INFN_E/GEM4FUSION: NEW DIAGNOSTICS BASED ON GEM AND TIMEPIX DETECTORS FOR MAGNETIC CONFINEMENT AND LASER PRODUCED PLASMAS

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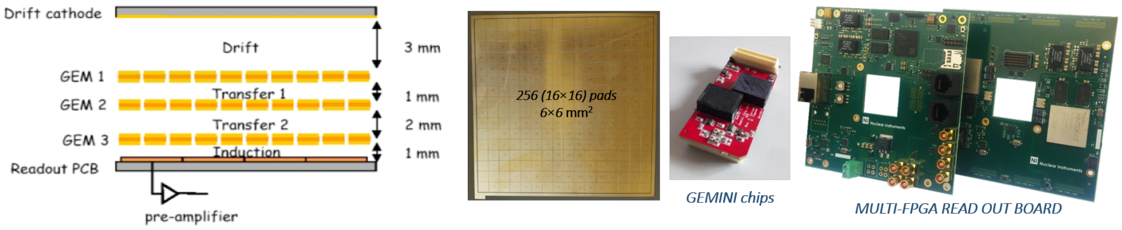
1 Introduction

Our research activity was born from a collaboration between ENEA and INFN in Frascati and the following report will outline the main results obtained in this last year. Our work has been focused on three main research lines: test and calibration of the new GEMINI front-end electronics of the GEM detectors, development and characterization of a new GEM detector in side-on configuration and measure of the X-ray spectrum on a laser produced plasma. Based on the accumulated work experience of these last years, a proposal for X-ray diagnostics on the new DDT Tokamak under construction at the ENEA Frascati research center has been submitted. In addition, after checking the potential of the new GEM detector, our group has managed to conclude an agreement with the diagnostic team of the ITER tokamak for the realization of a new diagnostic X-ray based on GEM detectors. In the present report, only the ITER proposal will be briefly shown because the job previewed in the contract just begun at the end of 2022 and will be object of the next year. Finally our group is working also on the characterization of Timepix-based detectors for the monitor of particles and neutrons, in particular on a new diamond detector based on Timepix3 for fast neutron detection on Tokamak. Details on this last activity that has interest also in the framework of the INFN-E project can be found on the report of the n_TOF project. In the present report, an important application of a Timepix3 for Radon measurements will be shown.

2 Characterization of the new GEMINI front-end electronics

Our GEM detectors cover an active area of 10 x 10 cm^2, with some alternatives which can be smaller (3 × 3 cm^2) or bigger (20 × 30 cm^2) depending on the specific applications. Regardless of their dimensions and applications, their layout follow a standard scheme which was tested and verified and is practically the same for all applications. Our GEM detectors are sealed chambers made of a cathode, three GEM foils and an anode. They have an input and output inlet so that a specific gas mixture can flow inside. The gas layer between the cathode and the first GEM foil (the "drift region") is the active volume of the detector and can be modified according to the specific application. Typically, its width is 3 mm, but this geometric parameter can be modified (fig. 1a).

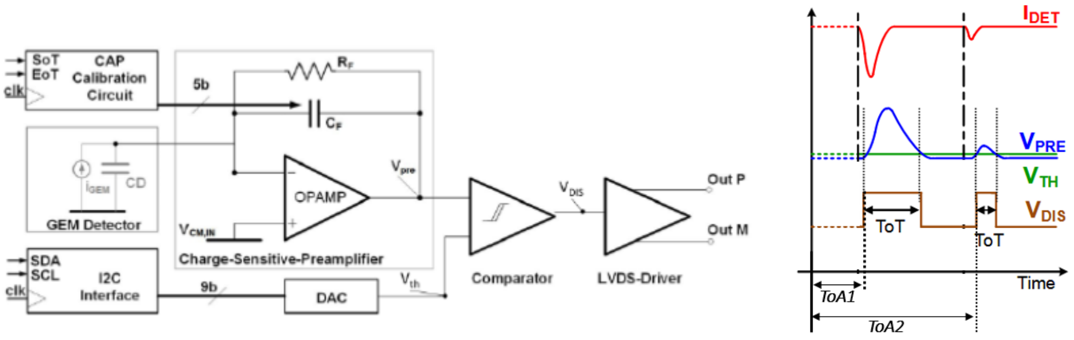
In general, the anode is divided in pads and a dedicated read-out electronic is mounted on its back side in order to obtain the required info on the particle (fig. 1b).



