Hydrodynamic simulation studies on avalanche and Streamer formation in GEM detector

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Introduction and motivation of the work:

- Particle models are usually employed to study the charge dynamics in gaseous ionization detectors [1].
- These models struggle when the number of electrons and ions are large.
- A hydrodynamic model [2] can help in investigating the behaviour under this extreme conditions.

Mathematical model and numerical implementation:

- Mass transport of diluted chemical species in a gas mixture.
- The electrons and positive ions are treated as charged fluids (concentration, c_i).
- Production of electrons and ions: Townsend source term - S_e; Photo-ionization source term - S_{ph}
- The dynamics heavily depends on the electric field(E) and the volume space charge density(ρ_v).
- The model is devloped in the COMSOL Multiphysics framework [3].
- Electron transport parameters are used from MAGBOLTZ [4] and primary ionizations from HEED [5].

Charge transport equations

$$\frac{\partial c_i}{\partial t} + \vec{\nabla}\cdot(-D_i\vec{\nabla}c_i + \vec{u}_i c_i) = R_i$$

$$R_i = S_e + S_{ph}$$

$$S_e = (\alpha(\vec{E}) - \eta(\vec{E}))|\vec{u}_e| n_e$$

$$S_{ph} = \xi Q E_{gas}\mu \Psi_0$$

Photon transport equation

$$\vec{\nabla}(-c\vec{\nabla}\Psi_0) + a\Psi_0 = f$$

Electric field and space charge density

$$\vec{E} = -\vec{\nabla}V$$

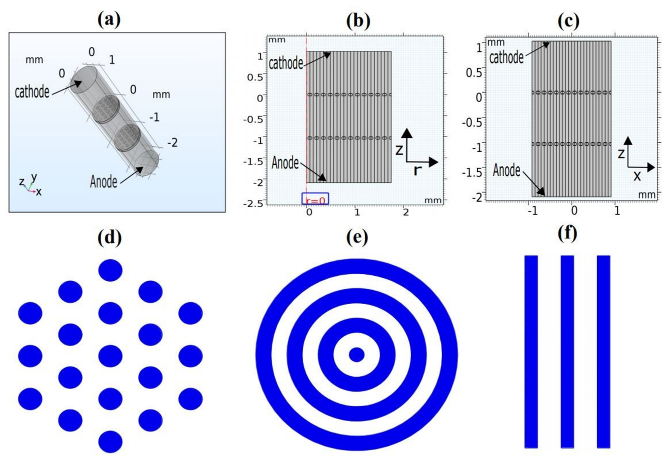
$$\rho_v = \frac{Q_e}{\epsilon_0}(n_i - n_e) \qquad \vec{\nabla}\cdot\vec{D} = \rho_v$$

Optimization of model Geometry:

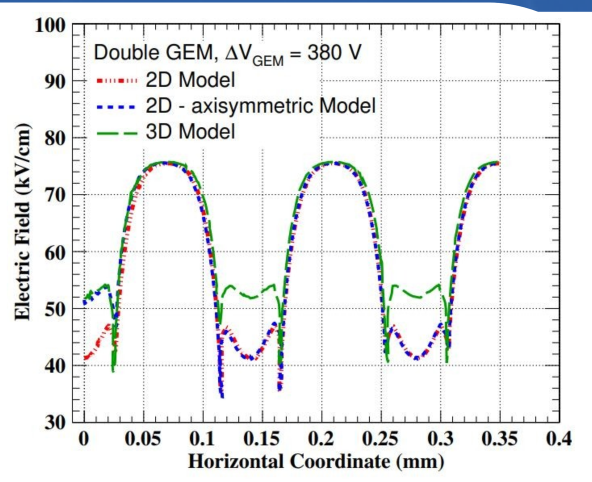
- Optimization parameter: Electric field
- Simulation model: 3D, 2D and 2D axisymmetric geometry of single, double and triple GEM structures.
- 3D model : Most accurate and realistic but demands huge computational resources and time
- 2D model : Inconsistent, because all are channels instead of holes and does not provide correct field maps.

