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A. Shevelev, V. Kiptily, I. Chugunov, E. Khilkevitch, D. Gin, D. Doinikov,
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A. Shevelev[1], V. Kiptily[2], I. Chugunov[1], E. Khilkevitch[1], D. Gin[1], D. Doinikov[1], V. Naidenov[1], V. Plyusnin[3] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*Ioffe Physical-Technical Institute of the Russian Academy of Sciences, Polytechnicheskaya 26, St. Petersburg, 194021, Russia*
[2]*EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*
[3]*Instituto de Plasmas e Fusão Nuclear, Associação EURATOM-IST, Instituto Superior Tecnico, Universidade Tecnica de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
** See annex of F. Romanelli et al, "Overview of JET Results", (24th IAEA Fusion Energy Conference, San Diego, USA (2012)).*

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ABSTRACT.
Hard-X-ray spectrometry is a tool widely used for diagnostic of runaway electrons in existing tokamaks. In future machines, ITER and DEMO, HXR spectrometry will be useful providing information on runaway electron energy, runaway beam current and its profile during disruption.

1. INTRODUCTION

Monitoring of runaway electrons (RE) is one of the most important issues for the safe tokamak operation. The large electric fields induced during the current quench phase may produce a large number of runaway electrons with energies as high as tens of MeV and the runaway current is more than 1MA. The final runaway energy can become sufficiently large as to cause serious damage to the machine structures. So, the diagnostic of runaway electrons in tokamaks is needed for machines protection. One of possible techniques for runaway electrons diagnosing is detection of Hard X-radiation (HXR). Interaction of the accelerated electrons with plasma species and tokamak structure causes a bremsstrahlung emission in the MeV range that can be detected with a gamma-ray spectrometer. A HXR spectrum generated by mono-energetic electrons represents continuously declining dependence, which is limited by the energy of electrons causing the radiation. The bremsstrahlung cross-section is proportional to Z^2 of target nuclei. Angular distribution of the radiation for relativistic electrons has a strong anisotropy in the direction of the electron velocity. All tokamaks without any exception are provided with a HXR monitoring system. It begins to operate just at the very first plasma discharge. The first and the most common goal of HXR measurement is simple evidence of the presence of runaway electrons in tokamak plasmas. For this purpose one or a few collimated or not collimated HXR intensity monitors (i.e. without energy resolution) are installed around a machine. The most widely used detectors are inorganic scintillators (NaI(Tl) and others) coupled with photomultipliers. As a rule, they work in current mode. Progress in computer technology, digital signal processing techniques and appearance of new fast and heavy scintillation detectors stimulates further HXR diagnostics development. It has become possible to carry out spectrometric HXR measurements with short acquisition time and obtain fast electrons energy distribution by means of deconvolution of measured bremsstrahlung spectrum. This work is devoted to a review of current status and achievements in HXR diagnostics development and its applications on different tokamaks.

2. HXR DIAGNOSTICS ON TOKAMAKS OF IOFFE INSTITUTE

HXR spectrometry techniques are widely used in all tokamaks of Ioffe Institute (Saint-Petersburg): FT-2, Tuman-3M and Globus-M [1,2]. The main goal of HXR spectrometry is an assessment of the maximum energy of RE and the temporal evolution of this parameter. Collimated scintillation spectrometers are installed at some distance from the tokamaks as intensity monitors and also do not require any interface with the machine itself. The application of several collimated spectrometers directed to different limiters in the equatorial plane of the tokamak chamber provides information on the influence of MHD activity on the behavior of a runaway electron beam. These spectrometers are equipped with new developed data acquisition systems using fast ADCs, which periodically digitize the signals from scintillation detectors. High frequency of digitizing (it was chosen 15-20MHz for NaI(Tl) detectors) and the big memory size allows writing the changes of voltage on anode of PMTs during discharge in order to reconstruct the time and energy distributions of hard x-ray radiation at the subsequent data processing using known detectors pulse shape. The use of two HXR spectrometers with high time resolution in experiments carried out on t Globus-M spherical tokamak [1] made it possible to detect HXR bursts correlating with different MHD modes: in the phase of plasma current plateau the measured HXR signals were modulated with periodical flashes. It was observed, that the HXR flashes with the period of oscillations in the range 0.07-0.3ms were synchronous with rotation of islands of the m/n = 2/1 MHD mode, while bursts with the period of 0.4-1.5ms correlated with saw-tooth oscillations. Time dependence of detector counting rate at saw-tooth oscillation during Globus-M shot is shown in figure 1. Digital recording of detector signal during tokamak shot allowed studying energy characteristics of fast electrons leaving plasma during saw-tooth oscillations. In Fig.2(a) spectrum of HXRs, which were detected between "teeth" flashes, is shown. Maximal energy of these HXRs is ~2.5MeV. On the other hand, maximum energy of HXRs recorded in the flashes is ~4.3MeV **(**Fig.2(b))**.** The difference between the spectra could be explained by the following way. During saw-tooth events fast electrons drop into the tokamak wall from the plasma core. These electrons have life time exceeding the life time of electrons on the plasma periphery, where the runaway beam is cleaned by rotating MHD islands.

