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A.E. Shevelev[1], I.N. Chugunov[1], V.G. Kiptily[2], D.N. Doinikov[1], D.B. Gin[1], E.M. Khilkevitch[1], V.O. Naidenov[1] 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*
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ABSTRACT.
Use of gamma-ray spectrometers on ITER could allow solving one of the most important issues for the safe tokamak operations - diagnosing runaway electrons. 2-D hard X-ray (HXR) emission measurements can provide important information on the runaway beam location in the ITER plasmas and allow estimating the value of the runaway current in the MeV energy range. The DEGAS code has been developed for deconvolution of gamma-ray spectra emitted from plasmas. Using the recorded HXR spectra, the code can reconstruct the runaway electron energy distribution. 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 DEGAS code. The deconvolution of spectra allows identifying nuclear reactions, which take place during plasma discharges, calculate their gamma-ray line intensities and determine the maximal energy of runaway electrons with accuracy, which satisfies the ITER Project Requirements. The DEGAS code was used for processing of spectra recorded in JET experiments. Application of the deconvolution technique for 2-D gamma-ray emission measurements, which can facilitate reconstruction of fast ion spatial distributions in ITER plasmas, is discussed.

1. INTRODUCTION

A Vertical Gamma-Ray Camera (VGC) for ITER is being designed in Ioffe Institute [1]. The gamma-ray spectrometry could provide time and spatially-resolved measurements of the gamma-ray source strength delivering unique information on confined alphas, fast ions and runaway electrons in ITER. Principles of the γ diagnostics are described elsewhere [2-4]. They are based on spectrometry of the gamma radiation generated during nuclear reactions, occurring between fast particles, fusion products, fuel components and plasma impurities.

Monitoring of runaway electron generation is one of the most important issues for safe tokamak operations. The diagnosis of runaway electrons in ITER is required for machine protection. The runaway's energy should be measured in the range up to100MeV with 20% accuracy and 10ms time resolution. The runaway current after thermal quench is controlled with 30% accuracy, and after failed breakdown - in the range up to 1 MA with accuracy 50kA [5]. Diagnosing the energy and spatial distributions of runaway electrons can be carried out with 2-D bremsstrahlung spectrum measurements.

Since the gamma diagnostics provide indirect data about explored quantities, such as, parameters of fast ions and runaway electron distributions, correctness of the interpretation of measured gamma and Hard X-ray (HXR) spectra is an important issue to be answered. This paper presents new techniques for experimental data analysis in the framework of ITER gamma-ray diagnostic system design.

2. RECONSTRUCTIONS OF FAST ION DISTRIBUTIONS FROM MEASURED GAMMA RADIATION

Reconstruction of an initial radiation spectrum is one of the primary goals of nuclear spectroscopy.

Its solution is complicated by the fact that the response of the detector to monochromatic gamma-rays represents a complex function depending on many detector characteristics and experimental conditions. Gamma-ray spectrometric measurements in experiments with hot plasma are especially complicated. Usually gamma-ray diagnosing is carried out at high neutron and continuous gamma-ray background. Therefore, the separation of gamma lines in the recorded spectrum, identification of their energies and finding their intensities is an essential task for the experimental data processing [3]. Attempts of reconstruction of initial energy distribution from the spectra measured by scintillation and semiconductor detectors were carried out earlier, for example, in the work [6]. The problem urgency has led to various techniques of deconvolution of spectra and images. In a number of works a comparison has been made between various methods on purpose to choose the most suitable one for spectra processing. It was shown that maximum likelihood estimation using expectation maximization (ML-EM) method [7], known just as Richardson-Lusi [8,9] method, is one of the best at gamma-ray spectra reconstruction: it shows good stability to the initial data noise and allows rather precise recovery of the initial spectra [6]. In all mentioned works the deconvolution methods were applied to the case when the initial spectrum is discrete. Besides, high statistics of spectra were guessed. At the same time, spectra recorded in fusion plasma experiments on tokamaks sometimes have rather low statistics. Moreover, a contribution of neutron induced radiation is present in the spectra. All these mentioned features make an application of the algorithms in experimental data processing more complicated.

ML-EM method has been studied for reconstruction of gamma spectra recorded in hot plasma experiments. Gamma-ray spectrum $y(\varepsilon)$ measured by a detector can be represented in the following form

$$y(\varepsilon) = \int_0^{+\infty} x(\varepsilon')\, h(\varepsilon, \varepsilon')\, d\varepsilon' + n(\varepsilon), \tag{1}$$

where x is an initial gamma spectrum, h - detector's instrumental function, n – noise and ε - gamma-ray energy.

Deconvolution problem consists of obtaining the initial spectrum x from the measured spectrum y using known instrument function h. Expression (1) can be presented in the matrix form as: $y = Hx + n$. Iterative algorithm ML-EM for the solution of this problem can be written, as:

$$x_i^p = x_i^{p-1} \Sigma_j h_{j,i} \cdot \frac{y_j}{\Sigma_k h_{j,k} x_k^{p-1}} \tag{2}$$

Transformation $x_i^p = \max(x_i^p, 0)$ is carried out at every step of data processing.

