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X-ray diagnostics for the measurements of a bremsstrahlung radiation spectra of the FT-2 tokamak plasma with a high photon counting rate

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The paper presents a new X-ray diagnostic system installed on the FT-2 tokamak for high-temperature plasma bremsstrahlung radiation spectra measurements. The design and technical characteristics of the diagnostics are described. A significant increase in the counting rate is shown while maintaining the spectral resolution of the developed system compared to the industrial device.

Keywords: plasma, bremsstrahlung radiation, SXR spectrometer, SDD detector.

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X-ray diagnostics for measuring radiation spectra within the energy range from 0.6 to 200 keV has been designed for the FT-2 small tokamak to study dynamic plasma processes in the modes of ohmic heating and current generation by lower hybrid waves. The possibility of its operation in a short discharge (40 ms) at a relatively low electron plasma temperature (300 eV) is ensured by a high photon count rate (in excess of $10^6\,\mathrm{s}^{-1}$) at a high energy resolution (less than 150 eV). This diagnostic system is planned to be used to measure the dynamics of electron temperature [1,2] at a frequency up to 1 kHz, the effective plasma charge, the longitudinal electric field, and the electron distribution function at lower-hybrid current drive [3,4].

This system uses one of the best silicon drift detectors (FAST SDD®) with a sensor area of $70\,\mathrm{mm}^2$, which is installed in the XR100-SDD module with a charge-sensitive amplifier and controlled by a PX-5 control and signal processing unit produced by AMPTEK [5,6]. The PX-5 unit converts pulse signals from the detector into trapezoids [7]; their amplitude is proportional to the photon energy and is measured by standard pulse counting algorithms [8]. The proportionality coefficient is determined through calibration. The maximum output quantum count rate is limited by a strong temporal overlap of trapezoidal pulses at which their amplitudes become impossible to determine. An increase in count rate necessitates a reduction in width of trapezoidal pulses, which results in distortion of their shape, exerting a profound negative influence on the energy resolution of the spectrometer and entailing the distortion of measured spectra. To maintain a high fraction of detected photons and an acceptable energy resolution of < 200 eV, the chosen detector with a nominal count rate up to $10^6\,\mathrm{s}^{-1}$ actually operates at a count rate below $10^5\,\mathrm{s}^{-1}$ in spectral measurements of tokamak plasma radiation [9]. Thus, the indicated spectrometer turned out to be inapplicable under the given experimental conditions at the FT-2 tokamak, since it does not allow one to achieve a time resolution sufficient for studying the dynamics of plasma spectra.

Therefore, the AMPTEK spectrometer was upgraded to reach the required parameters via hardware [10,11] and software [12,13] modifications. A differentiating pulse-forming amplifier with a 10–90% rise time of 45 ns (versus 90 ns for the amplifier of the PX-5 unit) has been designed for the new detection system. The amplifier has two independent channels with gain factors of $8-87$ and $2-12$, expanding the dynamic range of photon energy determination to 200 keV. Amplified pulses within a tokamak discharge are digitized by a fast 14-bit analog-to-digital converter with a sampling rate of 250 MHz. The detection and measurement of amplitudes of the recorded pulses are normally carried out after their digital filtering to a trapezoidal shape with the use of standard trapezoidal pulse detection algorithms. To increase the count rate while maintaining the energy resolution, detector pulses are converted into a Gaussian shape, and special algorithms are used to count them.

A ^{55}Fe isotope source emitting photons with an energy of 5.9 keV is used for detector calibration. To verify the calibration during a discharge, the same source is mounted in the vacuum volume of the spectrometer so as to irradiate the detector with an average flux of about 10 quanta per millisecond, which is significantly lower than the measured radiation flux from plasma.

A system of replaceable filters (beryllium ones with a thickness of 50, 100, 150, 200, and 250 μm and an aluminum filter 8.85 μm in thickness) positioned at a distance of 1198 mm from the plasma center are used to limit the input quanta flux to the detector and shift the spectral region of measurement (Fig. 1). In addition, a system of circular diaphragms with a diameter of 0.75, 1, 2, 3, and 6 mm and adjustable bladed diaphragms (horizontal and vertical) with a positional accuracy of 0.01 mm is used to limit the radiation flux from plasma. The circular diaphragms are located at a distance of 1213 mm from the plasma center, while the horizontal and vertical bladed diaphragms are positioned at a distance of 1370 and 1385 mm, respectively.

