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Calibration of soft-x-ray spectrometer for measurements of electron temperature from plasma Bremsstrahlung spectra in the FT-2 tokamak

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A soft x-ray spectrometer based on a silicon drift detector is installed in the FT-2 tokamak for measurements of Bremsstrahlung spectra at output count rates of $3 \cdot 10^6\,\mathrm{s}^{-1}$ and energy resolution of < 150 eV. The spectrometer is developed for measurements of fast dynamic of the distribution function of high energy electrons. It could be used for measurements of electron temperature from the spectral shape in the low energy range. Spectral calibration of the spectrometer and determination of thickness of beryllium window of the detector are performed for this goal. Obtained results are used for modelling Bremsstrahlung spectra and their comparison to that measured in FT-2 plasma.

Keywords: Diagnostic of plasma, Bremsstrahlung emission, SDD spectrometer.

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X-ray diagnostics is used widely to measure bremsstrahlung spectra of high-temperature plasma. The exponential tails of spectra provide data on the distortion of the distribution of electrons and their temperature averaged over the spectrum recording time. This time is limited from below by the photon count rate of the detector and the required energy resolution. Modern spectrometers use silicon drift detectors (SDDs) [1] providing a count rate up to $10^6\,\mathrm{s}^{-1}$. At low count rates, the detector resolution is as high as 130 eV. The resolution and shape of the measured spectrum deteriorate rapidly with an increase in count rate; therefore, measurements are carried out at an output rate less than $10^5\,\mathrm{s}^{-1}$ and a resolution as high as 150 eV. In this case, the time of accumulation of 1000 photons in the spectrum exceeds 100 ms, which is acceptable for large facilities with a long discharge duration [2,3]. At small-scale facilities, the accumulation time is commensurate with the discharge duration [4,5].

The X-ray diagnostics at the FT-2 tokamak was designed for measuring spectra with an accumulation time upward of 1 ms. It uses an AMPTEK FAST SDD® detector with a sensor area of $70\,\mathrm{mm}^2$ [6]. Weak pulse responses of the detector are amplified by a low-noise amplifier [7] and converted into pulses with a short rise time, which are digitized by an analog-to-digital converter (ADC) with a frequency of 250 MHz and a resolution of 14 bit. Gaussian filtering and novel photon energy measurement algorithms are used for fast counting of these pulses [8,9]. The application of these methods at the FT-2 tokamak provides a count rate up to $3 \cdot 10^6\,\mathrm{s}^{-1}$, which allows one to maintain an energy resolution of 150 eV [10].

This high count rate makes it possible to accumulate several thousand photons in 1 ms, which may be sufficient for measurements of the electron temperature based on the shape of a bremsstrahlung spectrum in the low-energy region. The electron temperature is normally measured based on the exponential tails of bremsstrahlung spectra; however, in experiments at small tokamaks and low temperatures, these tails are distorted by the runaway of electrons in the longitudinal electric field [11]. In the low-energy region, the radiation spectrum is cut off sharply by the beryllium filter at the detector window (see Fig. 3 in [10]). As the electron temperature varies from 0.1 to 1 keV, the position of the radiation spectrum maximum changes from ~ 0.7 to 1.2 keV, and its width changes from ~ 0.3 to 1.2 keV. The longitudinal field has little effect on the spectrum within this range, and its shape may be used to determine the electron temperature.

Precise calibration of the spectrometer at energies above 500 eV is required for such measurements. The detector is calibrated against the MnK_α 5895 eV line, which is emitted by the standard isotopic ^{55}Fe source. The energies of photons of other energies are calculated under the assumption that their energies E are related linearly to response amplitudes A: $E = kA$. However, this extrapolation overestimates the photon energy by more than 30 eV at low energies [12]. An additional error in modeling of the bremsstrahlung spectrum is introduced by the uncertainty in thickness of the beryllium window, which is large as 40%. The key uncertainty in spectrum modeling is related to the unknown efficiency of photon detection in the silicon layer of the detector at energies below the K-absorption edge in silicon (1840 eV) where the mechanism of photon energy absorption changes. According to [13], the many-fold reduction in efficiency is attributable to a reduced beryllium window thickness, incomplete collection of the charge produced in the process of photon detection in the silicon layer, or the algorithm for measuring the response amplitude in the low-energy region. It was established in [14] that the efficiency of photon detection is maintained at energies through to 100 eV.

