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# Performance of the prototype $LaBr_3$ spectrometer developed for the JET Gamma-ray Camera Upgrade[a)]

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In this work we describe the solution developed by the Gamma ray Camera Upgrade enhancement project to improve the spectroscopic properties of the existing JET γ-ray camera. Aim of the project is to enable gamma-ray spectroscopy in JET deuterium-tritium plasmas. A dedicated pilot spectrometer based on a $LaBr_3$ crystal coupled to a Silicon Photo-Multiplier has been developed. A proper pole zero cancellation network able to shorten the output signal to a length of 120 ns has been implemented allowing for spectroscopy at MHz count rates. The system has been characterized in the laboratory and shows an energy resolution of 5.5% at Eγ=0.662 MeV, which extrapolates favorably in the energy range of interest for gamma-ray emission from fast ions in fusion plasmas.

## I. INTRODUCTION

Gamma-ray spectroscopy is a plasma diagnostic technique which can investigate the behaviour of fast ions in high temperature fusion plasmas, as demonstrated at JET[1-6]. In particular, it plays a key role in the study of alpha particle confinement, which is crucial for plasma self heating in a high power discharge. Gamma-ray emission in thermonuclear plasmas is mainly due to reactions between fast particles and fuel ions or impurities. Of particular relevance is the detection of 4.44 MeV gamma-rays from the $^9Be(\alpha,n\gamma)^{12}C$ reaction, as it gives information on alpha particles in deuterium-tritium plasmas. At JET, a horizontal and a vertical neutron/γ camera[7] provide information on the radial profile of the neutron/γ emission source by collimated measurements along 19 channels. The Gamma-ray Camera Upgrade project aims to improve the spectroscopic properties of the existing γ-ray camera of JET in terms of energy resolution and high counting rate capability, in order to operate in the deuterium-tritium (DT) campaign. This requires a rather significant improvement of the existing CsI detector performance, in order to reach an energy resolution of 5% (En.Res. = FWHM/En) at 1.1 MeV and count rate capability in excess of 500 kHz. An important constraint is the limited available space which, for example, makes it impossible to use photo multiplier tubes. The use of fast, high light yield inorganic scintillators such as $LaBr_3$[8] together with Silicon Photo-Multipliers (SiPMs) can represent a good alternative to the existing CsI and photodiodes, given their high photon detection efficiency, high internal gain, insensitivity to magnetic field and an extremely compact size. SiPMs, which have experienced great improvements in the last years, still show voltage-temperature dependence[9] and a limited linearity but both issues can be corrected for[9]. In this work we describe the solution developed to meet the requirements. This combines the good energy resolution results achieved by M. Grodzicka et al.[10] and the promising counting rate capability reached by M. Nocente et al.[11]. The pilot detector was based on a $LaBr_3$ scintillator crystal (25.4 x 16.9 $mm^2$) coupled to a Silicon Photo-Multiplier (12x12 $mm^2$ , see Fig. 1). The final design with the electronic readout circuit of the pilot spectrometer will be presented together with the laboratory measurements at low count rate with radiation sources and at high count rate with a LED pulser.

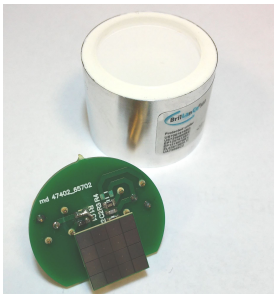

FIG. 1. LaBr3 crystal and Silicon Photo-Multiplier with its read-out circuit board.

