Technical Physics, 2022, Vol. 67, No. 1

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Calibration of neutron counters at the Globus-M2 tokamak

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Received May 21, 2021
Revised July 30, 2021
Accepted September 9, 2021

The paper discusses the results of the calibration of two corona neutron counters used to measure the total neutron yield from the plasma of the Globus-M2 tokamak. The calibration was carried out in the experimental hall of the Globus-M2 facility using an AmBe source. During the calibration, the source moved at a constant speed around the central solenoid in the equatorial plane of the vacuum chamber, and one of the detectors was gradually moved away from the tokamak along a line with a constant toroidal angle. The dependence of the calibration coefficient obtained depending distance of the detector from the tokamak is presented. The calibration technique made it possible to separate the contributions from the direct neutron flux emitted by the plasma and from the flux of neutrons scattered on the elements of the experimental hall in the detector signal.

Keywords: neutron diagnostics, spherical tokamak, neutron yield, neutron counters, thermonuclear fusion

DOI: 10.21883/TP.2022.01.52526.151-21

Introduction

A new electromagnetic system was designed and manufactured in the course of reconstruction of the Globus-M compact spherical tokamak, which was completed in 2018 [1–3]. This provided an opportunity to increase the toroidal magnetic field and the plasma current. In the first experimental campaigns of 2019–2020 at the Globus-M2 tokamak, the field and current values of 0.8 T and 400 kA were achieved [4]. The design values (1 T and 500 kA, respectively) are to be achieved in 2022. The increase in field and current strength had a positive effect on the confinement of high-energy ions produced upon injection of a beam of high-energy atoms. Neutrons are produced in plasma of the Globus-M/M2 spherical tokamak as a result of the interaction between high-energy particles with ions of the main plasma and with each other. Therefore, the total neutron flux from plasma of the tokamak increased significantly following the reconstruction [5]. In view of this, it became necessary to move neutron detectors away from the vacuum chamber to exclude the possibility of overload. The fraction of neutrons scattered by structural elements of the experimental hall in the flux to the detector increased as a result. The influence of neutron scattering is significant due to the lack of collimation for neutron counters and the specifics of layout of the experimental hall built from bricks and concrete. Thus, it was necessary to perform *in situ* calibration of neutron counters and estimate the contribution of scattered neutrons to the total flux to the detector.

1. Specifics of calibration

A closed source of fast neutrons type IBN-241-1-1 with americium-241 was used for calibration. Its neutron flux into a solid angle of 4πsr is $9.9 \cdot 10^4\,s^{-1}$. Since the active part of the source is no larger than 3×3 mm, it may be considered as a point source. Thin metal plates were installed inside the vacuum chamber when the Globus-M2 tokamak was opened for maintenance. Tracks (Fig. 1) were laid on top of these plates around the central solenoid. The source moved with a constant velocity along these tracks in the equatorial plane of the chamber. Thus, the region of neutron emission had the shape of a thin ring imitating a plasma column.

The calibration coefficients were calculated for two neutron detectors BDN-20 (gas-discharge counter SNM-11)

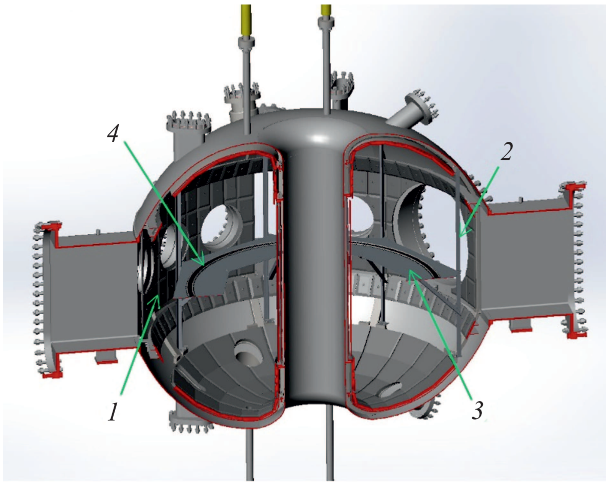

Figure 1. Vertical section of the vacuum chamber of the Globus-M2 tokamak with internal structural elements for the experimental calibration of neutron detectors. Vacuum chamber with graphite plates *1*, mounts for metal plates *2*, metal plates *3*, and tracks along which the source moved *4* are indicated.

