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The upgraded JET Gamma-ray Cameras based on high resolution/high count rate compact spectrometers[a)]

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The JET gamma-ray cameras have been recently upgraded within the Gamma-ray Camera Upgrade (GCU) project in support of development of high performance deuterium plasma scenarios and preparation of deuterium-tritium experiments. New, dedicated detectors based on a $LaBr_3$ crystal and silicon photo-multipliers have been developed and replaced pre-existing CsI detectors in all 19 channels. The new instrument gives opportunity making two-dimensional gamma-ray measurements with a counting rate capability exceeding 1 MHz and energy resolution better than 5% at 1.1 MeV. The upgrade is of relevance for fast ion and runaway electron physics studies in high performance deuterium discharges and also in plasmas with tritium at neutron yields in the range up to about $5*10^{17}$ n/s.

I. INTRODUCTION

The role of gamma-ray spectroscopy as fusion plasma diagnostics technique has evolved significantly over the time. Historically, gamma-ray spectroscopy was proposed to assess the fusion reaction rate as a complementary technique to neutron flux measurements or as unique technique in case of aneutronic fusion reactions[1,2]. More recently, as demonstrated at JET[1-9], gamma-ray spectroscopy has been proposed and used for studying the behavior of fusion reaction products as well as of other energetic ions. In particular, the JET gamma cameras play an important role providing measurements of the spatial distribution of the emitted gamma-rays which are mainly due to reactions between fast particles (p, d, t, α, ^{3}He) and fuel ions or impurities (^{9}Be, ^{12}C). At JET, as well as at ITER[10,11], the presence of beryllium impurities due to the first wall offers the opportunity for studying the fusion alpha particles in deuterium-tritium (DT) plasmas through the $^9Be(\alpha,n\gamma)^{12}C$ reaction which emits 4.44 MeV γ-rays. Experimentally, measurements in plasmas with tritium are particularly challenging due to the harsh environment given by the intense fluxes of 14 MeV neutrons that interact either with the detector itself[12,13] or with the surrounding tokamak structures. For this reason, at JET several diagnostics are undergoing upgrades and improvements in order to cope the high neutron/gamma fluxes expected in the next high-power D and DT campaigns and to enable gamma-ray spectroscopy at MHz counting rates[14,15,16]. Among these diagnostics, the JET gamma ray cameras (GC) have been very recently upgraded within the EUROFUSION enhancement program, achieving improvements both in terms of energy resolution and counting rate capability. The GC are made by a horizontal and vertical fan shape camera viewing the plasma along 10 and 9 lines of sight, respectively. Previously, CsI scintillators coupled to Pin-diodes were employed for gamma-ray detection, but they had almost no spectral capabilities and a slow decay time (0.5–4 μs), preventing the use of the system at high heating power of interest for fusion performance. The target of the upgrade consists of replacing the existing detectors with high performance spectrometers that combine high energy resolution (<5% at 1.1 MeV) and counting rate capabilities in excess of 500 kHz. Important space limitations, together with the needs of insensitivity to magnetic fields and the constraint of no modification of the frame, supports and

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shielding, led us to develop custom-made detectors which were not commercially available so far.

The developed solution is based on a $LaBr_3$ scintillator crystal coupled to a Hamamatsu Silicon PhotoMultiplier (SiPM) which is embedded in a readout electronic board implementing a CR differentiator circuit used for signal shortening. The full system is equipped with real-time temperature monitors and integrated power supplies which provide stabilized bias voltage and gain compensation for each SiPM. The data acquisition system (DAQ) is based on eight Analog to Digital Converters (4 channel each, 13 bits, 250 Msamples/s) and it implements real time algorithms on FPGAs which provide processed data for each detector.

In this work, the new system is presented together with in situ characterization measurements, collected with standard gamma-ray sources after the detector installation in the JET Torus Hall. The detector performances are described in terms of energy resolution, high counting rate capability and neutron resiliance. A discussion on the expected performance of the upgraded gamma cameras is also given based on measurements recorded at JET and at other nuclear facilities.

