EUROFUSION WPJET4-CP(16) 15367

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Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

CeBr3 –based detector for Gamma-ray Spectrometer Upgrade at JET

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** See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.*

One of the important techniques used at JET for studying fast ions is based on the measurements of gamma-rays which are produced as a result of nuclear reactions between ions and plasma impurities. The intense neutron and gamma-ray fluxes expected during DT campaign impose new requirements on the characteristics of the detectors used in these experiments. In addition to good energy resolution the detectors must also be characterized by a high signal-to-noise ratio and allow to perform measurements at high counting rate about 1 MHz. The scintillators which fulfill these requirements are, among others, $LaBr_3$:Ce, already tested at JET, and $CeBr_3$ with a scintillation decay time of ~20 ns. We report on measurements which were performed with a detector module equipped with a $CeBr_3$ scintillator and with an active voltage divider, designed and constructed at NCBJ. Standard gamma-ray sources, as well as a PuBe source were used for measurements. The comparison of the measured and Monte Carlo simulated spectra is also presented

Keywords: JET, Gamma-ray diagnostic, Gamma-ray spectrometer, Monte Carlo simulations,

1. Introduction

The numbers and species of energetic ions, spatial and energy distributions as well as behavior of these ions in tokamak plasma can be evaluated on the basis of the data provided by the gamma-ray diagnostics. The gamma radiation is emitted as a product of nuclear reactions between plasma impurities, such as beryllium or carbon, and fast ions appeared in the plasma. Such ions can be produced by fusion reactions e.g. confined α-particles and other charged products, but also there are ions accelerated by ICRH or injected to the plasma by NBI (fast protons, deuterons and other light ions). The gamma-ray radiation energy spectra provide information on ions' energies, while a spatial distribution of these ions could be reconstructed on the basis of time- and space-resolved measurements of gamma-ray emission profiles.

During the planned DT campaign at JET there are expected high neutron and gamma-ray fluxes. The gamma-ray detectors should fulfill special requirements, i.e. maximization of signal-to-noise ratio, proper detection of very high fluxes of radiation and high energy resolution [1-2]. The proposed $CeBr_3$ scintillator is characterized by a scintillation decay time about 20 ns, good energy resolution and a high detection efficiency, which make it a suitable detector to be used in the upgraded gamma-ray camera at JET. This scintillator is already considered as an alternative to $LaBr_3$:Ce crystal tested already at JET [1-3].

The paper reports on measurements performed at NCBJ in order to estimate the detection characteristics of a detector module composed of a 3"x3" $CeBr_3$ scintillator coupled with photomultiplier (PMT), and an active voltage divider designed and manufactured at NCBJ. This gamma-ray detection device after further precise calibration will be an appropriate instrument to replace the BGO scintillator detector which has been used up to now at JET.

The existing tangential gamma-ray spectrometer (KM6T) is currently equipped with BGO scintillator, which was designed for deuterium experiments see figure 1. The long scintillation decay time equal to about 300 ns, relatively low energy resolution and presence of oxygen in the chemical composition (which after irradiation with fast neutrons emits high energy gamma rays) make it not suitable for high gamma-ray doses in the presence of intense neutron fluxes expected during DT campaign [4]. Therefore, it is essential to exchange this diagnostic for the future DT experimental campaigns.

In the first place the horizontal spectrometer (placed inside the KX1 bunker) will be replaced and test measurements with the new instrument in the real field of gamma-rays, and neutron background of JET tokamak will be performed. The new movable gamma-ray shield and neutron attenuator (build of LiH) is already elaborated [5].

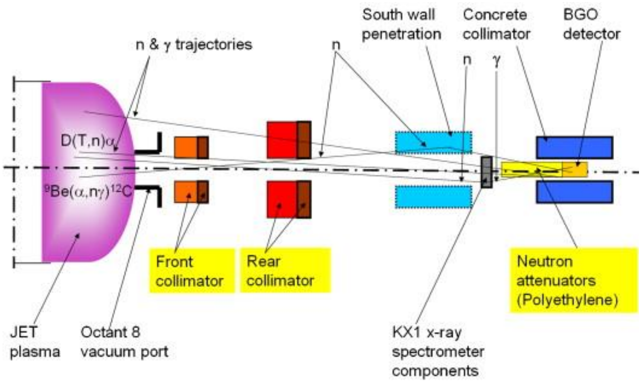

Fig. 1. Existing gamma-rays diagnostic KM6T used at JET during deuterium discharges [4].