Optimum model: 2D axisymmetric geometry due to the following reasons:

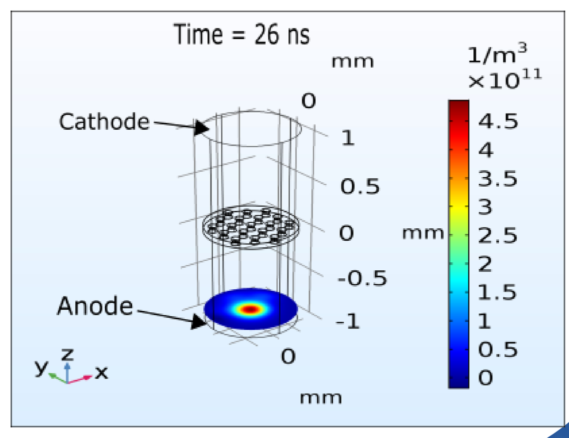
- GEM hole has natural axisymmetry in it.
- Correct field map for the central hole agrees well with the 3D holes. However, the Off-centres are circular channels and have a field difference of around 20%.
- Axisymmetric is also valid as the evolution of an avalanche in a 3D model shows axisymmetric nature.
- Less computational resources and time required.



[3D, 2D axisymmetric (r = 0) and 2D model of double GEM.]



[Electric field distribution in 3D, 2D axisymmetric and 2D model]



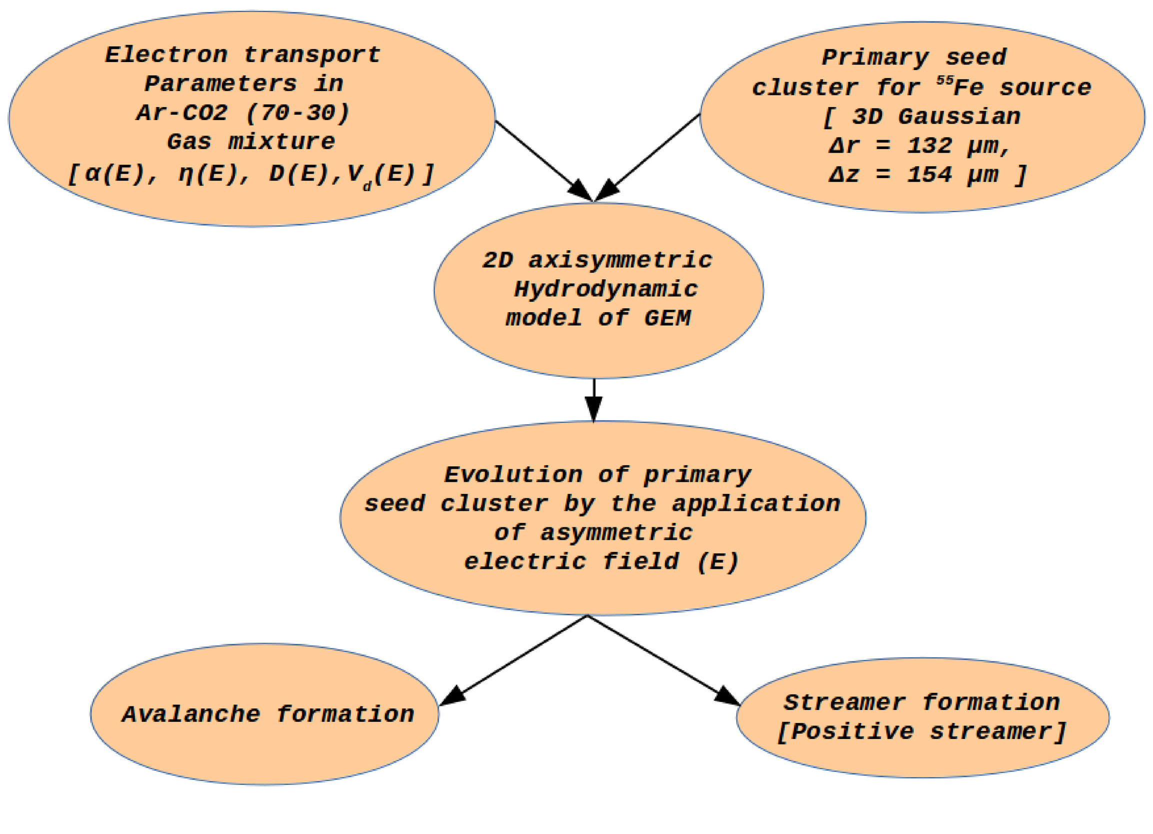
[Axisymmetric nature of an electron avalanche in a 3D model]

