Numerical simulation of charging up, accumulation of space charge, and formation of discharges

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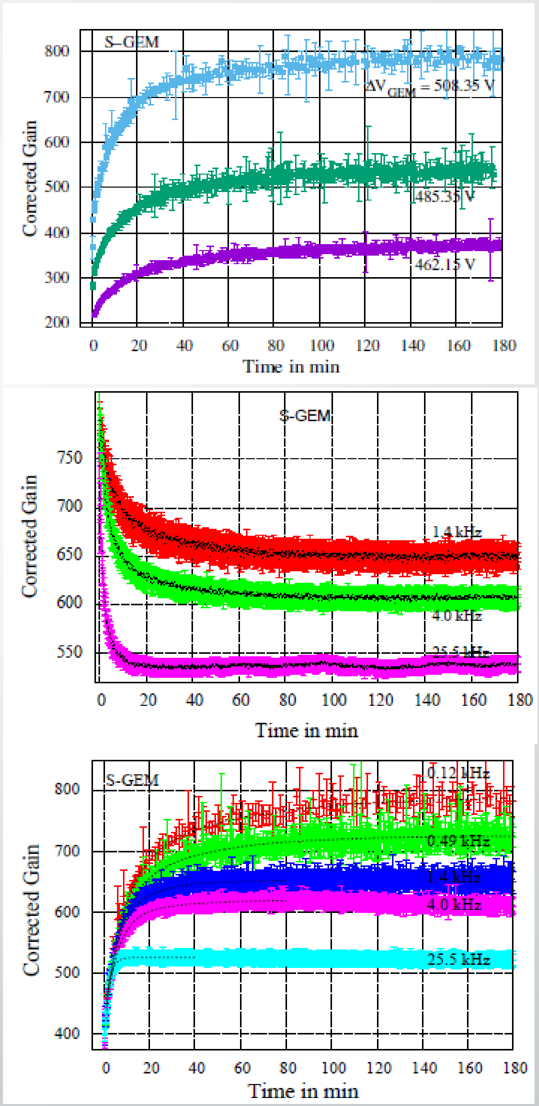
Brief Introduction

- Charging up → response non-uniformity, long-term stability.
- Accumulation of space charge → response non-uniformity and discharge formation
- Formation of discharges / sparks → instability and aging.
- This presentation will include
  - an overview of the numerical work that we have carried out by our group till recent past
  - new areas that are being explored at present
  - indicate future directions
  - rather than following the transport dynamics rigorously in the illustrated examples, we will try to evaluate the consequences few possible scenarios.
  - discuss only GEMs and RPCs.

Section 1: Charging up simulation

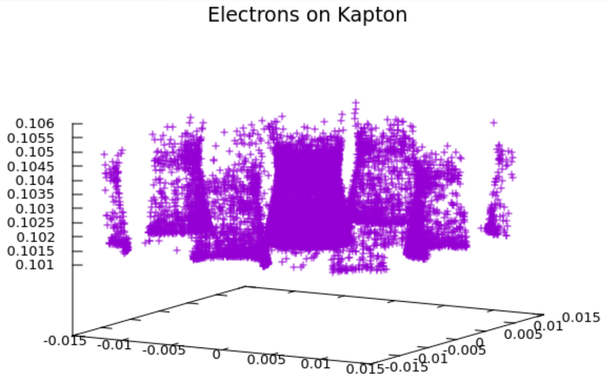
- The exact effect of charging up can depend on the experimental conditions. For example, muon imaging may have negligible effect, while high rate experiments can suffer significantly. Moreover, if the radiation rate changes, the radiation charging up effect may vary as well. The polarization charging up effect can vary if voltage configuration of detectors are modified.
- Avalanches occur in 10-s of ns, while charging up builds up over hours.
- Event rate can play an important role.
- Difficult to visualize a model that will be valid for all relevant time scales.
  - Avalanches need microscopic modelling
  - Charging up build-up needs macroscopic modelling
  - Event rate can be very slow (seconds) to extremely fast (ns).

