WPJET4-CPR(17) 16820

D Rigamonti et al.

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Preprint of Paper to be submitted for publication in Proceeding of 2nd European Conference on Plasma Diagnostics (ECPD)

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.

Characterization of a compact $LaBr_3$(Ce) detector with Silicon photomultipliers at high 14 MeV neutron fluxes

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ABSTRACT: A new compact gamma-ray spectrometer based on a Silicon Photo-Multiplier (SiPM) coupled to a $LaBr_3$(Ce) crystal has been developed for the upgrade of the Gamma Camera (GC) of JET, where it must operate in a high intensity neutron/gamma-ray admixed field. In this work we present the results of an experiment aimed at characterizing the effect of 14 MeV neutron irradiation on both the $LaBr_3$ and the SiPM that make up the full detector. The pulse height spectrum from neutron interactions with the crystal has been measured and is successfully reproduced by MCNP simulations. It is calculated that about 8% of the impinging neutrons leave a detectable signal of which less than < 1.3% of the events occur in the energy region above 3 MeV, of interest for gamma-ray spectroscopy applications. Neutron irradiation also partly degrades the performance of the SiPM and this is mostly manifested as an increase of the dark current versus neutron fluence. However, it was found that the SiPM can be still operated up to a fluence of $4x10^{10}$ n/cm^2, which is the highest value we experimentally tested. Implications of these results for measurements with the GC at JET are discussed.

KEYWORDS: Nuclear instruments and methods for hot plasma diagnostics; Spectrometers; Photon detectors for UV, visible and IR photons (solid-state); Radiation-hard detectors;

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Contents

1. Introduction

Gamma-ray spectroscopy aims at investigating the behaviour of fast ions in high temperature fusion reactors by observation of the gamma-ray emission produced in nuclear reactions between the energetic ions and impurities in the machine. The success of this technique has been demonstrated mostly at JET [1-5], where a number of gamma-ray diagnostics consisting of scintillator detectors, germanium detectors and two Gamma Cameras (GC), one horizontal and one vertical, are available. These latter systems are a fan shaped array of detectors embedded in a concrete shielding block and measuring gamma-ray emission along 9 vertical and 10 horizontal well collimated lines of sights. The main application of the diagnostics is to infer the fast ion spatial profile, which is obtained by a tomographic inversion of line integrated measurements. Of special interest is its use in plasmas with tritium, where the detection of the 4.44 MeV gamma-rays emitted by $^{9}Be(\alpha,n\gamma)^{12}C$ reactions in the plasma is one way to measure the profile of confined alpha particles [6].

In order to improve the data performance of the existing system, new detectors have been developed and are being installed at JET to enable gamma-ray spectroscopy in the forthcoming high power plasma campaigns with and without tritium. The upgrade makes gamma-ray measurements at MHz counting rates possible for the first time, in addition to an improved energy resolution (say 5% at 662 keV compared with 10-20% of the present system) in the harsh neutron-gamma mixed environmental background expected especially during operations with tritium [7, 8]. In order to meet these requirements, together with the important limitations provided by a very limited space available for the detectors - which rules out the use of conventional photo-multiplier tubes with magnetic shielding - the project team has developed a compact gamma-ray spectrometer based on a Silicon Photo-Multiplier (SiPM) coupled to a $LaBr_3$(Ce) scintillator crystal. The detailed design and characterization of the detectors are described in [8] and its capability to work at MHz counting rates is demonstrated in [7].

In this paper, we present instead experimental results on the effect of 14 MeV neutrons on the detector. The measurements were performed at the Frascati Neutron Generator (FNG) under controlled neutron fluxes. In particular, we have studied the background energy spectrum induced by 14 MeV neutrons interacting with the detector and that we successfully interpret by means of MCNP simulations. Results on the neutron damage of the silicon photomultipliers used as an alternative to conventional photo-multiplier tubes for our detector are also reported. Implications of these results on the use of the JET gamma-ray camera for different plasma conditions are finally discussed.