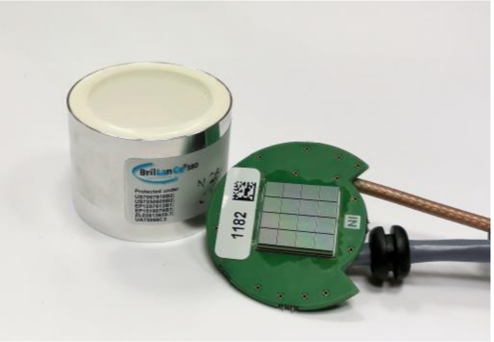

FIG. 1: Picture of the $LaBr_3$ scintillator crystal, the SiPM and its read-out circuit board

II. THE UPGRADED JET GAMMA-RAY CAMERAS

The severe requirements on the energy resolution and counting rate capability needed for the upgrade of the JET gamma cameras, together with the project constraints, led us to develop a new compact gamma-ray spectrometer based on a 25.4 mm x 16.9 mm (diameter x height) $LaBr_3$ scintillator crystal coupled to a 12x12 mm^2 SiPM (model S13361-3050NE-04) (see figure 1). Due to space limitations, the whole detector fits a cylindrical light-proof capsule of dimensions 35x35 mm^2 which is the maximum dimension allowed by the GC interfaces. SiPMs have been chosen as alternative to conventional PhotoMultiplier Tubes because of their very compact size, high internal gain and insensibility to magnetic field. On the other hand, the SiPMs show a strong gain-temperature dependence and gain-voltage sensitivity, as well as a limited linearity, which has to be monitored and corrected during the operation or off-line. In our design, the SiPM is placed on a Printed Circuit Board (PCB) provided with a temperature sensor and the read-out electronic circuit. Here a CR differentiator circuit is implemented to shorten the output signal length enabling high rate capabilities. A 41 ns (FWHM) signal (see figure 2) is achieved in order to reduce the probability of pile-up events with respect to the original signal length (about 300 ns FWHM). On the other hand, the CR circuit introduces a reduction of pulse amplitude, which is however acceptable for this application. The electronic circuit was built ad-hoc to match the existing JET cable impedance of 75 ohm. The output signal of each detector is fed to a data acquisition system based on the Advanced Telecommunications Computing Architecture (ATCA) able to digitize and simultaneously process the signals at 200 MSamples/s 13 bit[17]. Dedicated algorithms implemented on FPGAs have been developed for real time processing and data reduction to cope with the expected high counting rates[17]. The DAQ system offers the possibility to be operated in different modes depending on the needs and on the expected fluxes. The system allows storing in continuous mode each sample or individual events or to save the relevant information of each event, such as energy value and trigger time, with a significant reduction of the data storage requirements. A device for real-time temperature monitoring and SiPM stabilization[18] has been designed and implemented in the upgraded JET gamma-ray cameras. It allows communicating with each detector through a user-friendly interface allowing to set the optimized bias voltage value. Each temperature sensor is continuously read at fixed frequency (10 Hz) and the values are accessible through dedicated registers.

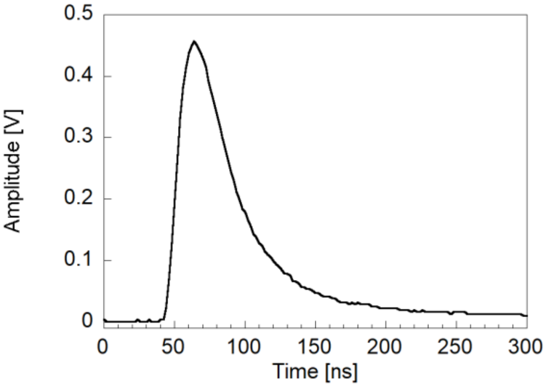

FIG. 2: Example of waveform obtained after the installation at JET and recorded with 80 m long cable.

The new compact gamma-ray detectors and auxiliary systems have been successfully installed in both horizontal and vertical JET gamma-ray cameras in 2017. The new system was tested with 80 m long cables connecting the Torus Hall with the Diagnostic Hall and is ready to provide data in the next D and DT JET campaigns.