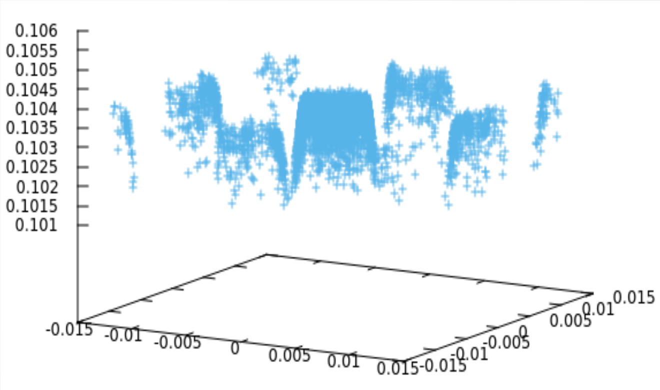


Studies on charging-up of single Gas Electron Multiplier, Kumar et. al, JINST, https://doi.org/10.1088/1748-0221/16/01/P01038

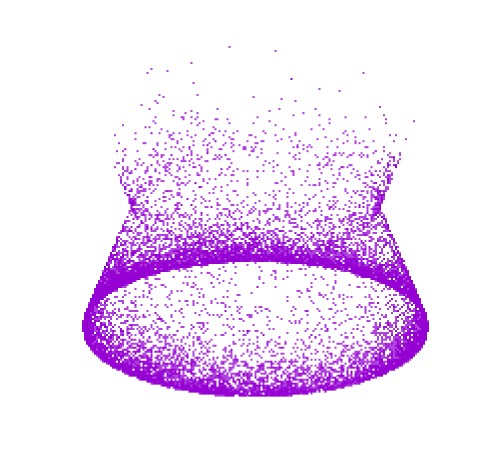
Deposition of charged particles in a GEM

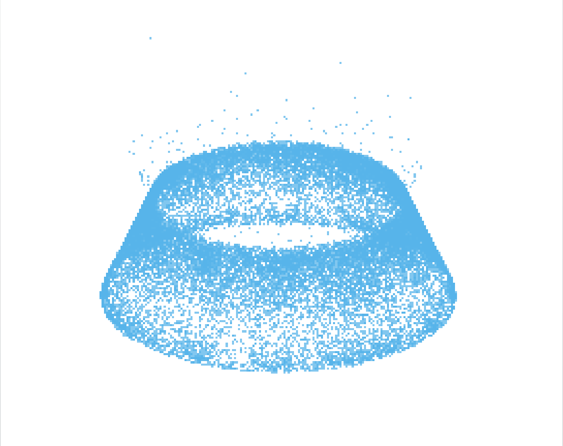
- More ions are towards the lower-middle of the Kapton foil.
- More electrons towards the lower-bottom of Kapton foil.
- Electrons are less constrained.
- There is considerable overlap.