2. Experimental setup

Measurements were performed at the Frascati Neutron Generator where quasi monochromatic 14 MeV neutrons are produced by the acceleration of deuterium ions on a tritiated-titanium target [9].

In order to separately study the response of $LaBr_3$ to 14 MeV neutrons and the damage of SiPM under neutron irradiation, we have performed two different experiments. In the first experiment, the 1” x 16.9 mm (diameter x height) $LaBr_3$ crystal was coupled to a standard Photomultiplier Tube (PMT) manufactured by Hamamatsu (model R9420-100-10) and equipped with an active base. The detector was placed at an angle of zero degrees with respect to the beam and at the distance of 33 cm from the target, which corresponded to a neutron flux of 3.5×10^4 n/cm^2/s at the detector position and a 57 kHz counting rate. As the detector signal has a length of 80 ns full width at half maximum, at this rate we estimate that the pile up probability is lower than 1 % and the distortion of the pulse height spectrum due to unresolved pile up events should be negligible. The neutron yield from the target was monitored as a function of time by the standard diagnostics of FNG and which is based on counting alpha particles produced by deuterium-tritium reactions in the target. Individual events from the detector were recorded by a 500MHz-14bit CAEN digitizer (model DT5730), both by digitizing each waveform and by an online processing of the signals with a standard charge integration algorithm. The detector was calibrated with ^{137}Cs (E_γ = 662 keV) and ^{60}Co (E_γ = 1173 and 1333 keV) radioactive sources before neutron irradiation.

In the second experiment, we placed a new Hamamatsu SiPM sample (model S12642-0404PB-50), without the $LaBr_3$ crystal, at a distance of 18 cm from the target in order to study the effect of neutron irradiation at increased fluxes, up to a fluence of 4×10^{10} n/cm^2, which was obtained within some hours of irradiation also by increasing the current of the deuterium beam.

A Keithley picoammeter Model 6487 was connected to the SiPM and used to monitor in real time the bias voltage of the device with a high degree of accuracy and its dark current with a precision of 1 pA. The SiPM was wrapped in an aluminum foil to provide shielding against possible electromagnetic pick up. Besides the dark current, we periodically measured the characteristic current-voltage (I-V) curve of the device at different values of the fluence during the irradiation as a way to track possible changes in the break down voltage of the device.

3. Results and discussions

3.1 $LaBr_3$ crystal response to 14 MeV neutron irradiation

The pulse height spectrum obtained by irradiating the $LaBr_3$ crystal with 14 MeV neutrons was recorded at a neutron flux of 3.5×10^4 n/cm^2/s and with an integration time of 1200 seconds (see figure 1). The overall shape of the spectrum is roughly exponential with a few characteristic peaks that stand out. We find that most of the events occur in the region E < 3 MeV. In the region nearby 4.44 MeV the shape is instead relatively flat and the absolute magnitude is suppressed by a factor about 300 compared to values at E < 1 MeV, which is beneficial for gamma-ray spectroscopy applications.

