Summer Student Project: GEM Simulation and Gas Mixture Characterization
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Abstract
This project is a numerical simulation approach to Gas Electron Multiplier (GEM) detectors design. GEMs are a type of gaseous ionization detector that have proposed as an upgrade for CMS muon endcap. The main advantages of this technology are high spatial and time resolution and outstanding aging resistance. In this context, fundamental physical behavior of a Gas Electron Multiplier (GEM) is analyzed using ANSYS and Garfield++ software coupling. Essential electron transport properties for several gas mixtures were computed as a function of varying electric and magnetic field using Garfield++ and Magboltz.

1 Introduction
1.1 GEM Basics:
Each experiment of the Large Hadron Collider relies on gaseous ionization detectors to track charged particles. A Gas Electron Multiplier (GEM) is a type of gaseous ionization detector developed in CERN in 1997. GEMs collect and amplify ionizing radiation of a passing particle by using a large electric field within a gas mixture. This electric field is created in small holes in a thin polymer foil, metal-coated on both sides. When the GEMs are subjected to a voltage gradient, electrons drift into the small holes, creating an avalanche and moving to a readout plate on the other side. As a result of this geometrical configuration and field conditions, proportional gains-amplification in the form of electron cascades- are very high ($\approx 10^3$) for all common gases.

A typical GEM hardware configuration consists in a 50-70 micrometers thick kapton foil, clad with copper on both sides. Using photo-lithography and acid etching, it is possible to achieve a high density and precision of holes with diameters between 30-50 micrometers.

When multiple GEMs are aligned in series, proportional gain and time resolution are increased. Schematic representations of single GEM and multiple GEMs are shown in Figure 1. It is possible to see the necessity to enclose the GEM into a bigger cathode-anode field. This zones are known as drift, transference and induction depending on the trajectory of the electron drift.

![Single GEM and Double GEM](image)

Figure 1: Comparison between Single GEM and Double GEM configurations

1.2 Specific Requirements for Gas Mixtures:
The gas mixture in a GEM has to achieve a series of requirements in order to be used in an effective, efficient and sustainable way. In first place, the mixture requires a gas in which the ionization process takes place. Usually noble gases like Ar, Ne or He are used for this purpose. In second place, a quencher gas is required as a way to prevent undesired secondary effects such as field emission or instabilities. Usually methane, carbon dioxide or isobutane are used as quenchers. Besides that, the final gas mixture must have adequate tracking and triggering properties. This properties are related to the following physical parameters:
• **DRIFT VELOCITY**: In the presence of an electric field, the electrons start drifting along the field direction with a mean drift velocity. The drift velocity is sensitive to changes in pressure, temperature and pollutants concentrations. For desirable tracking, drift velocity should be high and present small variation with respect to modification of electric and magnetic fields.

• **DIFFUSION COEFFICIENT**: Individual electrons in a gas mixture tend to deviate from the average electric field direction due to scattering on the atoms of the gas. This scattering produces variation in velocity called longitudinal diffusion, and variation in lateral displacement, called transverse diffusion. Ideally, an adequate gas mixture should have low diffusion coefficients.

• **LORENTZ ANGLE**: A magnetic field perpendicular to the electric field and the motion of the electron produces a deflection effect in the electron trajectory. This results in lower drift velocity and transverse dispersion. The angle which the drifting electron is deflected with respect to the electric field is called the Lorentz angle. The magnitude of this angle is dependent of both the electric and magnetic field. A small Lorentz angle is desirable for tracking reasons.

Finally, several additional considerations are essential for gas mixtures such as aging, security risks, toxicity, environmental impact and cost. Many gases with outstanding electron transport properties (such as CF4 mixtures) have problems to accomplish this environmental, economic and practical requirements.

## 2 Simulation Methodology:

### 2.1 Geometry Definition and Field Calculations:

In order to calculate electron trajectory, it is necessary to know the magnitude and direction of the electrical and magnetic field in each discrete position of the drift space. Due to GEMs' complex geometrical configuration, finite element analysis (FEA) software ANSYS was used. A single GEM configuration was modeled considering both the physical GEM and the surrounding drift and induction gas regions. This configuration is shown in Figure 2. An overall potential electrical difference of 300 V was supposed between each GEM and the drift and induction fields were supposed to be 3 kV/cm.

![Figure 2: GEM configuration modeled in ANSYS](image.png)

### 2.2 Avalanche Calculation and Electron Tracking:

Using the electric field conditions computed by ANSYS, Garfield++ and its interface with Heed were used to generate ionization patterns of fast charged particles and calculate electron avalanches in the gas. The specific gas mixture used for the simulated configuration was Ar:CO2:80:20. After the avalanche takes place, it is possible to calculate the total number of electrons/ions involved in it and the number of electrons who reaches the readout plate. In addition, several first ionization positions were analyzed as a way to approximate time response in the detector.

### 2.3 Transport Properties Calculations:

Garfield++ and its interface with Magboltz were used to calculate gas properties in three dimensional gas mixtures. Magboltz solves the Boltzmann transport equations for electrons in gas mixtures in presence of electric and magnetic fields. By this method, drift velocities, longitudinal and transverse diffusion coefficients were calculated as a function of electric field magnitude. Lorentz angles were calculated for different magnetic field magnitudes and angles between electric and magnetic field.

