Numerical modelling of gaseous ionization detectors

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Abstract: The working of gaseous ionization detectors can be broadly broken into few major steps: generation of primaries, their transport and amplification due to applied electromagnetic field, and, finally, induction of signal on pick-up electrodes due to movement of electrons and ions. Proper design and optimum utilization of such detectors require thorough understanding of each of these steps. Since they possess significant complexity, numerical modelling turns out to be an important tool to explore the dynamics and response of these detectors. There are several possible approaches that may be adopted to carry out detailed and realistic numerical simulation of gaseous detectors. Among these, the Monte-Carlo particle approach adopted by the Garfield++ toolkit is among the most prominent possibilities. Recently, a deterministic hydrodynamic approach has also turned out to be useful for this purpose. The steps necessary to create mathematical and numerical models of a gaseous detector is presented here, utilizing both particle and hydrodynamic approaches. Simple examples are used to illustrate the advantages and disadvantages of both the approaches.

1. Introduction

Ionization detectors depend on ionization of the detector media due to the passage of charged particle. This resulting signal is registered on suitable pickup electrodes and processed to understand the nature of the charged particle and its interaction with the detector media [1]. Depending on the experimental requirements, the detector medium can be gaseous, liquid or solid, or a mixture of these states. While gaseous and liquid detectors give rise to electron-ion pairs, solid state detectors lead to electron-hole pairs due to the interaction of the incoming particle and the medium. Variants of these detectors are used for both timing and tracking detectors quite commonly. In this paper, we plan to focus on gaseous ionization detectors.

Starting from the early days of Geiger-Mueller counters [2], gaseous ionization detectors has an illustrious history with very significant successes. Due to impressive position, timing and energy resolutions, adaptability to variety of geometries, small and large, reasonable expense, this group of detectors has been a constant factor in various particle physics experiments and related applications. During recent times, gaseous detectors are becoming increasingly popular in medium and low energy experiments, astrophysics and other societal applications as well [3].

Figure 1 shows typical operating principle of a gaseous ionization detector. A charged particle passing through a gas-filled counter will ionize the gas along its path. The applied voltage *V* between the electrodes will attract the positive and negative charges toward the respective electrodes causing a charge *Q* to be induced on readout electrodes. Based on the electromagnetic configuration, the charged particles may amplify quite significantly during their transport. Several variations on this theme exist and they will be mentioned next.

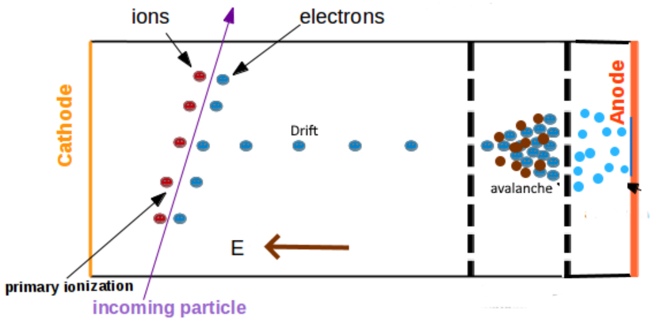
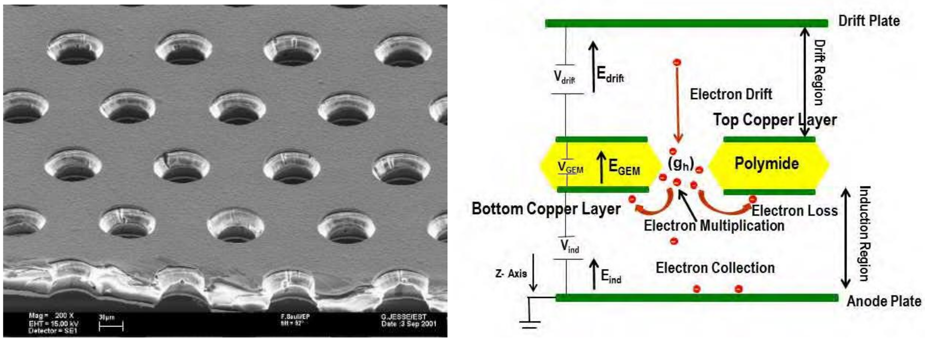


