Development of MPPC-based detectors for high count rate DT campaigns at JET

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The products of fusion reactions at JET are measured using different diagnostic techniques. One of the methods is based on measurements of gamma-rays, originating from reactions between fast ions and plasma impurities. During the forthcoming deuterium-tritium (DT) campaign a particular attention will be paid to 4.44 MeV gamma-rays emitted in the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction. Gamma-ray detectors foreseen for measurements in DT campaigns have to be able to register spectra at high count rates, up to approximately 1 MHz. For the Gamma-ray Camera at JET a new setup will be based on scintillators with a short decay time, e.g., $CeBr_3$, and a multi-pixel photon counter (MPPC). We present two methods of shortening output signals in modules based on MPPC. A short detector output signal is necessary in order to minimize the number of pile up events at high count rates. One method uses a passive RC circuit with a pole zero cancellation, whereas an active transimpedance amplifier is used in the other one. Due to the strong dependence of MPPC properties on temperature variation, a special device MTCD@NCBJ was designed and produced to stabilize the gain in MPPC-based scintillation detectors. We show that this device guarantees stable working conditions.

Keywords: gamma-ray spectrometry, scintillators, MPPC, energy resolution, decay time, tokamak.

1. Introduction

The understanding of behaviour of fast ions in the MeV range, e.g., fast electrons and fusion products, is important for the efficient operation of fusion plasma devices. In case of the Joint European Torus (JET), gamma-ray diagnostics, in particular gamma-ray cameras and gamma-ray spectrometers, are used to obtain information on the energy distribution of produced ions.

During the forthcoming deuterium-tritium (DT) campaign a particular attention will be paid to 4.44 MeV gamma-rays emitted in the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction. The distribution and characteristic of gamma-ray sources will be investigated by means of the Gamma-ray Camera equipped with appropriate detector modules. Gamma-ray detectors foreseen for measurements in DT campaigns have to be able to register spectra at high count rates, up to approximately 1 MHz. They should be characterized by a full width at half maximum (FWHM) about a few % for 3 - 6 MeV gamma-rays. Upgrading the existing Gamma-ray Camera at JET is a highly demanding task because of a limited available space for new detectors and a necessity to use existing cables at JET for new electronics.

For the Gamma-ray Camera at JET a new setup will be based on scintillators with a fast light output decay and a photodetector with a fast response time. A decay time for both $CeBr_3$ and $LaBr_3$:Ce crystals is about 20 ns. Their energy resolution is also similar and equal to a few %, so these scintillators are considered as the best for the upgraded detectors together with a multi-pixel photon counter (MPPC) as a photodetector [2016_PS].

Detectors used in experiments with high count rates should have a short pulse duration to minimize the number of pile-up events. Two methods were used to shorten output signals in modules based on MPPC: one method uses a RC passive differentiator circuit with a pole zero cancellation, whereas an active transimpedance amplifier (TIA) is used in the other one.

In this paper we investigate a performance of detectors based on fast scintillators ($CeBr_3$, $LaBr_3$:Ce) coupled to MPPC designed for high count rate measurements during a planned DT campaign at JET.

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

2. Properties of $CeBr_3$ and $LaBr_3$:Ce scintillators

Both $CeBr_3$ and $LaBr_3$:Ce scintillators have very good energy resolution (~3% at 1.1 MeV), short decay time (~20 ns), high temperature stability, high gamma-ray detection efficiency (~7% at 1.1 MeV for 1”×1” crystals) [2016_PS]. Crystals with such parameters allow for high count rate applications.

