WPJET4 Gamma Spectrometer Upgrade (GSU)

D28	Report on neutron-photon transport calculations (IV). Evaluation of detector response to neutron and gamma radiations.

1. Introduction

On JET the α-particle diagnostic is based on the nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$ between confined α-particles and beryllium impurity ions typically present in the plasma, *see GSU Project Management Plan* and references therein. The applicability of gamma-ray diagnostic is strongly dependent on the fulfilment of rather strict requirements for the definition and characterization of the neutron and gamma radiation fields (detector Field-of-View, radiation shielding and attenuation, parasitic gamma-ray sources). For operating this diagnostic at the high DT neutron fluxes expected in the future high-power DT campaign on JET, specific improvements are needed in order to provide good quality measurements in the DT campaign, characterized by a more challenging radiation environment.

In order to enable the gamma-ray spectroscopy diagnostic for α-particle diagnostic during the DT campaigns the following goals should be achieved:

- Maximization of the signal-to-background ratio at the spectrometer detector; this ratio is defined by terms of the plasma-emitted gamma radiation and the gamma-ray background.
- Establishing high count rate signal processing and energy-resolved gamma-ray detection.

In the DT experiments the gamma-ray detector must fulfil requirements for high count rate measurements. The existent BGO-detector with a relatively long decay time, about 300 ns, should be replaced by a new detector module (DM2) based on $CeBr_3$ scintillator, with an associated digital data acquisition system. The $CeBr_3$ scintillator are characterized by short decay time (~20 ns) and a high light yield about 45 000 photons/MeV. The coupling of the scintillators with photomultiplier tubes in specially designed detector modules will permit the operation at count rates over 2 Mcps. The $CeBr_3$ scintillator is an alternative to already tested at JET detectors based on $LaBr_3$:Ce.

The most important difference between these two crystals is connected with the presence of the long-lived naturally occurring ^{138}La isotope in $LaBr_3$:Ce. Such an intrinsic activity poses a serious limit for application in low count rate experiments.

The $CeBr_3$ scintillator was found to fulfil low noise measurement conditions. It shows 30 times reduction in internal activity in comparison with $LaBr_3$:Ce, see below. The $CeBr_3$ scintillator has a similar energy resolution, sensitivity and decay time as the $LaBr_3$:Ce scintillator. Moreover, the $CeBr_3$ scintillator seems to be more resistant for gamma radiation than $LaBr_3$:Ce. A 1 kGy dose of gamma radiation deteriorates the yield of $LaBr_3$:Ce by ~10% and worsens its energy resolution from 3.0 to 3.8%, while is almost negligible for $CeBr_3$.

$CeBr_3$ may also be more resistant to neutron radiation because of lower neutron capture cross section in Ce (~12 mb) than in La (~100 mb) at E_n ~30 keV.

These features make $CeBr_3$ an interesting alternative for JET plasma applications in spite of the excellent spectroscopic performances of $LaBr_3$:Ce scintillator.

Detector response function is used to determine an output of detectors when they are exposed to radiation sources, e.g., gamma-rays or neutrons. Such a function is needed to get a response of a detector to a known radiation source or to perform a spectrum analysis to find a type and quantity of a source irradiated a detector. In case if it is possible experimentally determined response functions should be used but Monte Carlo simulated distributions could be used as well.

2. Detector module DM2

The detector module prepared for the upgraded Gamma-ray Spectrometer at JET comprises a 3”×3” cylindrical $CeBr_3$ scintillator, encapsulated in a 0.5 mm thick Al housing and coupled to a R6233-100 PMT. It is equipped with a SMA connector for tests with LED sources.

The specification of a detector module DM2 based on $CeBr_3$:

- scintillator dimensions: 3”×3” (76 mm diameter, 76 mm high),
- low background,
- high resolution <4.3% FWHM at 662 keV scintillation crystal,
- 0.5 mm thick aluminium housing.

The photomultiplier R6233-100 PMT:

a 76 mm diameter PMT surrounded by an extra-long solid mu metal shield.

Additional features:

a fiber optics stabilization port with SMA connector.

Active voltage divider designed at NCBJ.