Figure 1 Schematic of an ionization detector

1.1. Possible detector configurations

In order to meet varied experimental demands, different detector geometries have been explored during the last more than a century. These can be broadly classified into wire, strip, parallel plate, and hole-based configurations. Prominent among various possibilities are, wire chambers: Geiger-Mueller counter, proportional counter, single / multiple wire chambers, drift chambers, strip chambers: Micro-Strip Gas Chamber (MSGC), parallel plate chambers: resistive plate chambers, Micromegas, and hole-based chambers: Gaseous Electron Multipliers (GEM), thick GEMs. There are mixed geometries such as the Micro-Hole Strip Plate (MHSP) chambers as well. Larger detectors, e.g., the Time Projection Chambers (TPC), based on these and other necessary components have also been designed, built and used with great success. Further details on these detectors can be found in [4] and many others.

In the context of this paper, it is necessary to introduce the GEM detector in some detail. The GEM concept was introduced by Fabio Sauli in 1996 [5]. It is a composite grid structure consisting of two metal layers separated by a thin insulator which is etched with a regular matrix of holes, as shown in figure 2. Applying a voltage V_{GEM} between the two conductive plates, a strong electric field is generated inside the holes (E_{GEM}) and the gas volume is divided in three regions: a low field drift region above the GEM where the primary charge is produced, a high field region inside the holes where the electrons are multiplied and an induction region below the GEM where a significant part of the avalanche electrons drift to the readout electrodes.



(a) (b)

Figure 2: (a) A microscopic image of a GEM foil and (b) basic working principle of GEM.

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The GEM foil is produced from an adhesive-less copper polyimide clad, with typical 50 μm polyimide thickness and 5 μm thick copper layers. Photolithography and chemical etching are done to form the copper layer on either side with a precision of 10 μm. Resulting exposed polyimide is chemically dissolved, the foil cleaned and electrically tested. The effective gas gain of a single GEM foil is not very high and often cascades of two or three GEMs are used. If more than one GEM is used, the gain per GEM can be reduced, which leads to a lower discharge probability. This is highly desirable for stable operation.

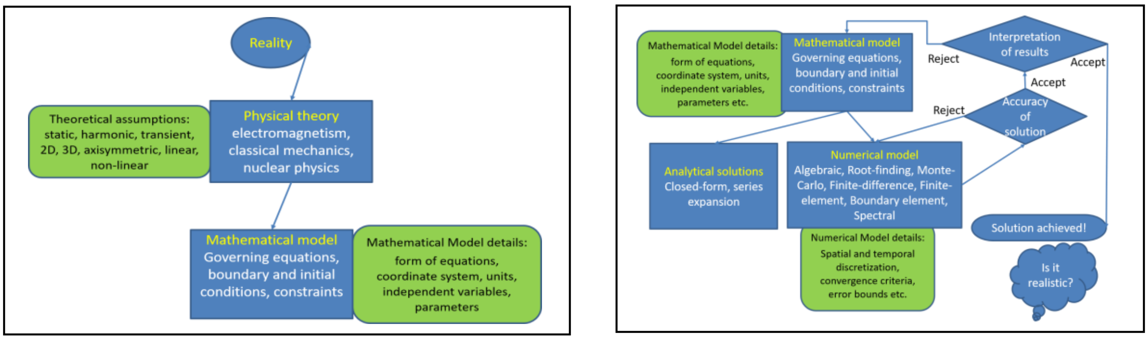
1.2. Why is numerical modelling important?

The variety of present and future possibilities makes it important to be able to interpret and understand the device physics of gaseous detectors. Due to the complexity of processes involved, a purely theoretical approach is found unable to progress far in dealing with realistic devices. As a result, numerical modelling has started playing an ever-increasing important role in analysing and interpreting these detectors. Such a model provides us with important insights that can help in optimization of experimental parameters, including environmental ones, interpret obtained data accurately and design better detectors in future. However, due to the presence of multiple aspects of physics and chemistry, as well as coexistence of large and small length and time scales, it is quite difficult to develop a model that works successfully under all possible circumstances.

