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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

nGEM fast neutron detectors for beam diagnostics

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Abstract

Fast neutron detectors with a sub-millimetric space resolution are required in order to qualify neutron beams in applications related to magnetically-controlled nuclear fusion plasmas and to spallation sources. A nGEM detector has been developed for the CNESM diagnostic system of the SPIDER NBI prototype for ITER and as beam monitor for fast neutrons lines at spallation sources.

The nGEM is a Triple GEM gaseous detector equipped with polypropylene and polyethylene layers used to convert fast neutrons into recoil protons through the elastic scattering process. This paper describes the results obtained by testing a nGEM detector at the ISIS spallation source on the VESUVIO beam line. Beam profiles (σ_x = 14.35 mm, σ_y = 15.75 mm), nGEM counting efficiency (around 10^{-4} for 3 MeV < E_n < 15 MeV), detector stability (≈ 4.5%) and the effect of filtering the beam with different type of materials were successfully measured. The x beam profile was compared to the one measured by a single crystal diamond detector. Finally, the efficiency of the detector was simulated exploiting the GEANT4 tool.

Keywords: GEM (Gas Electron Multiplier), Fast neutrons, Efficiency, Simulation

1. Introduction

Applications related to nuclear fusion and spallation sources will need sub-millimetric fast neutrons beam monitors. Two of such applications are the construction of the CNESM diagnostic system of the SPIDER NBI prototype for ITER in Italy [1] and the construction of the CHIPir beam line at ISIS-RAL in UK for single event effects studies [2]-[3] Examples of detectors that own such a space resolution to be used as beam monitors are single crystal diamond detectors [2] and Gas Electron Multipliers (GEM) based detectors. GEM [4,14,15,16] based detectors were invented at CERN as charged particle tracking detectors [5] but, if properly adapted, these can be used also as neutral particles detectors [6,17,18,19]. This paper describes the construction and test of a GEM detector prototype especially

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Figure 1: Front view of the nGEM detector installed on the Vesuvio beam line.

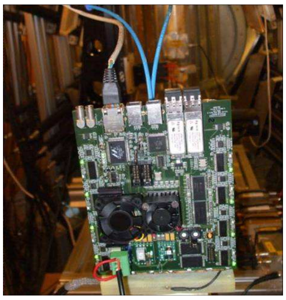

Figure 2: Rear view of the nGEM detector installed on the Vesuvio beam line.

developed for fast neutron detection. All the tests were performed at the ISIS-RAL (UK) VESUVIO electron Volt neutron beam line.

2. Experimental Setup

2.1. ISIS Vesuvio Facility

The measurements were performed with nGEM and diamond detectors placed in the neutron beam of the VESUVIO [7] beam line at a flight distance of about L=12.5 m from the neutron source. At ISIS, neutrons are produced by a 800 MeV proton beam with a double bunch fine structure and a repetition frequency of 50 Hz. The two proton bunches are about 70 ns wide (FWHM) and 322 ns apart. The proton beam delivers an average current of 180 Ah on a Ta-W target yielding about 30 neutrons per incident proton. In the energy range E_n > 1 MeV the neutron spectrum has approximately a 1/E_n behaviour.

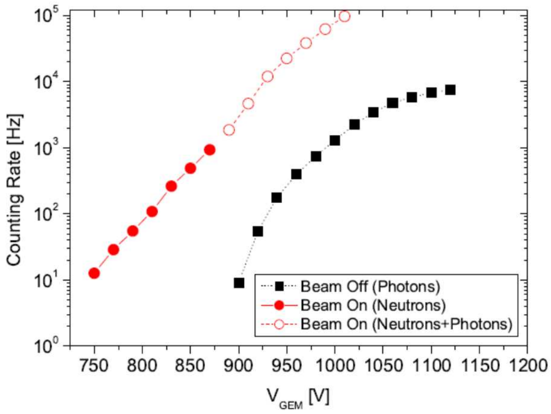

Figure 3: nGEM counting rate as a function of V_{GEM} when the beam was on (neutrons + photons) and off (photons); E_d (Drift Field) = E_{T1} (Transfer 1 Field) = E_{T2} (Transfer 2 Field) = 3 kV/cm, E_{Ind} (Induction Field) = 5 kV/cm