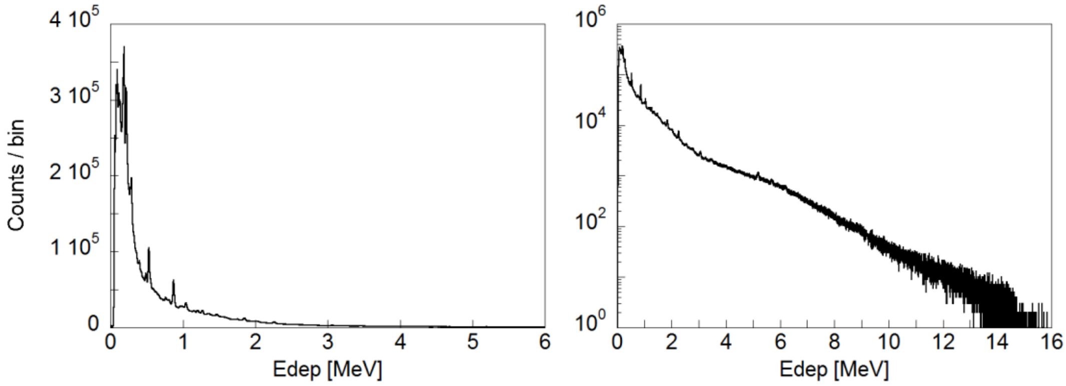

Figure 1. Energy spectra both in linear (left) and logarithmic (right) scale measured at FNG with a 1"x16.9 mm $LaBr_3$ crystal in 14 MeV neutron irradiation experiments. The counting rate at the detector is 57 kHz and the integration time is 1200 s.

At a more detailed level, as described in [10], we can ascribe the detailed structures appearing in the spectrum to reactions between 14 MeV (direct) neutrons and nuclei of the detector material (^{139}La, ^{79}Br, ^{81}Br). Inelastic neutron scattering is an important mechanism and is the main contributor to the visible peaks in the spectrum. In the high energy range of relevance for gamma-ray applications, however, the signal is dominated by the production of secondary particles from nuclear reactions in the scintillator material. These can either be charged particles (protons, deuterons, alphas), that deposit their full energy in the detector, or secondary neutrons from (n,2n) reactions and that lead to an additional background. Besides the direct neutrons, scattered neutrons as well as environmental gamma-rays contribute to the measured spectrum.

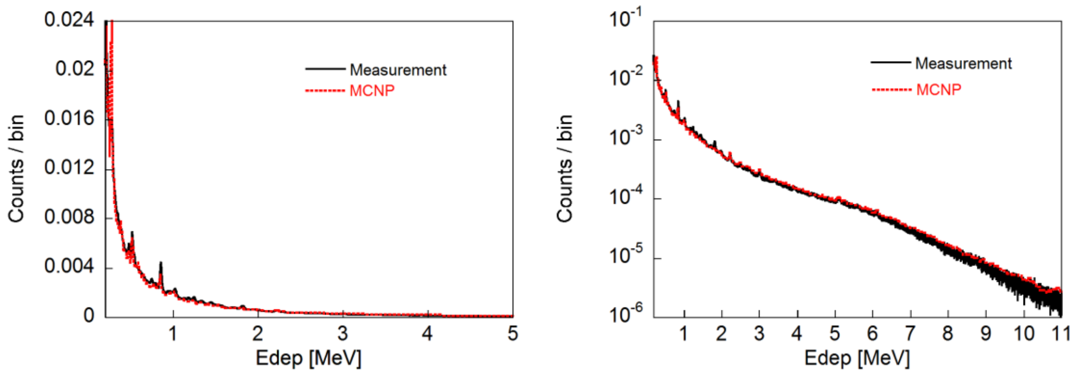

Figure 2. Comparison between the measurement (normalized) and the MCNP simulation both in linear (left) and in logarithmic (right) scale.

For a detailed understanding of the response, a MCNP model of the FNG facility [9] has been used to disentangle the signatures from scattered neutrons and gamma-rays and to evaluate the contribution of the direct neutron component based on the reactions listed in [10]. The comparison between simulation and measurements (see figure 2) shows a remarkably good agreement. By independently fitting the spectral shape of the three components to the data of figure 2, we find that 31% of the impinging radiation is due to environmental gamma-rays, while scattered neutrons contribute to 19%. The remaining fraction of 50% is due to direct 14 MeV neutrons which are detected with an efficiency of about 8.2%. Since the maximum counting rate that can be sustained by the detector is of a few MHz, our results imply that operations at impinging neutron fluxes up to a few 10^6 n/s/cm^2 can be coped with at JET.