In order to develop a realistic model of any physical system, the initial step is to identify mathematical model(s) describing different processes occurring within the system. These mathematical models are usually governing equations of various nature (algebraic, differential, integral, mixed etc.) with appropriate boundary and initial conditions. Since analytic solutions are the most exhaustive ones, attempts are made to solve the mathematical model using theoretical approaches, simplifying the model, if necessary. When acceptable analytic solutions are not available, we need to take recourse to numerical solutions. The latter approach is usually more capable of solving realistic problems. However, in order to choose and implement suitable numerical approach, several important steps need to be undertaken. The overall process has been described in figures 3(a) and 3(b).

(a) (b)

Figure 3: Process of developing numerical model of a physical system (a) from reality to mathematical



model, (b) from mathematical model to computational model.

1.3. Processes occurring within a gaseous ionization detector

Processes occurring within a gaseous detector can be represented as shown in Figure 1. The major steps are as follows:

1. Primary ionization of gaseous medium: Occurs due to the passage of energetic charged particles. This parameter is a function of the nature of the incident particle, the medium it is interacting with etc.
2. Transport of charged particles: Transport (drift and diffusion) of electrons (and negative ions, if any) towards positive electrode(s). Similarly, positive ions are transported towards negative electrode(s). The transport parameters depend on the gas mixture, electromagnetic field configuration etc.

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3. Avalanche: Multiplication as a result of ionizing collision of highly energetic electrons with the neutral molecules of the medium. The amount of multiplication depends on the prevalent effective Townsend coefficient that, in its turn, predominantly depends on the gas mixture, applied electric field etc.
4. Induction of signal: Signal is induced on readout electrodes due to the movement of charged particles. The magnitude of the induced signal crucially depends on the geometry of the device.
5. Collection of charged particles: The resulting charged particles are collected by various electrodes and other detector surfaces. Based on the nature of the surfaces, the charged particles may leave the system, or may lead to different sub-processes such as insulator charging up etc. These sub-processes may have profound effect on the dynamics of the detector, but will not be discussed here.

In this paper, we explore two important models, namely particle model and fluid model, either of which can be adopted to numerically simulate the physical processes occurring inside a gaseous detector. An application oriented approach will be pursued without going into the mathematical details. Simple examples will be discussed to illustrate the differences between these models and their suitability for a given problem.

2. Mathematical models

The first process, primary ionization, is governed by the famous Bethe-Bloch formula [6] that describes the mean energy loss per distance travelled by energetic charged particle through matter. A good approach to estimate the generation of this initial seed of electrons is through the use of a numerical solver such as HEED [7] and Degrad [8]. The former depends upon the photo-absorption and relaxation model in which the key ingredient is the photo-absorption cross section and has been used in examples shown in this paper.

Transport of charged particles may be described at various levels of detail. The most fundamental way is to try to solve the Langevin equation [9] that considers individual particles moving under the influence of deterministic forces exerted on them, as well as the random ones related to thermal and similar fluctuations. It is extremely difficult, if not impossible, to solve the Langevin equation for all the particles in a realistic problem. As a result, different levels of coarse-graining are imposed on the fundamental description. The Fokker-Planck equation [10, 11] reflects one such important representation in which rather than describing a particle position, the likelihood of finding a particle in a given position is sought for.

Transport properties such as drift velocity and diffusion of electrons can be obtained from the multi-term Boltzmann expansion [12]. The computer code Magboltz [13] carries out the task using Monte-Carlo approach and also yields Townsend gain coefficient, attachment coefficient etc. It is possible to trace the path of an electron and its multiplication by using the estimates from Magboltz using Garfield / Garfield++ [14, 15].

Finally, the induced signal on pickup electrodes can be obtained using Shockley-Ramo's theorem [16, 17]. A virtual field, namely, the weighting field for each pickup electrode needs to be estimated for this purpose. For a particular pickup electrode, this field is computed by setting its voltage to a specified value while all other electrodes are grounded [1]. It is also possible to integrate the effect of electronics into the simulation in order to replicate what is actually observed on an oscilloscope, or a data acquisition system [18].

All the steps, except the first one, needs detailed electromagnetic configuration of the detector. Usually, the Boundary Element Method (BEM, Green function-based approach) [19, 20], or the Finite Element Method (FEM) [21, 22, 23] can be used as the field solver for a given detector geometry.

