

Development of a GEM detector prototype with remote front-end electronics system for high-radiation environments

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Abstract: We present a novel Gas Electron Multiplier (GEM) detector prototype candidate for integration into the ITER Radial X-ray Camera. Triple-GEM detectors have demonstrated excellent performance in soft X-ray diagnostics, providing high sensitivity, broad dynamic range, and robustness against neutron/gamma backgrounds. However, the high neutron flux expected in ITER poses challenges for front-end electronics reliability. Tests performed at the Frascati Neutron Generator (FNG) showed that the front-end electronics failed at 14 MeV neutron fluxes of 1.6×10^5 n/cm²·s, while the GEM chamber remained operational up to 1.4×10^7 n/cm²·s, the highest flux achievable currently at FNG. To address this limitation, we developed a new front-end electronic system that can be displaced via micro-coaxial cables on a range from 20 to 200 cm. This paper presents the results of the laboratory tests carried out to evaluate the signal quality transmitted via cables of different lengths and the performance of the complete prototype under X-rays exposure.

Introduction: The application of triple-GEM detectors for soft X-ray diagnostics has been successfully demonstrated across various tokamak facilities [1]. Operating in photon-counting mode, with defined acquisition time windows, these detectors have enabled high-resolution 2D imaging of dynamic plasma phenomena, such as sawtooth oscillations and heating events, with high temporal and spatial resolution [2-5]. A major advancement has been achieved through the integration of the GEMINI (GEM INtegrated Interface) ASIC readout, developed by a collaboration between the CNR-ISTP Institute, the University of Milano-Bicocca, and the INFN Institute [6]. This readout allowed a packet-based readout with each pixels measuring deposited energy and time with a resolution of 0.5 ns. The analogic signal on each pad is digitized with the Time over Threshold technique that provides a measure of deposited energy, while an internal clock working at 2 GHz measures its Time of Arrival (ToA) with respect to a reference trigger signal. The current prototype

also introduces significant innovations in the electronics readout and in the detector composition itself. In particular, the front-end electronics were redesigned for remote operation via micro-coaxial cables, and the GEM structure was modified to minimize X-ray background. While conventional GEMs use copper electrodes on polyimide substrates, the new prototype employs two aluminum foils and one copper foil, thereby reducing fluorescence X-ray emission without compromising performance. The detector maintains a standard triple-GEM configuration, consisting of a drift region for X-ray photon conversion, three GEM stages for charge amplification, and a final 2D readout stage on a dedicated PCB.

Prototype Setup and Electronics: The prototype (shown in Figure 1) was assembled by coupling a sealed GEM chamber with a readout PCB through an O-ring closure. This configuration allows an easy substitution of the readout PCB to suit different experimental requirements. A dedicated $20 \times 3 \text{ mm}^2$ side window enables "side-on" measurements of X-ray absorption profiles up to 50 keV using Ar-CO₂ mixtures, with higher energies accessible using heavier noble gases like xenon or krypton.

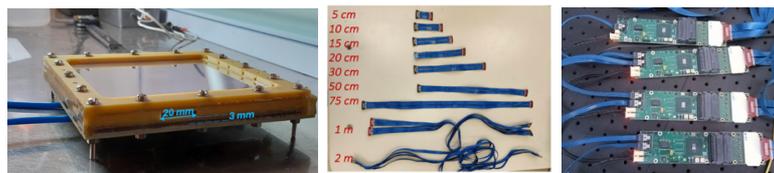


Figure 1- Picture of the assembled GEM camera. The side entrance window for measurement of X-ray absorption profile is highlighted in light blue (left); SAMTEC micro-coaxial cables (center); GEMINI 64D chips connected to the respective FPGA cards (right).

Micro-coaxial cables of varying lengths (from 5 cm to 200 cm) were produced by the SAMTEC Company as shown in the center panel of Figure 1. The custom PCB interfaces the GEM detector with the new GEMINI 64D chips, which can manage a maximum number of 64 channels and coaxial connectors. The PCB hosts a 16×16 matrix of $6 \times 6 \text{ mm}^2$ pads, covering a total sensitive area of $10 \times 10 \text{ mm}^2$. Data acquisition is handled by FPGA boards, which interface with a readout PC via a 10 Gbps optical link. This setup supports event rates up to 125 Mevents/s.

Experimental Test of the remote front-end electronics: To evaluate the quality of the signals transmitted through micro-coaxial cables of varying lengths, an experimental setup was devised to emulate X-ray interactions using a pulse generator. A GEM foil was connected to the readout PCB, receiving test pulses at 1 kHz frequency and 10 V amplitude. The front-end electronics, comprising the new GEMINI ASIC and FPGA boards, were connected but operated asynchronously, enabling the characterization of each cable

independently. A custom interface software tool, developed by the Nuclear Instruments company, was employed to monitor the new front-end electronics. Initial measurements established the minimum discriminator threshold required to eliminate electronic noise for cables ranging from 10 cm to 200 cm. Results indicated a clear, near-linear increase in the required threshold with cable length from a minimum value of 30 for 10 cm cables to 90 at 200 cm remaining well below the system's upper limit (512), as can be seen in Figure 2. To study the signal degradation, the ToT distributions were acquired for each cable using a fixed threshold of 110. The ToT spectra, shown in Figure 3 (left panel), fitted with Gaussian functions, revealed a gradual shift in the mean value and a broadening of the distribution as cable length increased, (central and right panels of Figure 3).