with a polyethylene moderator installed at the Globus-M/M2 tokamak. The signal in neutron counters of this type is produced in the $B^{10}(n,\alpha)\,\mathrm{Li}^7$ nuclear reaction. In the process of calibration, the first detector was moved gradually away from the tokamak chamber along the line with a constant toroidal angle, while the second detector remained stationary. The time of measurement of neutron fluxes at the chosen points, which correspond to the planned detector locations in future experimental campaigns, was chosen so as to reach the needed number of counts ($N \approx 1000$). The background signal was measured after the principal measurements. The neutron source in background measurements was positioned outside the detector room.

2. Data processing

The signal from a counter was sent to an ADC installed in a PC. The signal was read out at a frequency of 50 MHz. Since the count rate of detectors did not exceed 20 events/s in all measurements and the pulses did not overlap, neutron detection was identified as an event in which a pulse exceeded the threshold value.

The neutron count rate with account for background was determined in the following way:

$$\omega(R) = \omega_f(R) - \omega_b = \frac{N_f(R)}{t_f} - \frac{N_b}{t_b}, \qquad (1)$$

where R is the distance from the tokamak axis to the detector position, N_f is the total number of events detected in measurements with the source in time t_f, and N_b is the number of detected background events without the source in time t_b.

The standard deviation of the calculated count rate was determined as

$$\sigma(\omega) = \sqrt{\sigma^2(\omega_f) + \sigma^2(\omega_b)} = \sqrt{\frac{N_f}{t_f^2} + \frac{N_b}{t_b^2}}. \qquad (2)$$

3. Calculation of the calibration coefficient

The ratio of the total number of neutrons emitted by the AmBe source from the tokamak chamber, A, to the calculated detector count rate at the given spatial position, $w(R)$ (see (1)), is the sought-for calibration coefficient $\xi(R)$. If this coefficient and the number of counts at the detector, $X(R)$, are known, one may calculate the experimental neutron yield of the tokamak, Y_r, in the approximation of neutron emission from a thin ring:

$$Y_r = X(R)\frac{A}{\omega(R)} = X(R)\xi(R) \qquad (3)$$

Figure 2 presents the dependence of the obtained values of this calibration coefficient for the first detector on the distance from the tokamak axis to the detector position.

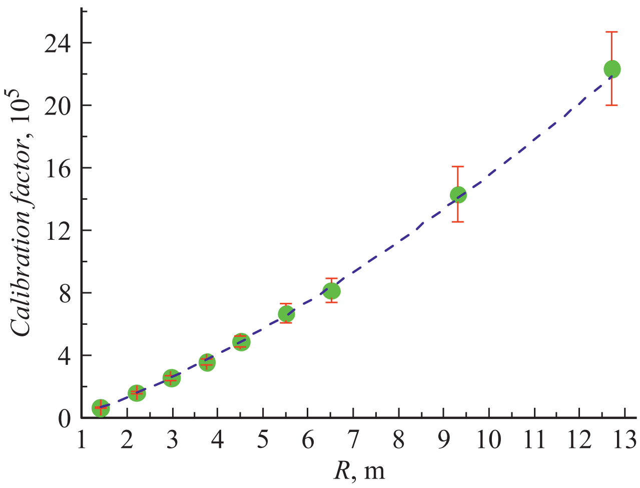

Figure 2. Dependence of the calculated values of calibration coefficient $\xi(R)$ (3) with confidence intervals 2σ (95% confidence level) for the first detector on the distance to the axis of the Globus-M2 tokamak. The dashed curve is the result of approximation.

