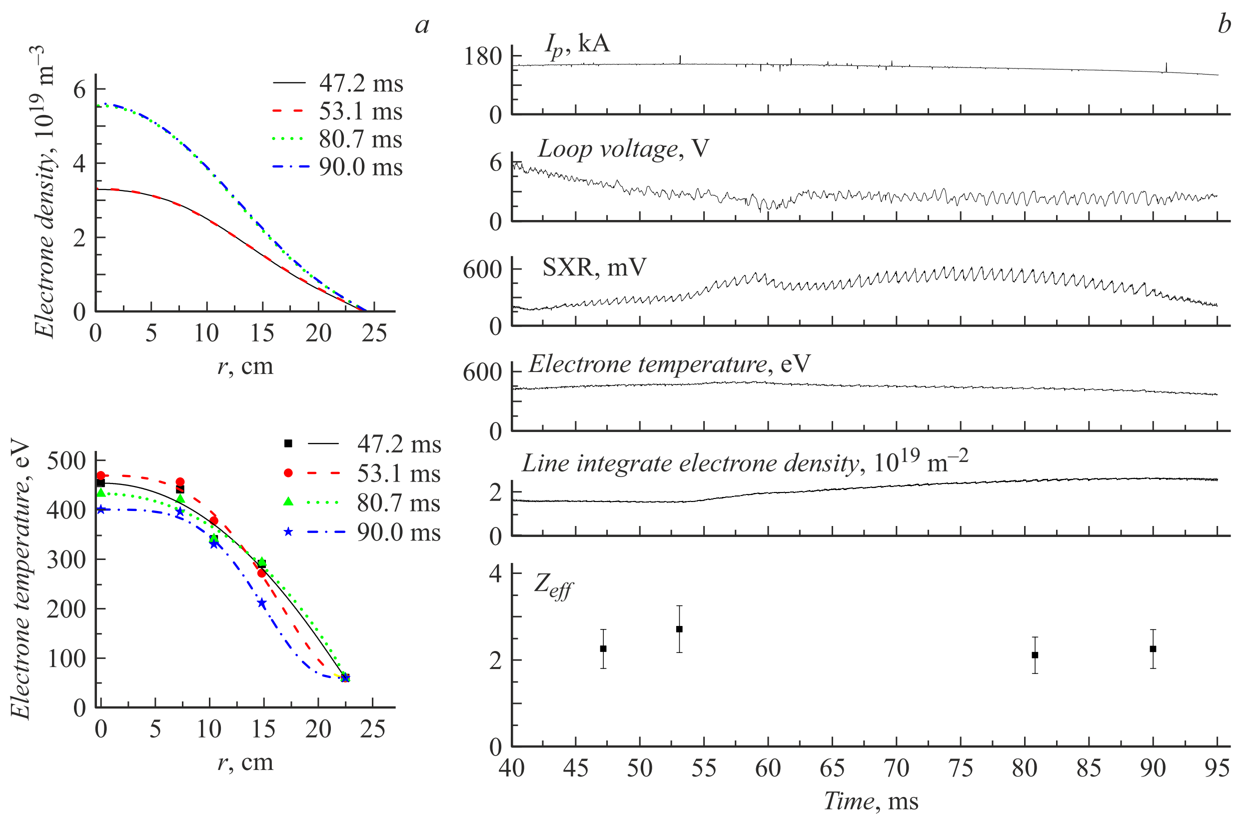

Figure 2. *a* — Radial profiles of electron density $n(r)$ (top) and temperature $T(r)$ (bottom) for different time intervals. *b* — Plasma parameters (top to bottom): current, loop voltage, X-ray radiation, maximum electron temperature at the center, chord-averaged electron density, and effective charge. Discharge No. 24032706. A color version of the figure is provided in the online version of the paper.

Thus, the first results of determining the effective plasma charge via bremsstrahlung radiation measurements in ohmic discharge at the TUMAN-3M tokamak have been reported. The diagnostic setup includes an X-ray detector, a filter, and a diaphragm. The radiation collection area with a small opening angle, as well as the sensitivity and speed parameters of instrument provide an opportunity to determine the Z_{eff} values averaged over area. Measurements with neutral injection discharges and verification of values against the ASTRA code calculations are planned to be performed in the future.

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Conflict of interest

The authors declare that they have no conflict of interest.

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