2. Experimental measurements

The detector module planned to be used in the Gamma Spectrometer, is composed of the $CeBr_3$ scintillator (76 mm in diameter, 76 mm height) encapsulated in a 1 mm thick aluminum housing and coupled with R6233-100 PMT (76 mm diameter). The voltage divider (VD) can be easily disconnected from the PMT. The measurements were performed using the standard VD (manufactured by Scionix), and an active VD, specially designed and constructed at NCBJ. This active divider can be used with typical supply voltage and with a PMT which is equipped with a standard 14 pin socket. It ensures constant gain coefficient during measurements performed under conditions of a high counting rate [6]. The test measurements presented in this paper were carried out with point-like sources which were placed at a chosen distance (0-80 cm) from the detector front surface.

3. Characteristic of the detector module

At NCBJ we performed measurements using standard gamma-ray sources and also a PuBe source. The exemplary spectrum recorded using the PuBe source is shown in figure 2.

The ^{238}Pu isotope is an alpha emitter with half-life equal to about 87 years. Gamma radiation is emitted due to the following nuclear conversions;

$$\alpha + {}^{9}Be \rightarrow {}^{13}C$$
$$^{13}C \rightarrow {}^{12}C^{*} + n$$
$$^{12}C^{*} \rightarrow {}^{12}C + \gamma(4.439 MeV)$$

Photons with energies above about 1 MeV interact with matter mainly through electron-positron pair production. Positrons could then annihilate with electrons inside the scintillator material and two 511 keV gamma quanta are emitted. Full energy of gamma quanta is deposited in material, when both of 511 keV rays are absorbed. Single- or double escape peaks are recorded, when one or two of 511 keV quanta escape the scintillator [7]. The full energy peak (FEP), as well as single- and double escape peaks (SEP and DEP correspondingly) with energies 4.4, 3.9 and 3.4 MeV respectively are clearly visible on the spectrum.

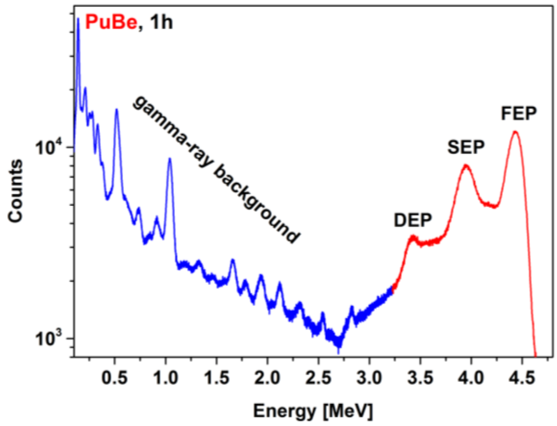

Fig. 2. Spectrum of gamma rays emitted from PuBe source, as recorded by means of $CeBr_3$ 3×3” scintillator. Full energy peak (FEP), single- (SEP) and double- (DEP) escape peaks are marked on the plot.

On the basis of the recorded spectra we estimated the energy resolution and detection efficiency of the tested detector module in a wide energy range. The results of these evaluations are presented in table 1.

Table 1. Detection characteristics of the 3”×3” $CeBr_3$ scintillator equipped with the active divider manufactured at NCBJ.

energy (keV)	source	FWHM (%)	detection efficiency (%)
511	^{22}Na	4.9±0.1	58±3
662	^{137}Cs	4.3±0.1	49±2
1115	^{65}Zn	3.5±0.1	37±2
1173	^{60}Co	3.3±0.1	34±1
1275	^{22}Na	3.3±0.1	33±2
1332	^{60}Co	3.3±0.1	33±1
4439	PuBe	2.7±0.1	14±2

In addition to the performed measurements we also compared intrinsic activity of $CeBr_3$ and $LaBr_3$:Ce crystals. In both scintillators peaks corresponding to natural background (1.461 MeV from ^{40}K and 2.615 MeV from ^{208}Tl) and contamination by α-emitting actinides (energies between 1.5 and 2.5 MeV) are easily observed. The $LaBr_3$:Ce shows an elevated background which is due to the presence of radioactive ^{138}La isotope in the natural composition of La element. This isotope produces peak of energy about 1470 keV and also some continuum above 780 keV [8].