Avalanche simulation:

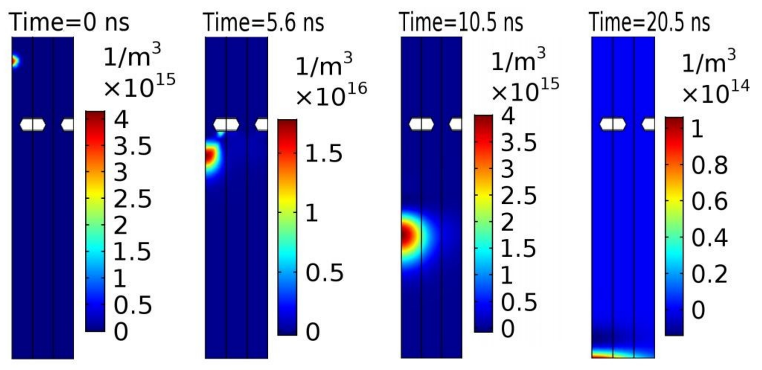
- Growth of primary seed cluster.

  Gas mixture : Ar-CO_2(70-30).

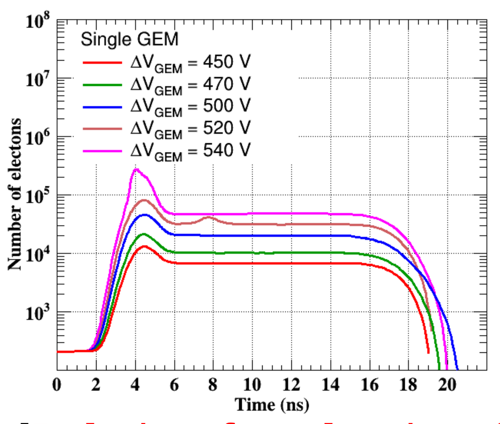
  Radiation source : ^{55}Fe.
- Transport of charged fluid in 2D axisymmetric gas volume.
- Amplification of charged fluid inside GEM holes.
- Total number of electrons and ions is estimated at each time step of the simulation.
- Evolution of electrons and ions for single,double and triple GEM structures.



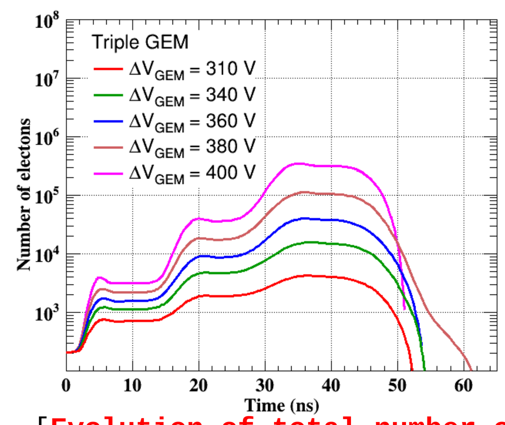
[Schematic view of hydrodynamic simulation work flow]



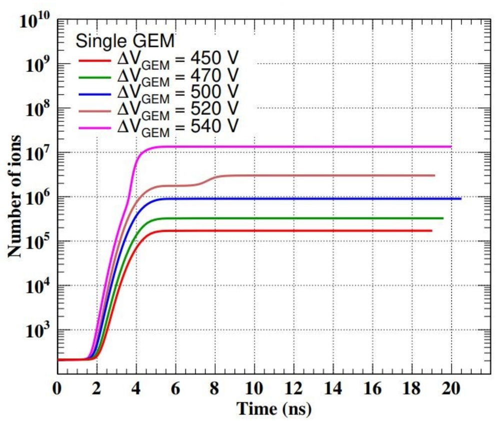
[Evolution of electron fluid (1/m³) in a single GEM at ΔV_{GEM} = 500 V.]



