Development of the DT_GEM: a gas electron multiplier detector for neutron diagnostics in controlled thermonuclear fusion.

triton burn-up.

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Abstract—

A new neutron flux monitor for fusion applications (DT_GEM) has been developed by means of a triple-GEM (Gas Electron Multiplier), a proton recoil converter and a low energy proton adsorber. The design and the optimization for the detection of 14 MeV neutrons have been performed using MCNPX and FLUKA Monte Carlo Codes and the detector has been tested under 14 MeV neutron irradiation at the Frascati Neutron Generator (FNG). Polyethylene is used as converter and an aluminum absorber sheet covers a triple 10x10 cm^2 GEM filled with an Ar/CO_2/CF_4 gas mixture. The detector is readout with 64 pads (10x6 mm^2) in a 4x16 matrix.

The DT_GEM design and the results of the first tests performed at FNG are presented and discussed in this paper. Excellent performances at high count rates in transient neutron flux, good efficiency, low sensitivity to gamma radiation and electronics stability under irradiation make the DT_GEM a promising detector for neutron diagnostics in fusion.

Index Terms—GEM, fusion diagnostics, neutron detector

I. Introduction

In controlled thermonuclear fusion devices the fusion power is assessed through the measurement of neutrons emitted from the plasma. The two reactions employed in fusion experiments (DD and DT) yield respectively 2.5 MeV and 14 MeV neutrons. These two neutron components must be measured separately in future fusion reactors such as ITER [1]. 14 MeV neutrons are generated not only during DT discharges but also in pure DD plasma where few % of the total neutron yield is due to 14 MeV neutrons produced by

The development of new detection systems for 14 MeV neutrons suitable to fusion reactors is still an open challenge, although liquid scintillators and diamond detectors already represent a viable chance [2]. Compact dimensions, high counting rate capability, good detection efficiency, stability under electromagnetic fields, radiation resistance, and insensitivity to γ-rays are key requirements. Possible good candidates for fast neutron detection in fusion devices are gas detectors based on the GEM (Gas Electron Multiplier) concept.

A GEM is a composite grid consisting of two metal layers separated by a thin insulator etched with a regular matrix of open channels [3]. By applying a potential difference between two electrodes (metal layers), a strong electric field is produced in the holes acting as multiplication channels.

Multiple GEM structures allow to reach high gain and several triple-GEM detector prototypes have been built and tested in the last years at LNF-INFN [4,5]. GEM-based detectors have been successfully used for neutron detection [6]; due to their high counting rate capability, they can play an important role also for neutron diagnostics in fusion devices.

This paper describes the design of a 14 MeV neutron detector based on a triple-GEM detector and its first experimental tests at the Frascati Neutron Generator (FNG) [7]. FNG, designed and built at ENEA Frascati, is a 14 MeV neutron generator based on the T(d,n)α fusion reaction and produces up to 10^{11}n/s in steady state or pulse mode. FNG can also produce 2.5 MeV neutrons via the D(d,n)^{3}He fusion reaction.

II. GEM AS A 14 MEV NEUTRON DETECTOR (DT_GEM)

In order to obtain a fast neutron detector sensitive to 14 MeV neutrons only, a triple–GEM has been coupled to a proton-recoil converter (polyethylene) and to an absorber (aluminum). The aluminum foil has the proper thickness to set an energy threshold for the protons produced by low energy neutrons (DD contribution). The recoil protons, generated by n,p reactions in polyethylene and having enough energy to cross the aluminum foil, lose their energy by ionization of the gas atoms. The generated electrons are amplified in the GEM layer structure giving a detectable signal.

A. Monte Carlo Calculations

The design and the optimization of the DT-GEM have been performed using the MCNPX [8] and FLUKA [9] Monte Carlo codes. In order to optimize the thickness of the proton-recoil converter, absorber and gas, several simulations with monoenergetic neutrons beams have been performed (Figure 1).

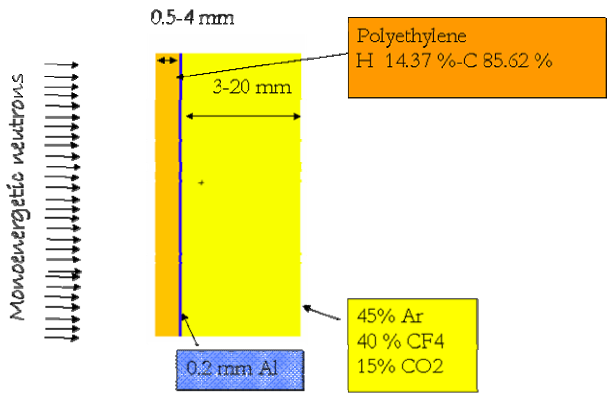

Figure 1 Monte Carlo simulations layout.