The most important difference between these two crystals is connected with the presence of the long-lived naturally occurring ^{138}La isotope. Such an intrinsic activity poses a serious limit for their application in low count rate experiments [2012_Quarati]. The abundance of this isotope is 0.0902% and its half-life is 1.05×10^{11} years. ^{138}La has two decay channels: by electron capture into ^{138}Ba with 66.4% probability and by beta decay into ^{138}Ce. The daughter nucleus emits 1436 and 789 keV gamma-rays, respectively. For ^{138}Ba, the K-shell and L+M–shell X-ray binding energies are 37.4 keV and 5.6 keV, respectively. Due to non-proportional response effects, an equivalent energy, i.e. the energy that is detected by $LaBr_3$:Ce, is only 35.5 and 4.5 keV [2012_Quarati]. K and L+M cascade peaks are detected in coincidence with the 1436 keV gamma-ray of the ^{138}Ba de-excitation. Both 1472 and 1440 keV gamma lines are observed. So, ^{138}La is a source of an additional intrinsic gamma-ray background and beta self-contaminant of the crystal.

Measurements with the 1"×1" $LaBr_3$:Ce scintillator, manufactured by Saint-Gobain Crystals, were performed at the National Centre for Nuclear Research (NCBJ). For the energy calibration, standard radioactive sources of ^{22}Na (511 and 1274 keV), ^{137}Cs (662 keV) and ^{60}Co (1173 and 1333 keV) were used. The intrinsic spectrum of the $LaBr_3$:Ce crystal registered during 45 hour live-time measurement is shown in figure 1. In addition to gamma lines, corresponding to ^{138}La, we registered peaks originating from natural background present in our lab, as marked in figure. 1. We also observe a contamination by α-radioactive isotopes from actinides.

In the region at ~1460 keV a peak was fitted with three Gaussian distributions describing two contributions from ^{138}La (1440 and 1472 keV) and one from ^{40}K at 1461 keV, see inset in figure. 1. In case of $CeBr_3$, in the spectrum only peaks related to a contamination by actinides are registered resulting in a lower intrinsic activity in comparison with a $LaBr_3$:Ce crystal [2015_Swider_ECPD].

A possible use of intrinsic ^{138}La gamma lines as a gain monitor is discussed in [2016_RSI_Rigamonti].

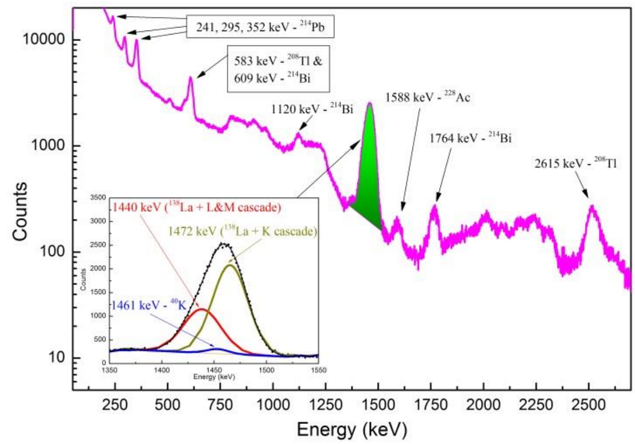

Fig. 1. Response of 1”×1” $LaBr_3$:Ce scintillator to natural background radiation.

3. MPPC-based detectors for high count rate measurements

Fast response time, high gain coefficient, high photon detection efficiency resulting in good energy resolution, low power/voltage operation, resistance to mechanical shocks, compactness and immunity to a magnetic field are the main advantages of a multi-pixel photon counter (MPPC), interchangeably called a silicon photomultiplier. MPPC is therefore an appropriate photodetector if operating in a harsh radiation environment and at a high count rate experiments in which a short output pulse duration is necessary to minimize the number of pile-up events.

Two setups were tested to compare a performance of detectors based on MPPC, developed for high count rate experiments: one method uses a RC passive differentiator circuit with a pole zero cancellation, whereas an active transimpedance amplifier (TIA) is used in the other one.

The system based on passive RC circuit is characterized by a relatively high input impedance. A large sense resistor causes a large time-constant and a slow response. A low signal-to-noise ratio may be unacceptable. It’s allows to shorten an output signal in cost of an amplitude. No active elements are used in such systems, so there are no additional heating sources.

In case of TIA, a faster response is crucial for high count rate measurements. A high output amplitude with low time-constant is an advantage, while active elements are a source of additional heating.