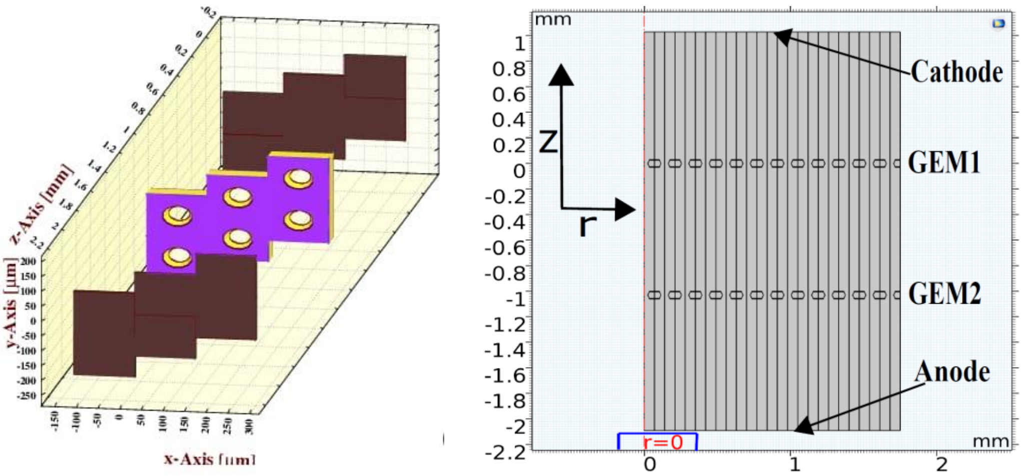
Adopting this particle model, Garfield / Garfield++ provides a seamless interface to all the necessary components to perform a very realistic simulation of the processes occurring inside a gaseous (or solid state) detector [24] leading to the final detector response as observed in an experiment.

Mathematically, the particle model of transport can be replaced by a fluid model by adopting a continuum description [25]. Here, it is assumed that the transport of the charged particles in an ionization detector can be treated as the movement of dilute species of charged fluids moving through a background fluid made up of the neutral medium of the detector. The assumption of continuum imposes several restrictions though. The internal structure in the matter under consideration is neglected and replaced by average bulk properties. However, such descriptions have found to work reasonably well even for complex detector structures, such as triple GEM devices [26, 27].

3. Numerical implementation

In this paper, we have used the Garfield-Heed-Magboltz-neBEM framework for particle model simulations. For fluid model, transport of charged species has been simulated using the Transport of Dilute Species (TDS) module of COMSOL [22], a commercial FEM package. The electric field, incorporating the space charge effect, has also been estimated using the same package. Besides transport, the remaining information (steps 1, 2 and 3) are obtained using Heed and Magboltz, as done in the Garfield framework adopted for the particle approach.

In both the approaches, a numerical model of the GEM detector has been created which contain geometry and material information of the device. Appropriate boundary conditions in the form of electric potential, displacement current have been specified on the numerical detector. For the particle model, the base device as shown in figure 4(a) has been assumed to have repeated for a specific number of times so that the edge effects are nullified. For the fluid model, the device has been considered to be axisymmetric, as shown in figure 4(b).



(a) (b)

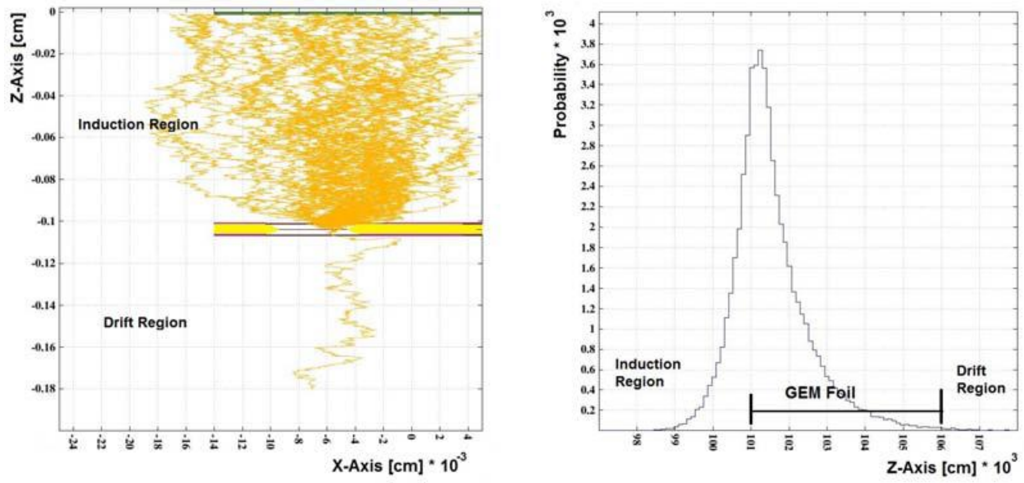
Figure 4: (a) GEM base device in the particle model, (b) Axisymmetric model of a double GEM in the fluid model.

