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Hydrodynamic simulation studies on avalanche and streamer formation in GEM detector

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Abstract. The dynamics of electrons and ions in gaseous ionization detectors have been studied reasonably well with particle simulation models developed using the Garfield++ numerical simulation framework. This is an important area of study since it allows prediction of the detector response in a given experimental situation. In this work, a fluid simulation model has been developed in the COMSOL Multiphysics simulation framework to simulate the avalanche and streamer formation in GEM-based detectors. Possible detector geometries in 2D, 2D axisymmetric and 3D coordinate systems have been explored to find the optimum numerical configuration. Transport of charged fluids has been simulated in the optimized model for various operating voltage ranges suitable for single, double and triple GEM detectors using Ar-CO_2 (70-30) as the gas mixture. Simulated gain variations have been compared with experimental observations. Effect of space charge and its relation to streamer formation have been studied.

1. Introduction

Numerical simulations are intended to provide the optimal design parameters for the successful operation of the detector in a given experimental scenario. Several studies on charge dynamics of electron avalanches in Gaseous Electron Multiplier (GEM) [1] based detectors have been performed in particle simulation approach by Garfield++ framework [2]. Although the particle model offers the real picture of charge dynamics of avalanches, it continues to struggle, to address the complicated dynamics of discharge evolution due to space charges created in the detector volume. A hydrodynamic model has been developed, which addresses this issue by incorporating the space charge phenomena and is able to model avalanches and streamer in a reasonable time frame. The present work has made an attempt to model the charge transport in GEM-based detectors based on hydrodynamic approach and to extract the parameters of interest, such as effective gain and to see the influence of space charges to the streamer formation with fair amount of success.

2. Hydrodynamic simulation

The hydrodynamic simulation has been performed in the framework of a finite element package, COMSOL Multiphysics software [3]. It incorporates the gas transport properties from MAGBOLTZ [4] and the primary ionizations obtained by HEED [5]. The mathematical model governing the evolution of charge dynamics is considered to be mass transport in which the electrons and positive ions are treated as diluted chemical species in the background gas mixture. The hydrodynamic equations solved for the transportation of charged fluids are described in [6].

2.1. Optimization of model geometry

Three Dimensional (3D), 2D axisymmetric and 2D model geometries of GEM-based detectors as shown in figure 1 (a), (b) and (c) have been attempted to find an optimum model configuration. Standard biconical hole structure of GEM consisting of inner diameter 50 μm and outer diameter 70 μm [1] has been utilized in these models. The geometrical parameters of these detector configurations include drift gap (1 mm), transfer gap (1 mm), induction gap (1 mm), drift field (2 kV/cm), transfer and induction field of 3.5 kV/cm.

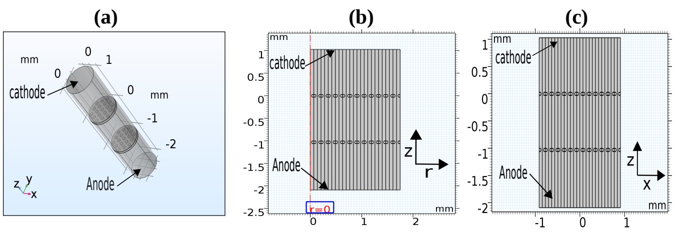

Figure 1. (a) 3D, (b) 2D axisymmetric and (c) 2D model of a double GEM structure.

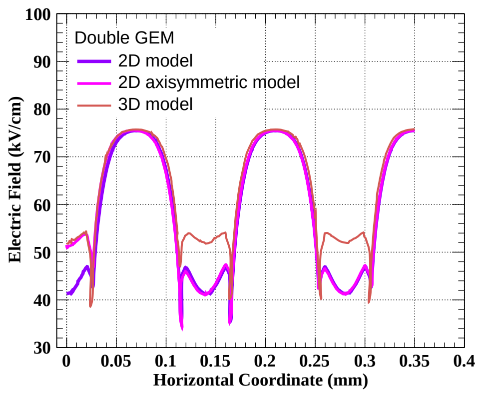

Figure 2. Electric field distribution at a voltage, $\Delta V_{\mathrm{GEM}} = 380V$ applied to the two GEM foils of a double GEM structure of 3D, 2D axisymmetric and 2D model.