3. HXR MEASUREMENTS ON JET

Most universal system for HXR monitoring of runaway electrons is realized on JET tokamak, where gamma-ray spectrometry system, consisting of high effective scintillation detectors having quasi-tangential and vertical lines of plasma view, is used in this aims. Recent upgrade of the system and installation of two $LaBr_3$(Ce) spectrometers with dimensions Ø76 × 152mm and having up-to-date data acquisition system has allowed to expand the counting rate range up to several MHz and, correspondingly, improve the system time resolution [3]. Besides the high effective spectrometers, gamma-ray camera consisting of 19 CsI 20 × 15mm detectors with 10 horizontal and 9 vertical lines of plasma view is enabled in HXR measurements on JET[4]. This system is intended for time, spatial and energy resolved measurements of bremsstrahlung originated in interaction of fast electrons with bulk plasma, gas puff or injected pellet. The essential advantage of this system is a possibility to observe the runaway electrons "in flight" before their interaction with the plasma facing components. The inverse reconstruction (tomography) of the measured HXR emissions on the stage of RE plateaux for the first time in JET provided the detailed data on temporal evolution and spatial structure of RE beams during disruptions. Examples of such reconstruction of HXR source profile in JET disruption are shown in Fig.2 [5]. These experiments have been carried out using either Massive Gas Injection (MGI) or constant gas puff. HXR measurements of RE plateaux (spectrometer views the central part of current carrying channel) detected the new phenomena. The appearance and gradual increase of the secondary maximum of HXR emission has been measured. The maximum of the second peak increased with the increase of RE plateaux duration in MGI triggered disruptions. The constant gas puff scenario did not reveal measurable HXR emission. It is likely, that observation of HXR is linked to interaction of RE beams with surrounding gas in case of MGI. Interaction of RE with wall also should be taken into account. The first JET operations with ITER-like Wall (ILW) have demonstrated that new environment does not favor to the RE generation at major disruptions. However, the generation of REs has been detected on the discharge start-up and current-rise stage in JET with ILW (Fig.3). Measured HXR spectra on these stages have been processed in order to study the parameters of REs generated. For these purposes the DeGaSum code has been used.

DeGaSum code has been developed in Ioffe Institute for deconvolution of gamma-ray spectra emitted from plasmas [6]. This code was modified to carry out reconstruction of energy distribution of runaway electrons using measured HXR spectra. Results of Monte-Carlo modelling of the gamma-ray spectrometer response functions and bremsstrahlung spectra calculated for electrons in wide energy range are used in the code. The DeGaSum code with modified algorithm for HXR spectrum y(ε) measured by the detector can be represented in the following form

$$y(\varepsilon) = \int_0^\infty d\varepsilon' \, h_d(\varepsilon, \varepsilon') \int_0^\infty d\varepsilon'' \, h_e(\varepsilon', \varepsilon'') f(\varepsilon'') + n(\varepsilon) = \int_0^\infty d\varepsilon' f(\varepsilon') \, h_{tot}(\varepsilon, \varepsilon') f(\varepsilon'') + n(\varepsilon),$$

where f is the electron distribution function; h_e is HXR generation function, i.e. function describing the energy dependence of density probability of bremsstrahlung emission in the direction of the detector during a transit of an accelerated electron with a fixed energy via visible by the detector plasma volume. h_e is calculated using MCNP code describing the interaction of monoenergetic electrons with plasma target, bremsstrahlung creation and transport of HXRs in direction of the detector location in proper geometry. h_d – detector's instrument function; h_{tot}- detector's response function to HXRs generated by fast electrons.

