

## **Reconstruction of Energy Distribution of Runaway Electrons from HXR Spectra Measured in the Globus-M Spherical Tokamak**

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**Introduction.** The easiest and generally used method to observe runaway electrons is registration of bremsstrahlung, which appears due to deceleration of the electrons in the materials of the tokamak chamber. Scintillation or semiconductor detectors are usually used for these goals. Measuring energy spectra of hard X-rays (HXR), on conditions of adequate statistics, it is possible to estimate maximum energy of electrons going out to the camera wall, but it is difficult to say something definite about energy distribution of the electrons. This report is devoted to the attempt of reconstruction of energy distributions of runaway electrons from measured HXR spectra using Monte Carlo calculations.

**Experimental Setup and Data Processing.** In the experiments on Globus-M spherical tokamak ( $R = 0.36$  m,  $a = 0.24$  m,  $BT < 0.6$  T, and  $I_p < 0.5$  MA) three scintillation detectors are used. Two detectors (NaI(Tl) crystals of  $\varnothing 150 \times 100$  and  $\varnothing 70 \times 70$  mm sizes, respectively) have lead shielding and collimators directed onto diaphragms in different poloidal sections of tokamak camera ( $135^\circ$  along the torus, see fig.1a). These detectors work in the regime of spectrometric counting [1]. Third unshielded detector is operated as a HXR flux monitor. Signals from the detectors are digitized by fast ADCs of high sampling rate (15 MHz). Advantages in using of fast ADCs were discussed in our previous report [1]. A special computer code has been developed for primary data processing. In processing the data stored in the PC hard disc during the discharge the program is used to separate superimposed pulses, calculate their amplitudes, and plot the amplitude spectra. The time intervals in which the amplitude spectrum is plotted can be specified and changed by an operator in processing. This technique of data processing allows to reach count rate of  $\sim 10^6$  cps.

**Monte Carlo simulations.** In order to reconstruct energy distributions of runaway electrons, which interaction with limiters and chamber walls induces bremsstrahlung, calculations using Monte Carlo N-Particle Transport Code (MCNP) were carried out. MCNP is universal code, which developed for calculations of neutron, photon, electron (or coupled neutron/photon/electron) transport [2]. A continuous slowing down model is used for electron

transport that includes positrons, K-X-rays, and bremsstrahlung. For photons, the code takes into account the incoherent (Compton) and coherent (Thomson) scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung.

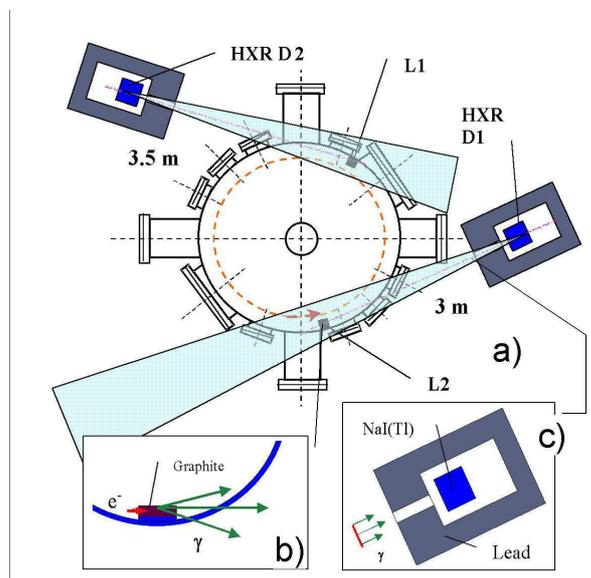


Fig. 1. Scheme of experimental setup.

Because of long distances between tokamak chamber and detectors and small solid viewing angle of the collimators, it was necessary to do some simplifications of geometrical description of chamber configuration and to carry out the calculations in two stages. At the first stage the simulations of deceleration of fast electrons in materials of limiter (a graphite plate on a steel substrate, see fig. 1b) were carried out. This process includes creation of bremsstrahlung quanta and

their transport through materials of chamber (stainless steel vessel with copper elements). Since the chamber walls are relatively thin (1.5-2 cm), most of photons pass through it without interaction. But there are some photons either scattered in materials of chamber or absorbed in them. The area, in which photon transport was calculated, was limited by cone of solid viewing angle of detecting block collimator (blue cones in fig. 1a). Quanta, those left the cone, were excluded from further calculations, since probability of hitting of them to the detector after multiple scattering is very small. A gamma-ray spectrum, calculated in the point of entrance to the collimator aperture was the result of first phase of the calculations. At the second stage gamma-ray source was placed on the plane surface near the collimator aperture. Photons are emitted normally to the plane in the direction of detector (fig. 1c). Energy distribution of the gammas corresponds to the spectrum calculated in the previous stage. The gammas coming through the collimator hit the crystal and either pass without interaction or leave in the crystal a part of their energy due to Compton scattering, or disappear there due to full energy absorption. Taking into account these processes, response functions of detector on gamma rays were calculated. Energy resolutions of used in the experiments detectors were taken into account. Applying this technique, response functions of detectors on bremsstrahlung, induced by fast electrons with known energy distributions

decelerating in the vacuum vessel, were calculated in energy range of 0.5-15 MeV with step of 0.5 MeV. The calculated response function of HXR detector (blue line) for electrons with fixed energy distribution  $5 < E_e < 5.5 \text{ MeV}$  (red line), is shown in fig.2.