The electric field configuration inside the GEM hole is taken as the optimization parameter as it affects the evolution of the charge dynamics significantly. Figure 2 shows the electric field distributions for different models. The 3D model provides correct field map in all the holes and is more accurate and realistic. However, it requires huge amount of computational time and resources to simulate the evolution of complex charge dynamics. The 2D axisymmetric model (r = 0, symmetric axis) gives correct field at the central hole and a field difference of $\sim$20% in the off-centre holes (circular channels) as compared to the 3D model. On the other hand, a 2D model of GEM was found to be inconsistent, because all are straight channels instead of holes and hence fails to provide a correct field map. Thus, 2D axisymmetric geometry has been considered to be the optimum model.

3. Results

The simulations have been perfromed in the optimized 2D axisymmetric model of single, double and triple GEM detectors with equal voltages applied to the GEM electrodes of mulit-GEM structures. In the model, the charge transport begins with the primary charged fluid constructed from the ^{55}Fe radiation source which emits photons of energy 5.9 keV into the gas volume of Ar-CO_2 (70-30).

3.1. Avalanche formation

The transport and amplification of primary electron and ionic fluid in the 2D axisymmetric gas volume under the action of electric field and diffusion is followed numerically. This provides the number of electrons and ions in the gas volume at each time step of the simulation. The effective gain has been estimated for single, double and triple GEM configurations and is shown in figures 3 (a) and (b) respectively. The simulation estimates of gain (Uncorrected) do not agree with the experimentally observed values [7] as the off-centre holes of the model contribute less because of the reduced field as discussed in section 2.1. To improve the simulated gain (Uncorrected), approximate correction factors have been derived by taking into account the contribution from the off-centre holes of the model, as described in detail in [6]. The gain estimates after correction (Corrected) matches fairly well with the measured values from the experiment [7].

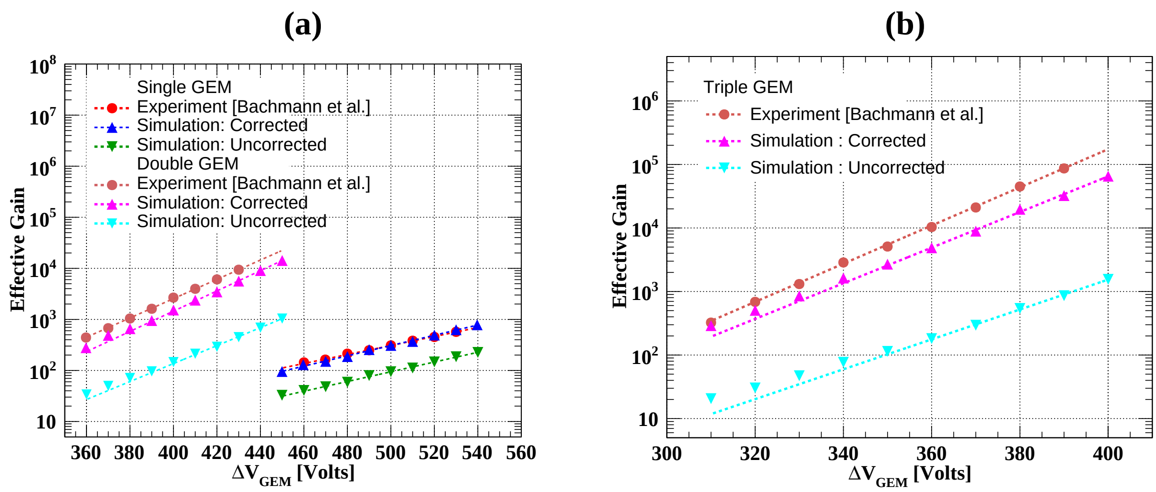

Figure 3. Numerical estimates of gain values in (a) single and double GEMs, (b) triple GEM with different voltages applied to the GEM electrodes and compared with the experimentally observed values reproduced frnom [7]. Dotted line indicates the fit performed to the experimental and simulated gain.