(a) (b)

Figure 1: *a) Layout schema of a triple-GEM detector in one of the standard configuration with 3 mm of active gas layer and area of* 10×10 cm^2*; b) pads PCB with the main elements of read-out electronics: GEMINI chip cards and FPGA boards.*

The detector can be controlled through a multi-FPGA board developed by the Nuclear Instruments company. The main component of this new read-out electronic is the chip GEMINI (GEM INtegrated Interface). Its Architecture has been presented in previous published papers [1; 2]. The chip has been developed in 0.18 μm C-MOS technology and is able to manage a maximum number of 64 channels, hence a maximum of 64 pads on the PCB anode. The architecture of a single channel is represented by the block diagram shown in fig. 2.

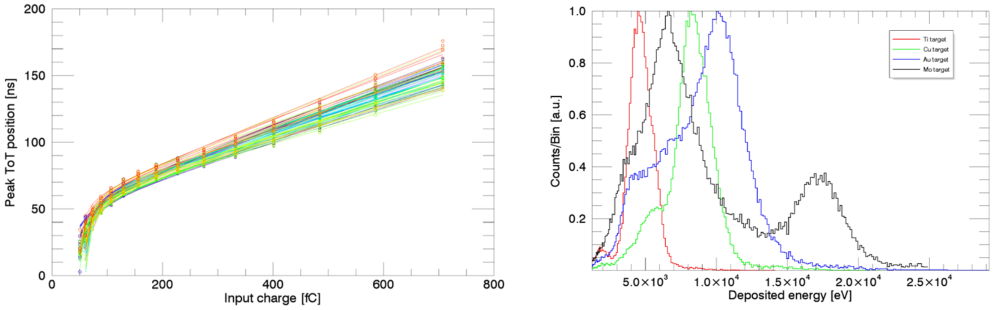


(a) (b)

Figure 2: *a) Block diagram of the GEMINI chip that highlights the main elements: control interfaces, Charge Sensitive Preamplifier, comparator the LVDS driver for data output; b) A simplified schema of ToT and ToA acquisition mode for a single channel.*

The first block at the pad signal output is a Charge Sensitive Preamplifier (CSP) which has an input capacitance $C_i = (A_0{+}1)C_F$, where A_0 is the OPAMP open-loop gain and C_F is the CSP feedback capacitance. The value of A_0 for the GEMINI CSP is set to 65 dB in DC with a band integrated input noise of 50 μV_{RMS}. The role of CSP is to increase the amplitude of the current pulse signal coming from the pad and extend its time width. The signal is compared with a threshold level and a 2 GHz internal clock begins to count when the pulse signal is over threshold and stops when it returns under. This is the so-called Time-over-Threshold (ToT) mode, a widely used technique which allows a digitized charge measurement. Once a threshold level V_{THR} and a time constant τ_F are fixed, ToT counts increase with the injected charge Q_{in}.

Time is measured when the signal passes the threshold with a time resolution until to 0.5 ns. A time stamp is registered for each hit. This provides the Time of Arrival (ToA) acquisition mode. For GEMINI chips both threshold and feedback capacity can be properly tuned. Charge calibration of this new detector has been performed in collaboration with the CNR-ISTP and Milano Bicocca group. We used the X-ray fluorescence coming from a Titanium target irradiated by an X-ray tube working at a high voltage of 10 kV. In this way, charge released by X-rays is due to the Ti kα line (4.5 keV) while the scan in charge has been performed changing the voltage applied on the GEM foils and then the detector gain. Results are shown in fig. 3a.



(a) (b)

Figure 3: *a) Charge calibration curves obtained with Ti fluorescence and scan in gain; b) charge distribution for fluorescence lines coming from different material targets: Ti, Fe, Au and Mo.*

After obtaining the calibration curves, it is possible to make a measure of the X-rays spectra. Fig. 3b shows the spectra obtained from some characteristic fluorescence lines of some materials with the GEM detector at a fixed gain.

3 The new side-on GEM detector

The idea to realize a new GEM detector in side-on configuration arises from the need to make charge measurements on the X emission from laser plasma. Typically X-ray emission from these sources lasts for few tens on ps and X-ray photons cannot be measured separately. Since the new electronics is able to perform charge measurements, this new detector has been conceived to estimate the X-ray spectrum from charge measurements. The next paragraph will the results obtained on a laser facility. The GEM detector is based on standard 10×10 cm^2 GEM foils with the usual gaps of 1, 2 and 1 mm gaps. The region between the cathode and the first GEM foil is 12 mm thick and has an entrance and exit window of 6×80 mm^2.

