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Applications of triple GEM detectors beyond particle and nuclear physics

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ABSTRACT: Micro-Pattern Gaseous Detectors (MPGD) have opened the way for the construction of detectors whose performance surpasses that of the previous generations in terms of spatial resolution, high-rate capability and increased radiation hardness. Led by the Micro-Mesh Gaseous Structure (Micromegas) and the Gas Electron Multiplier (GEM), some MPGDs are mature technologies used in a variety of experiments at high energy physics. What we report in this article is the experience explored in the last years with a compact GEM detector system in several applications as medical imaging, dosimetry and beam diagnostics for high energy beams and for nuclear reactors. For sake of shortness, only performance on soft X-ray and neutron detection will be described in detail. Also a description of the new promising highly pixelated GEM detector will be presented.

KEYWORDS: X-ray detectors; Radiation-hard detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Neutron detectors (cold, thermal, fast neutrons)
1 Introduction

After more than ten years from its invention, the detectors based on Gas Electron Multiplier begin to find several applications in different fields from high energy physics.

In order to have GEM detectors easily usable in different environments from high energy physics laboratories, it’s important to develop portable systems. All the components should be optimized, beginning with the detector and following with the high voltage power supply, the front-end electronics and the data acquisition system, for example, based on FPGA. The unique limitation for these detectors is the gas supply system, at least when the application involves high fluxes of particles. A serious study must be addressed in order to understand if the GEM detectors may be used without flowing gas. Once realized a complete system, developed over the past few years, several applications were explored. Using the triple GEM detectors we measured the huge gamma flux in radiotherapy or the weak flux of X-rays coming from radioactive waste or we monitored the high intensity beam for hadrotherapy. But what we describe in the following is the monitoring of tokamak burning plasma through soft X-rays and the improvements of neutron detection, that open the possibility to use this technology on homeland security and on all the applications in neutron spallation sources. Last, but not least, we describe the recent developments on a GEM detector with a micropixel readout, the GEMPIX, which has been built at CERN and INFN-Frascati for applications in the field of microdosimetry. After a brief description on the complete GEM detector system, some of these applications and results will be described in detail.

2 A complete GEM detector system

The triple GEM [1] detectors described below are made of three standard $10 \times 10 \text{cm}^2$ GEM foils produced by CERN, the characteristics and performance of which are described elsewhere [2]. In Frascati all the triple GEM detectors are built following the procedure developed for the LHCb
muon chambers that stretch the GEM foils before the gluing phase on FR4 frames. The detector is typically equipped with a cathode, suitably designed as a function of the particles to be detected. The anode is designed with 128 gold plated pads, whose dimensions fit with the spatial resolution needed by the application. The assembling of frames, cathode and anode is made in a cleaning room as shown in figure 1. The typical gas used is a well-known mixture Ar/CO$_2$ (70/30), but an Ar/CO$_2$/CF$_4$ (45/15/40) is used whether better spatial and time resolutions are required [2]. Suitable voltages are applied to the foils and the cathode so that the electrons generated by the gas ionization can acquire enough energy to develop avalanches inside the holes, with a gain that can reach after three stages a maximum value of $10^4$ depending on the gas mixture used.

The signal generated by the electrons drifting in the last gap is induced on a padded anode. The front-end electronics used to readout the pads are the CARIOCA-GEM chips [3], each of which holds eight channels of current-mode Amplifiers, Shapers and Discriminators (ASD). The discriminator, with a threshold defined by the acquisition program through a DC level, produces a digital LVDS signal. All the eight CARIOCA boards, housing two chips each are plugged on the detector as shown in figure 2. Afterwards, a custom made FPGA Mother Board is plugged on the boards on the back side of the detector.

The Board was designed and made by the Electronic Group at LNF-INFN in the mainframe of a INFN R&D project called GEMINI.

The FPGA board, shown in figure 3, uses a general purpose firmware developed in Frascati, and is able to perform counting and time measurements of discriminated LVDS signal coming from the 128 channels and can collect data into the local memory, with negligible dead time. The measurements can be triggered both through an external or internal trigger. The scaler registers have a depth of 32 bits and can be acquired through a maximum of 255 time slices, with a minimum of 30 $\mu$s each; the data transfer in this case is synchronized with the DAQ computer. With the asynchronized mode, it can acquire 60 thousand time gates with a minimum of 1 ms wide (the single gate data is not stored in the memory but directly sent on the local area network).

This board can do also time measurements; the arrival time of LVDS signals produced by the CARIOCA-GEM chips can be measured from the trigger in steps of 5 ns. This mode is particularly useful with a small Time Projection GEM Chamber, allowing a 3D reconstruction of the particle...
Figure 2. The CARIOCA boards mounted on detector; on the left the HV connector with filters.