3. Measurements with 3”×3” $CeBr_3$ scintillator

We performed measurements on an energy resolution and a detection efficiency in our laboratory at NCBJ. For measurements we used standard γ-ray sources: ^{137}Cs (662 keV), ^{65}Zn (1115 keV) and ^{22}Na (1274 and 511 keV). For more details see the NCBJ report on “*D18 Manufacturing of DM2 including: scintillator, photomultiplier, magnetic shielding, voltage divider and high voltage power supply*” (2015).

In October/November 2016 we carried out measurements at JET performed with the 3”×3” $CeBr_3$ scintillator equipped with the NCBJ dedicated active voltage divider. A mixed source No. AG-5430 was used in measurements at JET, see Table 1. Spectra were registered with a commercially available CAEN Desktop Digitizer DT5720. A typical spectrum is shown in Fig. 1.

Table 1. Radioactive mixed source No. AG-5430.

nuclide	gamma-ray energy (keV)	activity (kBq)	emission rate [$10^3 s^{-1}$]
^{241}Am	60	3.42	1.23
^{109}Cd	88	15.90	0.582
^{57}Co	122	0.579	0.496
^{139}Ce	166	0.725	0.579
^{203}Hg	279	1.40	1.14
^{113}Sn	392	2.58	1.68
^{85}Sr	514	2.88	2.83
^{137}Cs	662	2.77	2.36
^{88}Y	898	5.11	4.80
^{57}Co	1173	3.36	3.36
^{60}Co	1333	3.36	3.36
88Y	1836	5.11	5.07

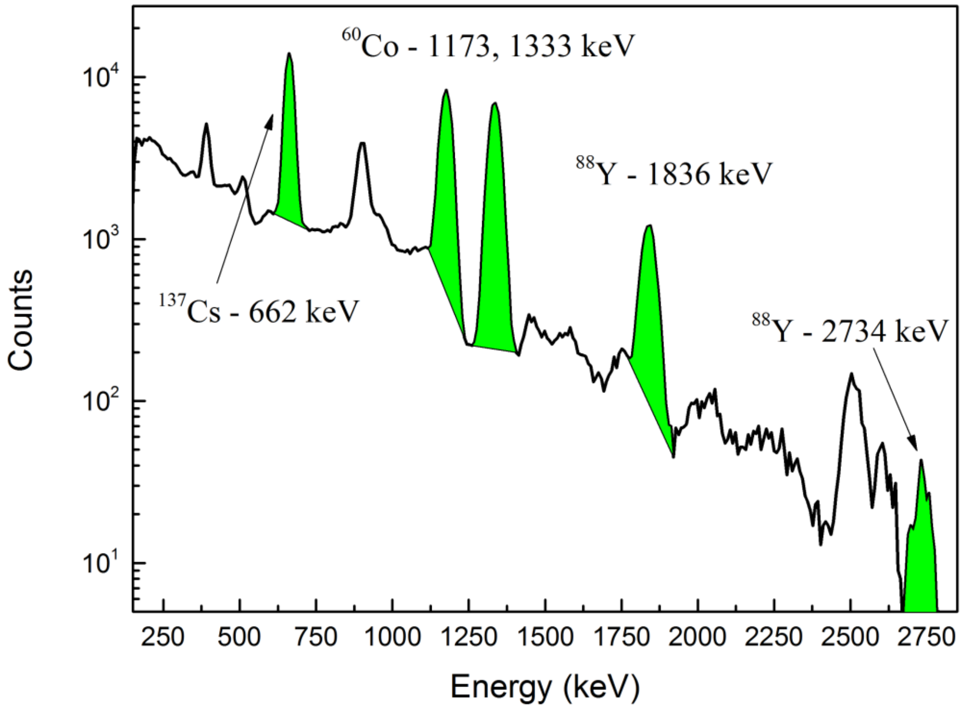

Fig. 1. Spectrum measured with a mixed radioactive source and registered with a 3”×3” $CeBr_3$ scintillator.

We determined an energy resolution, defined as a full width at half maximum (FWHM) for the most pronounced gamma lines, see Table 2.

Table 2. FWHM values for 3”×3” $CeBr_3$ scintillator measured at JET.