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## II. SILICON PHOTO-MULTIPLIER AND ELECTRONIC READ-OUT CIRCUIT

Silicon Photo-Multiplier detectors, also known as Multi-Pixel Photon Counters (MPPCs), are a relatively novel solid state photo-sensors. They are made up of multiple Avalanche Photo-Diode (APD) pixels connected in parallel and operating in Geiger mode which provide an internal high gain of the order of 10^6, depending on the operational condition. For each APD cell, the Geiger mode is activated when a reversed bias above the electrical breakdown voltage ($V_{bd}$) is applied. The chosen SiPMs are 12x12 mm$^2$ in size, made by 16 channels with 3464 pixels each and they are manufactured by Hamamatsu, model S12642-0404PB-50. The characteristic I-V curve of the device shows a steep increase of the current at the breakdown voltage, which is roughly 65 V. In order to achieve high counting rate capability, a short output signal is necessary to minimize the fraction of pile up events. For this purpose, the dedicated electronic circuit suggested in Nocente's article[11] has been developed by implementing a CR differentiator circuit on the MPPC read-out board of Fig. 1. The Fig. 2 shows an example of a signal from a $^{137}$Cs radioactive source after the CR differentiator. A signal width of 120 ns has been achieved without significant loss of the amplitude (about 60 mV at the 662 keV full peak from $^{137}$Cs).

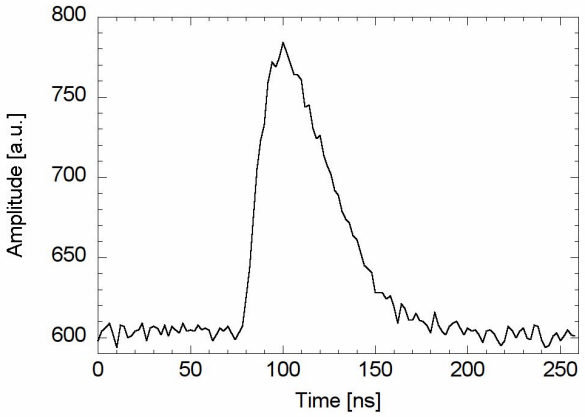


FIG. 2. Output signal from the $LaBr_3$ crystal coupled to the SiPM with the pole zero cancellation network.

## III. LABORATORY TEST AT LOW COUNTING RATE

### A. Measured spectra and energy resolution

Laboratory measurements with standard radioactive sources have been performed in order to characterize the MPPC response and its dedicated electronic readout circuit. The MPPC was coupled with a LaBr3 crystal (25.4 x 16.9 mm$^2$) and powered with a bias voltage of 65.2V – 67.5V provided by a TTi EX752M voltage supply. Optical grease and an aluminum foil were used to improve light collection from the scintillator. The output signal from the detector was fed into a waveform digitizer CAEN module DT5730 (14 bit, 500 Msps) equipped with CAEN software able to perform on-line measurements of the pulse area. In order to characterize the pilot spectrometer, several measurements have been performed at different bias voltage, revealing an improvement in the energy resolution by increasing

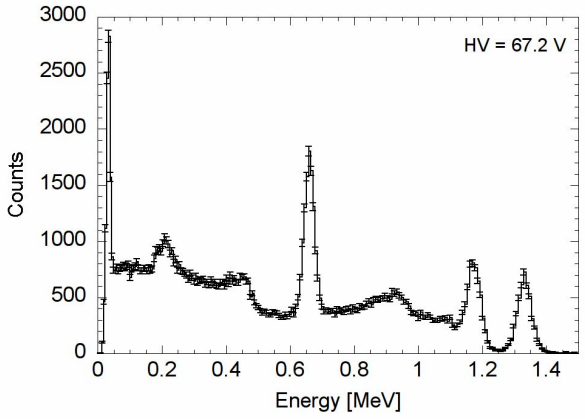


FIG. 3. Pulse Height Spectrum recorded with $^{137}$Cs and $^{60}$Co.