In both setups, the same Φ20 mm×15 mm cylindrical $CeBr_3$ scintillator was coupled to MPPC manufactured by Hamamatsu, model S12642-0404PB-50 and tested with two standard gamma-ray sources, strong ^{137}Cs with an activity of 400 MBq and a low activity ^{22}Na.

In figure. 2 the output pulses measured with a $CeBr_3$ crystal coupled to MPPC are shown. The pulse shape is described by a rise and fall time: the rise and fall times are here defined as the interval between the times at which the pulse reaches 10% and 90% of its maximum amplitude on the leading and falling edge, respectively.

In figure 2 (upper) the signal registered with TIA has a length of 175 ns with a rise time of 40 ns and a fall time of 95 ns. The signal registered with a RC circuit has similar parameters: a length of 175 ns with a rise time of 35 ns and a fall time of 100 ns. However, the TIA signal amplitude is a factor of 5 higher than for RC: 1000 mV for TIA and 210 mV for RC.

In figure 2 (lower) the signal registered with TIA has a length of 130 ns with a rise time of 15 ns and a fall time of 85 ns. The signal registered with a RC circuit has similar parameters: a length of 130 ns with a rise time of 30 ns and a fall time of 72 ns. However, the TIA signal amplitude is a factor of 10 higher than for RC: 570 mV for TIA and 51 mV for RC.

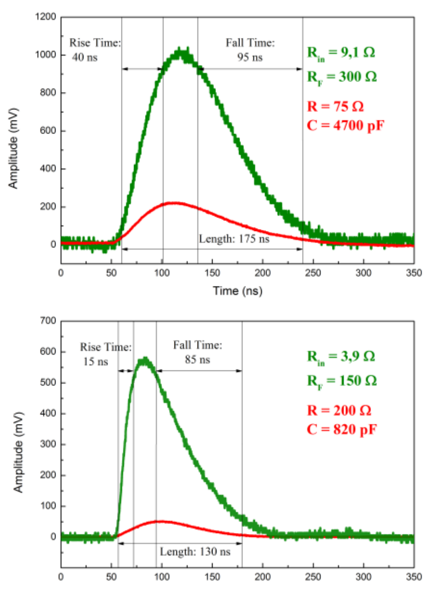

Fig. 2. Output pulses from $CeBr_3$ scintillator coupled to MPPC with a RC circuit (red) and TIA (green).

In setup with RC by changing a capacity a signal can be shorten, almost without limits, but in cost of an amplitude. In a setup with TIA, the shortening of a signal is limited by internal MPPC properties, e.g., capacitance and resistance.

In figure 3 a ^{22}Na spectrum measured with a detector based on $CeBr_3$ coupled to MPPC with TIA is shown for the shorter output signal length of 130 ns. The measured energy resolution, defined as a full width at half maximum (FWHM), for the 1274 keV gamma line is equal to (6.6±1.3)%. The same FWHM value was already obtained for the detector based on CeBr3 installed at JET for a longer output signal length of 800 ns.

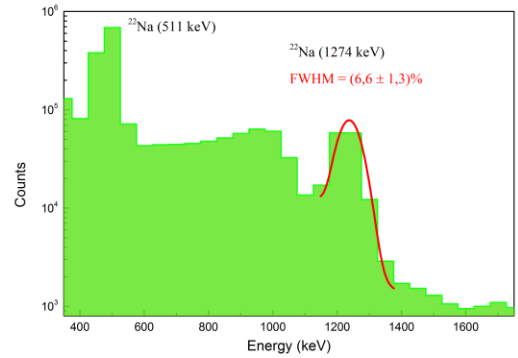

Fig. 3. ^{22}Na spectrum measured with $CeBr_3$ coupled to MPPC with TIA. The red curve is a Gaussian fit used to determine the FWHM for the 1274 keV gamma line.

Due to the fact that properties of MPPC are strongly affected by temperature, it is necessary to optimize MPPC operation at varying temperature. The MTCD@NCBJ temperature compensation device is using a measured dependence of a bias voltage on temperature to maintain a constant value of the MPPC gain. It includes an integrated temperature sensor and integrated power supply and allows for setting of MPPC bias voltage. More details about MTCD@NCBJ, including preliminary results obtained at JET, is given in Ref. [2016_PS].