Figure 2 shows the conversion efficiency expressed in terms of numbers of protons exiting from the polyethylene converter (and releasing energy in the gas) versus neutron energy for different converter thickness. By increasing the polyethylene thickness, the efficiency to 14 MeV neutrons increases (more than a factor 2 from 0.5 to 2 mm), while the efficiency to 2.5 MeV neutrons slightly decreases. A further thickness increase is useless because the efficiency tends to saturate since the thickness approaches the proton range in the material. Therefore, a 2 mm thick converter has been selected providing a conversion efficiency of 3.7×10^{-3} p/n for 14 MeV neutrons and 6.2×10^{-4} p/n for 2.5 MeV neutrons.

Since the proton-recoil converter is not energy-selective, a thin aluminum absorber is inserted in order to set a threshold at low neutron energy (~6 MeV). A thickness of 0.2 mm of aluminum has been selected in order to suppress the signal due to protons generated by DD neutrons in fusion reactor applications.

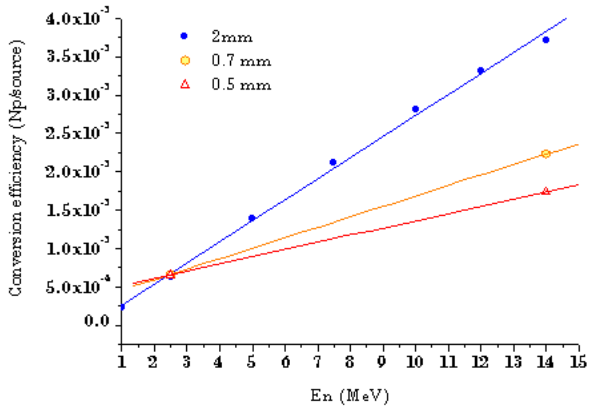

Figure 2 Conversion efficiency expressed in terms of numbers of protons exiting from a polyethylene converter versus neutron energy. Data refer to 0.5 mm, 0.7 mm and 2 mm of converter thickness.

Figure 3 shows the proton spectra generated by 14 MeV and 2.5 MeV neutrons entering the gas with and without 0.2 mm aluminium absorber.

With 0.2 mm of aluminum the p/n ratio for 14 MeV neutrons decreases of ~35% with respect to the configuration with polyethylene only, but the protons generated by DD neutrons are absorbed before reaching the gas drift gap and therefore they are not detected.

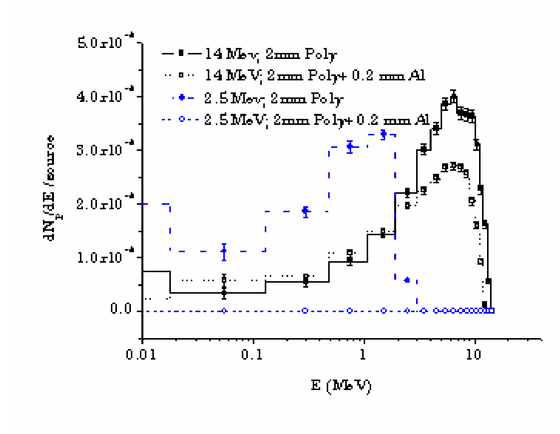

Figure 3 Spectra of the protons generated by 14 and 2.5 MeV neutrons entering the gas drift gap with and without 0.2 mm of aluminum sheet.

At least 30 cm of gas thickness at 1 Atm would be required to stop completely the protons generated by 14 MeV neutrons, hence, for viable dimensions, the protons will lose only a fraction of their primary energy.

Figure 4 shows the energy deposited in the gas by the protons generated by 14 MeV neutrons versus the gas thickness.

