MODELING GEM-BASED DETECTORS USING HYDRODYNAMIC APPROACH

Presented By

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Motivation

- Gas Electron Multiplier or GEM is a well accepted Micro Pattern Gaseous Detector (MPGD) around the world for its excellent spatial resolution, good time resolution, high rate capability and radiation hardness.

- To understand and optimize the operation parameters of this detector, details study of the underlying physics processes is essential.

- Previously several attempts have been made to simulate different phenomena of GEM using Monte Carlo methods and reported in *NIM. A* **870** (2017) 64 [arXiv:1710.00607] and *JINST* **9** P07025 (2014) [arXiv:1401.4009]

- Here a simulation model based on hydrodynamic approach will be discussed. Ease of incorporating space charge effect and simulating system of large number of particles have motivated such choice.

- The advantages, disadvantages and scope of improvement will be discussed as well.

Simulation framework

- The model is followed from the RD51–NOTE-2011-005, by Paulo Fonte and in RD-51 Open Lectures - 12/12/17–CERN by Filippo Resnati.

- The simulation framework utilizes hydrodynamic approach. The gas molecules, ions and electrons are considered as fluids.
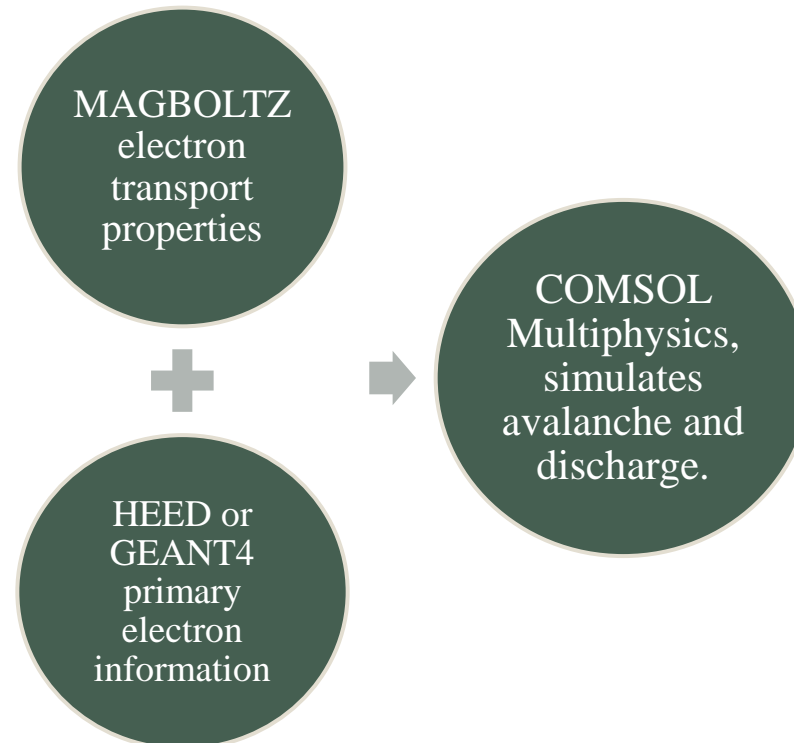
Governing equations

Hydrodynamic equations

$$\frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot (-D\vec{\nabla} n_e + \vec{u}_e n_e) = S_e + S_{ph}$$

$$\frac{\partial n_i}{\partial t} + \vec{\nabla} \cdot (-D\vec{\nabla} n_i + \vec{u}_i n_i) = S_e + S_{ph}$$

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

$$S_{ph} = Q_e \mu_{abs} \psi_0$$

Equations for photon propagation

$$\vec{\nabla}(-c\vec{\nabla}\psi_0) + a\psi_0 = f$$

$$c = \frac{1}{3\mu_{abs}}$$

$$f = \delta S_e$$

$$a = \mu_{abs}$$

Poisson's equation

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

$$\vec{\nabla}.\vec{D} = \rho_v$$

$$\vec{D} = \epsilon_0 \epsilon_r \vec{E}$$

$$\rho_v = \frac{q}{\epsilon_0}(n_i - n_e)$$

| Parameter	Description	Parameter	Description	Parameter	Description
n_e	Electron density	η	Attachment coefficient	μ_{abs}	Photon absorption coefficient
n_i	Ion density	D	Diffusion coefficient	f	Photon source term
$\vec{u}_e$	Electron drift velocity	S_e	Townsend amplification	δ	Photon emitted per ionization
$\vec{u}_i$	Ion drift velocity	S_{ph}	Photo-ionization amplification	c	Photon Diffusion
α	Townsend coefficient	ψ_0	Photon density	ρ_v	Space charge density

Ref: J. Datta et al, *JINST* **15** C12006 (2020), J. Capeillere et al, *J. Phys. D* **41** (2008) 234018.
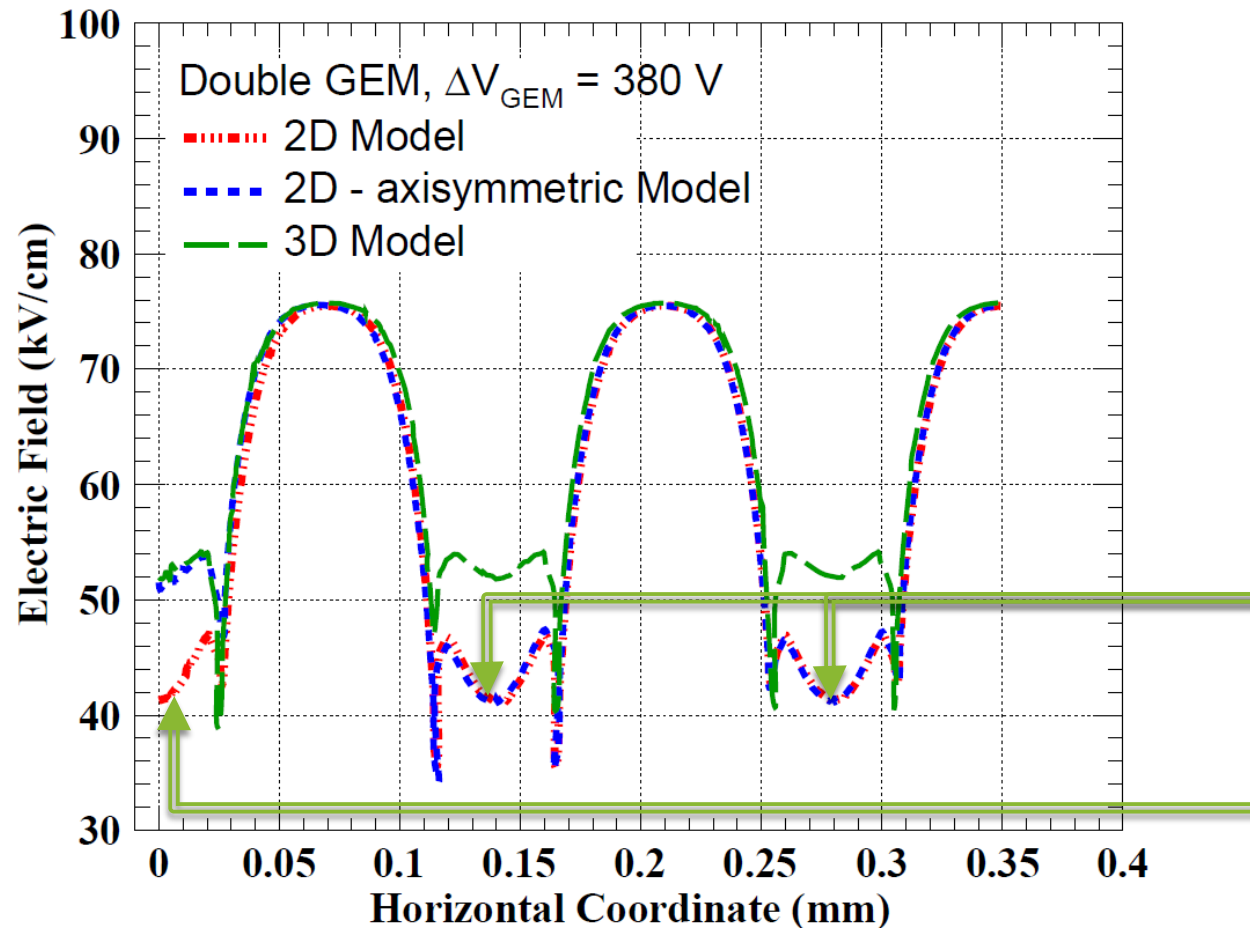
Choice of geometry