4. Results and discussion

Few test cases have been solved using the particle and fluid models in order to appreciate the differences between the two approaches and the information they yield. They are presented below.

4.1. Estimation of detector gain

Particle model: The primary electrons which reach the GEM hole from the drift volume are capable of creating an avalanche of secondary electron-ion pairs inside the hole, as shown in figure 5(a). Since each and every charged particle is being followed individually, it is easy to obtain information related to their starting and ending points. The starting points of secondary electrons are shown in figure 5(b). From this figure we can see that a large number of electrons have their starting point overlapping with the location of the GEM foil. Careful inspection also reveals that the part of the GEM foil adjacent to the induction region, facing the anode, has the largest number of starting points. This clearly shows that most of the electron multiplication takes place in this part of the GEM hole. In this particular configuration, some multiplication is also found to occur in the induction region beyond the GEM hole.



(a) (b)

Figure 5: (a) Electron transport in a GEM detector showing the effect of avalanche, (b) Starting point of electrons in different regions of a GEM detector.

Fluid model: Dilute charge species that are initiated from the drift volume at time = 0 ns multiply as they are transported through the GEM hole. This leads to an avalanche as in particle model and a resulting detector gain as shown in figure 6. While it is not possible to follow the trajectory of each charged particle, it is possible to estimate the total number of particles belonging to the negative and positive species as shown in figure 7. It is observed, in agreement with the particle model results, that there is large amount of charge multiplication when the electrons reach the GEM hole (around 3 -5 ns; it may be observed from figure 6 that the electrons are already past the GEM hole at 5.7ns). Moreover, as expected, the maximum number of electrons and ions increase as ΔV_{GEM} increases. The electrons are quickly moved out of the detector volume. but the ions remain in the detector till the end of the computed time (22 ns).