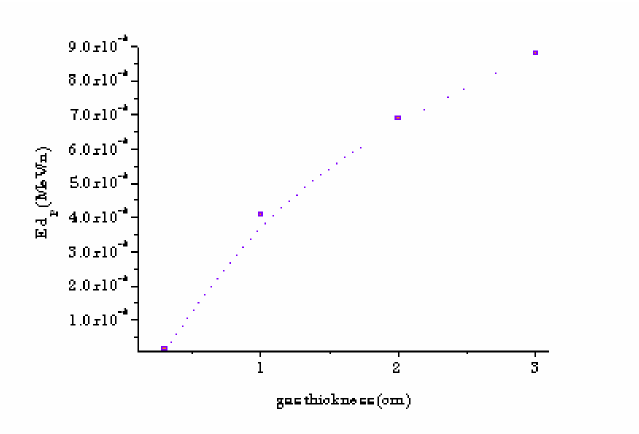

Figure 4 Energy deposited in the gas by protons generated by 14 MeV neutrons.

Choosing 10 mm of gas the protons lose 4.1x10^{-4} MeV/n by collisions with the gas atoms, and this energy is converted in detectable signal.

Once defined the chamber parameters, MCNPX simulations of the irradiation tests performed at FNG have been performed in order to calculate the neutron fluence on the DT_GEM and to evaluate the expected efficiency and response of the detector.

The detector has been located at 14.5 cm from the FNG target emitting neutrons almost isotropically.

Figure 5 shows the neutron fluence spectrum incident on the detector. The low-energy neutrons (those below the 14 MeV D-T neutron peak) are produced by the interaction of primary neutrons with the target materials.

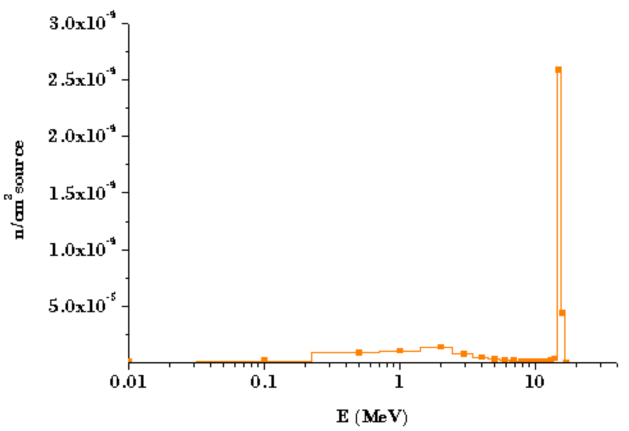

Figure 5 Neutron fluence spectrum on the GEM during FNG irradiation.

During the experiment, described in the next section, the calculated neutron fluence at the detector position is in the range: 7.4x10^{5} n/cm^2s - 1.1 x10^{7} n/cm^2 s.

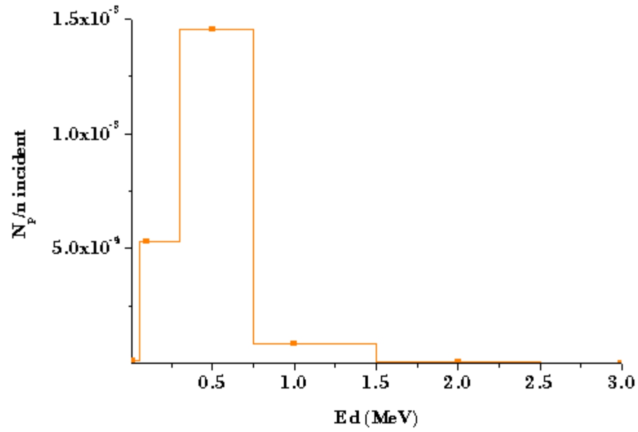

Figure 6 Number of protons (Np) versus energy deposited (Ed) in the first GEM.

Figure 6 shows the number of protons versus the energy they deposit in the first GEM. The expected signal is mainly due to proton energy deposition events correspondent to some hundred of KeV. The integral of the curve provides a conversion efficiency of ~2.03x10^{-3} n/p. The calculated proton fluence in the GEM during irradiation is in the range 1.6x10^{3} p/cm^2s-2.46x10^{4} p/cm^2s and the corresponding energy deposited is between 2.7x10^{2} MeV/cm^2s and 4.1x10^{3} MeV/cm^2s.

B. Detector assembly

The GEM foil is made by a 50 μm thick kapton foil, copper clad on each side and perforated by a high surface-density of bi-conical channels. Typical voltage differences of 300 to 500 V are applied between the two copper sides, giving fields as high as 100 kV/cm into the holes, resulting in an electron multiplication up to a few thousands. Three GEM foils are sandwiched between two conductive planes, one of which, the anode, is segmented in pads and connected to the readout electronics. The GEM foils define in this way three gaps: the drift, two transfer and one induction gap.