The developed technique was used for reconstruction of runaway electron distribution in JET. As it was mentioned above, MCNP simulations of bremsstrahlung fluxes in the location of gamma detector with vertical line of sight of JET camera have been fulfilled. The simulated bremsstrahlung distributions from JET plasma were used by DeGaSum code in calculations. Figure 4 illustrates the use of DeGaSum code for diagnostics of runaways in JET shot. In this shot a runaway beam arose at the end of the current rump-up. HXR spectra were measured by vertical NaI(Tl) detector and were deconvoluted by DeGaSum code. Total HXR spectrum recoded by the spectrometer is shown in the bottom figure by black dots. Deconvoluted electron spectrum is represented by red line and HXR spectrum corresponding to the runaway distribution is shown by blue line. Current of runaways with energy exceeding 2MeV was derived by integration of number of electrons, intersected the visible for the vertical spectrometer plasma volume. Time dependence of runaway current is shown in the Fig.4(c).

4. GAMMA-RAY SPECTROMETRY FOR DIAGNOSTICS OF RUNAWAYS IN ITER

Diagnostics of runaway electrons is one of the priority measurements that should be provided for machine protection. Gamma-ray system developed in the frame of ITER project could provide necessary data on maximum energy of runaways and their current. To estimate the runaway current a tomographic reconstruction of HXR emissivity profile should be done. For that, at least two fields of view of ITER plasmas are required. Gamma-ray spectrometers installed in the Radial Neutron Camera (RNC) could be used for horizontal observation of ITER plasmas. In this scheme gamma-ray detectors are installed behind the RNC Beam Dump and use the same line of sights of RNC. Totally 6 lines of sight with 50mm collimator diameter and 6 with diameter 10mm with plasma coverage up to 0.5 minor radius are available. The plasma volume intersected by the viewing chords along Z axis is round 25cm. The flight tubes between neutron detectors and of Radial gamma-ray spectrometers could be filled with lithium hydride neutron absorber. Big-size $LaBr_3$(Ce) scintillation detectors, providing high efficiency of high-energy gamma-rays registration, could be used in Radial Gamma Camera of ITER.

Vertical Gamma-Ray Camera (VGC) is under development in Ioffe Institute [7]. To provide vertical angles of plasma view Vertical Neutron Camera (VNC) design could be used. For the moment, 5 detector units of VNC are proposed to be allocated in Lower port # 14 and 6 units in Upper port #18. Gamma-ray detectors could be made on the base of $LaBr_3$(Ce) scintillation crystals of 2.5cm in diameter and 7.6cm in length. But the environmental conditions in Upper and Lower Ports are very harsh for gamma-ray spectrometric measurements. High temperature in the ports (up to 250^{o}C at baking) is required an arrangement of local cooling system for the detectors. In magnetic fields (up to 4T) only magnetic resistant photodetectors, as silicon diodes or micro-channel plate PMTs, should be used. Background neutron fluxes, which can reach 10^8 in Lower and 10^9 n/cm^{2}s in Upper ports, will not allow using semiconductor devices. So, for the moment it seems impossible to using scintillation detectors in Upper and Lower Ports in DT experiments on ITER. The most realistic option is installation of gamma-ray detectors in channels of Vertical Neutron Camera in low activation phase of ITER operation. After that, gamma-detectors could be replaced by neutron detector modules.