The basic procedure has been modified. For inhibition of oscillations in the presence of a background pedestal it was offered to carry out smoothing procedure at every j iteration that allows reducing the oscillation amplitude. For magnification of the algorithm resolving ability it was proposed to reduce a channel width in the initial spectrum by interpolation. The DEGAS code

(DEconvolution of GAmma Spectrum) realizing the deconvolution procedure described above and defining peak intensities in the reconstructed gamma-ray spectra has been developed in Ioffe Institute [10].

To realize the described algorithm it is necessary to carry out calculations of detector instrument functions with realistic geometrical and technical parameters in a wide energy range with as small energy steps as possible. Examples of scintillation detector instrument functions calculated using MCNP (Monte Carlo N-Particle) code are represented in figure 1.

In order to examine capabilities of the developed code, some experiments with gamma ray sources were carried out. NaI(Tl) detector ø150x100 mm of size and with energy resolution of 11.5% on 661.6keV line was used in the measurements. Response functions of this detector were calculated by MCNP code in 60–3000keV energy range with 20keV step. In the developed calculation model an isotropic gamma-ray source was placed in 25.5cm apart from the detector. ^{60}Co and ^{137}Cs radioactive sources with known activities of decay were installed the same distance from the real detector for measurements. Result of the measured spectrum processing is shown in figure 2. Accuracy of the sources activities determination was 1.5%.

The developed code was successfully used for processing of gamma-ray spectra measured in experiments on JET. Gamma-ray spectrometry system on JET consists of the BGO detector having quasi-tangential line of sight and NaI(Tl) and LaBr^3(Ce) spectrometers with vertical line of plasma view.

Response functions for BGO detector with a quasi-tangential line of plasma view have been calculated, as well as for other JET spectrometers. A polyethylene attenuator installed in front of the detector was also taken into account when designing the MCNP model in the calculations of the response functions. In figure 3 the spectrum measured during experiments with NBI injection and $3\omega_{c4He}$ heating of ^{4}He in helium plasma with *D* minority is shown. This experiment was described in [3], but we return to it to illustrate capabilities of the developed technique. The peaks at 3.09 and 4.44 MeV are from reactions $^{12}C(d,p\gamma)^{13}C$ and $^{9}Be(\alpha,n\gamma)^{12}C$ with single escape annihilation peaks which are visible well in the measured spectrum. However, two resolved peaks at 3.68 and 3.85 MeV related to the second and third level of ^{13}C nucleus in the reaction $^{12}C(d,p\gamma)^{13}C$ and small 3.22 MeV peak corresponding to the gamma transition from the second excitation level of ^{12}C nucleus in $^{9}Be(\alpha,n\gamma)^{12}C$ reaction were found after the spectrum deconvolution. The obtained data has made it possible to estimate energy distributions of *D* and ^4He ions. The gamma-ray emissivity in the case of fast ion nuclear reactions in fusion plasmas is defined by the reaction rate

$$R(\mathbf{r}) = \left(\frac{2}{m_p}\right) \int n_i(\mathbf{r})\, n_p(\mathbf{r})\, \sigma(\varepsilon)\varepsilon^{1/2} f_p(\varepsilon,\mathbf{r}) d\varepsilon, \quad (3)$$

where $f_p(e,\mathbf{r})$ is a fast ion distribution function; $n_p(\mathbf{r})$, $n_t(\mathbf{r})$ are densities of the fast ions and impurities, $\sigma(e)$ – an excitation function for the gamma transition, ε - energy of fast ions, m_p – fast ion mass. It should be noted that the Maxwellian approximation of the distribution function used for ICRH at fundamental harmonic is not valid for the 3^d harmonic. Figure 3b represents energy distributions of D and ^4He ions derived from the experimental conditions and using the data obtained from the reconstructed gamma-ray spectrum analysis based on the Stix solution of the Fokker-Plank equation [14,15]. The developed technique could be very useful for gamma-ray measurements with spectrometers in the Radial and Vertical Gamma Cameras in ITER. Operational conditions could not allow using high resolution semiconductor detectors in the cameras due to high neutron background level. Thus, the reconstruction of spectra measured by scintillation detectors could provide important information on fast ion energy distributions and optimize regimes of plasma heating.