The DT-GEM assembled for this test experiment is a triple 10x10 cm^2 GEM filled with Ar/CO_2/CF_4 gas mixture, the neutron converter is made with 2 mm of polyethylene and the cathode with 0.2 mm of aluminum. The drift gap has been set to 10 mm. Inside this gap the proton ionizes the gas producing primary electrons as a function of his momentum. Figure 7 shows a front view of the DT-GEM.

The detector read-out system consists of 64 pads 10x6 mm^2 in a 4x16 matrix (Figure 8). The Front-End Electronics (FEE) contain 64 preamplifiers and discriminators inside four ASDQ chips. The analog signals are discriminated through a variable threshold producing LVDS signal and are sent to a VME data acquisition system for rate measurements.

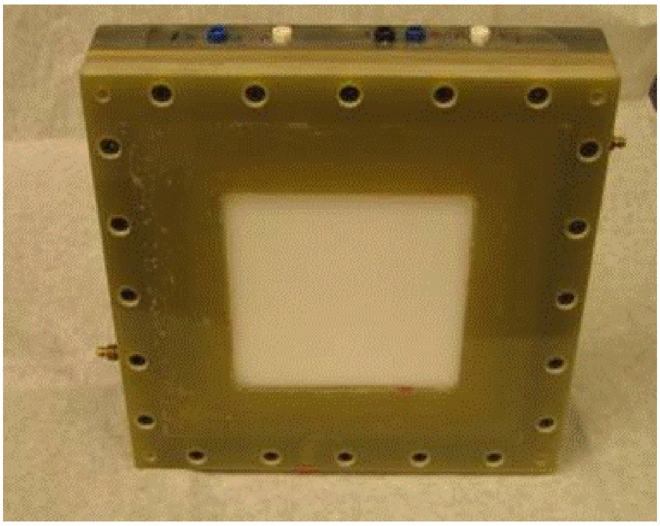

Figure 7 DT_GEM front view.

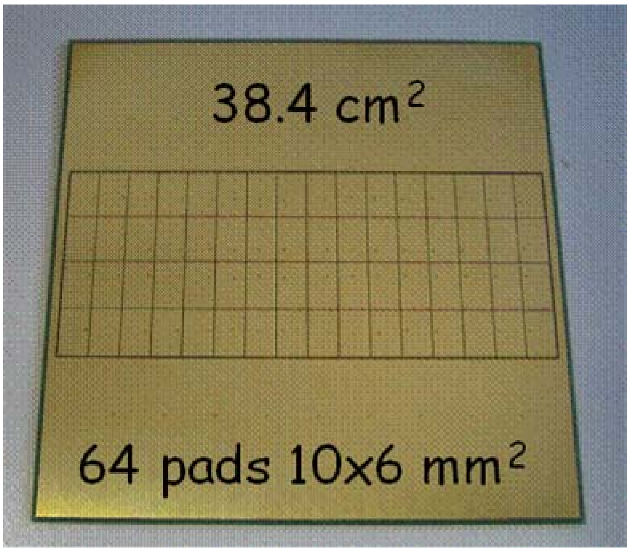

Figure 8 DT_GEM readout system.

Figure 9 DT_GEM localized in front of the DT-neutron source at FNG (14.5 cm from the target).

Setting the HV to 1110 V the signal due to photons is negligible, and similar count rates are obtained also at the end of the irradiation test when the background photon field is higher. With the current parameters the detector is insensitive to γ-rays.

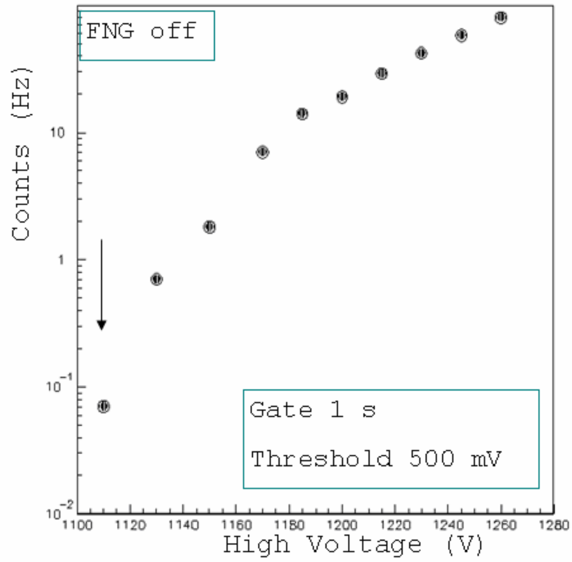

Figure 10 DT-GEM Count vs. HV at 500 mV threshold.