Electrons and ions on the surface of several GEM holes

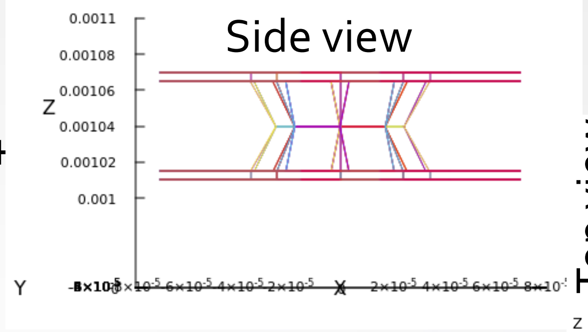


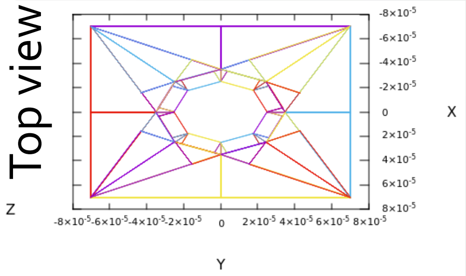


Electrons and ions on the surface of one GEM holes

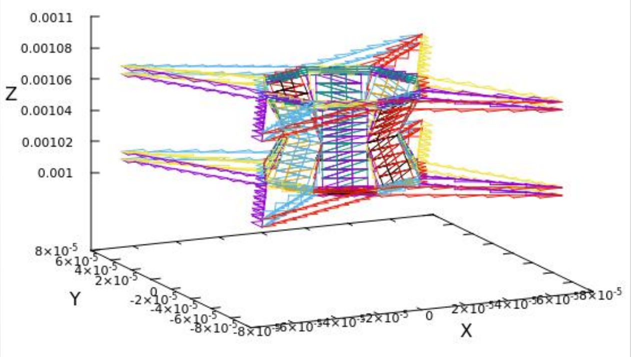
Two algorithms in particle model

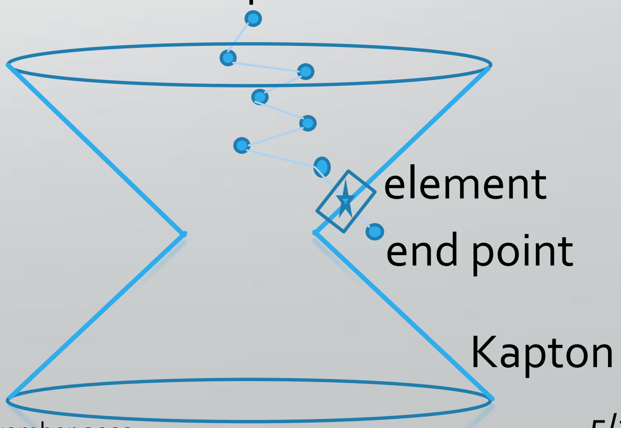
- Algo 1: Use end-points provided by Garfield++
  - Consider the ending point of charged particles. Garfield++ tries to terminate a drift line close to the boundary.
- Algo 2: Assign surface charge densities to elements
  - Identify the element on which the charged particles falls. Add all the charged particles on an element to estimate a surface charge density.
- For small number of charged particles, algo 1 is good.
- For large numbers, algo 2 may be more useful.



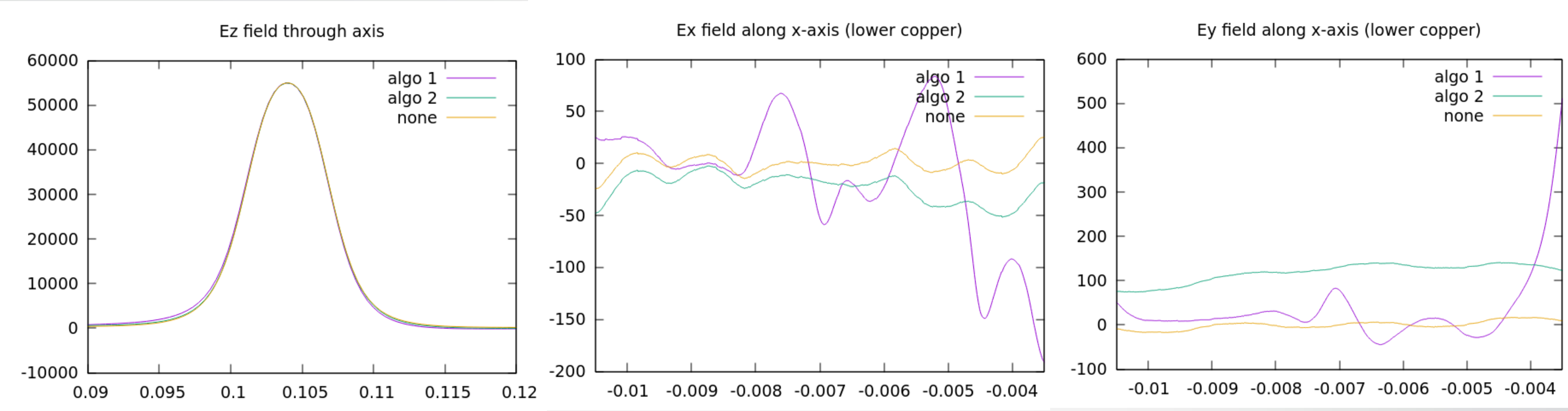


Some elements representing a GEM hole





Effects of charging up



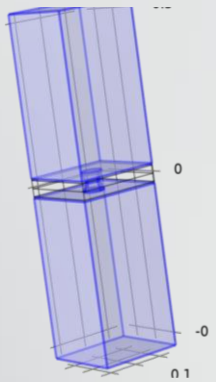
Note that the lines do not exactly overlap.