Figure 3. The FPGA motherboard.

track inside the drift volume [4]. The Ethernet protocol implemented on this board allows a direct connection with the DAQ computer that can collect the final data also through long distances.

The high voltage system used to power the GEM foils is the HVGEM NIM module shown in figure 4, and is the evolution of a system originally designed [5] in LNF-INFN for the LHCb muon GEM chambers. It consists of seven independent HV channels, six of which can provide up to 700 V and one up to 1400 V, allowing a very high portability of the GEM detector, as well as flexibility in the settings of the desired voltage to each electrode. In addition, each channel is equipped with a high sensitivity current meter for the detection of possible discharges and of the current driven by the detector within a 10 nA precision. When the GEM detector is used in high fluxes of particles this module allows to measure the intensity through the current readouts, with a dynamics of 1000.

3 Low energy X-ray monitor for burning plasmas in tokamaks

Soft X-ray diagnostics for a burning plasma experiment have to be radiation tolerant, easily shielded, and must own both low sensitivity to neutrons and gammas and energy measurement capability.
Figure 4. The HVGEM NIM module and the LabView console with the HV settings and the current monitor.

Figure 5. (a) The FPGA-based motherboard coupled with the GEM detector; (b) setup at KSTAR (pinhole is located on the port window). Broad view of the plasma (left) and zoomed view (right), together with the length of the tube connecting pinhole to the detector.

The general conception of these diagnostics should therefore evolve in the direction of pattern recognition for a real time feedback on the tokamak operation setting.

The X-ray GEM detector built for the tokamak KSTAR, in collaboration between ENEA and INFN Frascati, is a compact, portable and flexible detector, fully shielded. The metallic case was developed to house the detector and the electronic boards, not only for mechanical protection and interface with steerable mechanical mounting on the port, but also for shielding it against electromagnetic and radiofrequency disturbances. The installation on KSTAR, figure 5(a), was designed as a pinhole camera, to see most of the core plasma, with adjustable magnification (from $\times 10$ to $\times 30$). The relative distance of the camera with respect to the port, where the pinhole is mounted, can be adjusted in the range $55 \div 165$ cm to achieve the desired magnification, by means of a telescopic tube filled with Helium to avoid absorption in air, figure 5(b).
The detector was characterized for two gas mixtures at atmospheric pressure: Ar/CO$_2$ (70/30) and Kr/CO$_2$ (70/30). Specifically, two energy ranges of operation are available: $3 \div 15$ keV with Ar/CO$_2$ and $3 \div 30$ keV with Kr/CO$_2$.

In figure 6 soft X-ray pictures of the plasma core taken during the campaign 2013 are shown for different magnifications, in the energy range $3 \div 15$ keV.

The X-ray signal produced in the GEM detector arrives to $7 \times 10^6$ counts/s per pixel, being three-four orders of magnitude higher than the neutron background [6].

This GEM gas detector confirmed to be flexible, with high performance, robust, pretty insensitive to neutrons and gammas, adequate for an imaging tomography. After this very preliminary and short experimental campaign, it will be fully studied and exploited at KSTAR in the coming years, in a framework of a collaboration ENEA-INFN (Italy) and NFRI-KAIST (South Korea).

4 Fast neutron detection

The triple GEM specifically used for fast neutron detector has an aluminum cathode covered on the outer side by a polyethylene sheet, which makes it sensitive to neutrons by means of elastic (n, p) reactions on hydrogen. The produced protons with energy greater than one MeV, once crossed the aluminum sheet, ionize the gas producing hundreds of secondary electrons. The chamber gain can be lowered to reduce the contribution of smaller signals coming from the background, in particular gamma-rays, especially those travelling with the incident neutron beam and generated by the spal-
Figure 7. (Left) The experimental setup at FNG (ENEA-Frascati); (right) the linearity and the measured efficiency compared with the NE213 counter.

lation reactions and/or by the moderator/reflect/reflector/positioning system and those coming from the surrounding material activation.

In the configuration described above, neutron counting is performed by recording the recoil protons that ionize the gas in the drift gap. The detector was exposed to different neutron sources to characterize and measure the performance. First of all at FNG at Frascati-ENEA [7], a neutron source that uses fusion reaction DD and DT with two possible energies of 2.5 and 14 MeV respectively (see figure 7). An efficiency of $3.8 \times 10^{-5}$ was measured and a capability to discard protons emitted at $\theta > 45^\circ$ was proved [8]. Other prototypes with different thickness of polyethylene and aluminum show efficiencies greater than $10^{-4}$.