The neutron irradiation has been carried out for several hours at increasing neutron intensity values. The neutron flux incident on the detector was in the range $7.4x10^5$-$1.1x10^7$ n/cm^{2}s, as calculated by MCNPX.

III. IRRADIATION TESTS AT FNG

The DT_GEM has been mounted at a distance of 14.5 cm in front of FNG target (Figure 9). During the tests the 14 MeV total emission has been varied in the range $2x10^9$ n/s - $3x10^{10}$ n/s.

Before neutron irradiation, once defined the threshold to eliminate the electronic noise (500 mV), the chamber gain (high voltage, HV set) has been varied in order to minimize the sensitivity to γ-rays: the residual photon emission from the target due to previous n-irradiations (typical γ-ray energy ~1 MeV). Figure 10 shows the DT_GEM counts versus HV (threshold 500 mV).

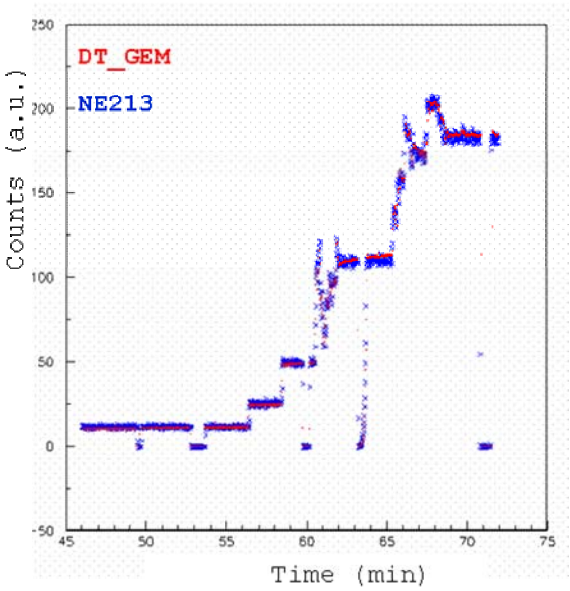

Figure 11 Neutron flux measurements vs. time.

The DT_GEM shows high performances in transient regimes. The temporal behavior of the GEM signal was in optimal agreement with the counts of the reference monitor (a NE213 scintillator placed few meters from the source) during step variations of the neutron generator intensity (Figure 11).

The number of hits measured by the GEM chamber exactly follows the neutron yield measured by the NE213 even during beam stops as shown in Figure 12.

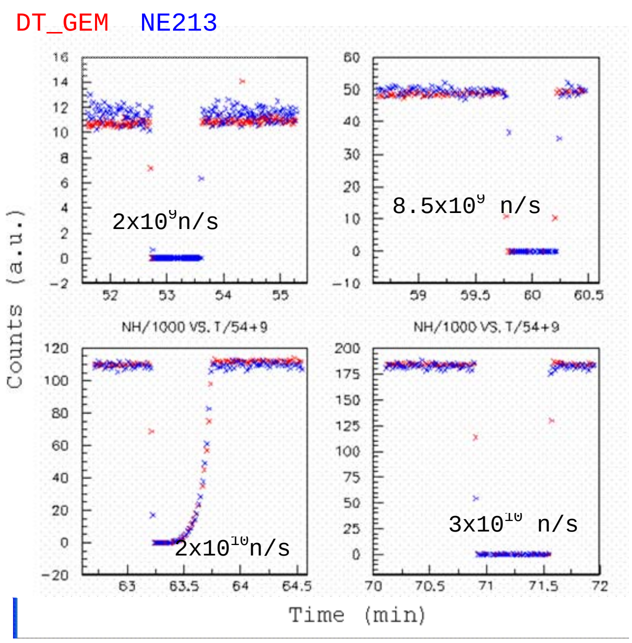

Figure 12 Detail of the signal behavior during beam stops at different neutron yield levels.