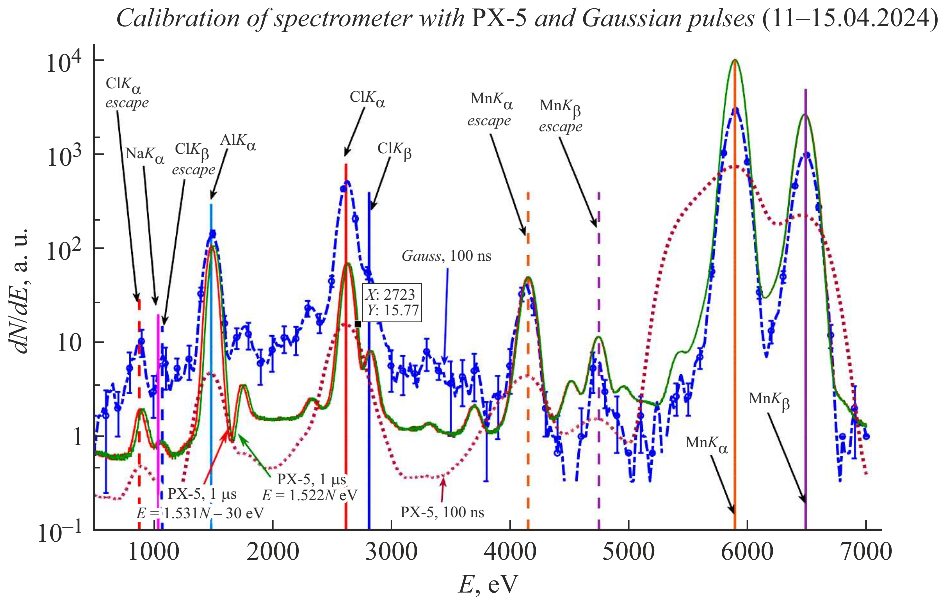
Calibration of spectrometer with PX-5 *and Gaussian pulses* (11–15.04.2024)

Figure 1. Spectra of the ^{55}Fe source emission and fluorescence of table salt.

In the present study, we examine the influence of these factors on the measurement of electron temperature based on the thermal part of plasma bremsstrahlung radiation. The fluorescence of table salt (NaCl) irradiated by the ^{55}Fe source is used to calibrate the detector in the low-energy region. The K_α 1041 eV sodium emission line is located below the K-edge. An additional (escape) peak distanced by 1740 eV from the ClK_β line is located nearby (at 1076 eV). These lines form a single emission peak. The escape peak of the ClK_α line has an energy of 882 eV.

Figure 1 shows the fluorescence spectra of table salt. Vertical lines indicate the energy of the main observed emission lines. Two solid curves represent the emission spectrum measured by the AMPTEK PX-5 module, which uses trapezoidal digital filtering and a standard pulse counting algorithm. The spectrum was measured at an input count rate of 8500 s^{-1} with accumulation of $1.3 \cdot 10^9$ trapezoidal pulses with a peaking time of 1000 ns. The spectrometer channels were calibrated against the MnK_α 5895 eV peak emission energy. The full width at half maximum (FWHM) of this peak was 134 eV. The solid green curve (a color version of the figure is provided in the online version of the paper) represents the spectrum constructed under the assumption of a linear dependence of the photon energy on channel number N: $E = 1.522N$ eV. At high energies, the emission peaks match the expected values closely; at low energies, they are shifted by approximately 30 eV in accordance with [12]. The $E = 1.531N - 30$ eV shifted linear calibration allows one to match the obtained spectrum to the actual emission lines within the entire energy range (see the solid red curve).

Measurements with high output count rates are infeasible at long pulse durations. Therefore, the calibration process was repeated with the PX-5 module at a trapezoidal pulse peaking time of 100 ns and a count rate of 2800 s^{-1}. The result is represented by the dotted brown curve in Fig. 1. The spectral resolution in the high-energy region (> 2 keV) decreases significantly. As the input flux increases, the resolution and the fraction of recorded pulses decrease rapidly. This is the reason why Gaussian pulse filtering is used to measure emission spectra with a high output rate at the FT-2 tokamak [7–10].

In calibration of the spectrometer with Gaussian filtering, intervals containing pulses with energies less than 3000 eV were selected from digitized ADC signals. This allowed for a significant reduction in processing time, since their percentage share in the flux is less than 0.2%. The resulting spectrum plotted based on 40 000 Gaussian pulses with a duration of 100 ns is represented in Fig. 1 by the dash-and-dot blue curve (together with the measurement errors in every fifth channel 20 eV in width). This spectrum was plotted under the assumption that the photon energy is proportional to the amplitude of a Gaussian response. The peaks in the calibration spectrum remain within ±5 eV of the expected energies throughout the entire energy range. The FWHM of peaks varies from 120 to 150 eV as the energy changes from 880 to 5900 eV, which is in good agreement with the SDD noise model [15].