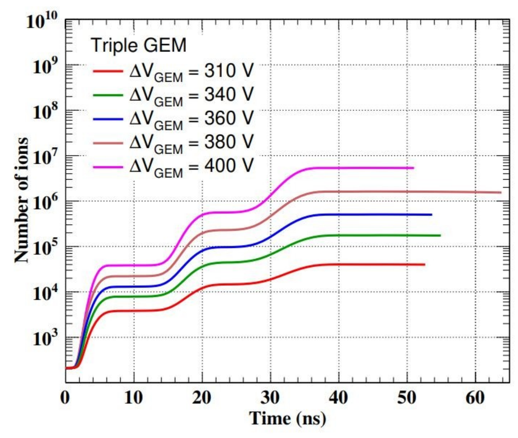
[Evolution of total number of electrons in a single GEM]



[Evolution of total number of electrons in a triple GEM]



[Evolution of total number of ions in a single GEM.]



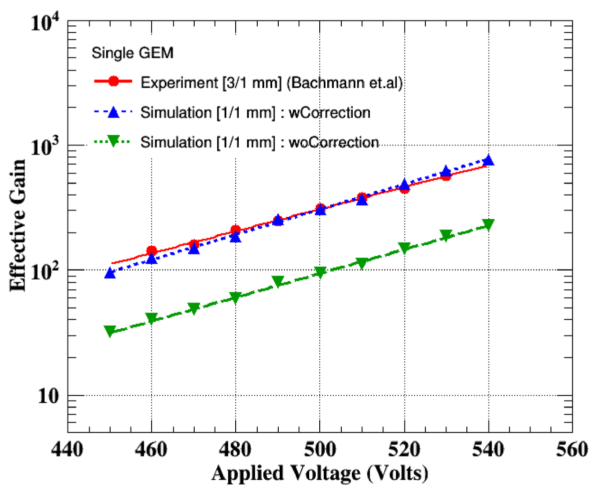
[Evolution of total number of ions in a triple GEM.]

Effective Gain estimate :

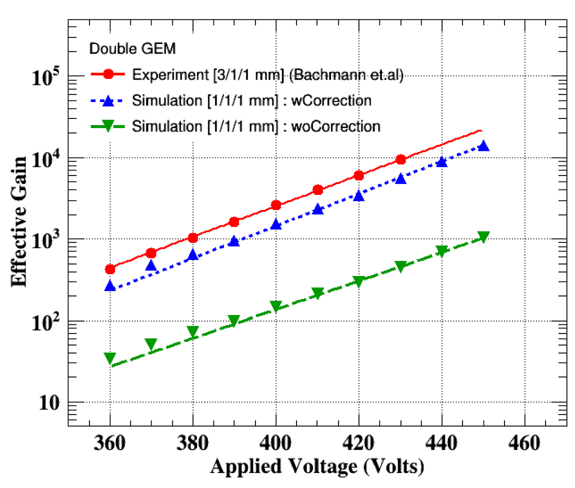
- Effective gain (G) is estimated by the following.

$$G = \frac{[\text{Total number of electrons collected at anode}]}{[\text{Initial number of primary electrons}]}$$

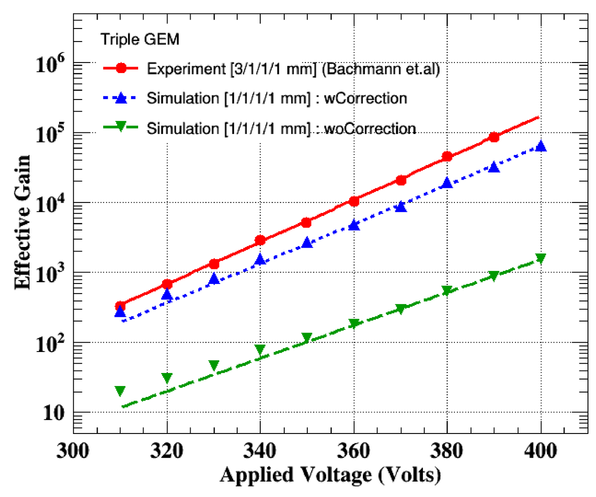
- Simulated gain variation with applied voltages in single,double and triple GEM structures.
- **Gain Correction:** Taken into account contribution from off-centre holes of 2D axisymmetric model.
- The gain estimates matches fairly well with the experiments [6,7].