III. RESULTS AND DISCUSSIONS

The detectors designed for the upgrade of the JET gamma-ray cameras have been fully characterized through in situ gamma-ray calibrations and previously, at nuclear facilities and laboratory in terms of energy resolution and high counting rate capabilities. After the installation at JET, the 19 detectors have been tested with ^{137}Cs, ^{133}Ba and ^{22}Na radioactive sources (see figure 3) showing excellent energy resolution depending on the bias voltage. At the optimum voltage of the SiPMs, the 19 detectors exhibit a mean energy resolution of about 5.2 % at 662 keV (see figure 4) which improves as a function of the energy[19,20] as $f(E) = \frac{(\alpha+\beta E)^{1/2}}{E}$. The magnification of the recorded spectra at low energy from 0.2 MeV to 0.75 MeV (see an example in figure 5), highlights the enhanced spectroscopic capability of the upgraded gamma ray cameras. For the first time, the gamma cameras were able to resolve the three γ-ray lines emitted from ^{133}Ba calibration source, which were not visible with the previous detectors. The spectrum also features the well-defined full energy peak of the ^{137}Cs and the full energy peak of the ^{22}Na at 0.511 MeV which arises on the Compton edge of the cesium line.

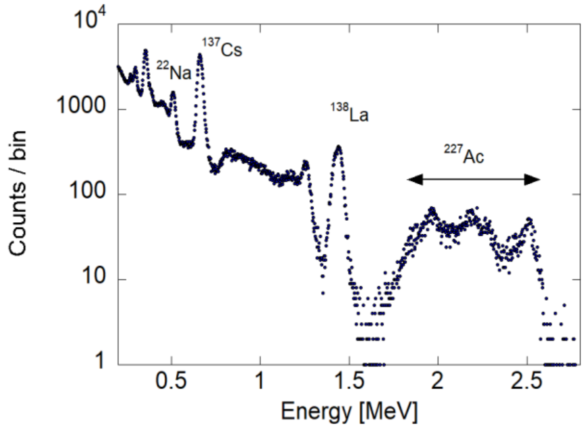

FIG. 1: Pulse height spectrum recorded by channel 5 of the horizontal gamma camera in a 12 hour calibration measurement.

These results extrapolate favorably to fast ion studies at JET through γ-ray spectroscopy. In particular, an energy resolution better than 3 % can be estimated at 4.44 MeV for γ-rays emitted from ^{9}Be(α,nγ)^{12}C reactions. This would allow spatially resolved measurements for tracking the fast ions and for studying instabilities effects driven by fast ions.

The peaks at energies above 1.3 MeV in figure 3 are produced by the decay of the unstable radioisotopes of ^{138}La and ^{227}Ac which are present in the crystal. Due to their low intensities they do not represent a strong interfering background in the measurements. On the contrary, the peak at 1.436 MeV can be used to monitor possible gain changes of each individual detector in between JET discharges[19].

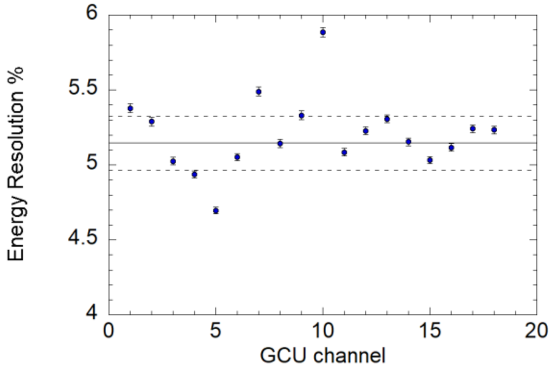

FIG. 4: Energy resolution of the 19 detectors evaluated for the ^{137}Cs full energy peak after their installation in the JET Torus Hall.

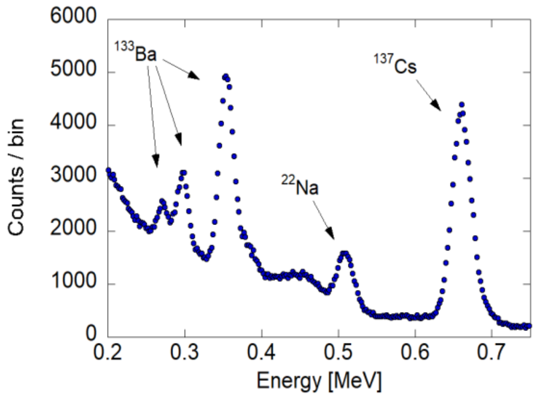

FIG. 5: Magnification of a pulse height spectrum recorded by channel 5 of the horizontal gamma camera a 12 hour calibration measurement.