3. DIAGNOSIS OF RUNAWAY ELECTRONS BASED ON HXR MEASUREMENTS

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 spectrometer. A HXR spectrum generated by homoenergetic 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. Also, it should be noted that the angular distribution of the radiation for relativistic electrons has a strong anisotropy in the direction of the electron velocity.
Modelling of HXR spectra generated by runaway electrons in tokamak plasma experiments is a big challenge. The runaway electron beam geometry and energy distribution should be taken into account. These electrons move along complex orbits, winding over magnetic flux surfaces and the detector finite solid angle need to be modelled. Also, a distortion of the bremsstrahlung spectrum in materials which exist between the plasma and the detector should be simulated obtaining a complex response function for a wide range of HXR energies. Insufficient statistics in the high energy part of the recorded spectra may generate uncertainties of the modelling.
The DEGAS code with modified deconvolution algorithm for measured HXR spectra can be used for reconstruction of energy distribution of runaway electrons. Gamma-ray spectrum $y(\varepsilon)$ measured by the detector can be represented in the following form

$$\begin{gathered} y(\varepsilon) = \int_0^\infty d\varepsilon'\, h_d(\varepsilon, \varepsilon') \int_0^\infty d\varepsilon''\, h_e(\varepsilon', \varepsilon'') f(\varepsilon'') = \\ \int_0^\infty d\varepsilon''\, f(\varepsilon'') \int_0^\infty d\varepsilon'\, h_d(\varepsilon, \varepsilon')\, h_e(\varepsilon', \varepsilon'') = \int_0^\infty d\varepsilon'\, h(\varepsilon')\, h_{tot}(\varepsilon', \varepsilon'), \end{gathered} \tag{4}$$

where f - is the electron distribution function, h_e - HXR generation function, h_d – detector's instrument function, h_{tot} - detector response function to HXRs generated by fast electrons.

The developed procedure was examined with model signals. For that, bremsstrahlung spectra corresponding to the HXR fluxes from monoenergetic electrons moving in the middle plane of JET camera were calculated with MCNP code for the NaI(Tl) detector located in the JET Roof Lab. Some of these spectra are shown in figure 5a. A model electron distribution, represented in figure 5b by blue line, was obtained. Detector response function for the HXR emission generated by electrons with the model distribution was simulated and deconvoluted. Result of the deconvolution procedure is shown in figure 5b by red line. One can see that despite the rather high relative error of the reconstructed electron distribution, the maximal energy of fast electrons was obtained with a reasonable accuracy.

Tests of the developed technique were carried out at HXR spectra processing in experiments on tokamaks Tuman-3M, the Globus-M and JET. Two NaI(Tl) ø70×70mm gamma-spectrometers are installed on Tuman-3M tokamak ($R = 0.53$m, $a = 0.22$m, $I_p < 180$kA), observing a poloidal diaphragm under various angles. Detector #1 has an opposite line of sight to the direction of electrons motion, whereas Detector #2 has an angle of the limiter observation coinciding with it. Response functions on bremsstrahlung caused by fast electrons stopped in the diaphragm have been calculated for both detectors in the energy range of 0.1-15MeV. HXR spectra recorded by the Detectors #1 and #2 during Tuman-3M plasma current ramp-up in a low density ($2\text{-}3\times10^{19}\text{m}^{-3}$) discharge are shown in figures 6a and 6b by black dots, respectively. Result of deconvolution procedure applied to the Detector #1 HXR spectrum is represented in fig.6c by red line. A result of a reverse convolution of obtained electron distribution with the detectors response functions are shown in figs. 6a and 6b by blue line. According to this analysis, in this shot runaway electrons escaped to a diaphragm during plasma current ramp-up could reach maximum energy of 4MeV. Obtained distribution functions for both detectors are in a good agreement with each other that confirms reliability of the applied technique.

The developed technique was used for reconstruction of the runaway electron distributions in JET tokamak. 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 in the DEGAS code. Figures 7-9 illustrate the application of the DEGAS code for runaway diagnosing in JET. In the discharge a runaway electron beam arose at the current ramp-up. HXR spectra were measured by vertical NaI(Tl) detector and deconvoluted with the DAGAS code. HXR spectra recorded by the spectrometer are shown in the top figures 7-9 by black dots. The deconvoluted electron spectra are represented by the red lines in the bottom figures. The runaway current produced by electrons with energy exceeding 2 MeV was derived by means of integration of the electron flux intersected the vertical spectrometer field of view. The time dependence of the runaway current is shown in figure 10d.

In addition to the gamma spectrometers, 2-D neutron/gamma-ray camera, which consists of 10 horizontal and 9 vertical lines of sight, is widely used for diagnosis of runaway electrons at JET. Equipped with ø20x15mm CsI(Tl) detectors, it is used for gamma and HXR measurements. The gamma-camera data are used for tomographic reconstruction of the poloidal profile of the bremsstrahlung source in JET. Examples of tomographic reconstructions of HXR source profile in JET are shown in figure 11. Some details on runaways studies on JET is discussed in [16].

A similar system can be developed for ITER. For tomographic reconstructions of runaways, at least two fields of view of ITER plasmas are required. In order to arrange a horizontal view the horizontal gamma-ray spectrometers installed in the Radial Neutron Camera could be used. The absence of vertical ports on ITER makes it much more complicated to develop the implementation of tomographic neutron and gamma-ray reconstruction systems. At the moment it is suggested to use one of divertor ports for vertical viewpoint implementation. In order to estimate intensities of HXR fluxes in Vertical Gamma Camera, a modelling of bremsstrahlung birth profile in ITER was carried out. Calculations were done for deuterium plasmas with 2% impurity of beryllium, argon and neon. A massive injection of Ar and Ne is considered to suppress development of runaway avalanches during discharges [17]. Calculated HXR spectra, which are related to the total runaway current 1 MA are shown in figure 12. The spectra recorded by the LaBr3(Ce) scintillation spectrometer (ø25x75 mm) were calculated for 10 ms time bin as requested for the ITER runaway electron diagnostics [5]. The calculated spectra satisfy the 20% accuracy required for measurements of maximum runaway energy in ITER.