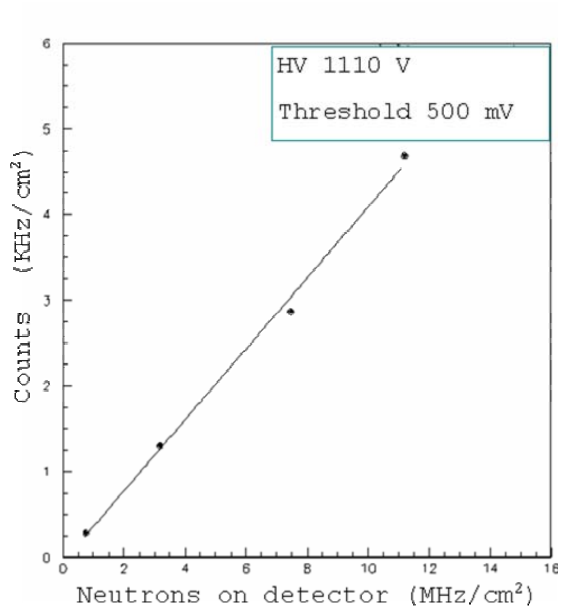

Figure 13 DT_GEM neutron efficiency.

Figure 13 shows the count rate of the DT_GEM versus the neutron fluence rate incident on the detector. The signal shows excellent linearity and a 14 MeV neutron detection efficiency of $4.1x10^{-4}$ counts/neutrons has been obtained at high count rates. The experimental efficiency is 20% of the calculated value: the difference can be attributed to the choice of the chamber parameters (HV and threshold) that have been set in order to minimize the electronic noise and the sensitivity to γ-rays. At higher chamber gains the neutron efficiency increases as well as the sensitivity to γ-rays.

In order to evaluate the stability of the detector system in the high radiation field, the chamber HV has been switched-off to measure the noise due to the neutron flux on FEE (Figure 14).

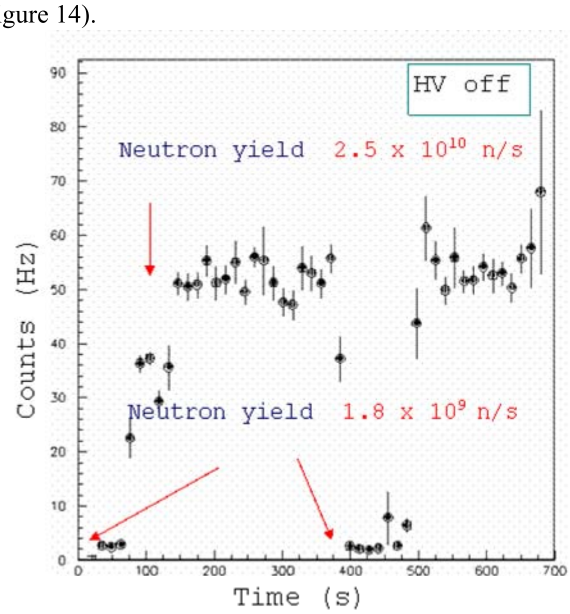

Figure 14 Effect of neutron irradiation on the detector electronics with HV switched-off.

Switching off the HV the residual counts in the readout systems are few Hz, indicating that at these irradiation levels the neutron effects on the electronics are negligible. Anyway, longer irradiations are required to verify the electronics stability.

IV. Conclusions

A new neutron flux monitor based on the GEM concept (DT_GEM) has been developed for fusion applications. Polyethylene is used as converter and a thin aluminum sheet covers a triple 10x10 cm^2 GEM filled with an $Ar/CO_2/CF_4$ gas mixture. The detector is readout with 64 pads, 10x6 mm^2 in a 4x16 matrix. The DT_GEM seems very promising for neutron diagnostics in fusion.

Irradiation tests with 14 MeV neutrons performed at FNG (range 7.4×10^5 MHz/cm^2 to 1.1×10^7 MHz/cm^2) have shown that the DT_GEM is characterized by: excellent performances at high count rates in transient neutron flux, good efficiency (4.1×10^{-4}), low sensitivity to gamma radiation, electronic stability under irradiation.

The results of the first test are satisfactory but further experiments are in progress in order to verify the insensitivity to DD neutrons and γ-rays and to optimize the detector's layout and the electronics. The design of a GEM-based detector suitable for DD neutrons is also under development.

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