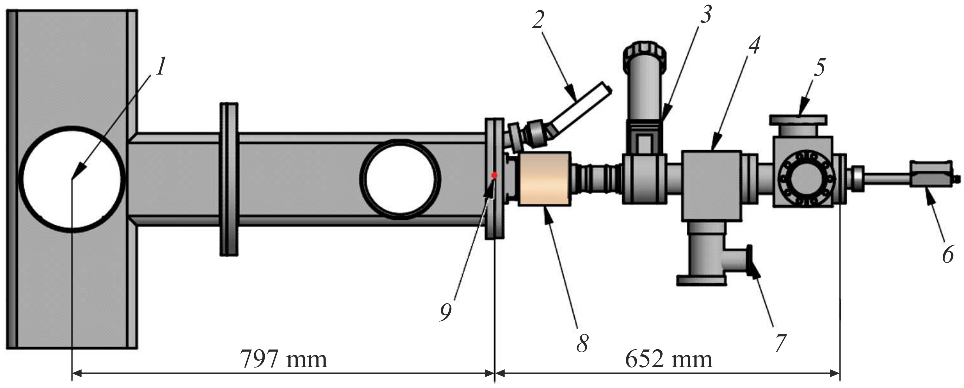

Figure 1. Three-dimensional model of the diagnostic system. *1* — Tokamak chamber, *2* — Mini-X2 AMPTEK calibration X-ray tube, *3* — gate valve, *4* — compartment with filters and circular diaphragms, *5* — compartment with bladed diaphragms, *6* — XR100-SDD AMPTEK detector module, *7* — output to the spectrometer pumping-out system, *8* — bellows element, and *9* — table rotation axis.

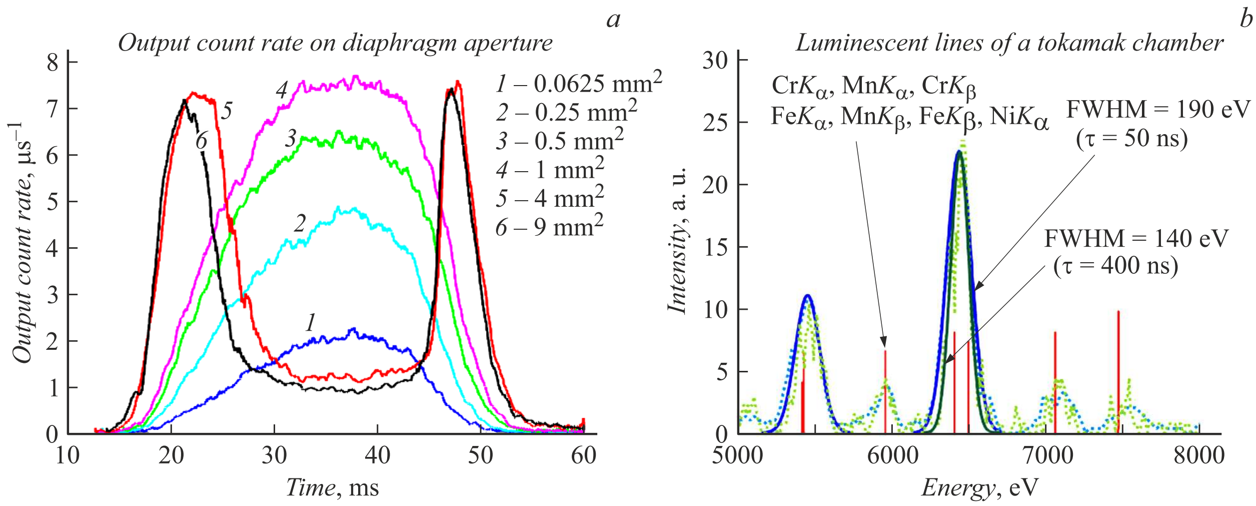

Figure 2. *a* — Dependence of the output quantum count rate on the area of bladed diaphragm aperture in repeat discharges. *b* — Luminescence spectrum of the tokamak chamber during a discharge; the spectrometer is directed tangentially to plasma. Two spectra are plotted with different τ pulse width settings in the Gaussian filtering method.