CONCLUSIONS

Gamma-Ray Spectrometry can be used as a primary diagnostic technique for measurement of the fusion alpha-particle energy and density profile, as well as current and energy of runaway electrons. As a supplementary diagnostic, it can be used for measurements of n_T/n_D in the plasma core, impurity density profile, energy distribution of fast ions and ^3He concentration profiles [5]. Diagnosis of runaway electrons can be performed in all plasma scenarios at current ramp-up and current quench phases of plasma discharge. Measurements of bremsstrahlung spectra can provide reconstruction of runaway beam profile and localization of injected gas during of the discharge. Analysis of measured HXR spectra provides maximum energy and allows reconstruction of the energy distribution of runaway electrons in the field of view of the diagnostics.

The DEGAS code for deconvolution of gamma-ray spectra recorded in plasma discharges has been developed. The deconvolution of gamma-ray and HXR spectra allows identification of nuclear reactions and calculation of gamma-ray intensities. Maximum energy of runaway electrons can be derived with sufficient accuracy to satisfy the ITER Project Requirements. The code was successfully tested in the experimental data analysis.

The gamma-ray spectrometry is successfully used on JET for studies of fast ions in the trace tritium plasma experiments, ICRF-heating of ^4He beams, ^3He-minority ICRF-heating experiments, etc. [17,18]. Also, this technique was very useful for runaway electron studies in low density ohmic discharges [19] and experiments with a massive gas injection for the disruption mitigation [17].

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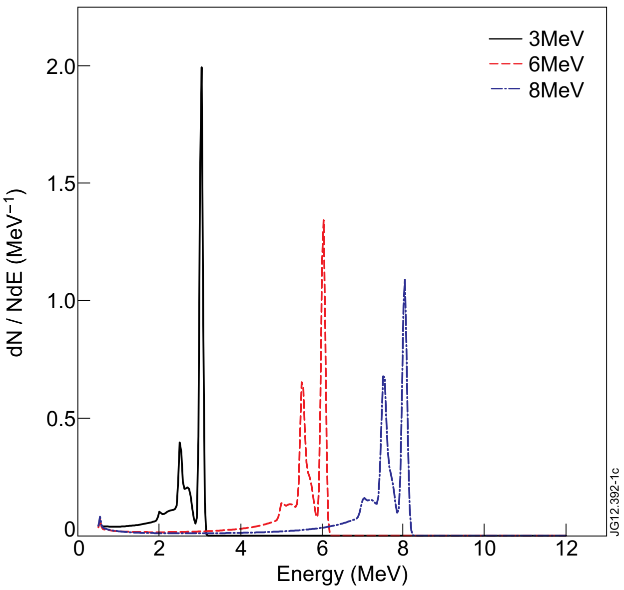

Figure 1: Examples of instrument function of NaI(Tl) detector calculated by MCNP code for 3, 6 and 8MeV monoenergetic gammas.

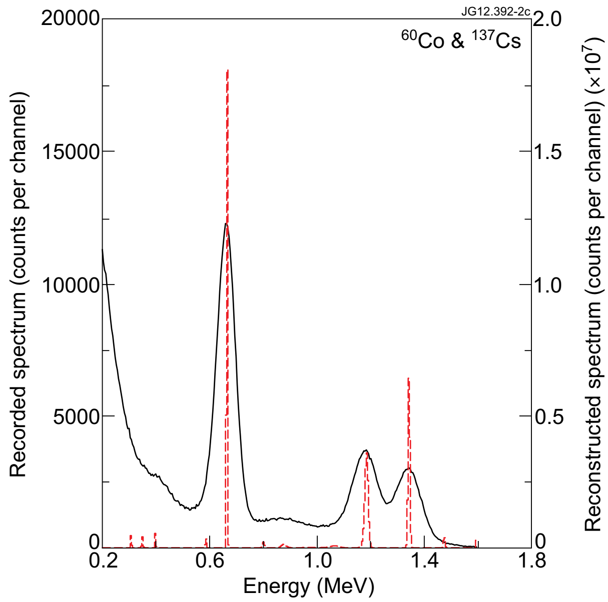

Figure 2: Spectrum of ^{60}Co and ^{137}Cs radioactive sources measured by NaI(Tl) detector (black line) and initial gamma spectrum reconstructed by DEGAS code (red line).