(a)

(b)

(c)
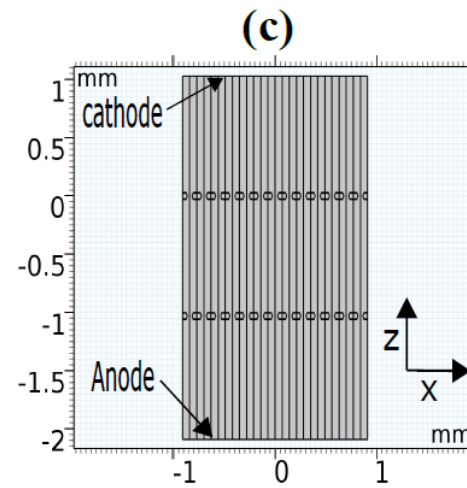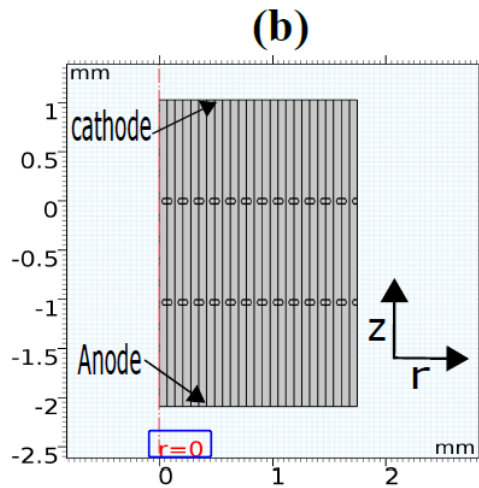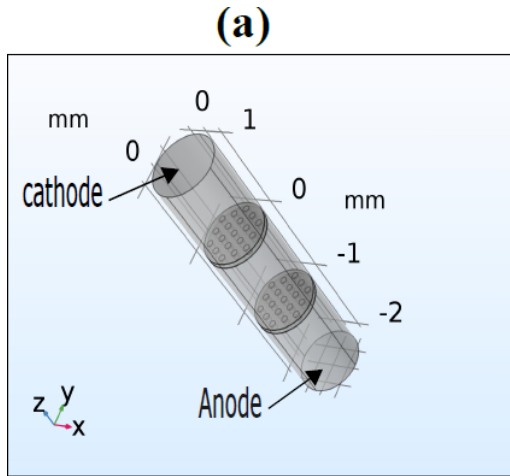
a) 3D geometry of GEM
b) 2D axisymmetric geometry
c) 2D geometry of GEM
d) Top view of 3D GEM foil
e) Top view of 2D axisymmetric model
f) Top view of 2D model.

(d)

(e)

(f)
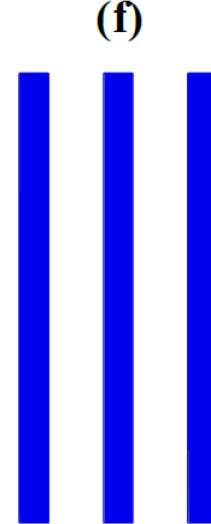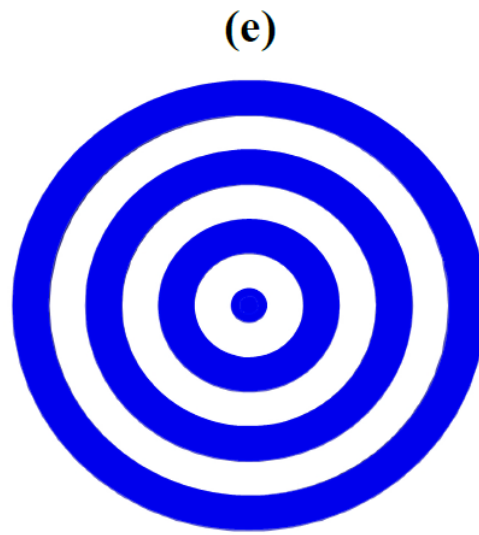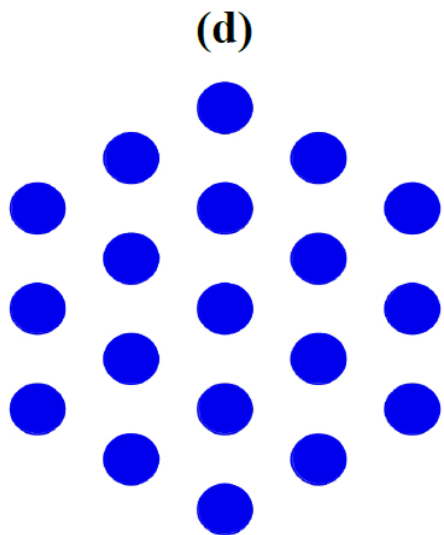
Ref: P.K. Rout *et al* 2021
JINST **16** P02018

Electric field configuration for different geometry

Double GEM, ΔV_{GEM} = 380 V
- ▪▪▪▪▪ 2D Model
- ▪▪▪ 2D - axisymmetric Model
- ▬ ▬ 3D Model

Ref: P.K. Rout *et al*
2021 *JINST* **16** P02018

- Using COMSOL Multiphysics the electric field for different configuration have been calculated.