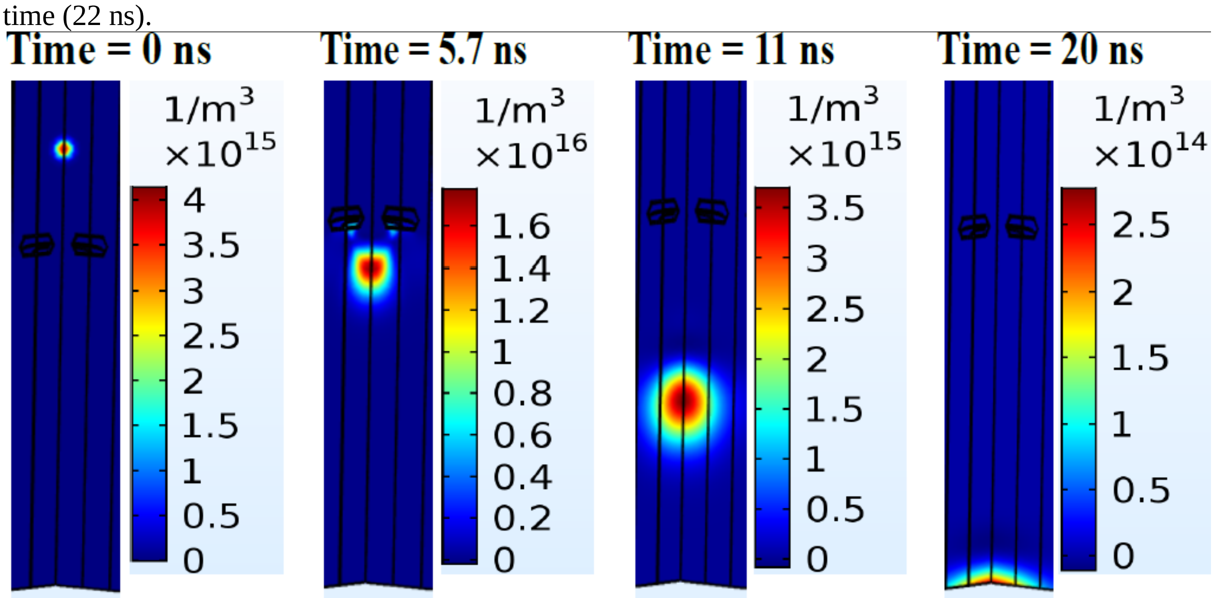


Figure 6: Avalanche formation in the 2D axisymmetric gas volume of a single GEM at ΔV_{GEM} = 500V. Charge density evolution of electron fluid (in $1/m^3$) and its position at different time steps of simulation in the gas volume until it reaches the anode.

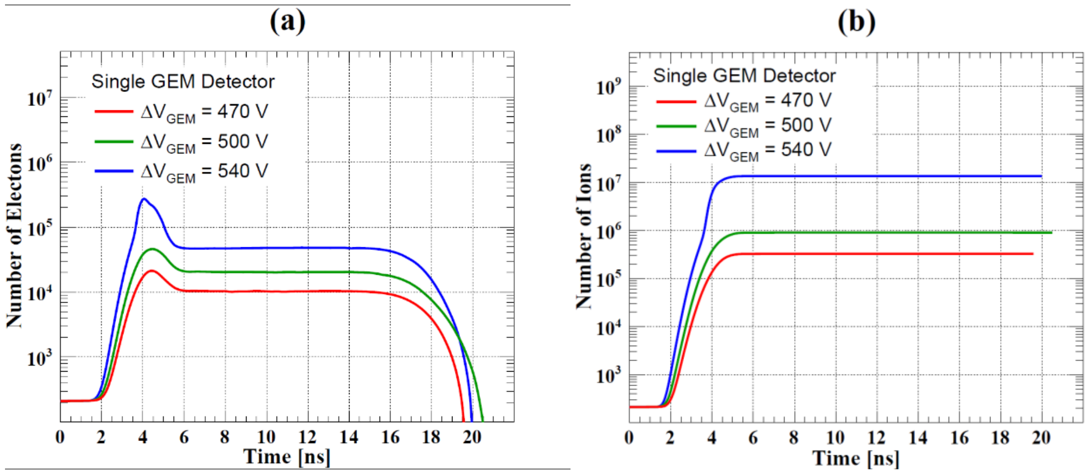
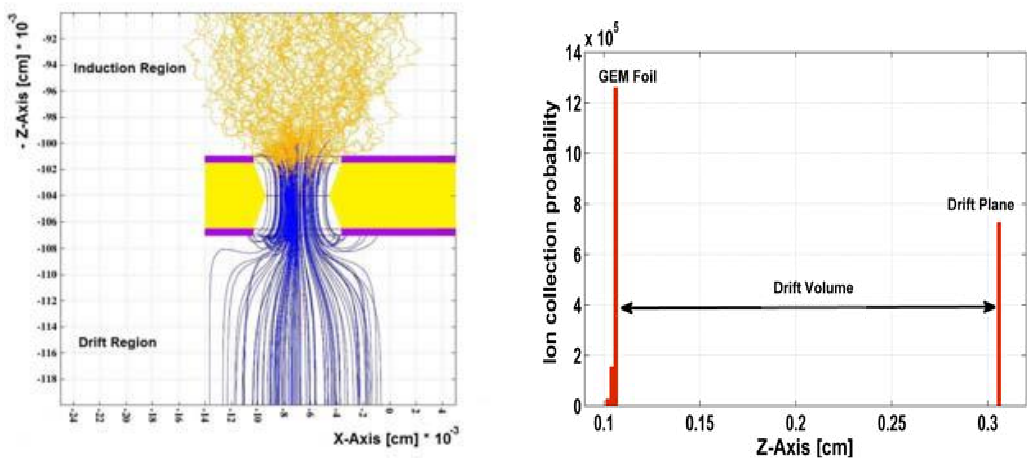


Figure 7: Temporal evolution of number of (a) electrons and (b) ions for a single GEM for various ΔV_{GEM}

In this subsection, a parameter such as detector gain, that can be assessed by both the models, has been considered. It has been observed that there are significant differences in the detailed results that these approaches yield. In the next two subsections, we take up two parameters that are easily amenable to only one of the approaches, at the present state of the art.