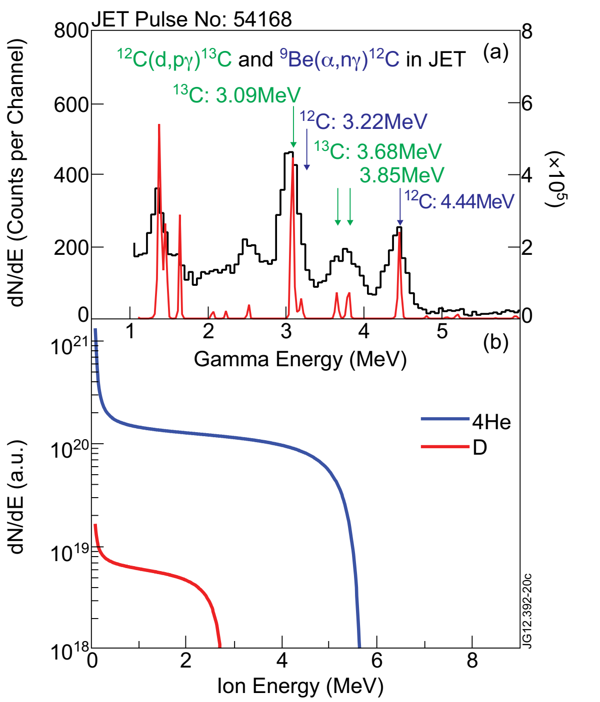

Figure 3: a) Black line: gamma-spectrum recorded at JET shot with ICRH heating of injected ^{4}He beam in ^{4}He plasma with D minority [3]. Red line: reconstructed gamma spectrum coming to the detector; b) Reconstruction of distributions of D (red line) and ^{4}He (blue line) populations derived from the top spectrum analysis using a generalised Stix formalism.

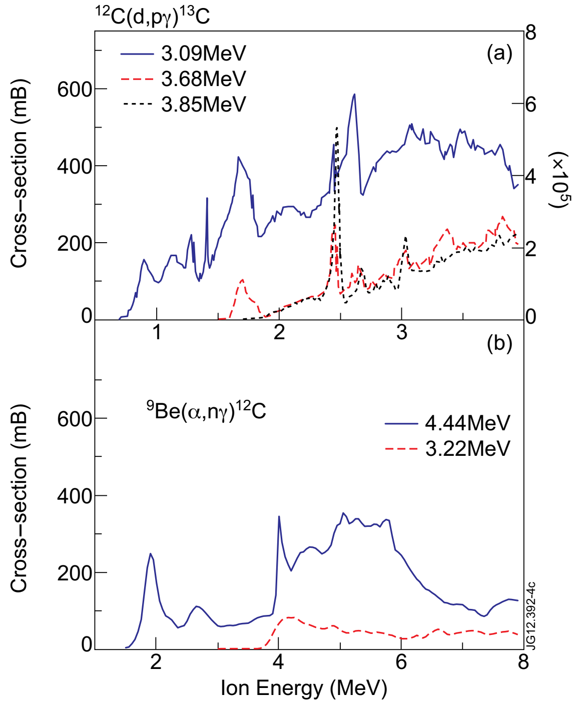

Figure 4: a) Excitation functions of 3.09, 3.68 and 3.85MeV gamma transitions in ^{12}C(d,pγ)^{13}C reaction[11]; b) excitation functions of 4.44 and 3.22 MeV gamma transitions in ^{9}Be(α,nγ)^{12}C reaction [12,13].

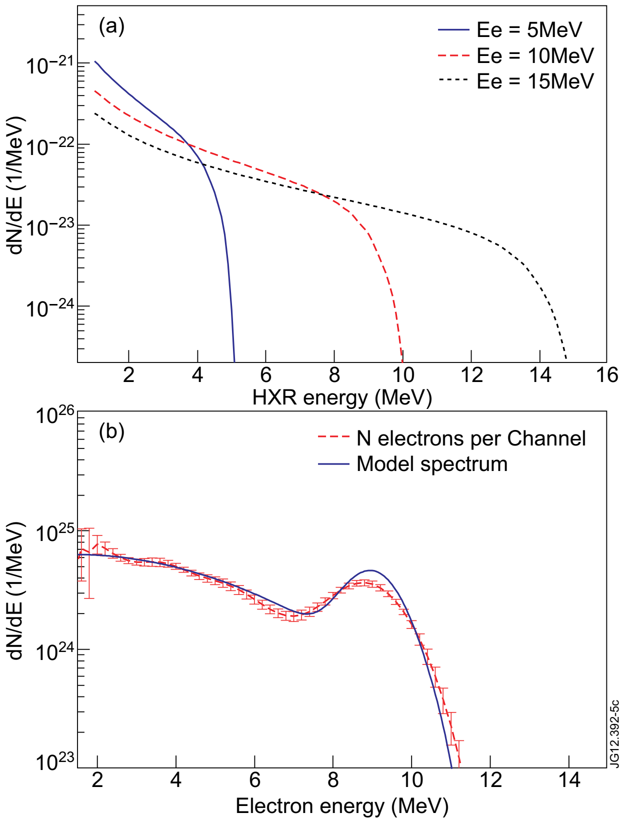

Figure 5: a) HXR spectra from monoenergetic electrons, which could be recorded by JET vertical spectrometer calculated by MCNP code; b) model (blue line) and reconstructed by DEGAS code electron spectra.