2.2. nGEM detector

A nGEM detector is a triple GEM chamber equipped with a solid-state fast neutrons converter cathode, similarly to what is done for detection of 14 MeV neutrons from fusion plasmas [8]. The cathode of a nGEM detector is composed by two layers: one polyethylene (CH_2) film 60 µm thick and one Aluminum layer 40 µm thick. In addition another polyethylene (CH_3) layer, 400 µm thick has been added on top of the cathode, out of the gas tight zone, in order to increase conversion efficiency. Incident neutrons are converted into protons by elastic recoil in the thin polythene (CH_2) film or in the external polypropylene (CH_3) sheet. Protons leaving the conversion layers with enough energy can cross the Al foil and reach the gas, thus ionizing it. Since the drift gap thickness (3 mm wide) is narrower than the proton range, only a fraction of the proton energy is deposited in the gas and detected. Ionization electrons liberated by protons energy release drift towards the GEM foils where they are multiplied [5]. The signal generated by electron cascade is induced on a padded anode (total of 128 pads, 12 x 6 mm^2 area) that is connected to the front end electronics. The front-end chip used to readout all the pads are the CARIOCA-GEM digital chips [9]. All the CARIOCAs are then connected to a custom made FPGA Mother Board [11] that analyzes the LVDS signal coming from the chips.
The detector active area was 10 x 10 cm^2, the gap geometry is the same as LHCb detectors [10] and the gas mixture employed in all the measurements is Ar/CO_2 70%/30%. Photos (rear and front views) of the detector installed in the VESUVIO beam line are shown in Fig. 1 and Fig. 2. The high voltage con-

figuration was generated using the HVGEM [11] NIM module and the potentials were applied to each electrode by means of passive resistive-capacitive filters properly designed for a Triple GEM detector.

3. Measurements

3.1. nGEM detector counting efficiency

The nGEM detector efficiency to different kind of particles was measured as a function of the effective gain by varying the sum of potential difference over the three GEM foils ($\Sigma\Delta V_{GEM} = V_{GEM}$). Two different measurements were performed: V_{GEM} scans when the neutron beam was on and off. The former is a measurement of the neutron detection efficiency while the latter gives a result in term of detection efficiency for particles non timely connected with the neutron beam, that is mainly photons coming from surrounding materials activation. Fig. 3 shows the result of the measurements. The counting rate of the detector is an increasing function of V_{GEM} but when the beam is off there is threshold value under which the chamber does not detect any particles: by applying a V_{GEM} < 900 V the photons background is completely rejected. Therefore the measurement when the beam is on can be split into two different components: up to V_{GEM} = 900 V only neutrons are detected while for higher values the counting rate is due to both neutrons and photons. Results obtained here are compatible with [12].

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3.2. Vesuvio beam profile measurements

A bi-dimensional Vesuvio beam profile reconstruction has been obtained by exposing the detector to the neutron beam for about 2 minutes. In order to be able to detect neutrons and to be insensitive to photons, the following electrical configuration was applied to the device: E_d (Drift Field) = E_{T1} (Transfer 1 Field) = E_{T2} (Transfer 2 Field) = 3 kV/cm, E_{Ind} (Induction Field) = 5 kV/cm and V_{GEM} = $\Sigma\Delta V_{GEM}$ = 870 V. This configuration corresponds to an effective gain that is about 100 and to a neutron detection efficiency of about 10^{-4} [13]. Figures 4 and 5 shows the measurements of the events above threshold (n_{OT}) in the horizontal and vertical directions. Counts of each pad have been referred to

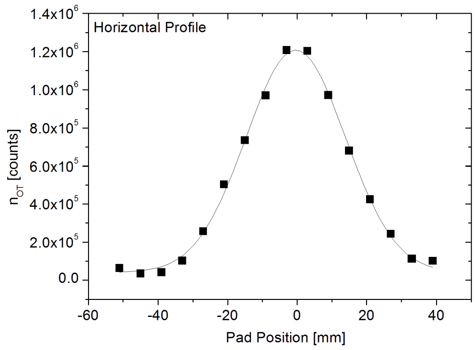

Figure 4: Events above threshold (n_{OT}) measured by the nGEM pads along the horizontal direction

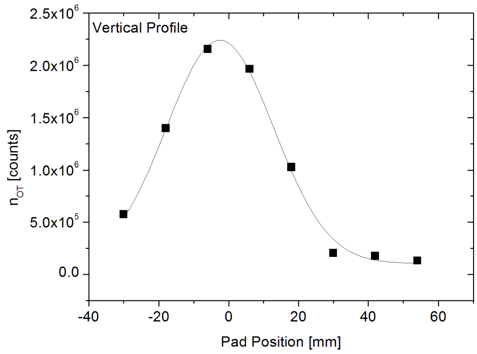

Figure 5: Events above threshold (n_{OT}) measured by the nGEM pads along the vertical direction

the centre of the pad: in order to make the x (y) image, all the y (x) counts relatively to the same x (y) have been summed. The step between each point in x (y) is 6 (12) mm corresponding to the pad width in that direction. σ_x = 14.35 mm and σ_y = 15.42 mm have been measured. The y-projection peak is not at the centre of the detector since the centre of the chamber was by purpose misaligned with respect to the beam centre in order to avoid direct irradiation of the FPGA located on the CARIOCA mother board.