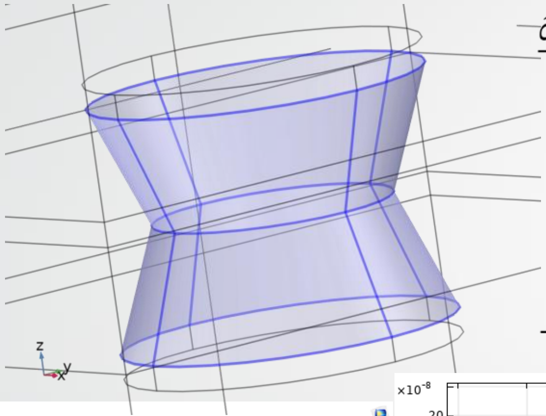
Points to be noted:

- Device geometry is unchanged from that shown earlier.
- Number of charge deposited per element has wide variation – no circular symmetry for one event.
- The symmetry may be regained due to overlap of a large number of events.

Hydrodynamic model - charge collection

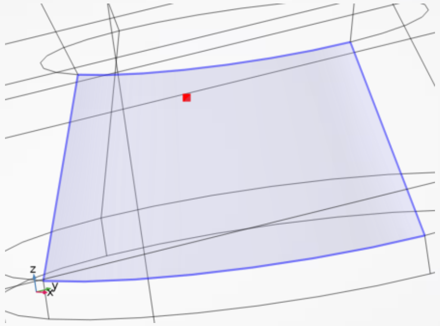
- This will, hopefully, also lead us to the long term model