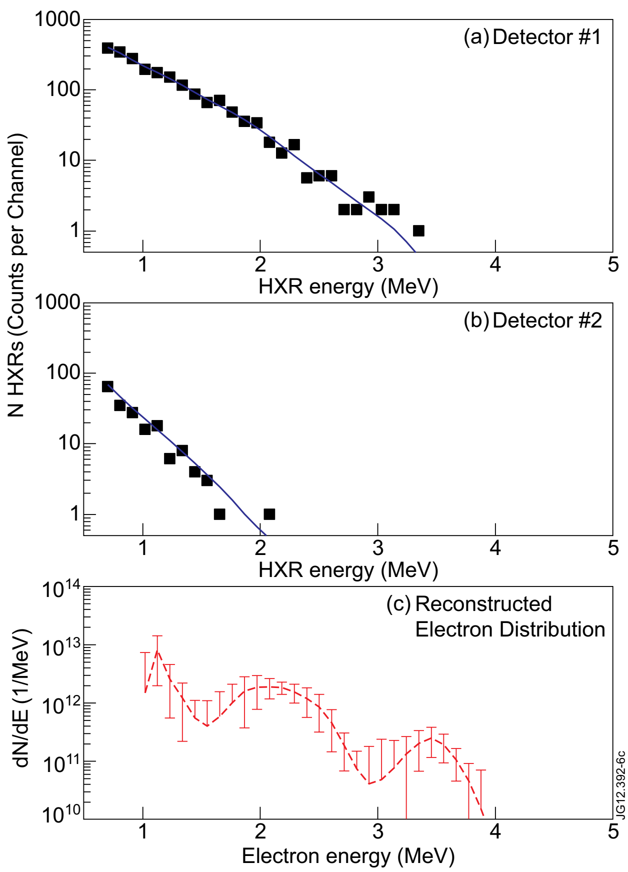

Figure 6: a) Black dots HXR spectrum recorded at Tuman-3M shot by Detector #1, blue line – HXR spectrum, corresponding to the electron distribution shown in figure (c) ; b) Black dots - HXR spectrum recorded at Tuman-3M shot by Detector #2, blue line – HXR spectrum, corresponding to the electron distribution shown in figure (c); c) Runaway electron distribution reconstructed from Detector #1 HXR spectrum.

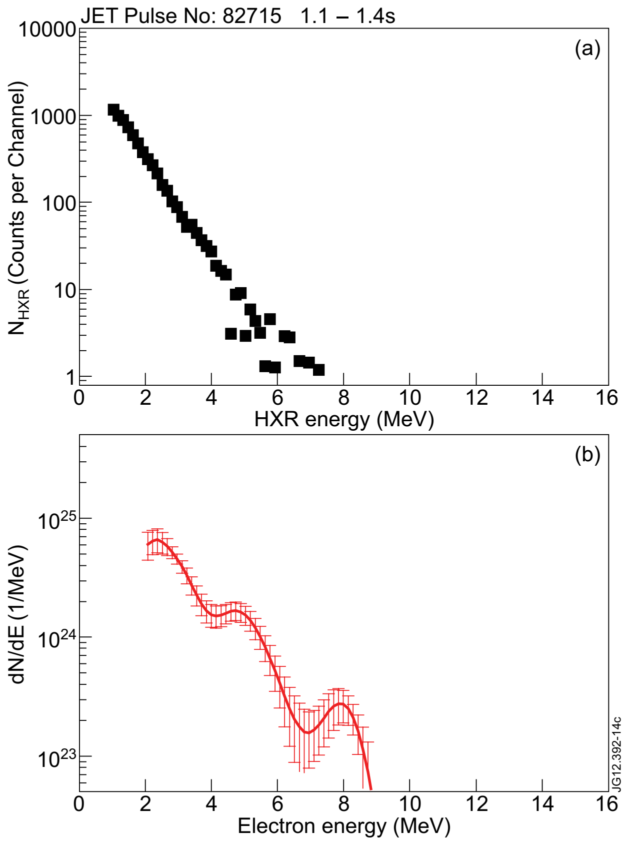

Figure 7: a) HXR spectrum, recorded at 41.1-42.4 s of JET Pulse No: 82715; b) Reconstructed energy distribution of fast electrons.