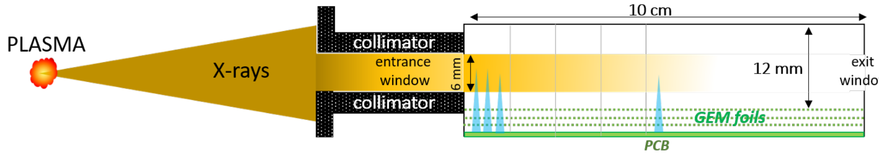
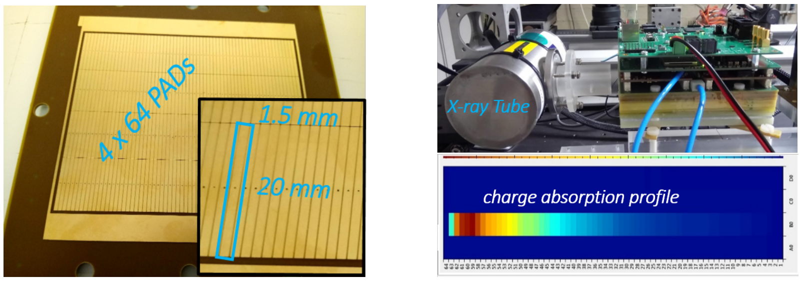


Figure 4: *Layout schema of the side-on triple-GEM detector with 12 mm of active gas layer and area of* $10 \times 10\ cm^2$*.*

The PCB anode is divided in four lines of 64 pads, each one having an area of 1.5×20 mm^2 (fig. 6a) Then all the gas in 96 mm deep can be exploited to measure the absorption profiles (fig. 6b). The charge collected from a single pad is due to the piled-up charge released by bursts of photons that interact in the overlying gas layer. This GEM detector in side-on configuration exploits a principle similar to Bremsstrahlung cannon [3; 4; 5] but is limited to X-rays spectra until 30-40 keV. This configuration can be useful also for measurements on hard-X ray photons because the gas layer now extends on 10 cm.

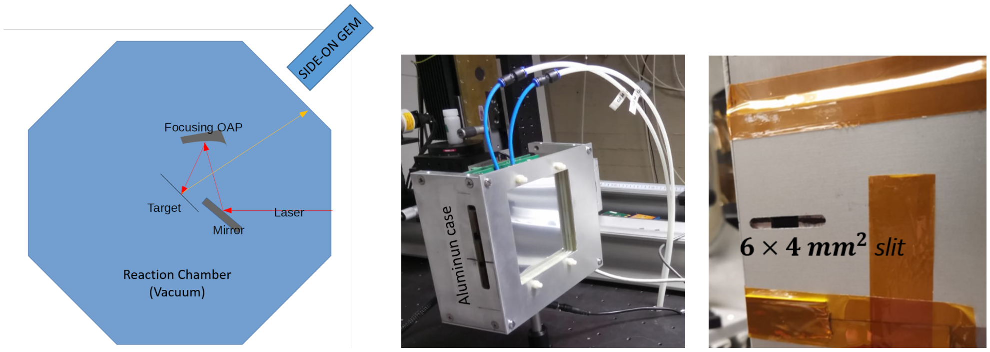


(a) (b)

Figure 5: *a) A photo of the pads pcb layout; b) A neasure of the absorption profile obtained in the NIXT lab with an X-ray tube.*

4 Profile measurements at the CNR-INO laser facility

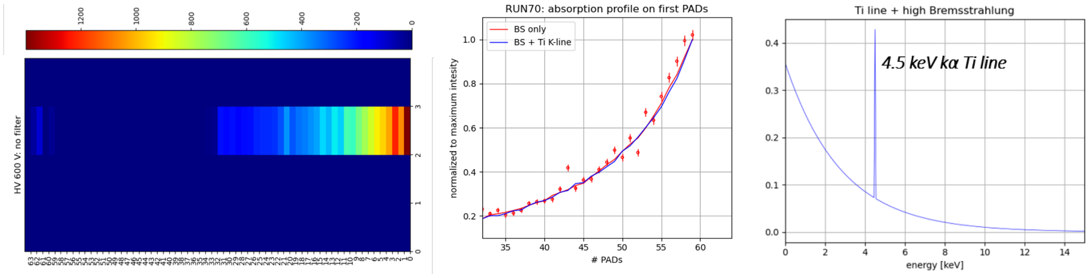
First measurements on the X-rays emission from a laser plasma have been performed on the laser facility at the CNR-INO research center. The used laser is a Ti:Sa CPA (Chirped Pulse Amplification) that can reach a power of 240 TW and a pulse duration of few tens of fs. We participated in an experiment designed to accelerate protons. The laser hit a Titanium plate and the protons were produced on the back side. The GEM detector was installed out in air in front of a port placed on the same side of the incident laser (fig. 7a). In this configuration, the detector will be able to observe the X-ray radiation passing through the port window, 1 cm in diameter an 50 μm in thickness. In order to screen the detector electronics from the electromagnetic pulse (EMP) disturbance, it was covered with an Aluminum case with only two openings at the detector windows (fig. 6b).