The energy resolution and detection efficiency of $CeBr_3$ and $LaBr_3$:Ce scintillators are compatible. However, $LaBr_3$:Ce is less appropriate to high doses of γ-radiation. Our measurements showed that the $LaBr_3$:Ce crystal irradiated by a 1 kGy dose of gamma radiation has detection efficiency lower by about 10% and energy resolution worse by about 25%, than those observed before irradiation, while $CeBr_3$ is almost resistant to such conditions. Cerium element has also lower neutron capture cross section than La (12 mb and 100 mb respectively, at neutron energy about 30 keV), which could make $CeBr_3$ scintillator more resistant to neutron background [8].

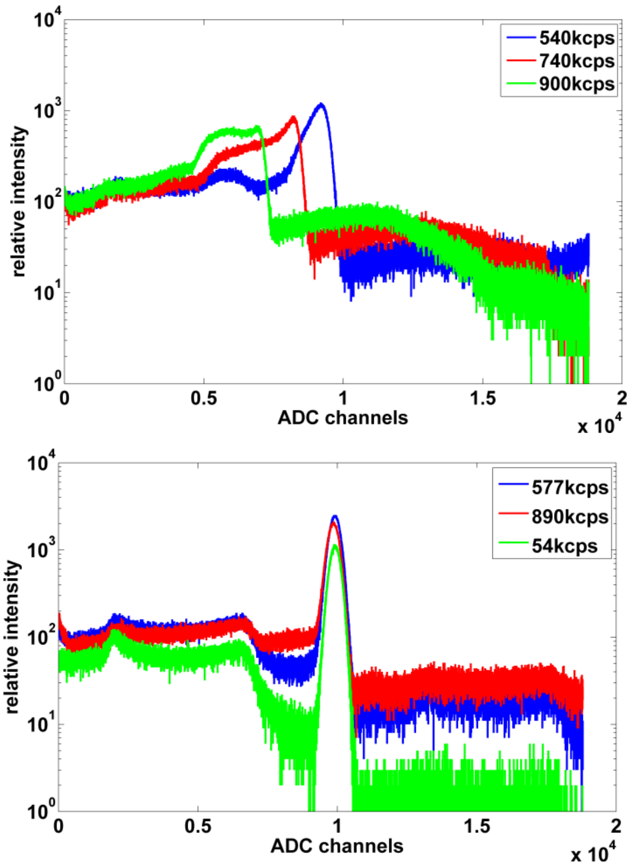

Fig. 3. ^{137}Cs gamma-ray spectra measured for different gamma-rays fluxes with the 3”×3” $CeBr_3$ scintillator equipped with the Scionix passive voltage divider (upper) or NCBJ active divider (lower). The measurements were performed using a CAEN digitizer.

We found that the performance of the PMT-based detector depends on the voltage divider used. During the measurements with high gamma-rays flux, high current and pile-up effects change the operating point and gain coefficient of the detector module. Therefore, in order to properly register spectra in such conditions, we should use an active electronics. The fully active voltage divider was constructed and tested in our lab in NCBJ. The divider is built of commercially available components, such as transistors, Zener diodes, resistors and capacitors [6]. The divider can be used up to 1.5 kV with a standard 14 pin PMT socket.

The measurements with high counting rates were performed using ^{137}Cs source with an activity equal to about 400 MBq. Changes of the gamma-rays flux was realized by positioning the source at various distance from the detector.

The detection efficiency and energy resolution estimated during measurements with low rates (non intensive gamma-ray fluxes) are independent on the used divider. However, at high counting rates, the difference in spectra recorded with the active and standard VD are easily noticeable, see figure 3.