Two gas mixtures, usually used in GEMs and drift chambers, were considered: \( Ar : iC_4H_{10} 95 : 5 \) and \( Ar : CO_2 : CF_4 40 : 15 : 45 \).
3 Results and Discussion:

3.1 Single GEM gain and first ionization:

The effective gain was computed for several conditions of drift field magnitude and peening coefficient, these results are summarized in Figure 3. These results represent the amplification effectiveness of the GEM. Also the point of first ionization $s$ and the average electron signal at the readout plate were calculated. These results are summarized in Figure 4 and Figure 5 respectively.

![Figure 3: Effective Gain vs Drift Field Intensity for several Peening Transfer Coefficients](image1)

![Figure 4: Distribution of first point of ionization ($s$) measured from the upper GEM plate](image2)

![Figure 5: Average electron signal at the readout plate](image3)
3.2 Gas Mixtures Properties:

Drift velocity as a function of electric field for both gas mixtures is shown in Figure 6. The $\text{Ar} : \text{CO}_2 : \text{CF}_4$ mixture is characterized by a higher magnitude of drift velocity and saturation point compared to the $\text{Ar} : \text{iC}_4\text{H}_{10}$ mixture. This behavior is explained by the high concentration of $\text{CF}_4$ in the mixture, a gas well-known by its optimal drifting properties. Based on this information, it seems that $\text{Ar} : \text{CO}_2 : \text{CF}_4$ mixture is more suitable for detector operation than $\text{Ar} : \text{iC}_4\text{H}_{10}$ mixture. However, the high electric field values for the saturation drift velocity in the $\text{Ar} : \text{CO}_2 : \text{CF}_4$ mixture and its narrow range are often pernicious for adequate detector operation and calibration.

![Drift Velocity versus Electric Field](image)

Figure 6: Drift velocity (cm/ns) as function of electric field (V/cm) for both gas mixtures.

Transverse and longitudinal diffusion coefficients as a function of electric field for both gas mixtures are shown in Figure 7. Both coefficients are significantly lower for $\text{Ar} : \text{CO}_2 : \text{CF}_4$, meaning again that the mixture is more suitable for detector operation.

![Transverse and Longitudinal Coefficients](image)

Figure 7: Transverse and longitudinal coefficients as function of electric field (V/cm) for both gas mixtures.

Finally, the Lorentz angle is a function of electric field strength, magnetic field strength, and the angle between them. In consequence, the first column in Figure 8 and Figure 9 shows the plots of Lorentz angles against magnetic field for a constant angle while varying the electric field magnitude. The second column in Figure 8 and Figure 9 shows the plots of Lorentz angles against magnetic field for a constant electric field while varying the angle between magnetic and electric field. For both gas mixtures, a higher electric field and a lower angle value between magnetic and electric field produce a smaller Lorentz angle. The $\text{Ar} : \text{CO}_2 : \text{CF}_4$ seems to have the lower Lorentz angle value in all the cases.
Although its optimal characteristics, a selection of Ar : CO$_2$ : CF$_4$ as operation mixture for a detector should consider other factors. The high concentration of costly, ozone-unfriendly and deteriorating CF$_4$ represents a
problem for long term operation.

4 Conclusions:

GEMs' physical behavior and gas mixtures properties were simulated with Garfield++ software. By this method, different geometrical configurations can be compared easily to take essential design decisions. It was seen that the obtained gain values, first ionization distribution and signal in the readout plate are consistent with expect values and theoretical behavior.

Regarding gas characterization, Garfield++ is a powerful tool to compute transport properties under different operation conditions. Drift velocities, diffusion coefficients and Lorentz angle confirmed the behavior that was theoretically expected. This means: increasing drift velocity and decreasing diffusion coefficients and Lorentz angles for increasing electric field. It has been seen that the effect of freon concentration in terms of transport properties is positive. However, as the analyzed gas mixtures suggest, the final design decision does not rely only in transport parameters, but in many other factors such as environmental impact, cost, aging behavior, security risks, etc. Since simulation is always subjected to numerical error and assumptions, experimental data is needed to guarantee desired performance.

5 Future Work:

Following the methodology of this project, more GEMs configuration should be analyzed. Drift distance, time resolution and electric field optimization have still broad study possibilities. The current LHC upgrade and future upgrades represent an outstanding opportunity to develop muon detection technology. In addition, Garfield++ simulation is useful for other gas ionization detectors such as Resistive Plate Chambers (RPCs) and Cathode Strip Chambers (CSCs).

Regarding gas characterization, finding transport properties for an arbitrary mixture with adequate accuracy and precision is very costly in computational terms. For future work scopes, a Garfield++ database of common gas mixtures should be implemented at least for the CMS Muon End-Cap simulation.

6 Side Work

In addition to the current project, the following tasks were accomplished during the Summer Program:

- DETECTOR AGING: A literature review of detector aging focusing in CMS was performed. The influence of gas mixture pollutants, specific concentrations, etc.- during long term operation was noted. Damage caused by neutrino irradiation was also considered.

- CATHODE STRIP CHAMBERS ASSEMBLY: Some assembly line work and data acquisition were performed in order to become familiar with CSC production. This work took place in the CSCs’ assembly facility at Prévesin site.

References