In order to estimate intensities of HXR fluxes in Radial and Vertical Gamma Cameras MCNP modeling of bremsstrahlung birth profile in ITER was made. The main aim for these simulations was estimation of gamma detectors count rates for application of this tool for diagnostics of fast electrons. Calculations were done for deuterium plasmas with $Z_{eff} = 1.5$ and electron density 5×10^{19} m^{-3}, argon and neon. Last gases were taken into the calculations since a massive injection of Ar and Ne is considered as a possible operation to suppress the development of runaway avalanches during discharges. The calculations have resulted the following count rates (for E>1MeV):

4.3×10^5 counts per second (cps) in D-plasma and 9.9×10^5 counts in argon for Radial spectrometer with quasi-horizontal line of sight (LoS); 4.1×10^5 cps for the spectrometer with the quasi-vertical LoS installed in Lower Port; 2.7×10^6 cps for the spectrometer with the quasi-vertical LoS installed in Upper Port. Statistics in the calculated HXR spectra satisfy obtaining the electrons maximum energy with 20% accuracy. The simulations have shown that gamma ray spectrometers of both Radial and Vertical Gamma Cameras could provide spectra with statistics sufficient for reconstruction of HXR emissivity profiles from ITER plasma.

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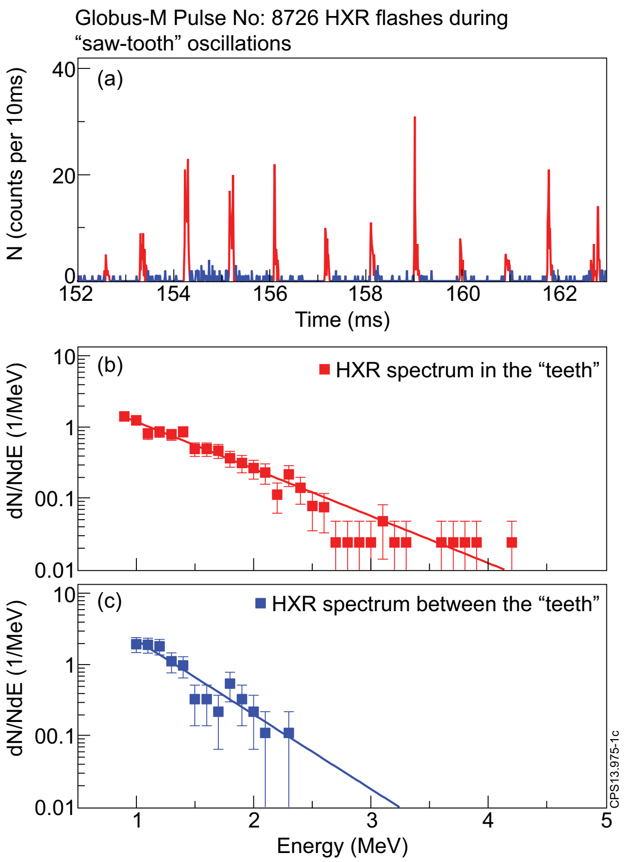

Figure 1: (a) Time dependence of NaI(Tl) spectrometer counting rate during saw-tooth oscillations recorded at Globus-M Pulse No: 8726. HXR spectra recorded at saw-tooth oscillations in Globus-M shot: (b) between flashes; (c) during saw-tooth events only.