4.2. Estimation of ion backflow

Estimation of the amount of ion backflow is considered to be an important task since the ions drifting back to the drift volume can disturb the homogeneity of the drift field and, thus, distort the detector response. The electron avalanche (in yellow color) and the ion drift lines (in blue) in case of a single GEM detector for a particular field configuration is shown in figure 8(a). The endpoints of the ions are shown in figure 8(b). The ion backflow fraction (IBF) can be estimated from the information available in this figure. It can be seen that the maximum number of ions are collection by the GEM cathode. Some ions also get attached to the Kapton foil, and a very small number gets collected at the GEM anode. However, from the point of view of IBF, it is important to note that quite a large number of ions are collected at the drift plane. These are the ions that move through the drift volume and have the potential of disturbing the uniformity of the drift field.



(a) (b)

Figure 8: For a single GEM detector, (a) the electron avalanche and the ion drift lines, (b) the endpoints of the ions on different location of the detector.

4.3. Transition from avalanche to discharge mode operations

It is very important to be able to predict the mode of operation (avalanche or streamer) of a GEM detector in a given experimental situation. The avalanche is usually preferred and a transition to streamer mode may indicate loss of stability, including significant damage to the detector. In figure 9, transition from avalanche to streamer is shown for a single GEM detector. It can be seen that ion concentration increases very rapidly within the GEM hole, the maximum value going from $3 \times 10^{21}/m^3$ to $2.5 \times 10^{26}\ /m^3$. This accumulation of ions amounts to significant space charge. This space charge, in turn, leads to large distortion of the field which increases several folds over the applied value (from around 200 kV/cm to 2000 kV/cm). As a result, there is copious production of charged particles which leads to the formation of a positive streamer.