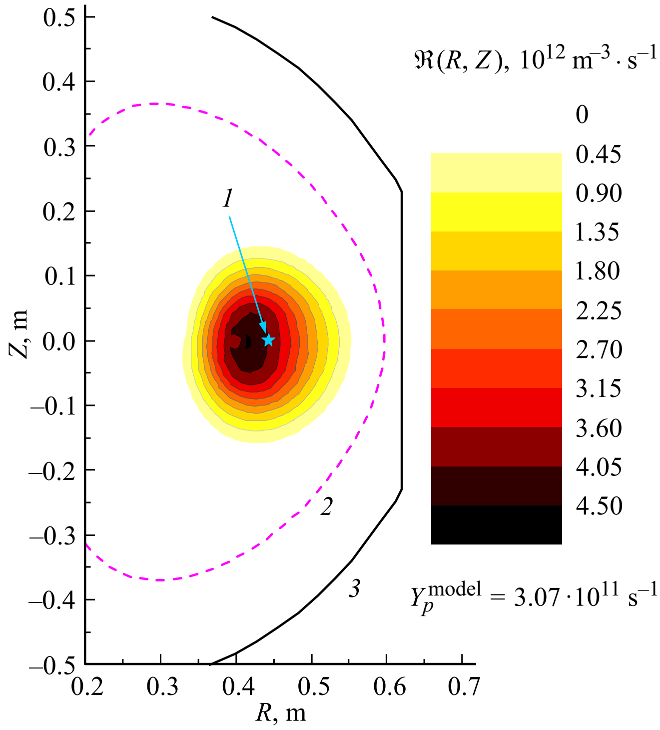

Figure 3. Calculated source function for neutrons produced in the interaction between deuterons $\mathscr{R}(R,Z)$. Position *1* of the AmBe source during calibration, plasma boundary *2*, and boundary *3* of the vacuum chamber are indicated. $Y_p^{\mathrm{model}} = \int_V \mathscr{R}(R,Z)dV$ is the total neutron yield of tokamak plasma calculated in the process of modeling.

In practice the region of neutron production depends on the parameters of the specific experiment: Fig. 3 presents the example of a calculated [6] spatial distribution of the neutron source $\mathscr{R}(R, Z)$ for a typical Globus-M2 tokamak discharge. In view of this, one needs to calculate the conversion coefficient, which reflects the geometrical differences of neutron sources, in order to determine the neutron yield of plasma Y_p. This is done by conducting three-dimensional Monte Carlo simulations of the direct (emission into a sphere) neutron flux to the detector $F(R)$ in the following two cases (Fig. 3):

1. Neutron emission from plasma. Source function $\mathscr{R}(R, Z)$ for neutrons produced in the interaction between deuterons is calculated for each discharge and used in this case. $F_p(R)$ is determined as a result of these calculations.

2. Neutron emission from a thin ring. The source is positioned in accordance with the calibration experiment. The total neutron flux from plasma is equal to the total neutron yield for the considered discharge $Y_p^{\text{model}} = \int_V \mathscr{R}(R, Z)dV$. $F_r(R)$ is determined as a result of these calculations.

The experiment is assumed to be toroidally symmetric in modeling. Calculations are performed under the assumption that the conversion coefficients for direct and scattered neutron fluxes are the same.

Neutron yield Y_p is then calculated using conversion coefficient $\mathscr{F}(R)$ of the form

$$Y_p = Y_r F_p(R)/F_r(R) = Y_r \mathscr{F}(R) \quad (4)$$

The results of calculations demonstrated that the considered effect is insignificant for typical discharges of the Globus-M2 tokamak. The deviation of $\mathscr{F}(R)$ (4) from unity exceeds 1% only in the immediate vicinity of the vacuum chamber.

4. Estimation of the contribution of the scattered neutron flux

The experiment on calibration of neutron sources allowed us to estimate the influence of scattering of neutrons by elements of the Globus-M2 experimental hall on the measured signal magnitude. Two quantities were compared for this purpose:

1. Flux $F_{\text{exp}}(R)$ to the detector measured experimentally in the process of calibration. The conversion coefficient of the number of counts per second $\omega(R)$ (1) into flux $F_{\text{exp}}(R)$ to the detector from the AmBe source was calculated in a different experimental hall where the influence of scattering is weak, meaning that the flux should be $\propto A/4\pi R^2$).

2. Flux $F_{\text{mod}}(R)$ to the detector determined in three-dimensional Monte Carlo simulations without regard to the effect of neutron scattering and the energy spectrum of neutrons. The contribution from the direct neutron flux from the source, which corresponds to uniform emission into a sphere $\propto A/4\pi R^2$, was modeled. The experiment was assumed to be toroidally symmetric in modeling.