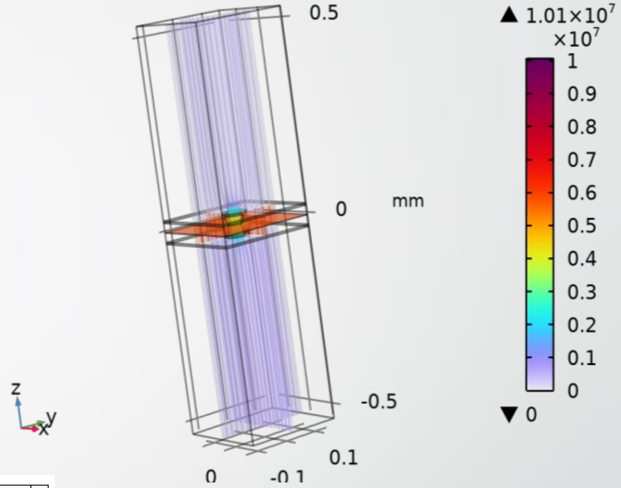


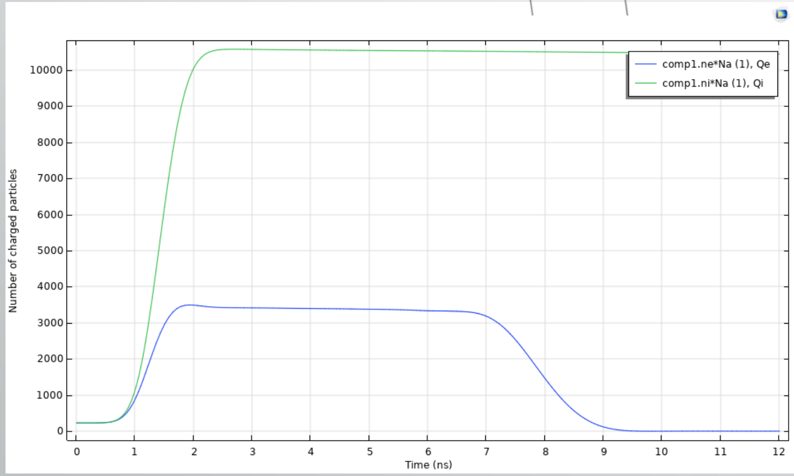


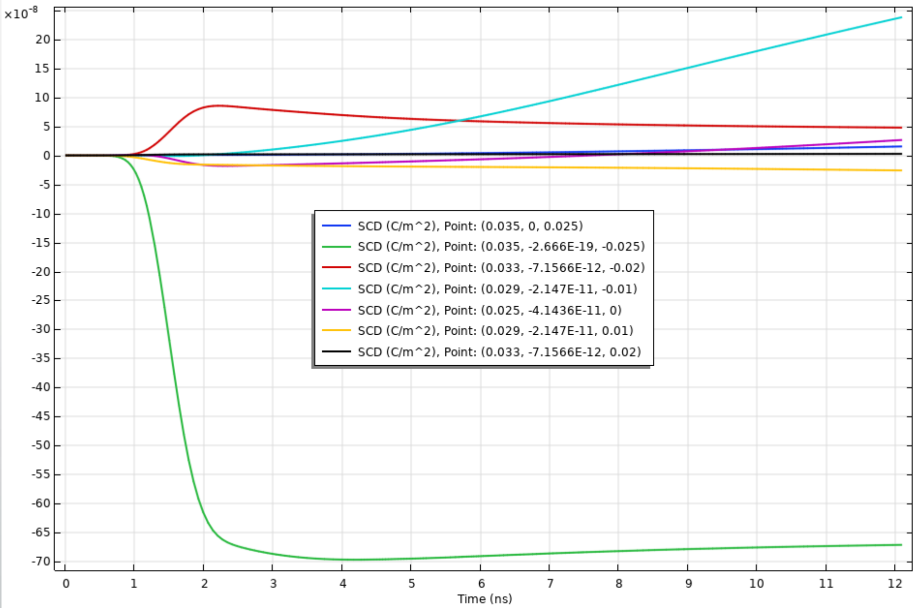
$$\frac{\partial \rho_s}{\partial t} = \mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e$$

$$-\mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$$





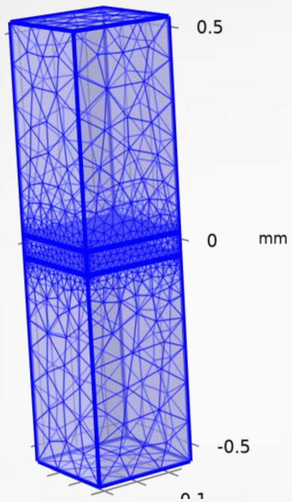


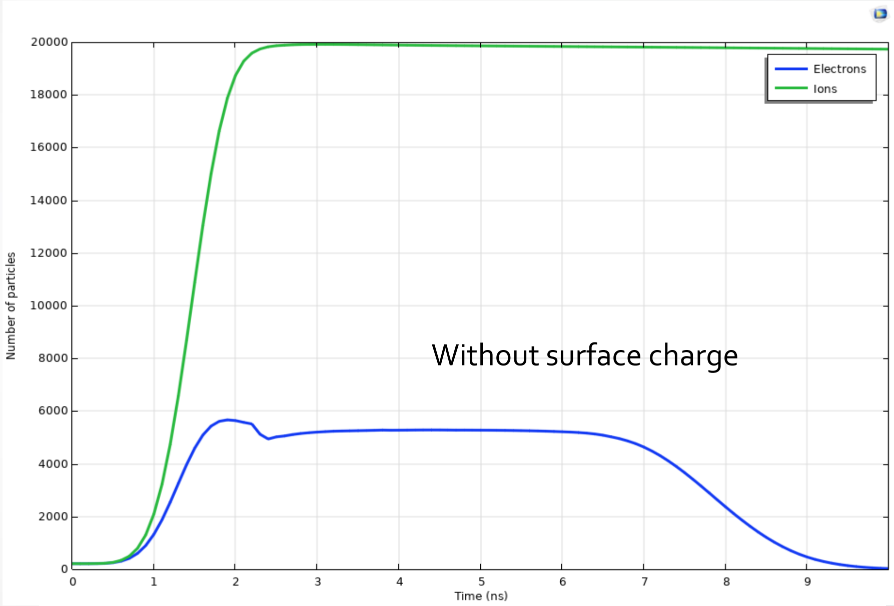


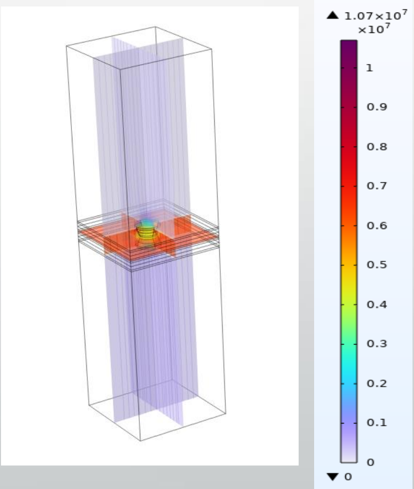
- Charge is accumulated more towards the induction / transfer volume.
- Hardly any charge is found on surface towards drift volume.
- More negative charges towards induction / transfer volume.
- Some positive charges around the middle of the hole.
- Note that only collection is simulated at present. Modelling loss of charges will need further efforts.