(a) (b) (c)

Figure 6: *a) Scheme of the experimental set-up: the GEM detector is placed out in air at a distance of about 60 cm; b) the GEM detector while mounting the Aluminum protective case with the side window; c) the* 4times6 mm^2 *slit on the Aluminum case*

For the measurements of the absorption profiles only one row of pads was used reducing the entrance window on the Aluminum box (fig. 6c). Each pad provides a measure of the charge released by a multi-photon interaction at a given depth in the gas. Fig. 7a shows a measured absorption profile for one laser shot on a thin Titanium target.



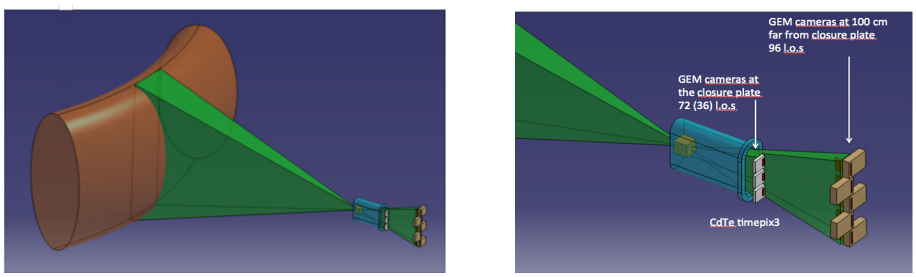
(a) (b) (c)

Figure 7: *a) a 2D image of the absorption profile as measured with the side-on GEM detector; b) the corresponding 1D absorption profile compared to the simulated profiles; c) expected spectrum according to the measured absorption profile.*

According to the physics of the laser-target interaction, the X-ray emission comes from two contributions: the Ti kα line due to ionization of Ti atoms and the Bremsstrahlung of the electrons accelerated by the potential difference inside plasma and that reach the solid target. The spectrum has been appropriately modeled and the absorption profile has been simulated through the FLUKA MC code. Simulation takes into account also that detector work in air and then the original spectrum is attenuated by the kapton window of the vacuum interaction chamber, the air gap and the 15 μm thick kapton window of the detector itself. The Simulated profile has been compared to the measured one in order to validate the model used for the X-ray emission. Fig. 8c shows the best-fit model used for measured profile. In fig. 8b, there is also a fit coming from the Bremsstrahlung continuum. As can be observed, the fits are almost overlapping and, as expected, this outlines that the main contribution comes from Bremsstrahlung. This represents an indirect way to obtain and study the X-ray spectrum emitted by laser produced plasmas and allows to validate theoretical models that describe the fundamental processes occurring in this type of plasmas.

5 Proposal of a GEM-based tomography system for the ITER project

In the last year, an agreement with the ITER project has been reached. The proposal provides the installation of 6 GEM cameras in side-on configuration with 6 lines of sight with a set of Timepix detectors to provides further details on the areas not covered by GEM detectors. Each GEM camera will have 16 rows with 32 pads (fig. 10).



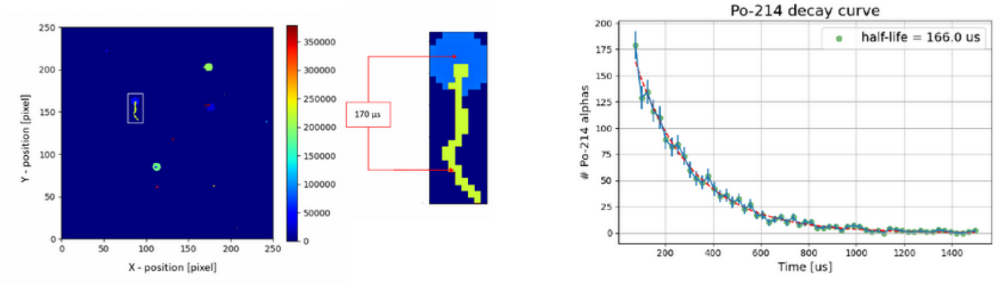
(a) (b)