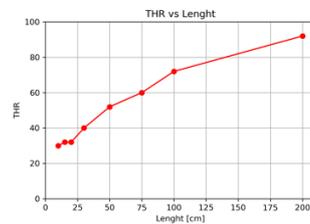


Figure 2- Threshold value required to suppress noise to negligible levels for each cable length.

This behavior reflects the temporal dispersion induced by longer signal transmission paths. Signal degradation could be quantified via the FWHM/max ratio (FWHM: full width at half maximum; max: ToT max), remaining $\leq 3\%$ for cables ≤ 100 cm and rising to 4% at 200 cm. Spectral resolution remains acceptable up to 200 cm; beyond that, it degrades, though the system fully functional operating in counting or current mode.

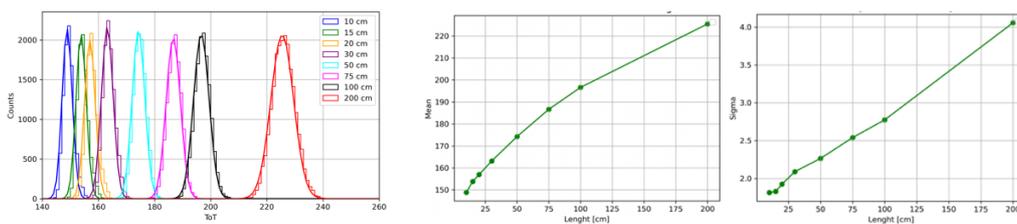


Figure 3 - ToT distributions for all cable lengths (left), with Gaussian fits; mean values (center) and sigmas (right) as function of cable length.

Experimental tests for new prototype validation: Finally, the new prototype was examined in terms of X-rays detection when it was exposed to a ^{55}Fe source. The adopted setup is shown in Figure 4. The detector was filled with a gas mixture of Ar/CO₂ (70/30) at atmospheric pressure and its front-end electronics were connected with cables of 100 cm. The source was placed to illuminate the detector diagonal, as shown in the 2D image at the center of Figure 4. The left panel displays the ToT distributions for the 5.9 keV X-rays and the argon

escape peak from the highlighted pads, along with the detector's global response (black histogram). A preliminary study on the signal resolution was performed focusing on the most intense pad (I8) varying the GEM voltage from 1100 V to 1170 V. The ToT distributions were fitted with a gaussian function and the fit results are summarized in Figure 5.

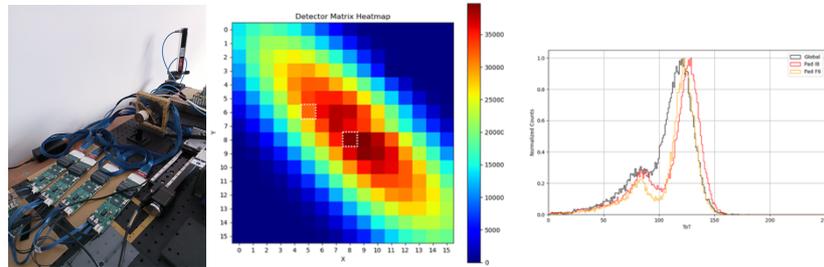
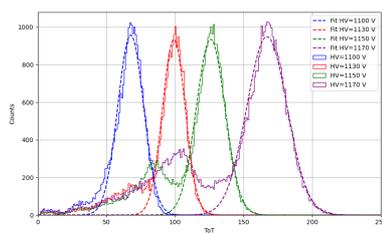


Figure 4 – Experimental setup with the ^{55}Fe source pointed on the diagonal of the GEM camera (left). Detector matrix heatmap (center); ToT comparison of the highlighted pads in the heatmap detector. The black histogram refers to the global response of the detector (right).

From this first check, the value of 1130 V resulted the working point of this hybrid camera.



HV (V)	Mean	Sigma
1100	67.71	9.41
1130	99.16	8.34
1150	125.96	10.55
1170	167.02	14.71

Figure 5 - Scan of the detector response in terms of ToT distributions fitted with Gaussian functions plotted against the applied voltage (left panel). Fit results reported in the table (right panel).

Conclusions: This work presented a hybrid GEM detector using aluminum and copper foils, designed to operate with remote front-end electronics. Tests with micro-coaxial cables of different lengths showed signal degradation with distance, but acceptable spectroscopic performance was maintained up to 200 cm. The detector's response to 5.9 keV X-rays from a ^{55}Fe source confirmed its effectiveness. These results demonstrate the feasibility of using GEM detectors with electronics located 1–2 m away, reducing neutron exposure and allowing better shielding for increased robustness in harsh environments.

References

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