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On the design aspects affecting performance of GEM based detector development for plasma diagnostics

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Abstract

The proposed work refers to the development of gaseous detectors for application at tokamak plasma radiation monitoring. The work highlights the most important part of the latest conceptual design of Gas Electron Multiplier (GEM) based soft X-ray radiation detecting system which is under development by our group, namely, photon detecting chamber. It is devoted to study X-ray emission of plasma radiation with focusing on tungsten emission lines energy region. This information is especially crucial for future ITER-like machines – e.g. WEST project. To develop the photon conversion and signal processing part of the proposed monitoring system many physical, technical and technological aspects are needed to be taken into consideration in the design and manufacture. The work presents main elaborations of research and development phase of the detector internal chamber design together with the results of preliminary tests and simulations.

KEYWORDS: Nuclear instruments and methods for hot plasma diagnostics; X-ray detectors; Electron multipliers (gas); Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Detector modelling and simulations.

1. Introduction

Tungsten, being a main candidate for the plasma facing material in ITER and future fusion reactor for some time [1], has recently started to be used as such on many machines, including on the WEST project, where an actively cooled tungsten divertor is being implemented. Inevitably, this forced a creation of the ITER-oriented research programs aiming to effectively monitor the impurity level of tungsten in plasma. The situation complicates further as, due to interaction between particle transport and MHD activity, such impurities might accumulate which could lead to disruption, especially, in case of long pulse tokamaks. Therefore, an appropriate diagnostic tool has to be developed which will not just monitor the level of impurity but will also reconstruct its distribution. From the very beginning of magnetic fusion plasma experiments soft X-ray (SXR) radiation measurement has become a regular way of accessing valuable information on particle transport and MagnetoHydroDynamic (MHD) phenomena, like sawteeth, snakes, magnetic islands, etc., leading to effective monitoring of the tokamak plasma properties. Combining the spectral information on plasma radiation with good spatial resolution of its detection should allow recovering fundamental information in order to estimate the level of the plasma contamination and consider its effects on plasma scenarios. For this purpose, an SXR
tomographic diagnostics with energy discrimination has been extensively considered for a while [2]. Detection system based on Gas Electron Multiplier (GEM) technology [3] has been recently proposed to be used as SXR tomographic system for ITER-oriented tokamaks and is under development by our group [4, 5, 6, 7], [8], [9], [10]. Detectors built on this technology are expected to satisfy the main constraints on dimension, spatial position and required energy sensitiveness imposed on any X-ray detector for tokamak plasma in ITER and/or DEMO. A detecting system, based on GEM technology detectors arranged to perform poloidal tomography, is an ultimate goal to be implemented for plasma impurities transport studies. When implemented, the detecting system should add to the safe operation of tokamak bringing creation of sustainable nuclear fusion reactors a step closer.

To develop the photon conversion and signal processing part of the proposed monitoring system many physical, technical and technological aspects are needed to be taken into consideration in the design and manufacture. Our research is devoted to design a new diagnostics for poloidal tomography focused on the metal impurities radiation monitoring, especially tungsten emission. This work reports on some aspects of the current status of the design of such detecting system to be installed for tests at WEST project tokamak. Two GEM based detectors of planar and cylindrical geometry, constituting this system, are to be installed in a poloidal section of WEST project tokamak and are going to be put inside of the vertical and outside of the horizontal ports, respectively [7], [8], [10]. There were presented main details of the overall design, concerning simulations selecting the optimal gas mixtures and window material, geometry of the detector chamber and magnetic field influence [10], preliminary neutron tests [11] as well as first concept of the detection module acquisition and processing electronics [12], [13], [14], [15], [16] with the elaborated data acquisition method [17] allowing 1 ns of time resolution in online mode and up to 100 µs in offline mode for satisfactory data statistics. Within this work we will focus on the design of the internal structure of the detector, mainly on the choice of its most important component – GEM foil [18].