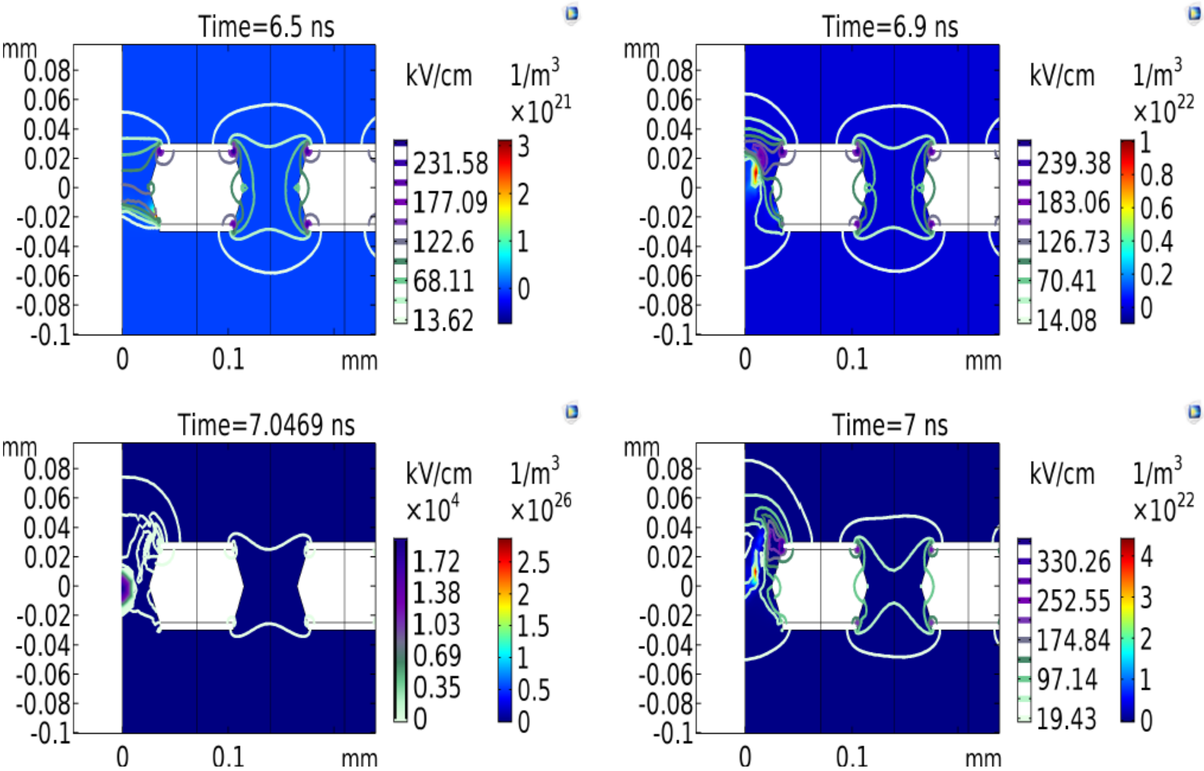


Figure 9: Distortion of total electric field due to space charge and evolution of ion concentration during streamer formation in a single GEM at ΔV_{GEM} = 570V in clockwise direction.

5. Summary

In this paper, an attempt has been made to provide an introduction to two important approaches of carrying out numerical simulation of gaseous ionization detectors. In particular, discrete (particle) and continuum (fluid, hydrodynamic) models have been discussed.

On one hand, discrete, or particle simulations yield very detailed information about the device dynamics but are extremely computation intensive. As a result, at present state of computational systems, it may be difficult to pursue this approach for problems such as avalanche to streamer transition. This is also because of difficulties related to estimation of effects of space charge accumulation that, once again, are computationally expensive. But there are certain problems like estimation of IBF in which only this approach is appropriate.

On the other hand, fluid simulations are fast but yield less information. Since the charged species are considered to be dilute solvents, it is straightforward to incorporate space charge effects and study difficult problems such as avalanche to streamer transition. However, individual information of charge particles is not available, due to which it is not possible to estimate parameters such as IBF.

We may conclude that both the approaches are extremely capable and successful in their own sphere of application space. It may be noted here that there are lot more to explore in each of these tools and large number of other options available. Multi-Physics issues make the work of numerical simulation of gaseous detectors more complex, but rewarding.

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References:

[1] Blum W, Riegler W, Rolandi L, 2008 Particle Detection with Drift Chambers, Springer-Verlag Berlin Heidelberg.
[2] Geiger H and Muller W, 1928 Die Naturwissenschaften **16** 617
[3] Sauli F, 1992 Nuclear Instruments and Methods in Physics Research A **323** 1.
[4] Sauli F, 2014 Gaseous Radiation Detectors, Fundamentals and Applications, Cambridge University Press.
[5] Sauli F, 1997 Nuclear Instruments and Methods in Physics Research A **386** 531.
[6] Bethe H, 1932 Zeitschrift für Physik**76** 293.
[7] Smirnov I B, 2005 Nuclear Instruments and Methods in Physics Research A **554** 474.
[8] Biagi S F, 2019 http://degrad.web.cern.ch/degrad/.
[9] Langevin P, 1908 C. R. Acad. Sci. Paris. **146** 530.
[10] Fokker A D, **1914** Ann. Phys. **348** 810.
[11] Planck M, 1917 Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin **24** 324.
[12] Kumar K, Skullerud H R and Robson R E, 1980 Aust . J. Phys. **33** 343.
[13] Biagi S F, 1999 Nuclear Instruments and Methods in Physics Research A **421** 234.
[14] Veenhof R, 1998 Nuclear Instruments and Methods in Physics Research A **419** 726.
[15] Schindler H and Veenhof R, 2018 Garfield++ | simulation of ionisation based tracking detectors, http://garfieldpp.web.cern.ch/garfieldpp/.
[16] Shockley W, 1938 Journal of Applied Physics **9** 635.
[17] Ramo S, 1939 Proc. IRE **27** 584.
[18] Bhattacharya P et al., 2019 Nuclear Inst. and Methods in Physics Research, A **916** 125.
[19] Majumdar N, Mukhopadhyay S, 2006 Nuclear Instruments and Methods in Physics Research A **566** 489.
[20] Mukhopadhyay S and Majumdar N, 2006 Engineering Analysis with Boundary Elements **30** 687.
[21] https://www.ansys.com/
[22] https://www.comsol.com/
[23] https://www.elmerfem.org/
[24] Bhattacharya P et al., 2015 Nuclear Inst. and Methods in Physics Research A **793** 41.
[25] Datta J et al., 2020 JINST 15 C12006.
[26] Rout P K et al., 2021 JINST **16** P02018
[27] Rout P K et al., 2021 JINST **16** P09001