γ energy (keV)	γ-ray source	FWHM (%)
662	^{137}Cs	4.62±0.02
1173	^{60}Co	3.45±0.02
1333	^{60}Co	3.29±0.02
1836	^{88}Y	2.71±0.04
2734	^{88}Y	2.23±0.26

4. Monte Carlo simulation of a detector response

We performed Monte Carlo simulations to evaluate a detector response to gamma radiation which allows to reconstruct spectra measured with a 3”×3” $CeBr_3$ scintillator. For all simulations we used the Geant4 code due to its well-defined physics, flexibility and good reliability. The FTFP_BERT physics list, containing all standard electromagnetic processes and accounting for scintillation, was applied.

We simulated a detector response to monoenergetic gamma-rays with an energy from 0.1 to 6.1 MeV to cover the energy range of the used sources. The geometry used during simulations was the same as in dedicated measurements. Experimentally determined FWHM values were used in Monte Carlo simulations.

In Fig. 2 examples of a comparison of measured and simulated gamma-ray spectra are shown: in the upper part for ^{137}Cs and in the lower part for PuBe source. The histograms represent a total energy deposited in the scintillator. We have assumed a point-like source in simulations.

To investigate an influence of source shape on simulated spectra, a cylindrical source (diameter=2 cm, height=3 cm) was used as input. In Fig. 3 a corresponding spectrum is shown in comparison with a spectrum obtained for a point-like source.

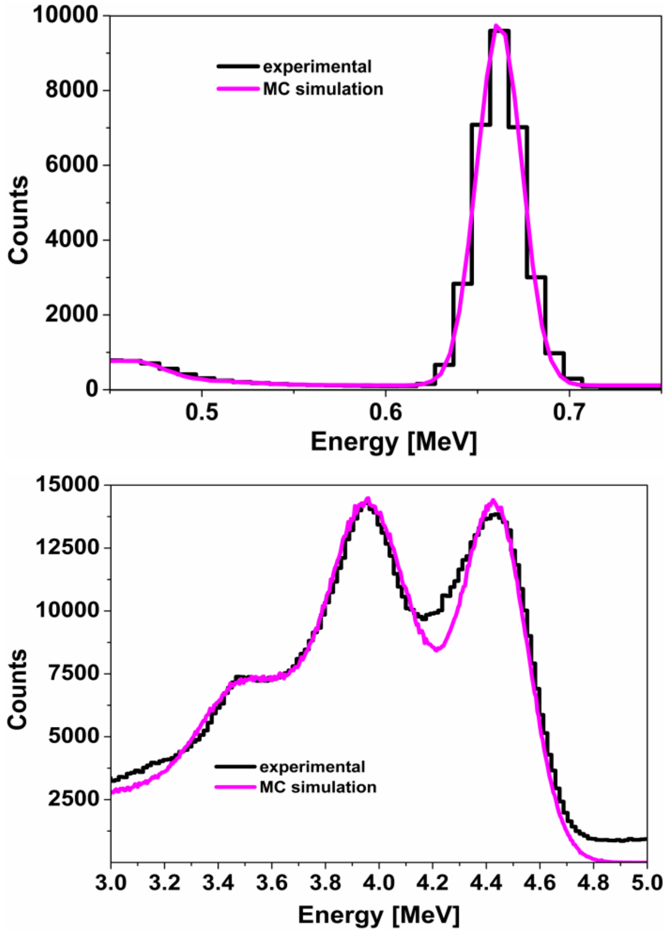

Fig. 2. Gamma-ray spectra of ^{137}Cs source (0.662 MeV, upper) and PuBe source (4.44 MeV, lower) simulated using Geant4 (magenta), as compared with the measured signals (black).

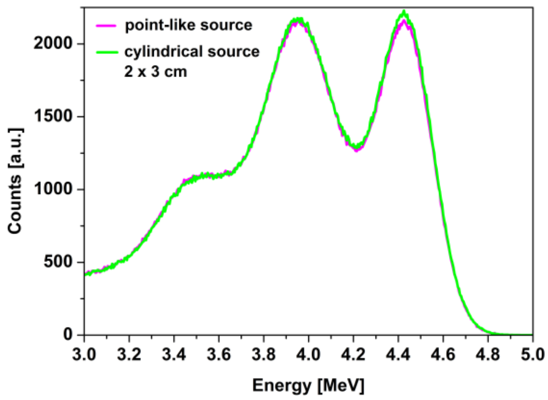

Fig. 3. Gamma-ray spectra of PuBe source, emitting a gamma line with an energy of 4.44 MeV simulated for point-like (magenta) and cylindrical source (green).