2. Photon sensitive detector chamber
2.a. Effect of configuration inside the detector chamber

The GEM detector [3], [19] is based on collection of electrons created by direct photoionization and amplified within the gas mixture under applied high electric field that initiates an electron avalanche (see Figure 1 illustrating triple GEM detector). The large electric field (up to 100 kV/cm) in small (50-70 µm diameter) holes of GEM foil (both sides coppered thin polymer film of 50 µm thickness) causes secondary ionization of electrons and creation of electron avalanche inside the holes. The avalanche goes consecutively through one GEM foil or a cascade of GEM foils experiencing further multiplication. At the proper conditions, three GEM foils powered by high voltage result in primary electrons multiplication of 10^1-10^5 times. This avalanche is injected into the final segment of the detector, called induction gap, and is collected on the patterned readout/anode plane. In this way induced anode current signals are detected by electronics. These current signals generated by the detector carry all information required for energy estimation and position reconstruction of absorbed photon. The essential metrology issue is then (i) to identify the created charge of electron cloud at the readout plane, called cluster, by its charge quantity (comparable to the photon energy in proportional mode of detector operation) and (ii) to estimate its position (corresponding to the projection of the primary photon absorption point on the readout plane considering that the diffusion is the only process changing the shape of the charge cloud during the drift (no strong distortion due to uniform electric field)). Energy distribution of cluster charge, reflects the energy spectrum of X-ray source and distribution of cluster charge position corresponds to the spatial shape of the incident radiation.

The detector geometry (Figure 1) should be carefully derived for each application of GEM detector. For example, length of the drift gap is often a compromise between minimal parallax effect of radiation detecting and good photon detection efficiency of the detector. The length of the drift gap has also impact on detector energy resolution: smaller drift would effect in better resolution. For the transfer gap to result in fast detector smaller lengths are preferable, but safety aspects, such as spontaneous discharges and GEM foils spacing, considering electrostatic force between foils to be compensated by the mechanical tension of the foils, have to be accounted at the same time. The last gap of the structure, the GEM-to-anode distance, is usually tended to be minimized to the smallest possible induction area to cope with fast readout schemes. On the other hand, good spatial resolution needs opposite requirements [20] of broad distribution of the induced electron cloud on the readout anode plane. Taking into account
all the mentioned above, 5:2:2:2 spacing (numbers represent distances in mm) in the GEM detector was proposed for the SXR measurements of plasma radiation. Photon detector efficiency for the chosen geometry is presented elsewhere [8] together with the gas mixture choice and appropriate window/chamber materials [10].

**Figure 1.** Schematic view of the detector photon sensitive volume. Three GEM foils are positioned in the 5:2:2:2 spacing.

It is worth noticing that to avoid non-uniform field through the detector by pressing and bending the GEM foils due to their impedance to the gas, it was decided to make holes around the active area of GEM foil to create a bypass for the gas around the active area of GEM foils.

### 2.b. GEM foil design effects
The most important part of the GEM detector, which defines capabilities and parameters of its operation, is GEM foil [18]. Within this work we will focus on application of two eventual GEM foils with different types of holes: double conical (**Figure 2**, left part) and cylindrical (**Figure 2**, right part) ones. Their shape is responsible for amplification of electron charge inside the hole, ion feedback, charging up effects etc., it is also revealed in the rate capability of the detector. To estimate the influence of the hole shape on the created electric field and amplification factor of GEM foil calculations using Garfield++ were performed for single GEM detector of 5:2 spacing. In **Figure 2** there are shown two models used for simulations.
**Figure 2.** GEM detector cell created in the Gmsh software. In Garfield++ the cell is multiplied periodically forming a structure of the GEM foil. Left column presents cross section of double conical hole, right column presents cylindrical one, in ($x, y$) and ($z, y$) planes.