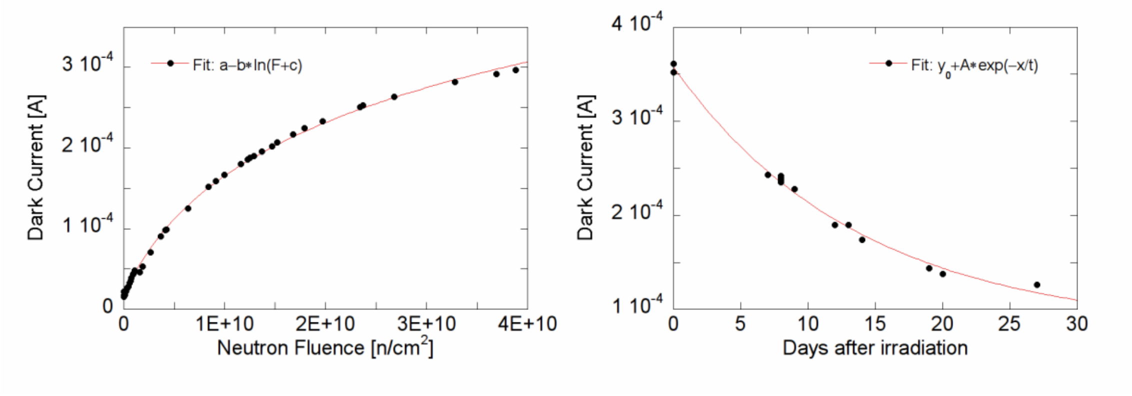

Figure 3. (Left) Dark current measured at FNG as a function of the neutron fluence at the detector. (Right) Dark current measured after the neutron irradiation experiment. The dark current partially decreases after few days.

3.2 Resistance of SiPM to high 14 MeV neutron flux

The effect of neutron damage of the Silicon photomultiplier has been studied by measurements of the dark current and pulse height spectrum as a function of the neutron fluence. As shown in figure 3 (left), the SiPM dark current increases as a function of the neutron fluence F and the data points are experimentally well fitted by the curve $f(F) = a - b \cdot \ln(F + c)$; here, a, b and c are experimental parameters. The graph on the right of figure 3 illustrates that, after irradiation, a self-recovery process takes place and the dark current decreases exponentially on the time scale of a few days down to an asymptotic value that, however, is larger than that measured before the irradiation experiment. This phenomenon occurred at room temperature with no applied bias voltage and is consistent with the findings of [11].

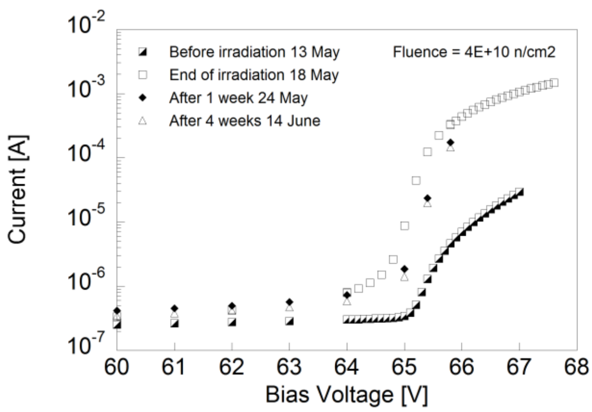

Figure 4. Characteristic current-voltage curve before and after the neutron irradiation

As far as the current-voltage curve of the device after irradiation is concerned (figure 4), we observe that, in general, it has a higher value after irradiation, but this decreases on a time scale of a few days in a way consistent with the behavior found for the dark current. The breakdown voltage of each curve is however the same in all cases and this suggests that no permanent damage occurred to the device, up to the maximum fluence we tested, i.e. $4x10^{10}$ n/cm^2. An independent confirmation comes from the calibration spectrum of figure 5, which we obtained with a ^{60}Co source displaced in vicinity of the $LaBr_3$+SiPM detector right after the end of the irradiation experiment. The two 1173 and 1333 keV emission peaks are clearly visible. The measured energy resolutions are 5.1 and 5.2%, respectively, which compare to the values before the irradiation. We also observe a high background in the spectrum and that we ascribe to the activation of the FNG experimental hall and materials near the detector.