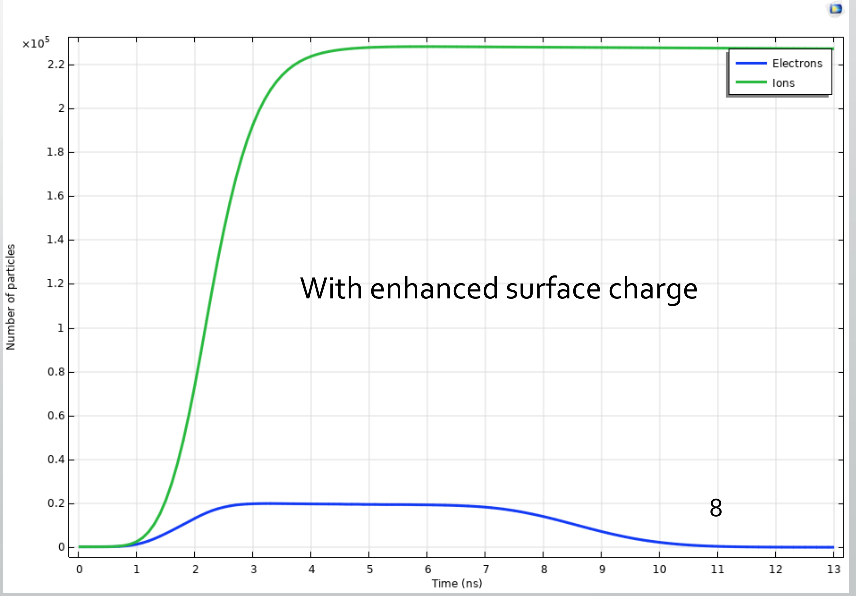
Charging up effects using hydrodynamic model

- The same event is simulated using a hybrid model.
- Initial conditions, transport properties are obtained from Garfield++.
- Electric field, charged particle transport using Comsol, an FEM package.
- With enhanced surface charge applied manually (collected charges made 100 times), the gain value is found to increase significantly.