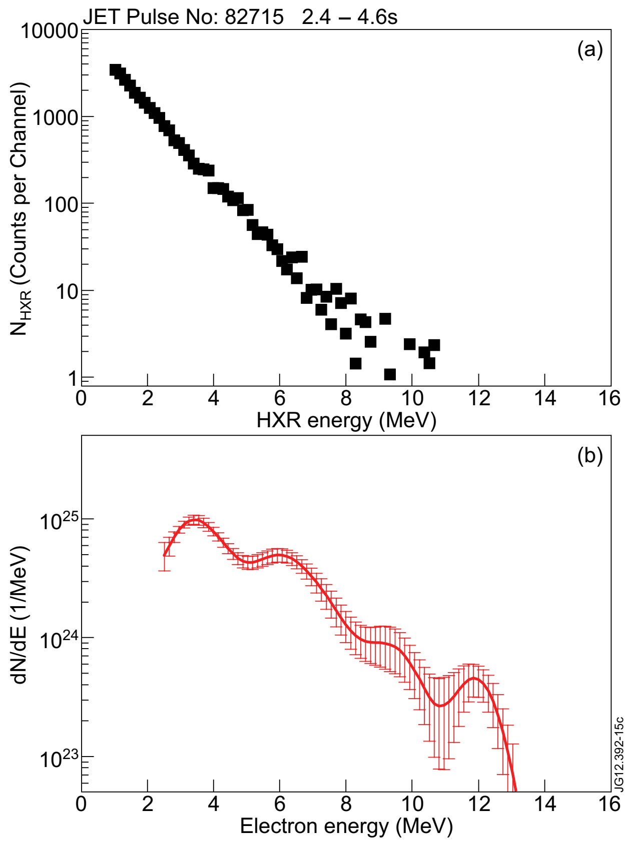

Figure 8: a) HXR spectrum, recorded at 42.4-44.6 s of JET Pulse No: 82715; b) Reconstructed energy distribution of fast electrons.

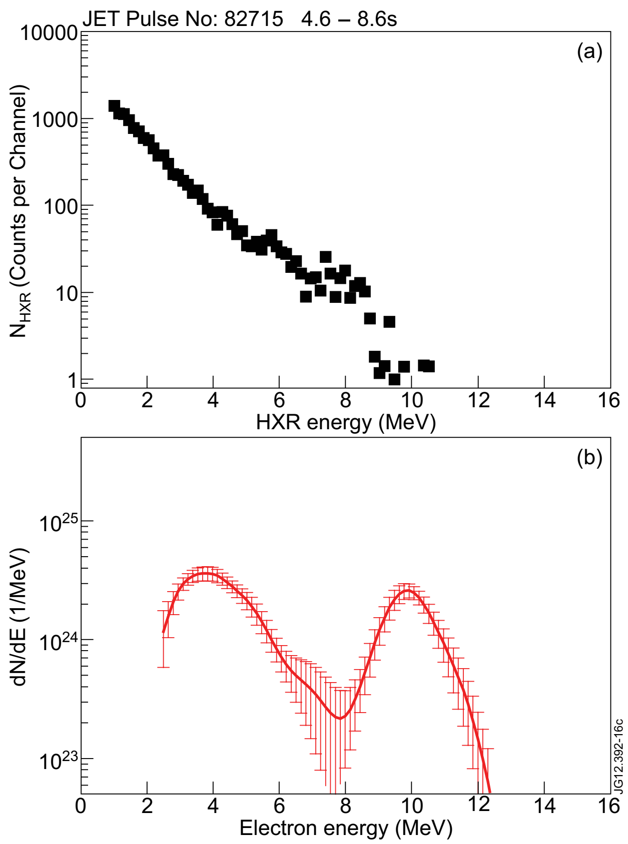

Figure 9: a) HXR spectrum, recorded at 44.6-48.6 s of JET Pulse No: 82715; b) Reconstructed energy distribution of fast electrons.

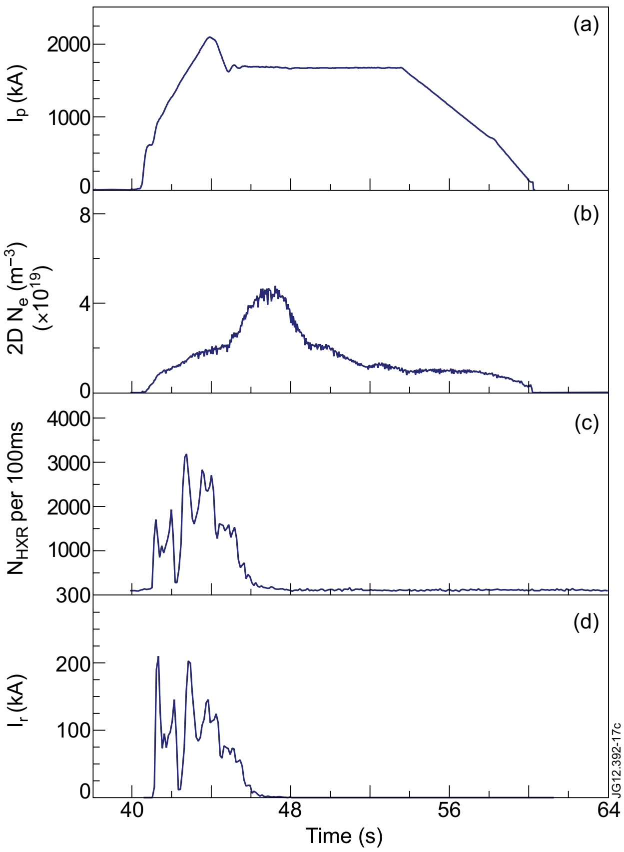

Figure 10: a) Plasma current of JET Pulse No: 82715 (I_p=1.7 MA, B_t=2T, T_e=1.8 keV, P_{NBI}=2.3 MW); b) Electron density of the JET shot; c) Intensity of HXRs recorded by detector; d) Reconstructed runaway current in the visible for vertical spectrometer volume of electrons exceeding 2MeV.