- For the Central hole of 3D and 2D-axisymmetric model the electric field configuration are in accordance but that of 2D model is far off.

Side holes (3D model)/ Channels (2D axisymmetric model, 2D model)

Central hole (3D, 2D axisymmetric model)/ Channel (2D model)

Boundary conditions

- To incorporate the loss of charged species through the electrodes, it was assumed that the electrode boundaries, that are drift cathode, anode, GEM cathode, GEM anode, are open boundaries.

- The dimension of the simulation volume was chosen such a way that it can contain the whole avalanche and discharge.

- The charged species get accumulated on the surface of the dielectric material. So the dielectric boundaries were chosen to be opaque for them.

Initial seed cluster

- In hydrodynamic approach instead of considering individual primary electrons they will be presented by a seed cluster.

- The properties of the seed cluster has been determined from the information provided by HEED and GEANT4 simulation.

- The number of electrons present in the seed cluster is equal to the total number of primary electrons generated in each event as simulated by HEED and GEANT4.

- The cluster is presented as a 2 variable Gaussian distribution with mean radial position lies on the symmetry axis of the model and the mean axial position equal to the weighted mean of the primary electrons.
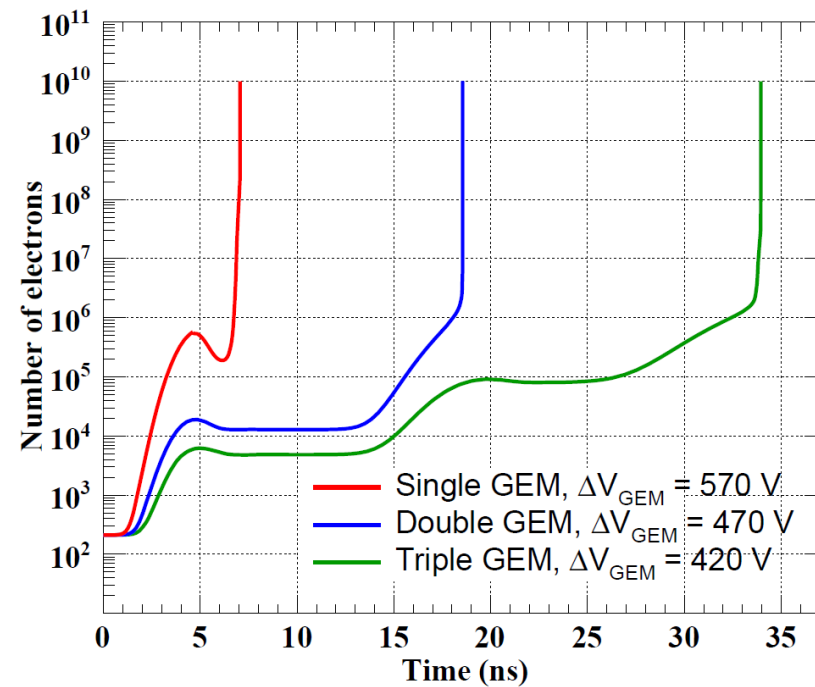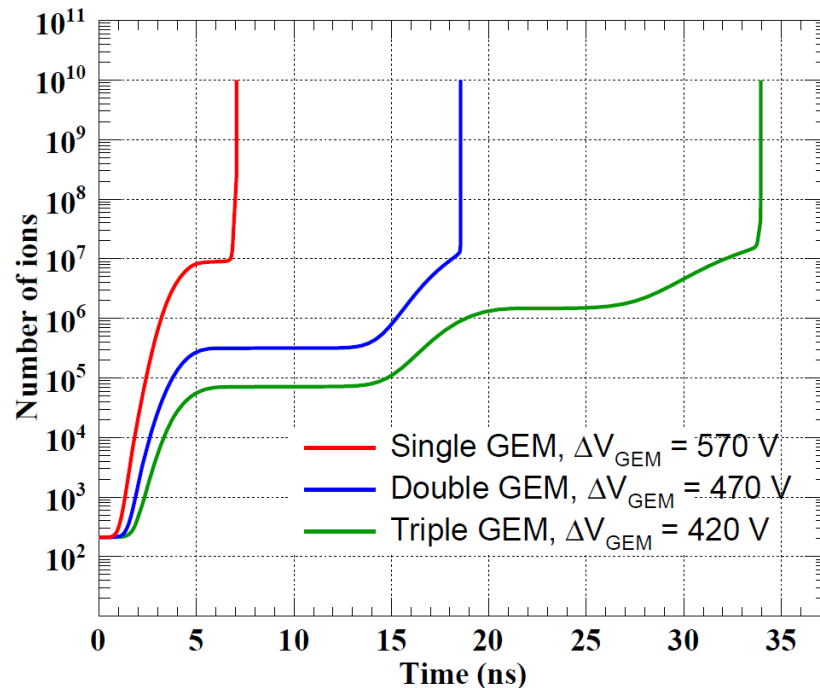
Time evolution of avalanche
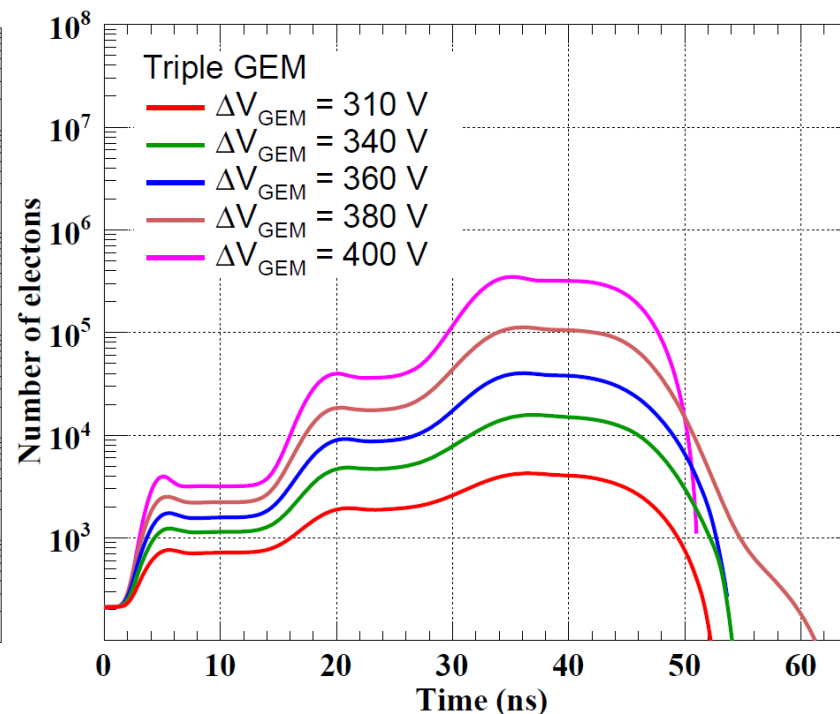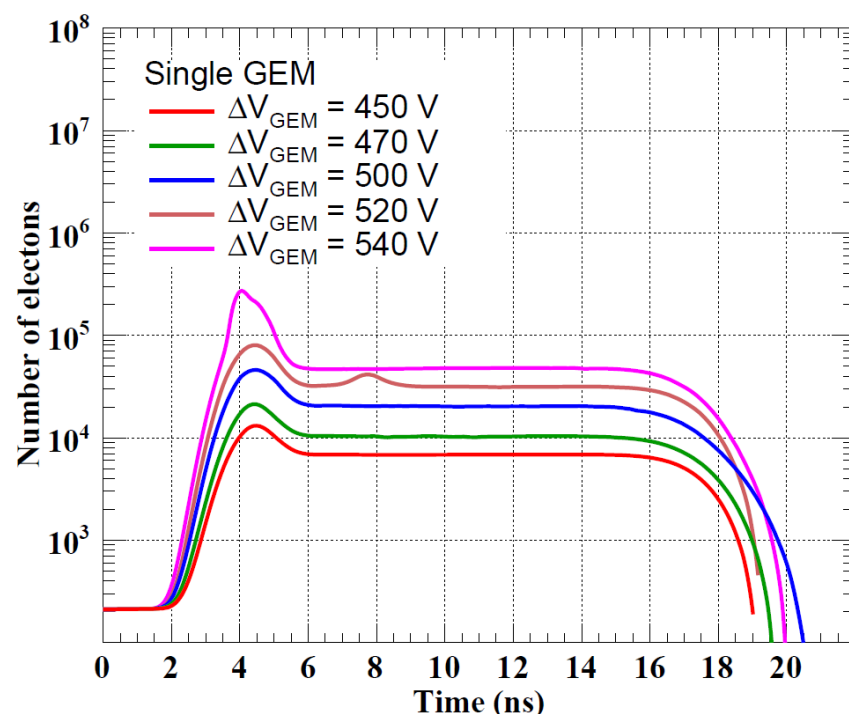
Ref: P.K. Rout *et al* 2021 *JINST* **16** P02018