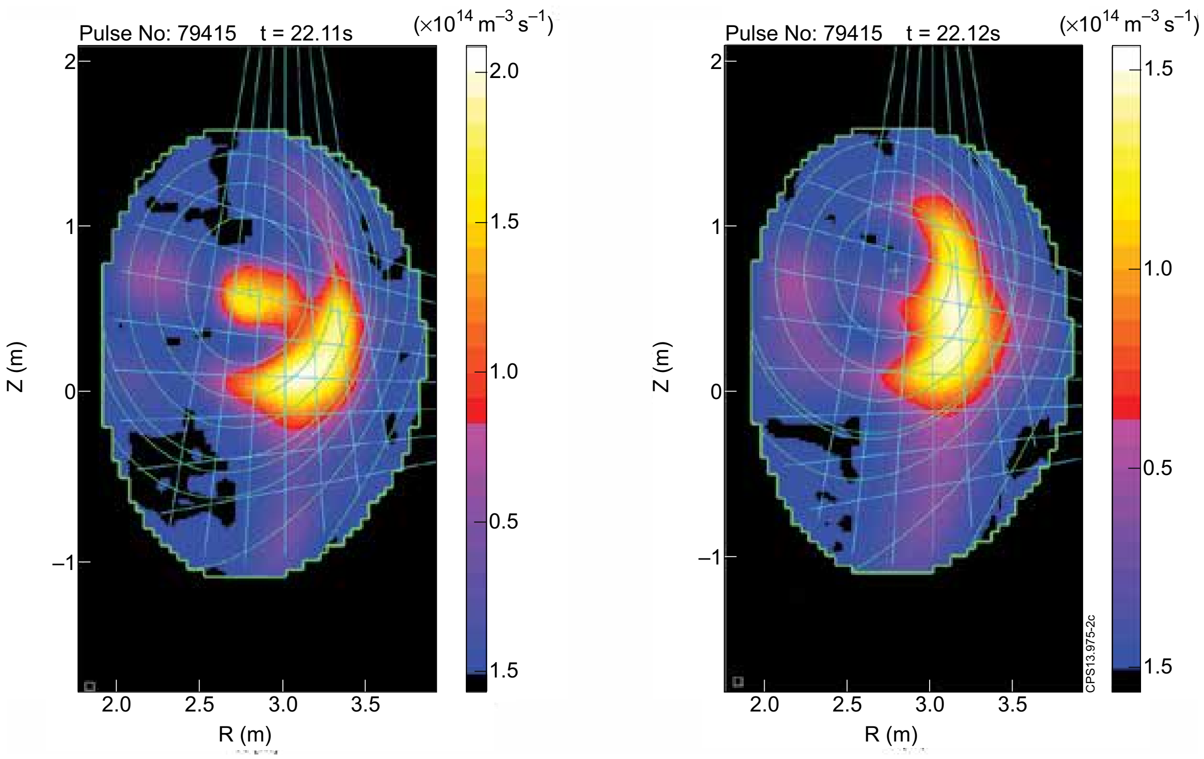

Figure 2: Tomography reconstructions of HXR emission profile at JET shot with MGI disruption.

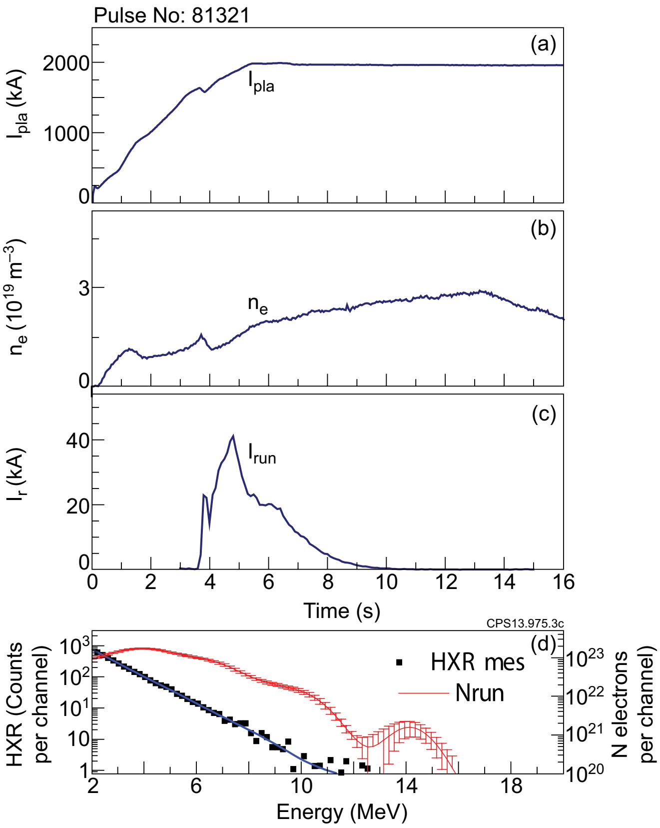

Figure 3: (a) Plasma current of JET Pulse No: 81321; (b) Line averaged electron density; (c) Reconstructed runaway current in the visible for vertical spectrometer volume of electrons exceeding 2MeV; (d) Measured HXR spectrum (black line), reconstructed electron distribution (red line) and HXR spectrum corresponding to the electron distribution (blue line).