3.2.1. Comparison between nGEM and diamond detector

The horizontal nGEM beam profile reported in Fig. 4 has been compared to the beam profile measured by a commercial single crystal diamond detector (4.5x4.5x0.5 mm^3) installed on the same beam line in front of the GEM detector. In order to map the full beam, the diamond detector has been moved in

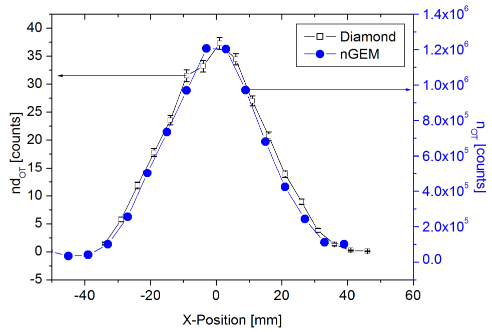

Figure 6: n$_{OT}$ measured by nGEM in the horizontal direction. Also shown is the same profile measured with a diamond detector.

steps of 5 mm recording the counting rate at each position. A threshold of 10 MeV was applied to neutron energy deposition inside the crystal. Fig. 6 shows both the events recorded by the diamond detector over this threshold (nd$_{OT}$) as a function of the horizontal position and the same plot of Fig. 4. In order to compare the results of this two different detectors, the peaks of the two profiles were forced to superimpose. The results are very similar since σ_{Diam} = 15.75 mm and σ_{nGEM} = 14.35 mm

3.3. nGEM counting rate stability

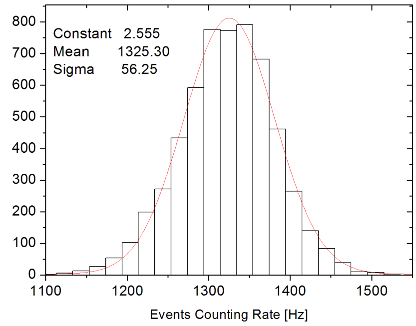

Figure 7: Histogram of events counting rate in one run

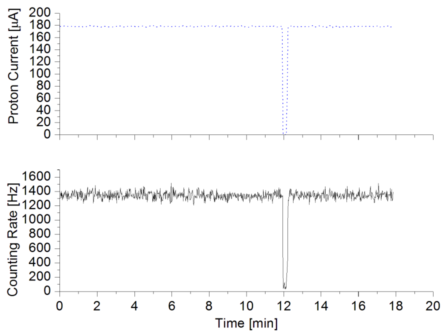

Figure 8: ISIS proton current (top) and nGEM events counting rate (bottom) as a function of time

One of the most important features that a beam profile monitor has to own is the counting rate stability in time. Many factors, like the charging up effect [14] or the variation of atmospheric parameters, can influence the behavior of the detector. Figure 7 shows the histogram of the recorded nGEM counting rate normalized to the ISIS proton current during more than 1 hour and 30 minutes. The value of the FWHM of the fitted Gaussian divided by the most probable counting rate gives a measurement of the nGEM detector stability in time: a value of about 4.7% has been measured in this case. In addition, Fig. 8 shows the nGEM events counting rate and the proton current as a function of time during the initial part of a run: nGEM counting rate exactly follows the variation of the beam current giving the possibility to on-line monitor the neutron beam flux.

3.4. The effect of different material filters

In order to confirm the detection of fast neutrons by the nGEM (when V_{GEM} = 870 V) and not of thermal neutrons or of gamma rays, filters of different materials have been put in the beam line in front of the chamber. Filters of lead, cadmium, polyethylene and aluminum, whose thicknesses are reported in table 1, have been used in order to filter out, respectively, high energy gamma rays, thermal neutrons, fast neutrons and low energy photons. The second column of Table 1 shows the remaining counting rate for each filter normalized to the rate measured without any material. The other columns report the expected rate normalized to rate with no-material assuming fast neutron, thermal neutron and gamma rays as interacting particles. Comparison between second and third columns confirms that the detected particles are fast neutrons.