Time evolution of total electron number in case of avalanche has been shown here. With time the number of electrons initially increases inside the GEM hole. After exiting the GEM hole few of them are lost due to absorption ate GEM anode. In the induction gap the number remains constant and decreases once reaches to the anode. In case of multi GEM loss of electron also occurs due to the diffusion in the transfer gap

Time evolution of discharge

Ref: P.K. Rout *et al* 2021 *JINST* **16** P02018

Time evolution of total electron and ion number for single, double and triple GEM in case of discharge have been shown here. Unlike the total when discharge occurs the number of electrons and ions starts rising very fast. Unlike the electrons, loss of ions cannot be observed in the plots. Due to the much less drift velocity and diffusion coefficient of the ions, in this small time frame they cannot reach to the cathode or dielectric. So their loss can't be realized here.

Fluctuation of parameters

- In experimental scenario the growth of avalanche experiences many source of fluctuations. Out of these sources two are
  - Fluctuations of the electron transport properties.
  - Fluctuations of seed cluster.

- Fluctuation of seed cluster are following
  - Fluctuation of total number of primary electrons (n).
  - Fluctuation of the mean z-position.
  - Fluctuation of the radial spread (r-spread).
  - Fluctuation of the axial spread (z-spread).

Fluctuation considered

Fluctuation	Energy resolution calculation	Discharge probability calculation
Fluctuations of the electron transport properties	NO	NO
Fluctuation of total number of primary electrons (n).	NO (Work initiated)	YES
Fluctuation of the mean z-position	YES	NO
Fluctuation of the radial spread	YES	YES
Fluctuation of the axial spread	YES	NO

- To compare these parameters with experimental data, simulation of energy resolution has been done for Fe^{55} gamma source and discharge probability has been calculated for Am^{241} alpha source.
- The primary ionization due to alpha source is nearly uniform through out the drift gap, so mean z-position and its spread have not been varied.

Energy resolution

Parameter	Description
E	Energy of the gamma source (5.9 keV)
ΔE_{FWHM}	Full width at half maxima of the measured energy distribution
σ_E	Standard deviation of the measured energy distribution
F	Fano factor (~0.23)
$\sigma_{\bar{G}}$	Standard deviation of the average gain
$\bar{G}$	Average Gain
$\bar{n}$	Mean number of primary electrons (211)
Δ_0	Other systematic fluctuations (zero)