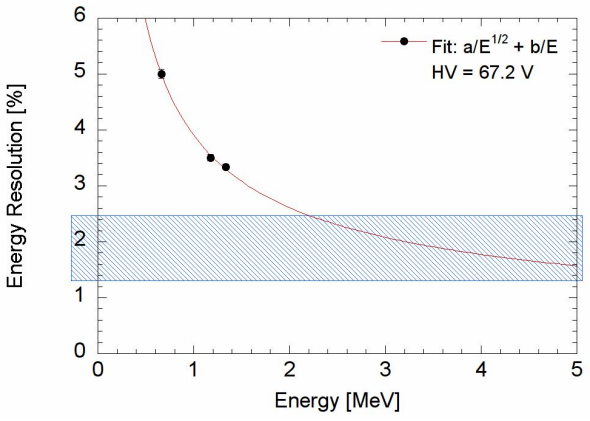


FIG. 4. Measured energy resolution as function of the energy. Error bars are of the same magnitude of the black dots.

the applied voltage up to 67.5 V. Fig. 3 shows the calibrated pulse height spectrum of $^{137}$Cs ($E_\gamma$ = 662 keV) and $^{60}$Co ($E_\gamma$ = 1173 and 1333 keV) radioactive sources measured at $V_{bias}$=67.2 V (roughly 2.3V over $V_{bd}$). The peaks of the spectrum were fitted by a Gaussian function on a background described by polynomials. An energy resolution (En.Res. = FWHM/Energy) of 5.5 % was obtained at 662 keV which improves to 3.7% for 1333 keV gamma rays. As displayed in Fig. 4, the trend of the energy resolution is well fitted by the curve[12] $f(E) = ( a/\sqrt{(E)} + b/E )$ which extrapolates favorably in the energy range of interest (<2.5% in the range 3–5 MeV) for the observation of 4.44 MeV gamma-rays from the $^9$Be(α,nγ)$^{12}$C reaction at kHz counting rates.

The limited linearity of the SiPM has been investigated at the National Centre for Nuclear Research (NCBJ, Poland) mainly by measuring the 4.44 MeV gamma rays emitted by a PuBe source and that resulted in three peaks in the pulse height spectrum: a full energy peak (4.438 MeV), a single escape peak (3.927 MeV) and a double escape peak (3.416 MeV). Among the other sources we used are $^{137}$Cs and $^{65}$Zn ($E_\gamma$ = 1.116 keV). Measurements have been performed in a climate chamber at stable temperature to prevent peak shifts due to temperature changes. Results (see Fig. 5) indicate that there is a non linear relation between the channel position and the gamma-ray energy, but this is of the order of 20 % at 4.5 MeV and can be easily corrected for.

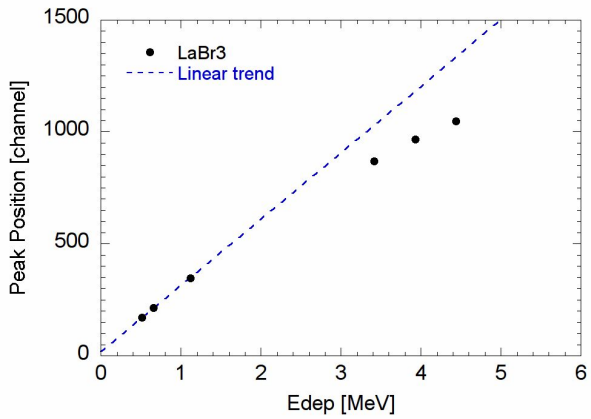


FIG. 5 Linearity of the MPPC. Linear trend has been extrapolated by fitting first two point corresponding to energies 0.511 keV and 0.662 keV respectively. Error bars are of the same magnitude of the black dots.