4. nGEM efficiency simulation

In order to understand which is the fast neutron energy range where the nGEM detector is sensitive, a simulation of the interaction of neutrons of different energies using the GEANT4 tool has been performed. The simulation does not take into account the full detector since the geometry comprises only CH_3, CH_2, Al and Ar/CO_2 drift gap layers without

Material	Counts	No Mat	Fast n	Th n	γ
No Mat	1307	100%	//	//	//
Pb (5cm)	442	34%	37%	15%	73%
Cd (1mm)	1208	93%	98%	0%	97%
CH_2 (25 cm)	139	10%	9%	0%	29%
Al (2.5 cm)	858	65%	73%	79%	75%

Table 1: effect of filters of different materials and thicknesses on the nGEM counting rate. (V_{GEM} = 870 V). For the fast neutrons column and for the gamma ray column an average energy of 6 MeV and 2.2 MeV has been respectively considered when performing the calculation

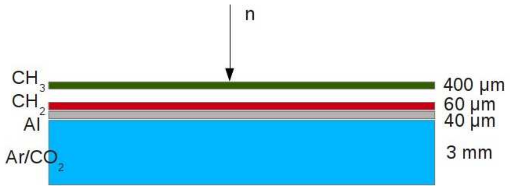

Figure 9: The experimental setup simulated using the G4 tool

introducing GEM foils and anode (see Fig. 9). A mochromatic neutron beam irradiates the setup and all the secondary particles generated by its interaction are recorded. The signal is generated by the energy deposited in the drift gap gas by recoil protons created either in the polypropylene or polyethylene layers: a count is recorded when this deposited energy is greater than a certain threshold and the efficiency is calculated as the number of counts divided by the total number of generated neutrons. In order to simulate the nGEM efficiency as a function of neutron energy, 10^7 neutrons have been generated for discrete energies in the range 2-100 MeV.

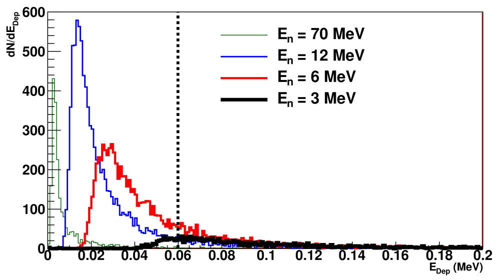

Figure 10: Simulated proton recoil energy deposition in the gas gap for different incident neutron energies. The threshold used to calculate the efficiency is shown as a dashed line

Figure 10 shows the recoil proton deposited energy distribution inside the drift gap for four neutron energies. Neutrons of higher energy generate protons of higher energy that deposit less energy in the gas: as a consequence the peak of the distribution moves

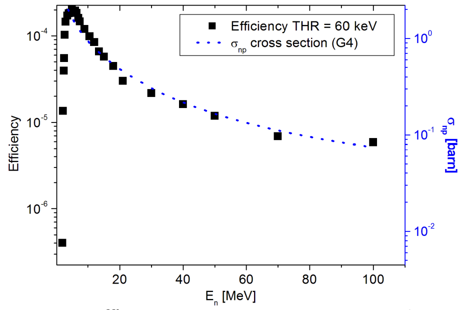

Figure 11: nGEM efficiency (threshold = 60 keV) as a function of different neutron energies and comparison with the *np* cross section

to the left when the neutron energy is increased. The threshold level used to calculate the counts is reported as a dashed line and it was set to a value of 60 keV, corresponding to the energy threshold effectively used during the test at ISIS. Figure 11 shows the result of the simulation of the nGEM efficiency as a function of the neutron energy and compares it to the neutron/proton elastic scattering cross section (σ_{np}). Efficiency increases up to a value of neutron energy around 6 MeV, since protons with an energy lower than this value produced in the CH_3 layer have a very high probability to be stopped before reaching the gas. The decrease after 6 MeV is explained by the simultaneous decrease of σ_{np}.

5. Conclusions

Results obtained by the test of the nGEM prototype shows that this detector is fully able to detect fast neutrons in the energy range 3-15 MeV with an efficiency higher than 10^{-4} while this efficiency decreases with increasing energy. The Vesuvio beam profile has been successfully reconstructed and comparison with single crystal diamond detector shows that both device measure the same profiles. Efficiency in detecting fast neutrons, insensitivity to other neutral particles as thermal neutrons and gamma rays and counting rate stability demonstrate that this kind of detector can be used as fast neutron beam monitors. Furthermore after an irradiation of five consecutive days, the FPGA did not show any damaging effect

Acknowledgments

This work was set up in collaboration and financial Research) of F4E and of INFN-Group 5 (Technology Research).

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