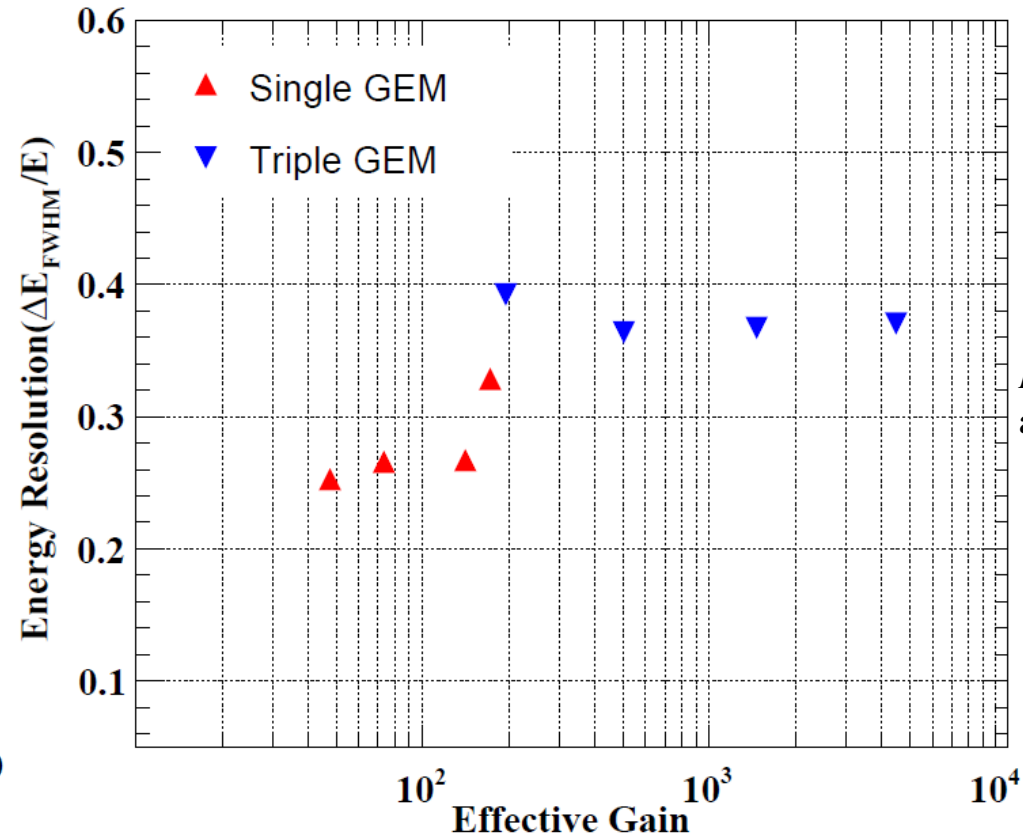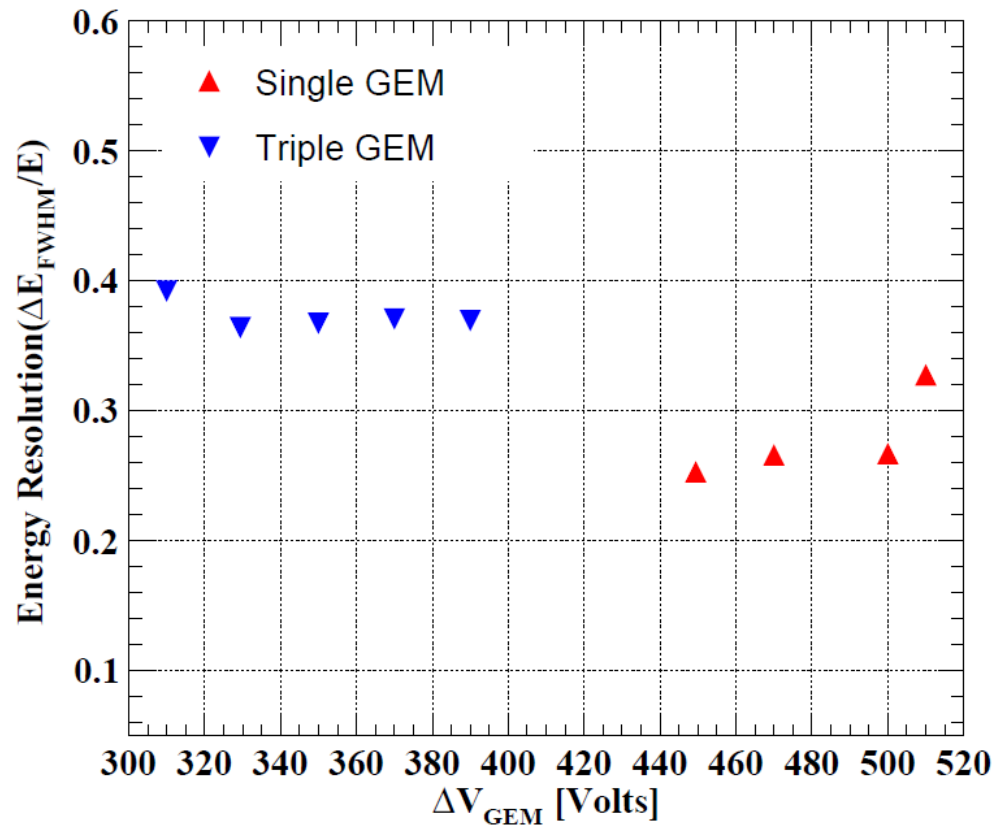- The simulation for energy resolution has been done for Fe^{55} gamma source (5.9 keV).

- The energy resolution has been defined as

$$\frac{\Delta E_{FWHM}}{E} = 2\sqrt{ln4}\ \frac{\sigma_E}{E} \approx 2.355\ \frac{\sigma_E}{E}$$

where $\frac{\sigma_E}{E} = \sqrt{\frac{F}{\bar{n}} + \left(\frac{\sigma_{\bar{G}}}{\bar{G}}\right)^2 + \Delta_0^2}$

Ref: "Development of Micro - Pattern Gaseous Detectors – Micromegas", Jonathan Bortfeldt
"Numerical estimation of discharge probability in GEM-based detectors" P.K. Rout *et al* arXiv: 2103.12849
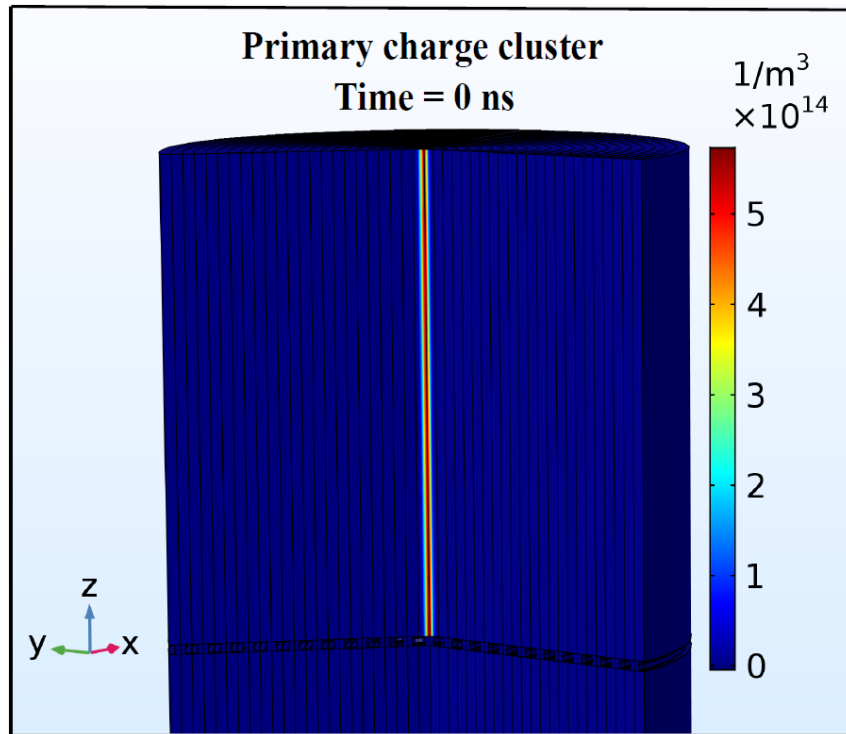
Energy resolution

Ref: P.K. Rout *et al*
arXiv: 2103.12849

- The simulated energy resolution for single GEM is around 25% and that of triple GEM is around 35 % which is similar to the reported results in the work by S. Y. Ha et al. (J. Korean Phys. Soc.55(2009) 2366.)