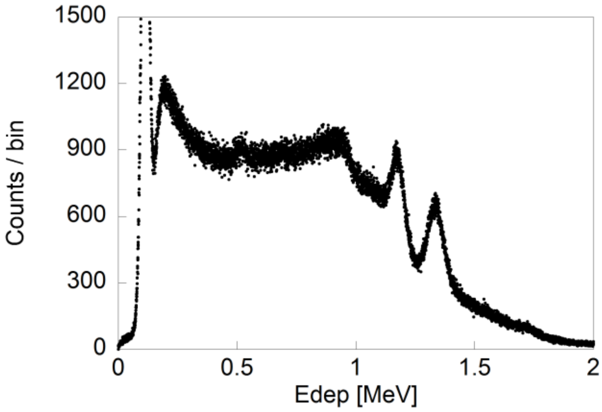

Figure 5. Gamma-ray energy spectrum measured from a 60Co gamma-ray source. The high level of background is also due to the environmental activation post irradiation

The extrapolation of the SiPM irradiation results to measurements at JET is very favorable. The estimated neutron fluxes for the next JET DT plasmas are in the range 10^7 n/s/cm^2 on the central channel of the vertical camera and 10^8 n/s/cm^2 for the horizontal camera, when the total neutron yield from the plasma is about $2x10^{18}$ n/s. This is the record value obtained so far in a DT plasma for less than 1 s in a transient scenario. The maximum fluence we have tested at FNG therefore corresponds to about 400 s and 4000 s integration time of a full power DT discharge, in steady state conditions, for the horizontal and the vertical cameras, respectively. Since the expected duration of the heating phase in full power DT plasmas at JET is about 5 s, and it is foreseen that only few discharges will reach record conditions, we conclude that neutron damage of the SiPM is not an issue for our applications. A different consideration applies instead to the extent of direct neutron interactions with the crystal. In this case, as discussed, the system can tolerate a maximum direct neutron flux of a few 10^6 n/s/cm^2. A water attenuator, which provides a 14 MeV neutron attenuation factor of 100, is installed in front of the vertical camera, and a thinner one provides an attenuation of about 15 for the horizontal one. Furthermore, calculations reveal that, due to the relatively poor gamma-ray shielding available at JET, the direct neutron and background gamma-rays, mostly in the range $E < 1$ MeV, might be comparable. This implies that, in DT, the background counting rate is the limiting factor and might constrain the application of the cameras up to yields in the range 10^{16} n/s, well below those expected in a record discharge at steady state. On the other hand, no limitations are foreseen for applications in deuterium plasmas, where the projected neutron yields are always below 10^{16} n/s.

4. Conclusions

The effect of 14 MeV neutron irradiation on a new compact gamma-ray spectrometer, based on $LaBr_3$ and Silicon Photomultipliers and developed for the Gamma Camera (GC) at JET, has been studied. The pulse height spectrum resulting from neutron interactions with the $LaBr_3$ crystal has been measured and is successfully interpreted by MCNP simulations. It was found that about 8% of the impinging neutrons leave a signal in the detector and only about 1% of the events occur in the energie region above 3 MeV. Neutron induced damage of the Silicon Photo-Multiplier (SiPM) is also observed, mostly as an increase of the dark current of the device as a function of the fluence. The breakdown voltage is however unchanged and the SiPM can still be operated up to a fluence of $4x10^{10}$ n/cm^2.

When projected to applications at JET, our results reveal that, due to the unavailability of suitable attenuators, the background counting rate from direct neutron interactions with $LaBr_3$ is the limiting factor and might constrain the use of the gamma-ray camera up to neutron yields in the range 10^{16} n/s in DT plasmas. For comparison, the highest neutron yield obtained so far in DT is 10^{18} n/s, albeit in a transient phase only. No limitations are instead expected for operations in D plasmas. Damage of the SiPM by neutron interactions is in general of no concern both for DT and D plasma operations.

Acknowledgments

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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