### B. Comparison with a standard Photo-Multiplier tube

A comparison in terms of energy resolution with a conventional Photo-Multiplier Tube (PMT), manufactured by Hamamatsu (model R9420-100-10), was done. In order to reduce the effect of the geometric efficiency, an aluminum mask with a hole of the same size as the MPPC has been used to cover the PMT surface coupled to the $LaBr_3$ crystal. In this way, the only small difference in the collecting area between the PMT and the MPPC was due to the geometrical Fill Factor (FF) of the MPPC itself, which is the ratio of the effective photosensitive area to total area[13]. Results show that energy resolution values of the MPPC operating in the optimal condition are comparable within few fractions of % to those with a PMT having the same collecting area (see Table. I). These values are also close to those expected from the statistical fluctuation of the number of photoelectrons generated at each energy and that can be estimated at each energy (see the column labelled as "Calculated")[14].

TABLE I. Comparison between the energy resolution of the PMT covered with the aluminum mask and the one of the MPPC.

| Peak Energy (keV) | Measured EnRes (%) | Calculated (%) |
|---|---|---|
| PMT with mask (collecting area 12 x 12 $mm^2$) | | |
| 662 | 4.7 | 4.1 |
| 1173 | 3.8 | 3.1 |
| 1333 | 3.4 | 2.9 |
| MPPC 12 x 12 $mm^2$ | | |
| 662 | 5.5 | 5.0 |
| 1173 | 4.0 | 3.8 |
| 1333 | 3.7 | 3.6 |

## IV. LABORATORY TESTS AT HIGH COUNTING RATE WITH A LED PULSE

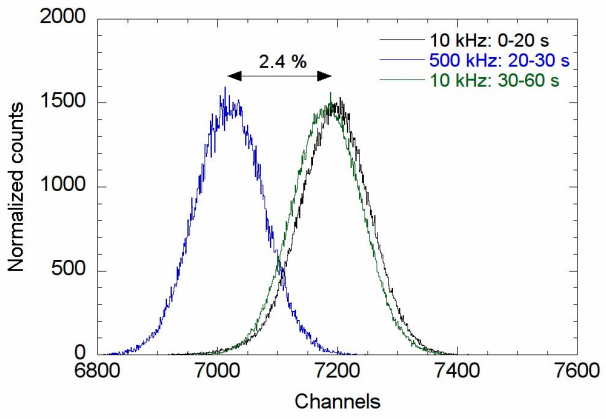


FIG. 6. JET-like measurement with a perturbation windows of 10 seconds at high counting rate.

### A. Measurements with LED pulse

In order to simulate the high rate environment expected at JET, a mock up of high counting rate measurements[15] has been performed in the laboratory by using a blue LED powered by Keysight (model 81150A) pulse generator. With this setup, we were able to illuminate the MPPC with blue light at a chosen intensity and at increasing counting rates up to about 1 MHz. A $^{137}Cs$ source was then placed close to the LaBr3 crystal and used to monitor the effect of the LED light (perturbation) on the position and energy resolution of the corresponding full peak at 662 keV from 137Cs. We have observed that the mean position of the $^{137}Cs$ progressively drifted as the counting rate from the blue LED was increased. This effect was mainly caused by the voltage drop across a resistor placed between the power supply and the MPPC and could be easily reduced by decreasing the value of this resistor, without any appreciable effect on other detector parameters. The peak shift was then observed to increase at higher MPPC bias voltages and at larger intensities of LED perturbation source. Both parameters control the current that flows in the device and that is increased at higher intensities and rates, resulting in an augmented drop on the input resistor. Several measurements allowed investigating and reducing the shift of the peak position in the pulse height spectrum due to the high counting rate. By selecting a sufficiently low resistance (10Ω) as input, we were able to reduce the shift to 5% at the $^{137}Cs$ peak, when the LED was operated at 500 kHz and with an equivalent energy of 2 MeV. Part of the contribution to this shift may also come from local heating of the MPPC induced by the larger signal current, as we did not perform our tests in a climatic chamber. This second contribution can however be reduced by adjusting the MPPC gain with a temperature feedback sensor[9].

Dedicated tests at counting rates up to few MHz were also successfully performed by using reactions emitting gamma-rays at nuclear accelerators and in a condition that closely mirrored the radiation load expected from a deuterium-tritium plasma at full power at JET. The experimental setup and results of these measurements are addressed in Nocente's article[16].