Primary electrons for discharge simulation

Ref: P.K. Rout et al arXiv: 2103.12849

- The discharge probability has been calculated for Am^{241} alpha source.
- We have compared our simulated discharge probability with the experimental results presented by Bachmann et al. (NIM A **479**, 294-308 (2002)).
- The information regarding the primary electrons was calculated using GEANT4, where we have tried to mimic the experimental setup.
- The discharge simulations were carried out for vertically passing alpha particles. The probability of such events, calculated from GEANT4 simulation, has been multiplied to get the final discharge probability.
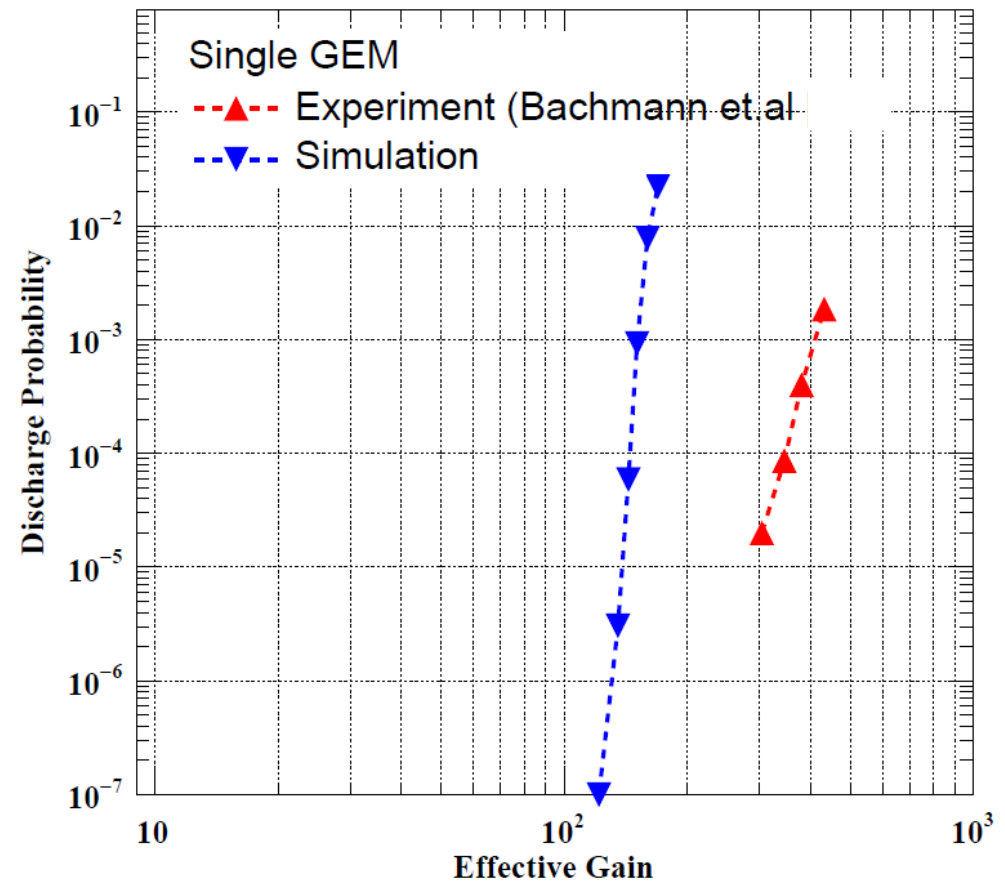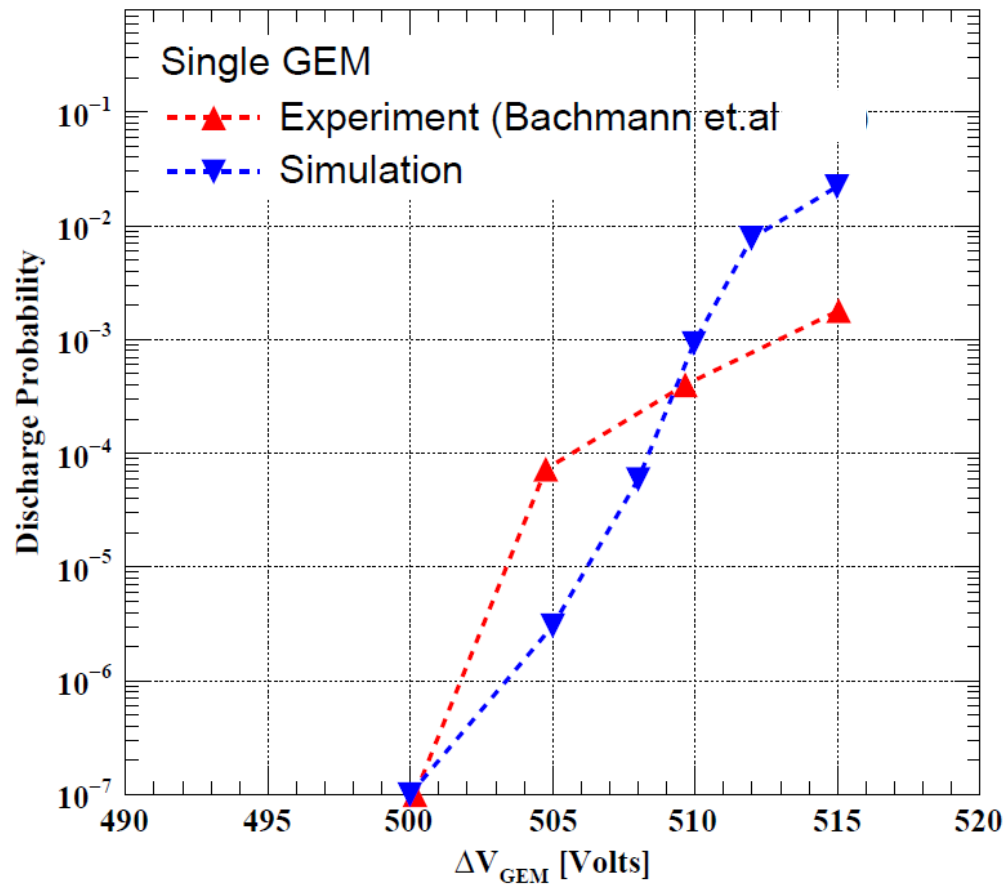
Discharge probability calculation
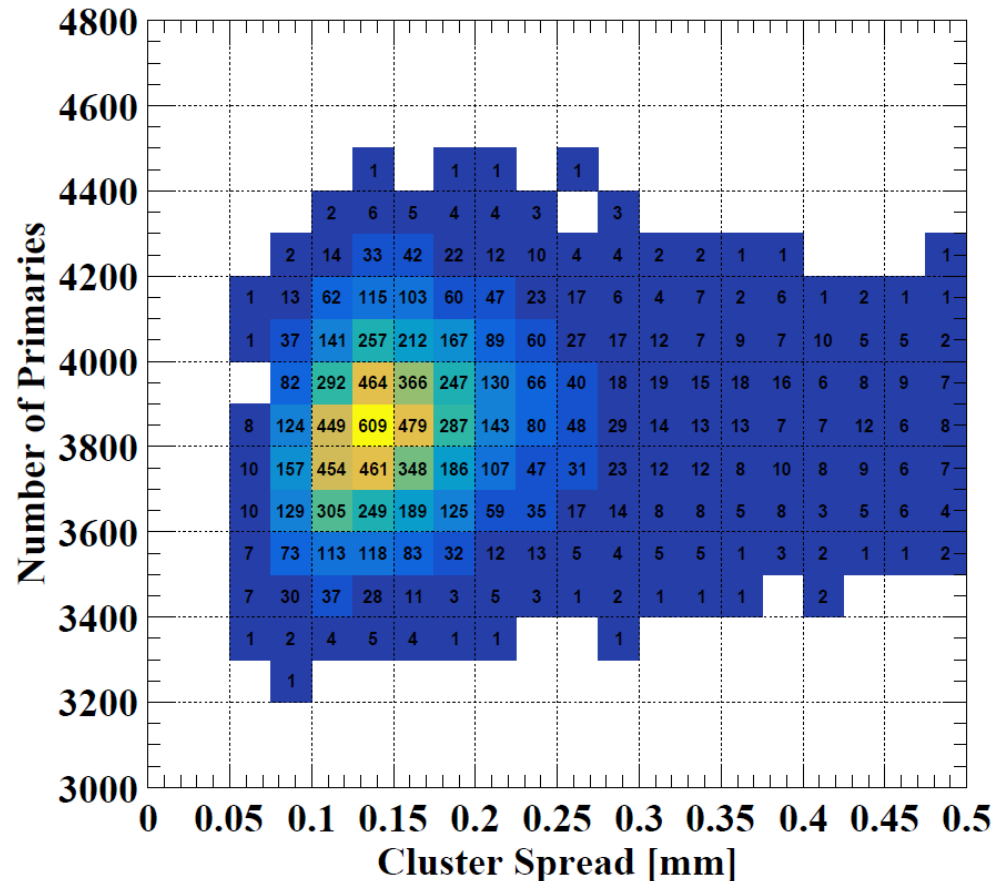
Ref: P.K. Rout *et al* arXiv: 2103.12849