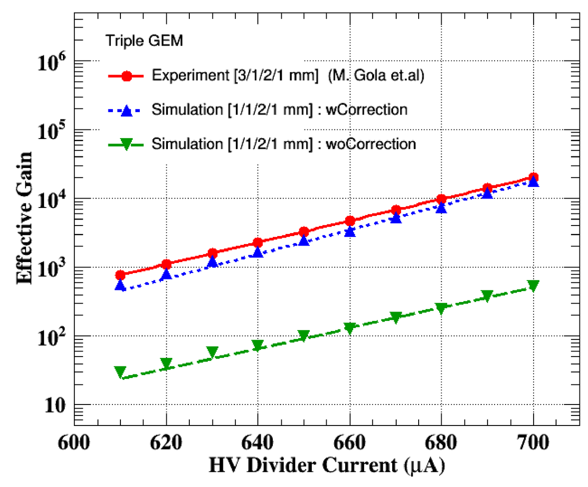
[Numerical estimates of gain values compared with experimentally measured gain values [6] for a single GEM.]



[Numerical estimates of gain values compared with experimentally measured gain values [6] for a double GEM.]



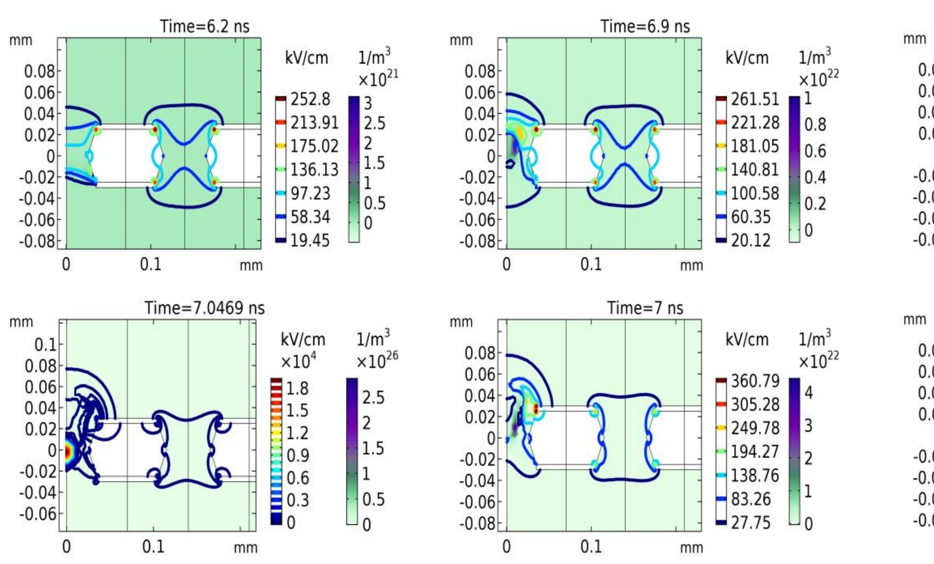
[Numerical estimates of gain values compared with experimentally measured gain values [6] for a triple GEM.]