### B. JET-like measurements

In order to investigate the behavior of the pilot spectrometer during a JET shot, a 60 seconds measurement with two LED pulses has been performed. A LED pulse was used as reference pulse with fix amplitude (corresponding to 3 MeV gamma rays) and fixed repetition rate (10 kHz). The second one, corresponding to a gamma ray of 662 keV, worked as perturbation source in a temporal window of 10 seconds in which its repetition rate was speed up to 500 kHz in order to simulate the experimental conditions of a JET shot. The recorded spectrum has been analyzed by sampling the measurement in temporal windows before, during and after the high rate flux. Results are shown in Fig. 6 and they highlight a modest shift of 2.3%, which is judged acceptable.

## V. LaBr3 INTRINSIC RADIOACTIVITY AS GAIN MONITOR SYSTEM

Due to spatial and cabling constraints, a gain monitor system based on a LED fiber optic, cannot be installed on each detector of the Gamma Ray Camera at JET. However, the intrinsic radioactivity of the $LaBr_3$ crystal can be used as a gain monitor to verify the detector stability[12]. Fig. 7 shows a spectrum of the detector intrinsic radioactivity integrated over 20 minutes, which is the average time in between two JET discharges. A clear peak at 1.47 MeV is observed and can be used to monitor peak shifts of few % from one discharge to the next one. Here we also note that the natural radioactivity of $LaBr_3$ does not interfere with peaks expected from fast ions in the plasma (E > 3 MeV), as it does not extend above 2.6 MeV.

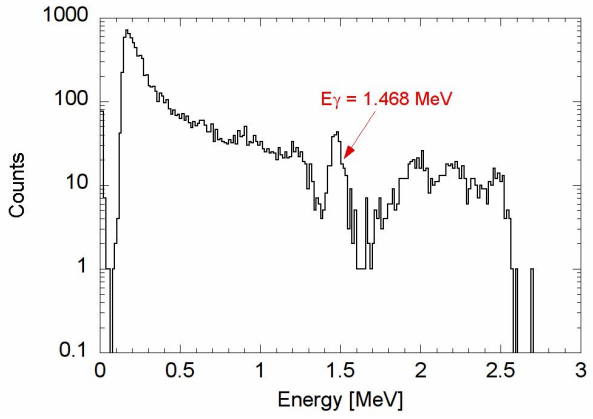


FIG. 7. Intrinsic activity spectrum of a 25.4 x 16.9 $mm^2$ $LaBr_3$ crystal collected in 20 minutes of measurement.

## VI. CONCLUSIONS

A dedicated pilot spectrometer based on a LaBr3 scintillator crystal (25.4 x 16.9 $mm^2$) coupled to a Silicon Photo-Multiplier SiPM (12x12 $mm^2$) has been developed in order to meet the requirements needed for the Gamma Camera Upgrade project. A read-out electronic circuit has been built by implementing a proper CR differentiator able to shorten the output signal width up to 120 ns, allowing for gamma-ray spectroscopy at MHz counting rates and good energy resolution. Laboratory measurements with standard radioactive sources show an energy resolution of about 5.5% at 662 keV at the bias voltage of 67.2 V which extrapolates to <2.5% in the range of interest for plasma diagnostics (3-5 MeV). Mock up measurements at high count rate with LEDs revealed a peak shift in the measured spectra, which has however been minimized by choosing a sufficiently small input resistor for the read-out board. The intrinsic radioactivity of the $LaBr_3$ crystal can be used to monitor gain changes in between shots. The overall performance of the system is significantly better than that of CsI detectors of the present gamma-ray camera and will allow for improved measurements of the γ-ray emission profile in fast ion experiments of the next JET campaigns and, later on, in high performance deuterium-tritium plasmas.

## VII. ACKNOWLEDGMENTS

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