3.2. Space charge based streamer formation

At higher voltages applied to the electrodes of GEM foils, evolution of electrons and ions during the transition from avalanche to streamer mode have been observed for single, double and triple GEM structures, as shown in figures 4 (a) and (b) respectively. Significant distortion of electric field has been observed due to accumulation of ionic space charges in the bottom electrode of the GEM foil. The discharge limit for single GEM has been found to be $\sim 8 \times 10^5$ electron-ion pairs, whereas for double and triple GEM it occurs at a value of nearly 2×10^6 electron-ion pairs. These values obtained from simulation are close to the experimentally observed discharge limit of 5×10^6 for GEM-based detectors of similar configuration and using the same gas mixture [8].

4. Conclusion

A hydrodynamic simulation framework has been developed to study the charge dynamics of avalanche and streamer evolution in GEM-based detectors. Simulation estimates of gain for

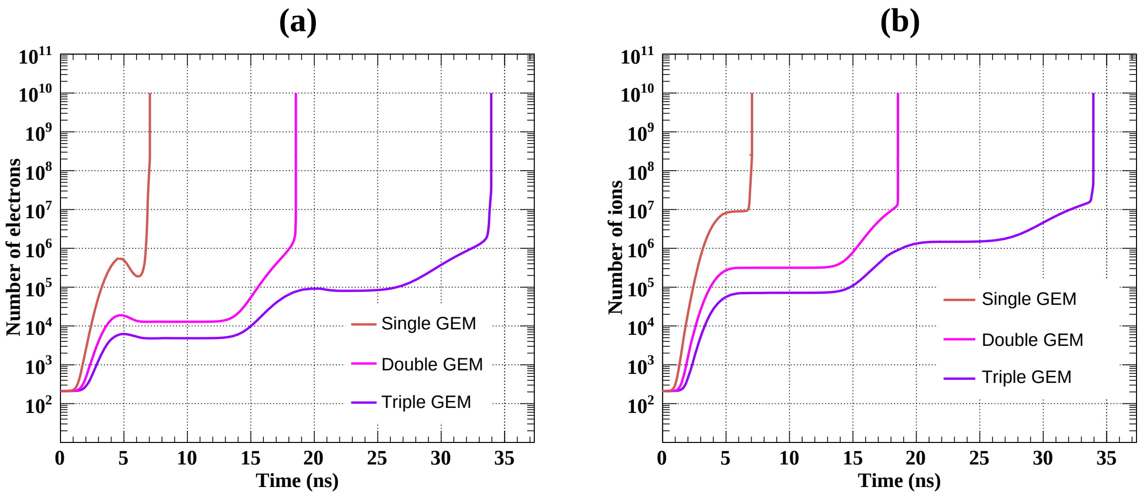

Figure 4. Time evolution of electrons (a) ions (b) during transition from avalanche to streamer mode operation for single ($\Delta V_{\mathrm{GEM}} = 570V$), double ($\Delta V_{\mathrm{GEM}} = 470V$) and triple GEM ($\Delta V_{\mathrm{GEM}} = 420V$) structures.

single, double and triple GEM configurations of 2D axisymmetric model agrees fairly well with the experimentally observed values [7]. The effect of space charges from avalanche to streamer transition has been modelled with some success. This simulation model can be extended to estimate the discharge probability in GEM-based detectors and help in the optimization of design parameters of experiments.

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