The detector is mounted at a distance of 1430 mm from the plasma center. To perform measurements along different observation chords, the instrument is positioned on a movable table with its angle of inclination to the horizontal being adjustable within $\pm 6^\circ$. The table pivot point coincides with the input diaphragm of the diagnostic system with a cross section of 22×6.5 mm, which is oriented horizontally and installed at a distance of 797 mm from the plasma center.

The maximum output quantum count rate provided by the diagnostic system was determined by adjusting the aperture of the bladed diaphragm mounted in front of the detector in repeat discharges of the tokamak (Fig. 2, *a*). As the aperture increases, the output quanta flux increases to a limiting value of $7.5 \cdot 10^6\,\mathrm{s}^{-1}$ and drops sharply afterward. The spectral resolution of the instrument (defined as the width of the 6.4 keV iron spectral line at half maximum (FWHM)) is up to 140 eV [14] (Fig. 2, *b*).

An example of spectral dynamics is presented in Fig. 3. The spectra were collected within a single tokamak discharge in observation along the central chord. The accumulation time for each spectrum is 1 ms, which corresponds to the detection of more than 1500 photons. The spectra measured in the stationary discharge part agree closely with the chord-average spectrum modeled according to [15] for plasma with a Maxwellian electron distribution and temperature and density profiles determined by the Thomson scattering method in the discharges under study. The measured spectra feature a dip below the K edge of silicon absorption, which is caused by a reduction in detection efficiency within this energy range. A numerical calculation or measurements of the detection efficiency are needed to reconstruct the plasma radiation spectrum.

Thus, a soft X-ray spectrometer for measuring plasma bremsstrahlung spectra at the FT-2 tokamak has been designed and tested. The photon count rate provided by it is

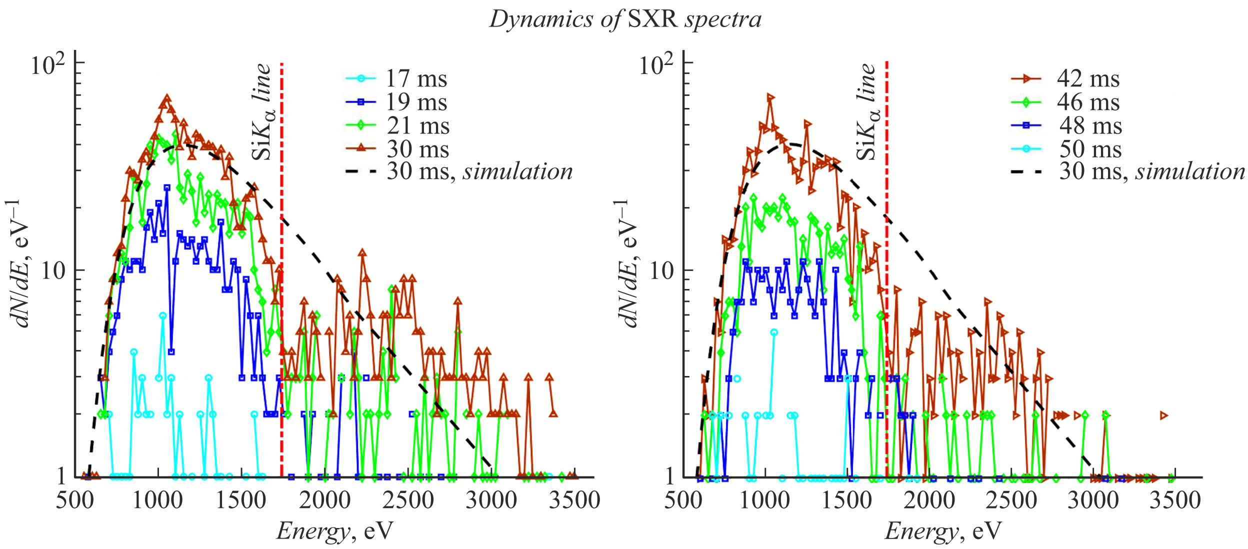

Figure 3. Dynamics of measured plasma spectra in a single tokamak discharge. The spectrum accumulation time is 1 ms. The electron density is $4.2 \cdot 10^{13}\,\mathrm{cm}^{-3}$, the central electron temperature is 550 eV, and the output quantum count rate is up to $2.2 \cdot 10^6\,\mathrm{s}^{-1}$.

more than an order of magnitude higher than that specified by the manufacturer. At the same time, the spectrometer retains a high energy resolution needed for the planned physical research.

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Conflict of interest

The authors declare that they have no conflict of interest.

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