- Number of primary electrons has been varied in steps of 100 between 3200 to 4500.

- Spread of the cluster has been varied in step of 0.025 mm between 0.05 mm and 0.5 mm.

- A discharge has been identified by the total number of electrons ($\approx 5 * 10^6$), which has been found in our earlier work and supported by experimental data also (NIM A **870**, 116-122 (2017), 2021 *JINST* **16** P02018).

- From simulation it was found out, for each applied voltage, for what value of cluster spread and primary electron number, discharge occurs.

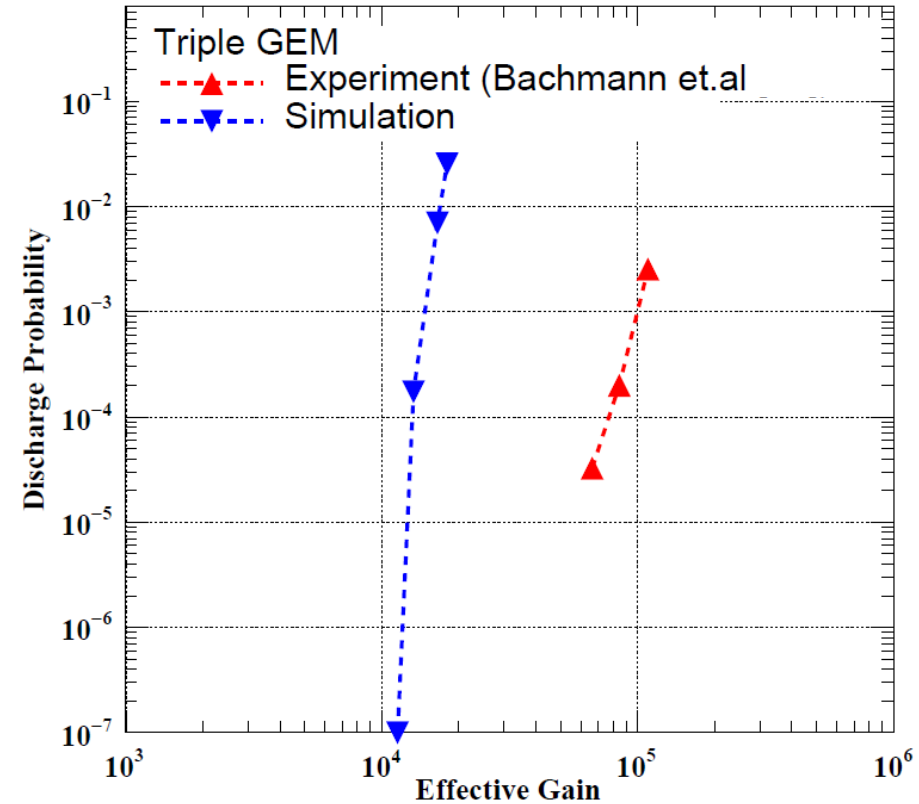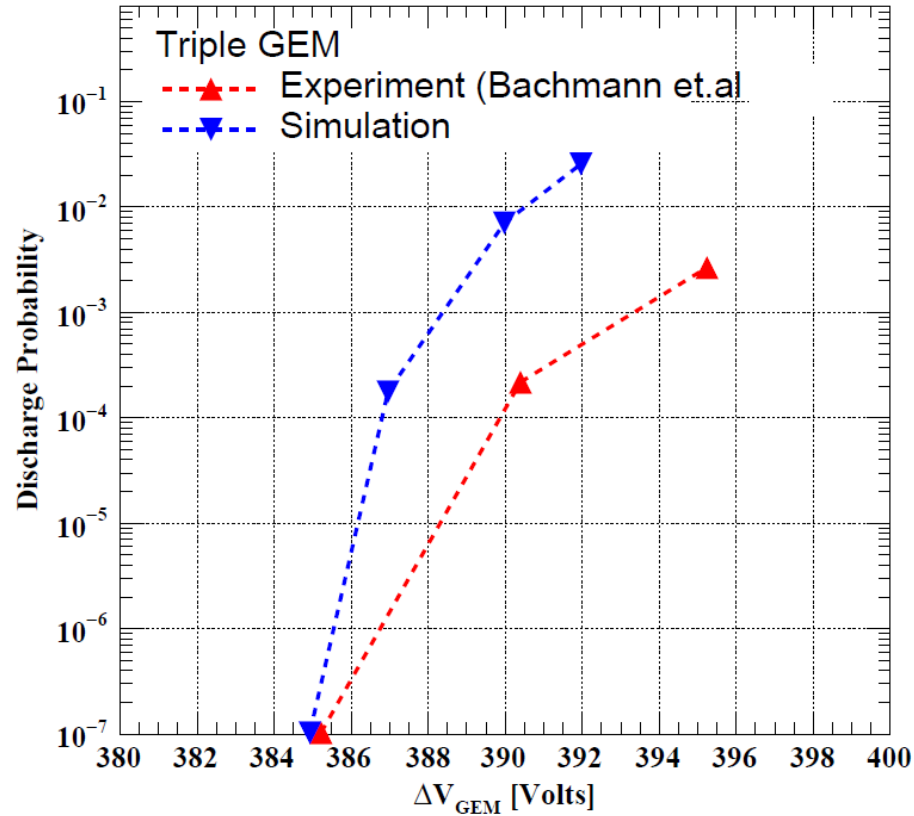- The effect of charge sharing has been included.