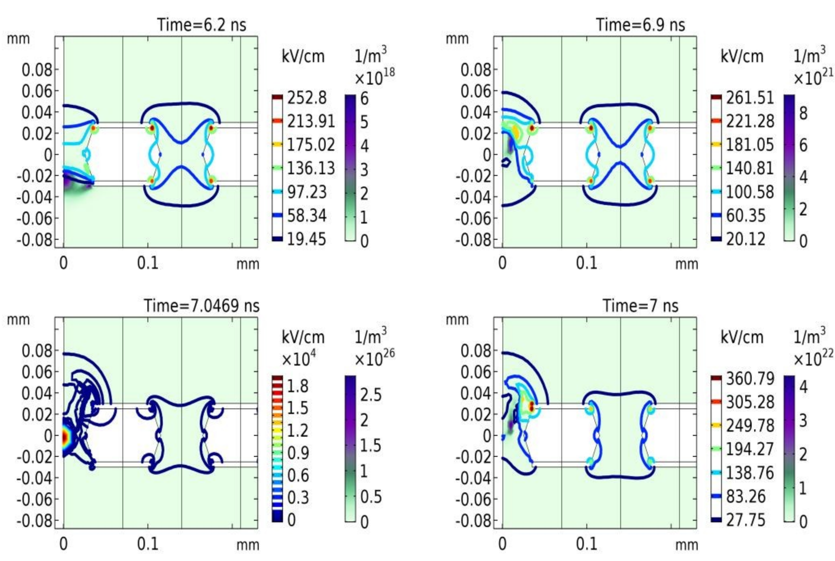
[Numerical estimates of gain values compared with experimentally observed gain values [7] for a triple GEM.]

Streamer development:

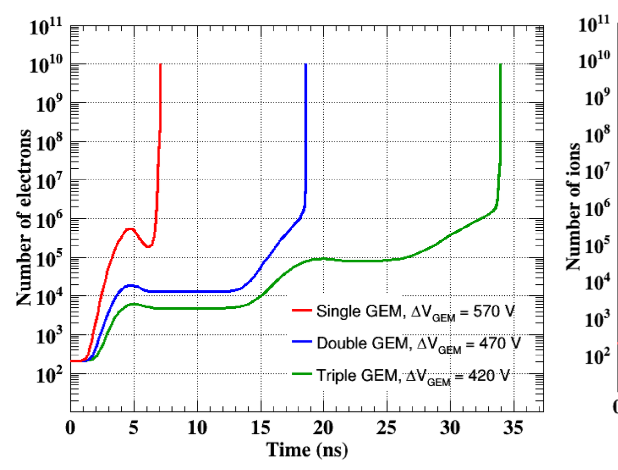
- Streamer initiation: electric field due to space charges becomes equal to applied field [8,9].
- Significant distortion of electric field observed due to accumulation of ionic space charges.
- Positive streamers observed from GEM bottom electrode to top electode.
- Discharge limits observed: ~8x10⁵ for single GEM. ~2x10⁶ for double and triple GEMs.
- Values obtained are close to the experimentally observed discharge limit 5x10⁶ [10] for GEM-based detectors.



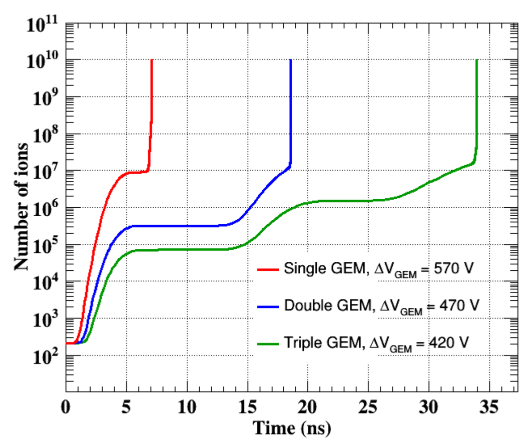
[Streamer development in a single GEM at ΔV_{GEM} = 570 V.Evolution of ion density (1/m³) is associated with strong distortion of electric field.]



[Streamer development in a single GEM. At ΔV_{GEM} = 570 V. Evolution of electron density (1/m³) associated with strong distortion of electric field.]



[Evolution of total number of electrons with time during transition from avalanche to streamer mode.]



[Time evolution of total number of ions during transition from avalanche to streamer mode.]

Conclusion:

- A hydrodynamic simulation framework developed to study the charge dynamics of avalanche and streamer evolution in GEM-based detectors.
- 2D axisymmetric geometry found to be suitable for the simulation.
- Simulation estimates of gain agrees well with experiments [6,7] quantitatively.
- The computationally difficult transition from avalanche to streamer modelled with fair amount of success.
- Positive streamers observed dominated by ion transport from GEM bottom electrode to top electrode.
- This simulation model can be extended to estimate the discharge probability in GEM-based detectors and help in the optimization of certain design parameters of experiments.

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