If a source with a known spectrum is used, spectral calibration allows one to determine the thickness of the beryllium detector window based on the position of the lower spectrum boundary and its slope. In the present study, plasma of the FT-2 tokamak with its electron temperature and density profiles measured by Thomson diagnostics is used for this purpose. The lower boundary of the plasma bremsstrahlung spectra is below 700 eV at all temperatures. The influence of the electric field on spectra may be neglected in this region. The spectrometer is mounted so

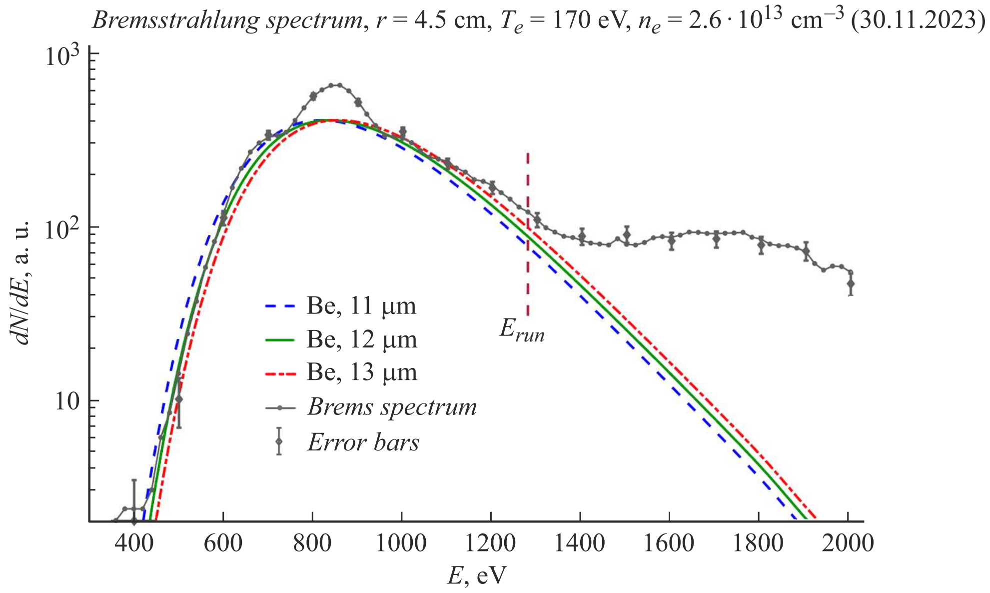

Figure 2. Spectrum of plasma bremsstrahlung radiation and its modeling.

as to provide an opportunity to set the measurement chord anywhere from the lower edge of plasma to the upper one. When measurements are performed at the center of plasma, radiation is collected along the entire chord, which leads to a distortion of the position and slope of the spectrum boundary. Emission lines of impurity ions emerge in the spectrum at the edge of plasma. Therefore, the thickness was estimated based on the spectrum recorded from the center of plasma at a radius of 4.5 cm, where the electron temperature and density are 170 eV and $2.6 \cdot 10^{13}\,\text{cm}^{-3}$, respectively. We assume that the detection efficiency in the region of the lower spectra boundary varies with energy at a lower rate than the transmittance of beryllium foil. The results of evaluation will show whether this assumption is correct.

Figure 2 presents the measured and simulated bremsstrahlung spectra in the low-energy region. The analytical form of the Gaunt factor [16] was used in modeling of radiation spectra; the instrument function of the detector and the beryllium window thickness were also taken into account. Three simulation options with window thicknesses of 11, 12, and 13 μm are shown in Fig. 2. The closest agreement with measurements is observed at a thickness of 12 μm (with a value of 12.7 μm specified by the manufacturer). The model characterizes the spectrum well up to the calculated electron runaway limit E_{run} found in a longitudinal plasma field of 0.59 V/m [11]. Additional peaks with energies of 660 and 850 eV, which are apparently associated with the emission of impurity ions, are visible above the bremsstrahlung spectrum.

Thus, accurate spectral calibration of the X-ray spectrometer in the region of low photon energies was performed. An estimate of thickness of the beryllium window at the detector input was obtained and turned out to be close to the standard value. The low-energy photon detection efficiency is determined primarily by the beryllium window, and the bremsstrahlung spectra are calculated based on simple models of radiation absorption in silicon. This is confirmed by a close agreement between the measured and model spectra at energies up to the electron runaway one.

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Conflict of interest

The authors declare that they have no conflict of interest.

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