As a result we reproduce measured spectra. No significant difference was seen in Monte Carlo simulated for point-like and cylindrical sources.

A good agreement between measured and Monte Carlo simulated spectra shows a usefulness of such simulations for calculating a scintillator-based detector response in a wide energy range of gamma-rays.

Irradiation of $CeBr_3$ material with 14 MeV neutrons leads to activation of various elements, present in the detector, its surrounding, shielding etc.

The gamma lines observed during experiment are, e.g.:

- 536 keV, 650 keV and 7574 keV from reaction with ^{81}Br,
- 1014 keV, 2836 keV from reaction with ^{27}Al,
- 1779 keV from reaction with ^{28}Si,
- 1261 keV, 4438 keV and 4945 keV from reaction with ^{12}C (prompt radiation, radiative neutron capture),
- 2223 keV from reaction with ^{1}H (prompt radiation),
- 6129 keV from ^{16}N decay.

C, N and H are present in the surrounding – table, holder, etc., Si is present in shielding.

As an example, in Fig. 4 a Monte Carlo simulated spectrum of 14 MeV neutrons registered in a 3”×3” $CeBr_3$ scintillator is shown. The distance between point-like neutron source and a scintillator is 20 cm.

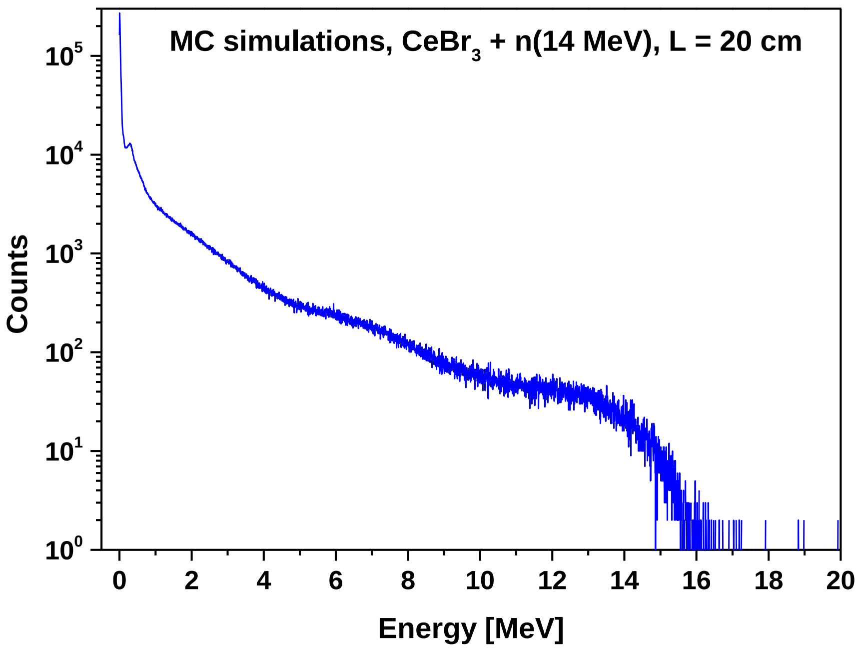

Fig. 4. Monte Carlo simulated spectrum of 14 MeV neutrons registered at 3”×3” $CeBr_3$ scintillator.

For a better understanding of measured spectra detailed knowledge of a detector setup, including its surrounding, is necessary.

5. Conclusions

1. 3”×3” $CeBr_3$ scintillator response function was determined in measurements carried out at JET.
2. Monte Carlo simulations were performed for both point-like and cylindrical gamma-ray sources using the Geant4 code.
3. A good agreement between measured and Monte Carlo simulated spectra shows a usefulness of such simulations for calculating a scintillator-based detector response in a wide energy range of gamma-rays.
4. For detailed studies of detector response function it would be useful to have an accurate description of a detector surrounding.

The report was prepared by the NCBJ team

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