A second measurement was performed at VESUVIO at ISIS [9] on a neutron beam line at a distance of about 12.5 m from the water moderator. The working point (gain) of the detector was determined by performing a scan as a function of sum of the voltages applied to the GEM foils ($V_{\text{GEM}}$) when the neutron beam was turned on and off. The former is a measurement of the neutron detection efficiency while the latter gives a result in terms of detection efficiency for gammas coming from the activation of surrounding materials (see figure 8). The final working point was 870 V, corresponding to a gain of about 100.

Figure 9 shows the intensity 2D plot on a plane perpendicular to the neutron beam axis, collected over an integrated proton beam current of 355 mAh (with an average proton current of 178 mA) [10]. The intensity distribution is well described by a bi-Gaussian with FWHM of about 15 mm as expected from technical designs and previous measurements. The time structure of the VESUVIO neutron pulse was measured by recording over a period of 3 ms the GEM counting rate within 100 ns wide time slices. The rate distribution over the whole period is shown in figure 9, where the proton beam time structure from the accelerator is also plotted. Because of the time structure of the proton beam, the arrival time onto the detector cannot be associated to a unique neutron energy value.

Results obtained by the tests described above assess that GEM detectors are fully able to detect neutrons in real time, with good spatial description and high time resolution, in the energy range 2–20 MeV. Efficiency in detecting fast neutrons (around $10^{-4}$), low sensitivity to pho-
Figure 8. nGEM counting rate as a function of $V_{\text{GEM}}$ when the beam was on (neutrons + photons) and off (photons).

Figure 9. (Left) 2D image showing the beam intensity for an integrated proton beam current of 355 mAh; (right) time spectrum recorded over an acquisition window of 100 ns delayed with respect to the ISIS clock to obtain a time scan over about 3 ms. A reference proton beam signal is also shown.

Tons ($10^{-6}$) [11], linearity to irradiation and high counting rate stability (around 5%), make these devices suitable for fast neutron beam monitoring at spallation neutron sources.

5 Thermal neutron detection

A thermal neutron detector based on Triple GEM technology equipped with a borated cathode (1 µm thick B4C) was realized and tested at the VESUVIO neutron beam line at ISIS [9]. This type of detector can be used only as beam monitor due to its low efficiency (1%) [12]. Also in this case the working point was determined by performing a VGEM scan when the beam was on and off (see figure 10).

The counting rate is an increasing function of $V_{\text{GEM}}$ and, as expected, the detector starts to detect thermal neutrons at a voltage as low as $V_{\text{GEM}} = 710$ V that corresponds to an effective gas
gain of about 10. A wide counting rate plateau is present between 825 V and 925 V while for $V_{GEM} > 925$ V the detector becomes sensitive to the gamma-ray background. The working point of the detector is determined to be 870 V because such a low gain gives also the option to completely reject the gamma-ray background that is always present during neutron measurements. The presence of a such a wide plateau (even wider than the one found for fast neutrons) confirms that GEM technology is very well suited to be used for thermal neutron detectors. The measured efficiency at the working point is $(9.5 \pm 0.8) \times 10^{-3}$ and the expected efficiency for a 1 µm thick layer of natural $\text{B}_4\text{C}$ is about $8.6 \times 10^{-3}$.

In order to increase detection efficiency, another triple GEM thermal neutron detector, with side-on geometry was recently conceived (S-GEM). The detector has a cathode specifically built for thermal neutron conversion, with a series of thin strips of $^{10}\text{B}$ deposited on glass supports as shown in figure 11. A detailed description of the detector and the functional simulation made by FLUKA can be found elsewhere [13].

The neutron beam impinges laterally onto the detector rather than onto the cathode, as typically happens in almost all GEM-based detectors applications. When a neutron is absorbed into the $^{10}\text{B}$

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Figure 10. Counting rate as a function of $V_{GEM}$ when the beam was on (neutrons + photons) and off (photons).

Figure 11. (Left) Scheme of the GEM chamber for the thermal neutron. (Right) View of cathode of the side-on triple GEM detector.
layer, an alpha particle and a $^7$Li ion are produced. These charged particles ionize the gas in the drift region of the detector, thus producing secondary electrons. Moved by the electric field, these particles reach the three GEM foils where they are further proportionally multiplied in cascade, inducing a detectable signal on the anode. Thanks to the high ionization of the alpha inside the gas, the GEM chamber can work at a low gain; this allows to have a very low gamma background as shown in figure 12: the half zone of detector without boron strips measures a rate $10^5$ times smaller.