Figure 8: *a) scheme of the GEM and Timepix diagnostic system proposed for the ITER tokamak b) a detailed view of the system that highlights the 6 GEM cameras.*

In order to validate the GEM installation on a ITER port, the agreement provides a first study to test the remotization of read-out electronics. The reason for this requirement is especially the expected very high neutron flux of about 10^8 n/scm^2 that can severely damage the front-end electronics. The main steps as stipulated in the contract are the neutron irradiation testing of the GEMINI chips to tests their radiation hardness, upgrade of the GEM prototype with long cables to remotely the all the front-end electronics (GEMINI chips and FPGA boards), test in laboratory of the maximum distance that can be reached with cables and project of a neutron screen to reduce the dose on remotized electronics. Preliminary test on neutron irradiation have been performed in September 2022 on the FNG (Frascati Neutron Generator) facility and will continue in 2023.

6 Radon measurements with a CdTe Timepix3

In this last year, a work on the measure of decay products from Radon has been completed. The aim of these measures was the characterization of the morphological track analysis of a Timepix3 detector. In this case a CdTe Timepix3 with negative polarization has been used. Obtained results demonstrated an optimal potential of Timepix3 detectors for particle discrimination, particularly for the analysis of decay products from Radon. The negative polarization of this detector produces a negative electric field that efficiently collects the Radon products that are positive charged. In this case, in addition to the morphological and spectroscopic analysis of the reaction product particles from Radon, it was also possible to identify the fast α decay of ^{214}Po after the β of ^{214}Bi (fig. 9a and 9b)



(a) (b)

Figure 9: *a) a 2D image of the tracks observed after alphas and beta decay of Radon decay chain; two superimposed tracks but separated in time have been highlighted b) the reconstructed exponential time decay observed for close tracks with an estimated half-life of 166 μs as expected for α decay of* ^{214}Po.

The present work highlights the potentiality of Timepix3 in field of radio-protection and represents a possible improvement based on Timepix technology [6] respect to the traditional Radon monitor techniques. Further details can be found in the related publication (A. Tamburrino et al.) that was also awarded at the AIRP congress for the category of young researchers.

7 List of Conference Talks by LNF Authors in Year 2022

1. A. Tamburrino, Rivelatore Timepix3 per la misura dei prodotti di decadimento del radon, XXXVIII Congresso Nazionale Airp, Milano, 28–30 settembre 2022
2. L.Foggetta, The use of Timepix silicon detectors for detecting beam characteristics in different particle beam types and their daily use, 6th International Conference Frontiers in Diagnostic, Technologies, 19-21 October 2022
3. D. Pacella, Feasibility study for out-vessel GEM gas detectors for 1-D energy resolved X-ray imaging at ITER, 6th International Conference Frontiers in Diagnostic Technologies, 19-21 October 2022

8 Publications

List of papers published by Frascati INFN_E members in 2022:

1. A. Tamburrino, G. Claps, F. Cordella, F. Murtas, D. Pacella, Timepix3 detector for measuring radon decay products, Journal of Instrumentation, 2022, 17(6), P06009
2. G. Pucella et al., Overview of the FTU results, Nuclear Fusion, 2022, 62(4), 042004

References

1 . A. Pezzotta, G. Corradi, G. Croci, M. De Matteis, F. Murtas, G. Gorini, A. Baschirotto, GEMINI: A triple-GEM detector read-out mixed-signal ASIC in 180nm CMOS, in 2015 IEEE International Symposium on Circuits and Systems (ISCAS) (2015), pp. 1718–1721

2 . A. Muraro et al., Development and characterization of a new soft x-ray diagnostic concept for tokamaks, Journal of Instrumentation, Volume 14, Article number C08012 (2019)

3 . C. D. Chen, J. A. King, M. H. Key, et al., A Bremsstrahlung spectrometer using k-edge and differential filters with image plate dosimeters, Rev. Sci. Instrum. 79, 10E305 (2008)

4 . A. Hannasch et al., Compact spectroscopy of keV to MeV X-rays from a laser wakefield accelerator, Sci Rep 11, 14368 (2021)

5 . P. Koester, F. Baffigi, G. Cristoforetti, et al., Bremsstrahlung cannon design for shock ignition relevant regime, Rev. Sci. Instrum. 92, 013501 (2021)

6 . M. Caresana, L. Garlati, F. Murtas, S. Romano, C. T. Severino and M. Silari, 2014 Real-time measurements of radon activity with the Timepix-based RADONLITE and RADONPIX detectors, JINST 9 P11023