The upgrade of the JET gamma-ray cameras is also motivated by the need to sustain high counting rates[21]. Monte Carlo simulations, in fact, revealed that the background gamma-ray fluxes[21] will induce MHz counting rates in the detectors for both D and DT plasmas. This is mainly due to neutron-induced γ-ray background when neutrons interact with the existing shielding. As shown by Rigamonti et al.[19] and Nocente et al.[22], the behavior of the detector at high counting rate has been investigated by irradiating the detector with LED pulses and/or gamma-rays in laboratory and at the TANDEM-ALPI nuclear accelerator in Legnaro (Italy). Measurements highlighted a gain shift of the SiPM sensor related to the increases of the current flowing in the SiPM itself when operating at high rates. As a consequence, a voltage drop across the SiPM occurs, which reduces the effective operating point of the device. This results in a downward shift of the peak position in the spectra which can be corrected offline thanks to time resolved measurements. An acceptable drift in the peak positions of about 5 % at 1 MHz has been observed when a gamma-ray distribution with equivalent energy equal to the one predicted for the gamma background at JET impinges on the detector. The increasing average current flowing in the SiPM is proportional to the counting rate and to the equivalent energy deposited in the crystal. Finally, the gain shift is also related to the operating bias voltage of the SiPM, which determines the number of fired pixels of the SiPM and, therefore, the current. By operating the detector with dedicated settings, we have managed to show that operations up to 8 MHz are feasible in a high counting rate mock up experiment with LEDs. However, the data interpretation is particularly challenging in this case due to the severe pile up contribution. For this reason, we expect to be able to operate the GC up to neutron yields in the range of about $5*10^{17}$ n/s at JET[13], i.e. above the maximum performance expected in high power deuterium and trace tritium experiments, but below the record deuterium-tritium performance, which is projected to achieve neutron yields up to 10^{19} n/s.

The upgraded JET gamma-ray cameras now combines tomography with spectroscopy information. The enhancements in the energy resolution and in the counting rate capabilities bring favorable expectations for the study of the fast ions in the MeV energy range. A final point to note is also the capability of the GC to contribute to runaway electron (RE) studies. In this case, there is need to measure the bremsstrahlung spectrum in the MeV range generated by REs and from which their energy distribution can be derived[23]. From the diagnostics point of view, the detector must be able to sustain MHz counting rates, which is within the capabilities enabled by the present upgrade. A preliminary study has positively shown that SiPM based detectors can be applied for these measurements[24], even though some specific aspects, such as the energy non-linearity and the limited dynamic range to energies up to about 20 MeV must be corrected for.

IV. CONCLUSIONS

A dedicated compact gamma-ray spectrometer based on a $LaBr_3$ scintillator crystal and a Silicon photomultiplier (SiPM) has been developed to meet the target requirements for the upgrade of the JET gamma-ray cameras. The SiPM is integrated in a PCB that houses the read-out electronic circuit. Here a CR differentiator is implemented to shorten the output signal length enabling the MHz counting rate capabilities. The high light yields offered by the $LaBr_3$ scintillator crystal, instead, allows spectroscopic measurements with enhanced energy resolution. The full system is also equipped with real-time temperature monitors and integrated power supplies which provide stabilized bias voltage and gain compensation for each SiPM. The data acquisition system is based on eight Analog to Digital Converters (4 channel each, 13 bits, 250 Msamples/s) which implement real time algorithms on FPGAs providing processed data for each detector.

The new system has been successfully installed and tested on both the horizontal and vertical JET gamma-ray cameras during 2017. In general, the upgraded JET cameras now makes gamma-ray measurements possible in deuterium plasmas at the highest neutron yields expected and in plasmas with tritium up to yield of $5*10^{17}$ n/s. The instrument is of relevance for fast ion physics studies in conditions approaching the maximum JET capabilities, which is among the core missions of this machine towards a new fusion energy breakthrough in deuterium-tritium.

XII. ACKNOWLEDGMENTS

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