A first measurement was made at TRIGA reactor at the ENEA-Casaccia [14]. The reactor can be operated at different powers from a few Watt to 1 MW with a neutron flux of about $2 \times 10^6$ n/cm$^2$/s at the maximum power featuring a Maxwellian spectrum with about 70 meV full width half maximum. By running at different powers (and thus at different neutron fluxes) it was possible to check the detector response in terms of detector’s counting rate as a function of the incident neutron rate from the beam line. Figure 12 reports the correlation between the S-GEM count rate and the neutron rate provided by the reactor along the extraction port chosen for the measurements showing a good linearity over 6 orders of magnitude. The slope of the fitting line provides an estimation of the detection efficiency that comes out to be 4.8%.

A second measurement has been done at the neutron spallation source nTOF at CERN [15] in 2012. Using the beam trigger, it was possible to synchronize the GEM data acquisition in order to select a given neutron energy window and measure the detector efficiency as a function of neutron energy between thermal and 2 eV. Thanks to FPGA board firmware with the multi gate mode it was possible to measure the neutron flux as a function of the energy at the same time. Figure 13 shows the acquisition of 150 slices each one with a 1 ms gate. The corresponding energy distribution of the neutrons was then calculated from the TOF using the classical kinetic energy formula. Positioning the GEM detector at the center of the beam, it was possible to measure the efficiency as a function of neutron energy as shown in figure 13.

The efficiency results are in good agreement with the 4% obtained previously at the Casaccia reactor. Since the beam is larger and longer than the sensitive area of the boron strips, the GEM was mounted on a step motor in order to draw a complete image of the beam. The reconstruction of the beam image comes from a horizontal and a vertical position scans.
Figure 13. Temporal evolution, energy spectrum and measured efficiency as a function of the energy.

Figure 14. Beam profile reconstruction for thermal neutrons.

In figure 14 is shown the reconstruction of the whole beam for the complete part of analyzed spectrum. Our reconstruction is in good agreement with the one obtained by simulations [15].

After these promising results, new prototypes are under construction trying to improve the efficiency and the spatial resolution working on Boron deposition and the anode design. Preliminary analysis on recent measurements performed at Oak Ridge in the U.S. shows efficiency of 30% and a millimetric resolution on neutron beam position. Careful studies and developments are planned for the near future for the boron deposition on cathodes, addressing on reliability, mechanical resistance, big surface and aging issue.

6 GEMpix: a triple GEM structure read by 50 micron pixels

There is another device recently designed and realized within a collaboration between CERN and INFN that improves the portability and the spatial resolution of the GEM detectors for future medical and industrial applications. After important trials made by few groups [16–18] in the past years, a compact triple GEM detector with CMOS pixel readout chip has been made, within the
Figure 15. (Left) The Quad-Medipix with the ceramic board and four CMOS chips. (Right) The new board with GEM frames glued on top. The two boards are successively mechanically coupled to match the two active areas.

Figure 16. Three pictures taken with GEMpix: (left) alpha particles from Americium, (center) cosmics-rays and X-rays from $^{55}$Fe, (right) Compton electrons produced by $^{60}$Co gammas.

MEDIPIX [19] and ARDENT [20] collaborations. The detector consists in two independent parts. One board, already designed for other purposes, called Quad-Medipix, with a socket for a ceramic board that houses a $2 \times 2$ matrix of Medipixes CMOS readout chip as shown in figure 15.

The other board specifically designed and realized in LNF-INFN, consists of a new triple GEM layout with an active area of $28 \times 28$ mm$^2$ that matches exactly the area of the four Medipixes. The electrodes path of the new GEM foils has been designed to keep away from the chip wire bonding, avoiding in this way dangerous sparks between GEM and Medipixes wires. The new GEM foils have been produced by CERN. The triple GEM frames are glued on a new board that houses also the HV filters and the connector for the HVGEM module, as shown on figure 15. The two halves are then mechanically coupled through an O-ring for the gas tightness and so doing the last GEM foil overlaps the four Medipixes 2 mm above, forming the induction gap. With this type of detector a gas mixture with Ar/CO$_2$/CF$_4$ allows to have a contained lateral diffusion maximising the spatial resolution. The detector now is in a characterization phase through measurements with radioactive sources. Some events obtained with alphas, X-rays and Compton electrons are shown in figure 16.
Three types of GEMpix have been built up to now to better investigate the capability of this detector in medical and industrial applications. The Medipix readout can be configured to have time and charge measurements for each pixel cluster at the same time; this could be used for a 3D reconstruction of the particle tracks in the drift volume and for a detailed ionization energy measurement along the path. This could be particularly interesting for microdosimetry and cancer treatment studies.

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