4. High count rate measurements

The described above detector setup, based on 20×15 mm $CeBr_3$ coupled to MPPC with TIA and MTCD, was also tested during high count rate measurements at the Legnaro National Laboratories (LNL) and at the ENEA Frascati.

A beam of 10 MeV protons from the TANDEM-ALPI accelerator of the Italian Institute of Nuclear Physics at LNL, was collimated onto a target of ^{27}Al placed in a cylindrical vacuum chamber. The highest counting rate was 340 kHz for a detector placed at a distance of about 50 cm. More details about this experiment can be found in [2016_RSI_Nocenete].

A typical spectrum obtained for $CeBr_3$ coupled to MPPC, with TIA and MTCD measured at 30 nA current with a maximum rate of ~340 kHz during 120 s is shown in figure. 4.

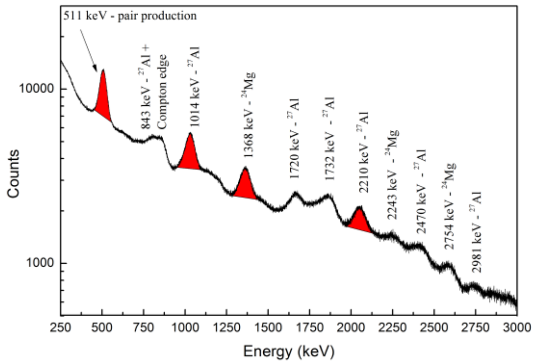

Fig. 4. Typical spectrum obtained at LNL for 20×15 mm $CeBr_3$ coupled to MPPC, with TIA and MTCD measured at 30 nA current with a maximum rate of ~340 kHz during 120 s.

An energy resolution and a peak position were used as figure of merit (FoM) to characterize the performance of the detector setup operating at different count rates.

In figure. 5 the energy resolution is shown as a function of both gamma-ray energy of pronounced peaks and a counting rate. The measured peak position shift is less than 3% from the average value.

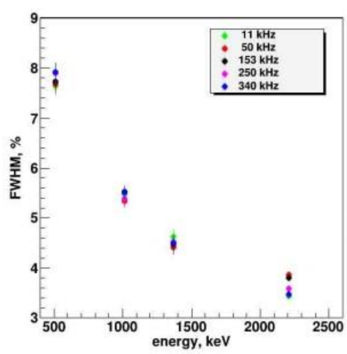

Fig. 5. Energy resolution as a function of counting rate. When not indicated, error bars are the same size or smaller than the symbols.

The 14 MeV neutron irradiation measurements were performed with the Frascati Neutron Generator (FNG). More details about FNG and similar experiments can be found, e.g., in [2015_Cazzaniga].

A $CeBr_3$ scintillator coupled to MPPC with TIA was irradiated with a neutron flux from 0.4 to 2.1×10^{10} n/s. As in case of measurements in LNL, both FWHM and a peak position were determined. In table 1 obtained results are shown for 511 keV gamma line. We observed a deterioration of a detector energy resolution for higher neutron fluxes. In addition, if FWHM values from two measurements at 1.1×10^{10} n/s are compared, a worsening energy resolution by ~10% is observed for the second measurement as higher radiation dose is cumulated in the detector.

Table 1. FWHM and a peak position for 511 keV gamma line.

n/s ($\times10^{10}$)	FWHM (%)	peak position
0.4	9.1	1402
1.1	9.8	1396
2.1	9.9	1374
1.1	10.9	1332
1.4	11.2	1342
1.9	14.9	1148

4. Conclusions

We investigate a performance of detectors based on fast scintillators (CeBr3, LaBr3:Ce) coupled to MPPC designed for high count rate measurements during a planned DT campaign at JET.

Results obtained in measurements performed both in laboratory conditions and with an accelerator and a neutron generator show that this device guarantees stable working conditions.

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