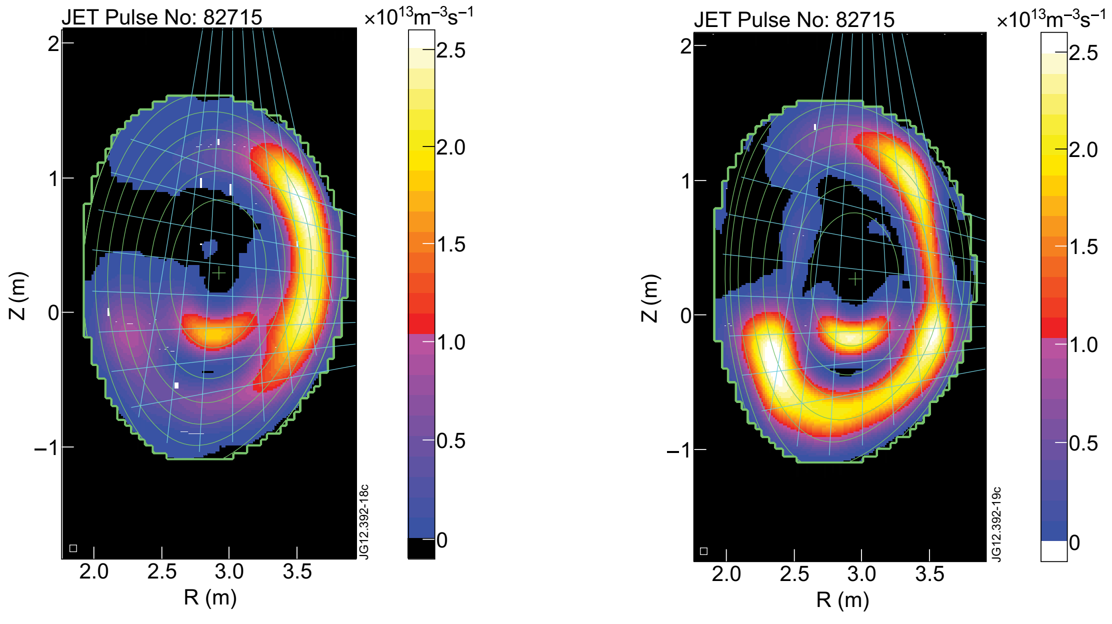

Figure 11: Tomography reconstruction of HXR emission profile in the JET Pulse No: 82715(I_p=1.7MA, B_t=2T, T_e=1.8keV, P_{NBI}=2.3MW): a)41.1-41.8s; b) 42.4-43.4s.

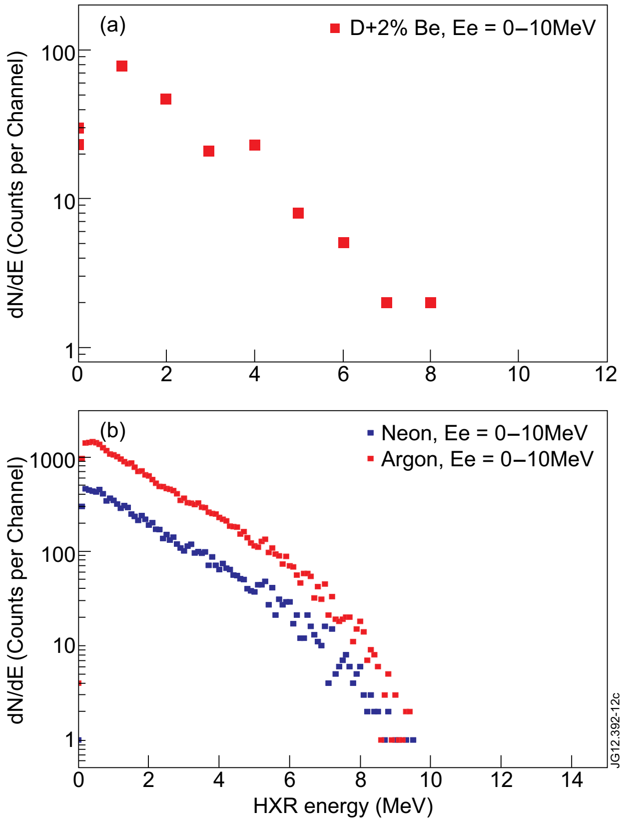

Figure 12: HXR spectra corresponding to a flat electron distribution 0-10 MeV calculated for one of central detectors of VGC generated in a) deuterium plasma with 2% of beryllium impurity, b) argon (red dots) and neon (blue dots).