The calculated electric fields corresponding to cylindrical and double conical holes are shown in Figures 3-4. As it could be seen electric field in the hole centre for the cylindrical configuration is higher than for double conical one. It is worth noticing that results of simulation were obtained for “clean” detector (no charge prehistory).
Figure 3. The calculated electric field in the GEM foil hole. Top figure is for the cylindrical hole, bottom figure - for the double conical hole.
The results of preliminary simulations with the low statistics (see Figure 5), illustrating amplification factor of the two holes configurations, demonstrate that for the unperturbed detector number of produced electrons is bigger for cylindrical piercing of GEM foils. This effect relates to the hole shape dependence of the charging up effect, which becomes apparent in a small change of the detector gain under rate dependent irradiation due to charge accumulation on the Kapton surface distorting the electric filed inside the amplification area. This result is consistent with the experimental data for the starting point of uncharged detector irradiation [21], [22]. Experimental results demonstrate that cylindrical holes are characterized by more stable detector gain due to the fact that cylindrical shape best minimizes charging up effect of the insulator, which would point out that size and shape of the hole has an important role in determining the level of charge up effect in certain foils. In fact, to encompass the picture of the gain calculations fuller charging up effect should be taken into account. This effect is then relates to the pre-history of detector state which is considered as accumulated charges on the insulator surface. Such very time-consuming simulations in fact show the superiority of the well
balanced cylindrical hole: charging up and charge neutralizing effects are well compensated [23]. Our preliminary calculations pointed also that time dependencies for these two types of holes do not influence on the time duration of the current signal (electron avalanche discharging on the readout plane). On the other hand, calculations show better electron transmission for the foil with conical holes.

2.c. High rate effects on GEM foil performance
The design of the position and energy sensitive X-ray detector for tokamak plasma, should be driven by many requirements, such as large detection area matching the aperture of the single window of the spectrometer, good spatial resolution, high charge gain capability, detection stability for a wide range of photon rates, acceptable energy resolution capability and so on. As plasma radiation is of high intensity radiation source, whose activity could reach extreme values of photon fluxes. As it was estimated for Tore Supra different scenarios depending on the heating power, on the impurities present in the plasma etc., SXR radiation flux could come to $10^3$-$10^9$ photon s$^{-1}$cm$^{-2}$ [24]. Therefore, in order to develop a suitable detector for plasma radiation monitoring, good rate capabilities should be provided. These capabilities are dependent on the GEM foil structure used for photon detecting, namely size, shape and pitch of the holes. The GEM structure allows one to construct a gas detector of relatively high gain and operating at radiation flux up to $10^5$ mm$^{-2}$s$^{-1}$. Taking into account energy discrimination requirement, detector should operate in the proportional mode with stable relatively low gas gain ($\sim 10^3$) with high dynamic range to prevent discharges and space-charge saturation. In order to fulfil these constraints it is necessary to examine the GEM foil and apply its adequate configuration. To check the detector rate capability for standard double conical GEM hole high rate tests were performed using X-ray tube of 8 keV emitted photons. The results for small surface (about 1 mm$^2$) irradiation with the intensity of up to 2 MHz are presented in Figure 6 for two gas flow rates. Effective gain was derived from the anode current which was measured after some time needed for stabilization of charging up. Considerable variations of the effective gain are observed starting at about 0.1 MHz photon intensity due to significant space charge accumulation at the particular rate. Different gas flows result in higher gain for larger flows due to gas purity impact on the creation of electron-ion pairs under irradiation. This result is crucial for

![Figure 6](image-url)  
Figure 6. Dependence of triple-GEM detector gain on the high rate of 8 keV photons for double conical shape of the GEM foil holes.
the development of GEM based detector for plasma radiation monitoring on account of its high brightness. The same experiment is necessary to be conducted for GEM foil with cylindrical holes. These data would allow defining the GEM hole type applicable for plasma radiation monitoring diagnostics.

3. Summary
This work presents some issues of the conceptual design of the detecting unit for poloidal tomography to be installed for the first tests at the WEST project tokamak. It concerns the detectors internal structure geometry and choice of particular GEM foils. Preliminary simulations were performed on this purpose for two GEM hole shapes: double conical and cylindrical ones, resulting in higher electric field and effective gain for uncharged detector for cylindrical holes. As it was shown by experimental results, some variations of the effective gain were observed for the double conical holes vs high photon flux. Conduction of the similar tests for another GEM holes shape is needed. More stable dependence of the effective gain is expected for the cylindrical amplification volume due to well-balanced charging up effect, what could be more suitable for plasma diagnostics application.

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