Figure 4 presents the results of comparison for the first detector. It was assumed prior to calibration that the direct flux at fixed points closest to the tokamak should predominate over the scattered one and, consequently, the fluxes to the detector determined by modeling and with the use of the conversion coefficient should be approximately the same. It can be seen from Fig. 4 that these assumptions turned out to be true. The calculated values are $\sim 15\%$ higher than the experimental ones at the first two fixed points due to the fact that the scattering of neutrons by structural elements of the facility was neglected in modeling. At a distance of ~ 3 m from the tokamak axis, the modeled and experimental fluxes are equal. As the distance from the detector to the vacuum chamber increases further, the flux measured in the process of calibration becomes higher than the modeled one. This is attributable to the fact that the fraction of scattered neutrons in the total flux to the detector produces a significant contribution to the measured signal. The performed calibration enables us to make allowance for this effect in future experimental campaigns where the detectors are expected to be positioned at a distance of $\sim 7-12$ m from the tokamak axis.

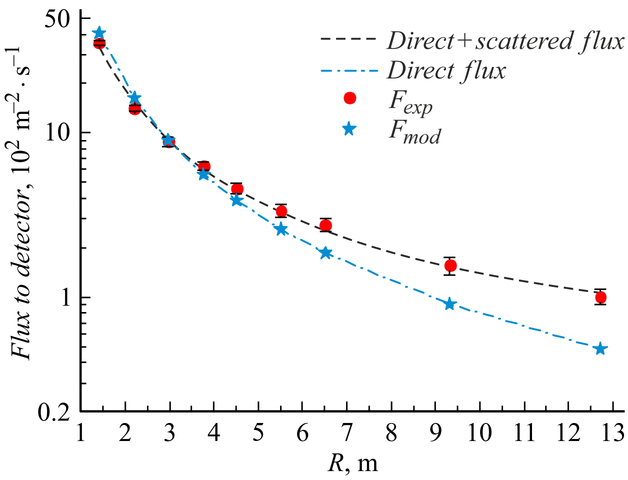

Figure 4. Comparison of modeled and experimentally measured neutron fluxes. Stars denote the neutron flux to the first detector obtained in three-dimensional simulations of the direct neutron flux from the AmBe source. Circles represent the neutron flux to the first detector (combined signal from direct and scattered fluxes) measured experimentally in the process of calibration. Confidence intervals 2σ corresponding to a confidence level of 95% are indicated for the experimental points.

Conclusion

The calibration of corona neutron counters in the experimental hall of the Globus-M2 tokamak with an AmBe source allowed us to calculate calibration coefficient $\xi(R)$ (3) that relates the locally measured number of counts to the total experimental neutron yield from plasma. The comparison of the calculated flux to the detector and the flux measured experimentally in the process of calibration revealed that the influence of neutrons scattered by elements of the experimental hall on the magnitude of the measured signal increases with distance between the detector and the vacuum chamber of the tokamak.

The AmBe source used in calibration has an energy spectrum with an average neutron energy of $\cong 4$ MeV. However, in experiments at the Globus-M2 tokamak neutrons are producedin in the $\mathrm{D} + \mathrm{D} \to n + {}^3\mathrm{He}$ reaction and thus have a different energy spectrum with an average neutron energy of $\cong 2.4$ MeV. As was demonstrated in [7], such differences in energy spectra of sources produce systematic errors of the calibration coefficient as large as 10%. Thus, the next step is calculation of the correction to calibration coefficient ($\xi(R)$), taking into account the specifics of calibration mentioned above.

Funding

Experiments were performed at the Unique Scientific Facility Globus-M Spherical Tokamak, which is a part of the Material Science and Diagnostics in Advanced Technologies Federal Center for Collective Use (unique identifier RFMEFI62119X0021). The calibration of neutron detectors, data processing, and calculation of the calibration coefficient (Sections 1−3) were performed with support from the Russian Science Foundation, project No. 21-72-20007. The contribution of scattered neutrons was estimated (Section 4) under the state assignment of the Ioffe Institute of the Russian Academy of Sciences (No. 0040-2019-0023).

Conflict of interest

The authors declare that they have no conflict of interest.

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