Result for single GEM

- The simulated discharge probability differs from the experimental one by at least one order of magnitude, but the trend in simulation closely follows that of the experiment.

Ref: P.K. Rout *et al* arXiv: 2103.12849; Bachmann et al NIM A **479**, 294-308 (2002).

Result for triple GEM

- The simulated discharge probability differs from experimental result by at least one order of magnitude, but the trend in simulation closely follows that of the experiment.

Ref: P.K. Rout *et al* arXiv: 2103.12849; Bachmann et al NIM A **479**, 294-308 (2002).

Discharge probability as function of asymmetric voltage distribution

- $\Delta V_{GEM1} > \Delta V_{GEM2} > \Delta V_{GEM3}$ and $(\Delta V_{GEM1} - \Delta V_{GEM2}) = (\Delta V_{GEM2} - \Delta V_{GEM3})$. ΔV_{GEM2} is constant.

- The simulated discharge probability is different from the experimental results by order of magnitude. But the trend in simulation closely follows that of the experiment, which leads to similar conclusion from both the experiment and simulation.
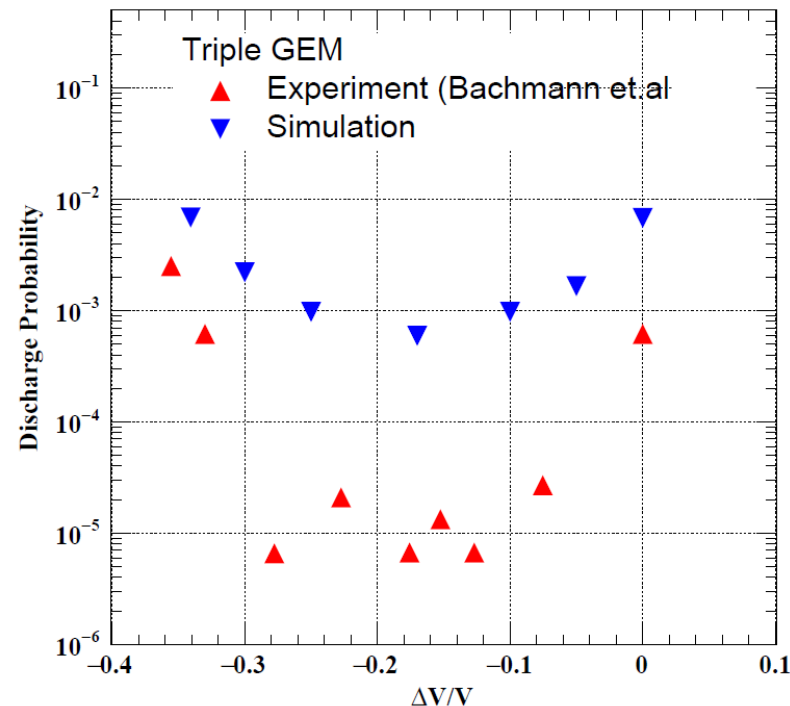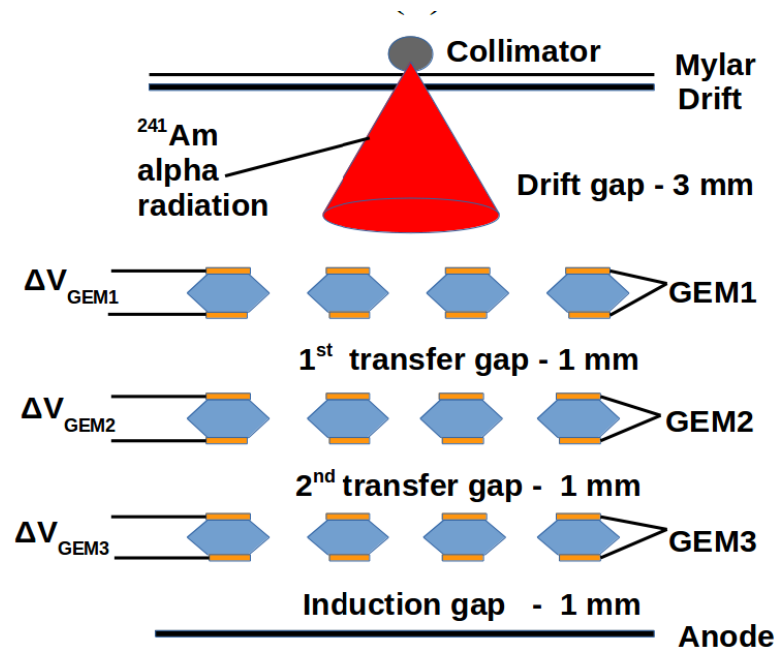
Ref: P.K. Rout *et al* arXiv: 2103.12849; Bachmann et al NIM A **479**, 294-308 (2002).

Conclusion

- The hydrodynamic approach to simulate avalanche and discharge has been discussed.

- The model uses 2D axisymmetric geometry to simulate the time evolution of avalanche and discharge in the detector assuming the gas molecules and charged particles as fluid. Space charge effect has been included in the model.

- Assuming the particles as fluid takes away the source of different fluctuations in detector properties that are usually observed in experiment.

- As a 2D axisymmetric model has been assumed, it deviates from the actual 3D scenario.

- This method is fast and in reasonable time one can simulate energy resolution and discharge probability of GEM.

- The simulated discharge probability differs from the experimental data by orders of magnitude.

- Even with all the approximation and assumptions the simulation model is capable to reproduce the similar trend of different detector properties as observed in experiments which leads to similar conclusion as the experiment.

- We are working on improving the model by making it more realistic.

Our Group

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Acknowledgement

Thank you