4. Monte Carlo simulations

In order to numerically reconstruct the spectra recorded by the used detector we performed simulations of the spectra measured by $CeBr_3$ scintillator irradiated by gamma-rays of chosen energies. We decided to choose Geant4 toolkit [9,10] due to its well-defined physics, flexibility and good reliability [11].

We performed simulations of the detector response to monoenergetic gamma-rays of energies equal to the energies of the calibration sources, i.e. 662 and 4439 keV.

The geometry used during simulations was chosen to match the geometry of performed measurements. The point-like isotropic source was placed at a chosen distance from the scintillator front surface. The presented histograms represent total energy deposited in the scintillator by impeding radiation. The physics used in our simulations includes gamma-rays as well as photon processes (e.g. photoelectric effect, gamma conversion, scintillation, cherenkov radiation, etc.)

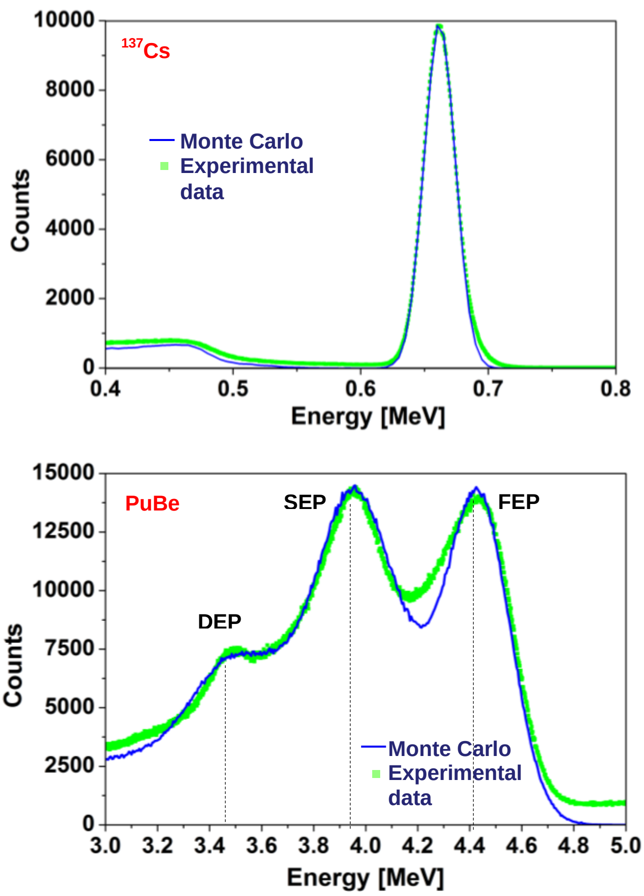

Fig. 4. Gamma-ray spectra of ^{137}Cs source (662 keV, upper) and PuBe source (4.44 MeV, lower) simulated using Geant4 toolbox, as compared with the measured signals.

The results of the simulations are presented in figure 4. The full energy peaks as well as single- and double-escape peaks are distinctly visible on the plotted histograms (spectrograms).

The observed differences between measurements and simulations could be the effect of not taking into account the surroundings of the detectors, like walls and stands. The real sources of radiation have their dimensions, while sources used in simulations were point-size. It could cause observed inaccuracies of these calculations.

5. Summary

The $CeBr_3$ scintillator is characterized by a good energy resolution and high detection efficiency for gamma-rays with energy up to 6 MeV, which make it suitable to use in the JET DT campaign. The short scintillation decay time allows to perform measurements with count rates up to about 1 MHz. The intrinsic activity of the scintillator is lower than that of the $LeBr_3$:Ce, which makes it a good choice for a low background gamma-ray measurements.

The next step of the simulations will include background radiation, either from natural sources or artificial ones. Taking into account intensive neutron radiation from JET discharges we are expecting signals generated by neutrons as well, which should be especially high during the oncoming DT campaign at JET.

We also intend to better reproduce detector geometry and its surrounding, i.e. shielding, walls and various stands used during measurements and introduce optical characteristics of the scintillator and its housing (refractive index, absorption, reflectivity, etc.) and take it into account in the spectra simulations [12].

Acknowledgments

This scientific work was partly supported by Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the years 2015-2017 allocated for the realization of the international co-financed project.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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