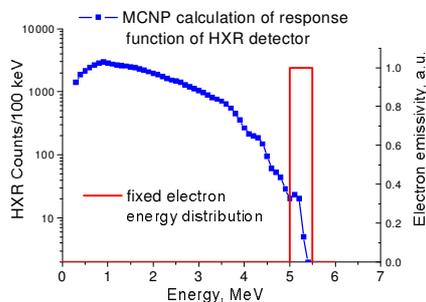


Fig.2. Calculated bremsstrahlung spectrum for  $5 < E_e < 5.5 \text{ MeV}$ .

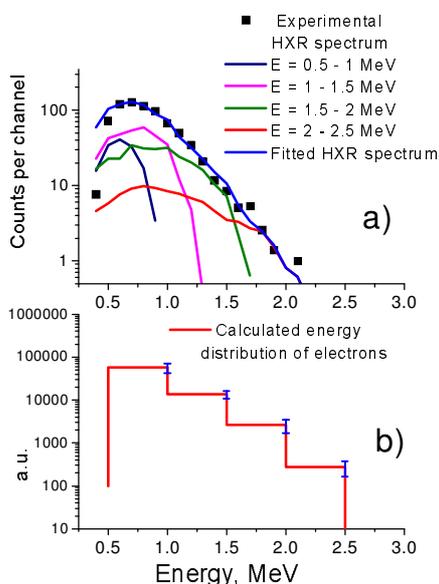


Fig.3. Estimations of electron energy distributions

In order to obtain data about evolution of the electron energy distribution the spectra of HXR measured in different moments during plasma discharge were used. Electron energy distributions were obtained by fitting of superposition of simulated spectra to the experimental one by least-squares method. Fig. 3a shows an example of experimental spectrum (black scattered line in the top figure) processing. Response function of detector on HXR from camera wall is described by function:  $N_{HXR}(E_{HXR}) = \sum_i A_i W_i^e(E_{HXR})$ , where  $W_i^e(E_{HXR})$  – response function calculated for fixed i-interval of electron energy ( $\Delta E_e = 0.5 \text{ MeV}$ ) in range of 0.5-15 MeV. Coefficients  $A_i$  are fitted by least-squares method. Function of energy distribution of fast electrons is described by set of coefficients  $A_i$  (see fig. 3b). In fig. 3a resulting fitted response function of detector is shown by blue line, which is obtained as a superposition of functions calculated for different energy ranges (other color lines). These estimations are relative, but if geometry of experimental setup does not change, these distributions can be compared between different time intervals and discharges.

**Experimental results and discussion.** In fig. 4 (1-6) main waveforms obtained in the shot #8726 ( $I_p=190 \text{ kA}$ ,  $n_e \sim 1 \cdot 10^{13} \text{ cm}^{-3}$ ) are shown. On the phase of plasma current ramp-up with low density ( $0.5-1.5 \cdot 10^{13} \text{ cm}^{-3}$ ) microwave radiometer (wavelength is 0.8 cm) records intensive non-thermal radiation on  $\sim 3f_{ce}$ , initiated by fast electrons with quite high transversal energy. After  $\sim 10 \text{ ms}$  from the current rump-up beginning and microwave signal growth the SXR and HXR radiation intensity increase is observed, that witnesses appropriately about the “fan” instability development [3]. The intensive MHD perturbation

appearing at 27 ms leads to powerful rejection of electrons from periphery of plasma to chamber walls at 31 ms. Signal of radiometer after the MHD-flash has low level. HXR signal appears ~6 ms after the MHD-flash before “sawteeth” oscillations, those are observed at 38-48 ms on quasistationary phase of the discharge. During reconnections of magnetic

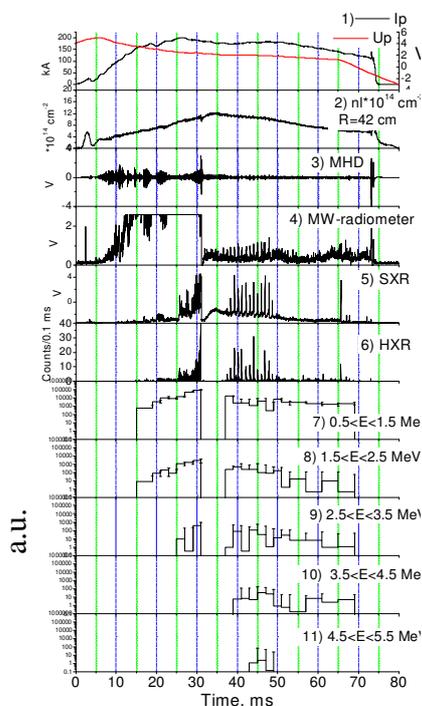


Fig.4. Waveforms of shot #8726 (1-6) and estimated electron distributions (7-11).

force lines at back traces of “sawteeth” the strong HXR flashes and microwave radiation are observed [1].

In fig. 4 (7-11) the estimations of relative flux of electrons going to the chamber walls during the discharge in different energy ranges are shown. These data show that the biggest part of fast electrons runs away from plasma at the current rump-up during development of “fan” instability. However maximal energy of these electrons is relatively small (does not exceed 3 MeV) and is approximately equal to double value of threshold longitudinal energy. It was also revealed, that maximal energy of fast electrons, going to the chamber walls during the direct trace of “sawtooth” does not exceed 3 MeV, but at back traces it reaches up to 5 MeV. Total number of fast electrons escaping on quasistationary phase of discharge is significantly lower than before MHD-event at 31 ms. This can be explained

in the following way: after the MHD-event plasma already has quite high level of density and decreased vortex electric field, that diminish the runaway productivity. Thus, these experimental data provide information about influence of “fan” instability, MHD perturbations and “sawteeth” oscillations on formation and behavior of fast electron beam in different discharge and plasma conditions.

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**References:**

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