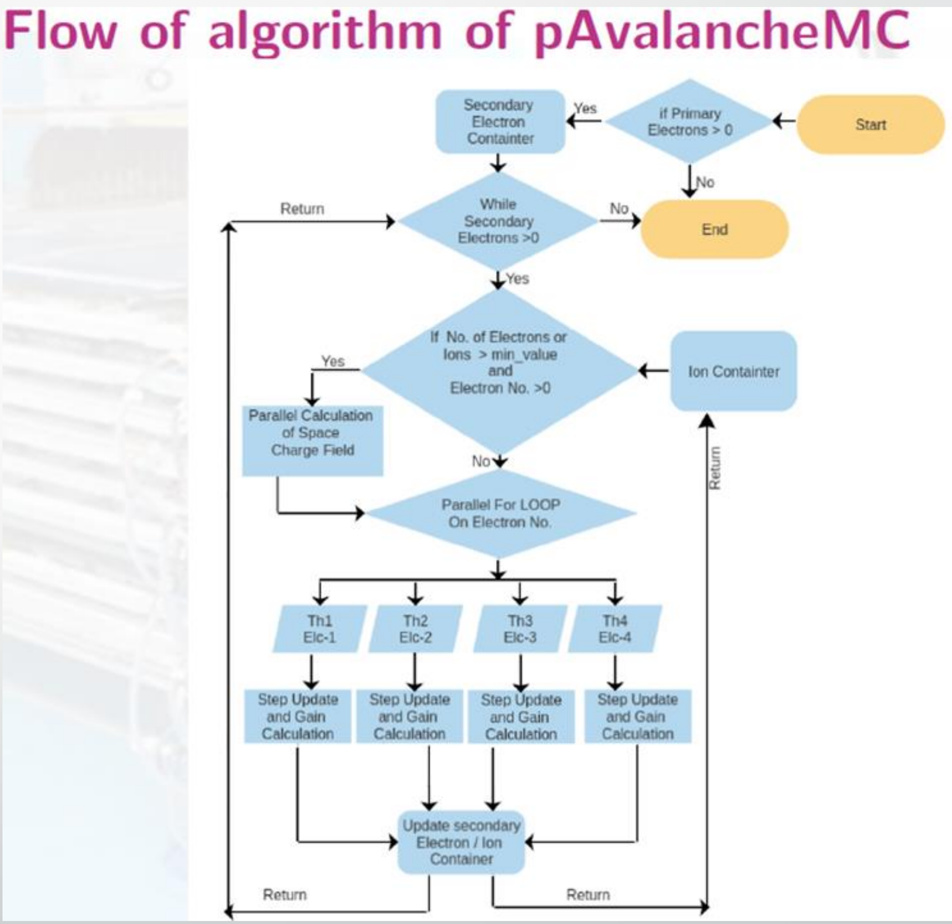


Section 2: Space charge simulation

- Since ions move rather slow, some accumulation of ionic space charge is almost always unavoidable.
- Given suitable combination of parameters, and presence of an ionic cloud, electron clouds can also form.
- True for almost any gaseous detector – wire chambers, RPC, MPGDs, TPCs (imaged for visualization)
- In effect, applied electric field gets distorted, modifying detector response.
- Can lead to discharges / sparks.
- Models valid for both short- and long-term are necessary.

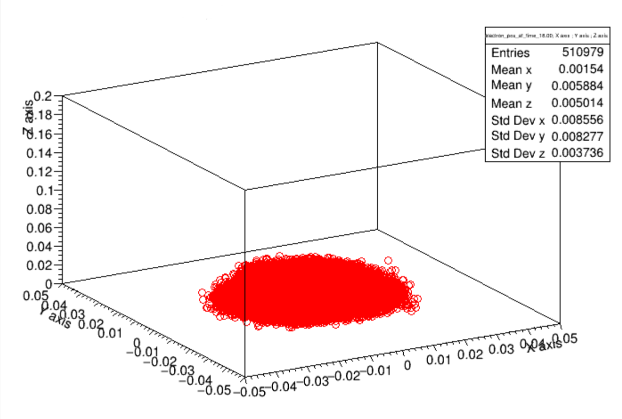
RPC space charge using particle model

- In Garfield++, a new class has been added to the existing framework:
- `pAvalancheMC` (loosely based on class `AvalancheMC`)
- The new class contains several new functions such as
  - `SetNumberOfThreads(20)` – carries out OpenMP parallelization.
  - `SpaceChargeEffectOn()`
  - `SetMinSpCharge(1e4,0)`
  - `SetGridElements(dthta, dx, dy, dz, dr)`
  - `SetElectrodePropertise(thickness, thickness, gasgap, epsilon, true);`
  - `SetElectrodeLocations(electrode_Center1_alongz, electrode_Center2_alongz, gas_Center_alongz);`
  - `GlobalTimeWindow(time);`
- etc …
- Till now, specific to RPCs.

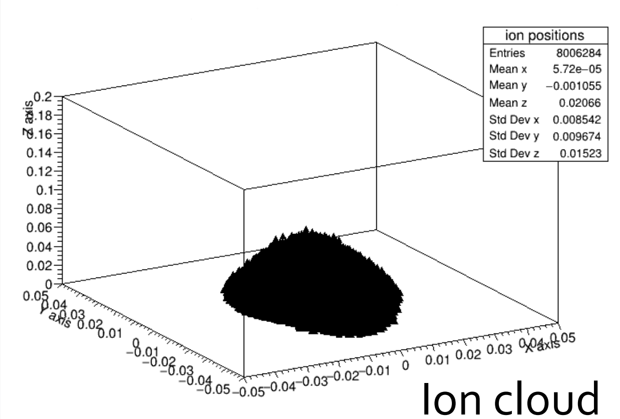


Space charge with particle model

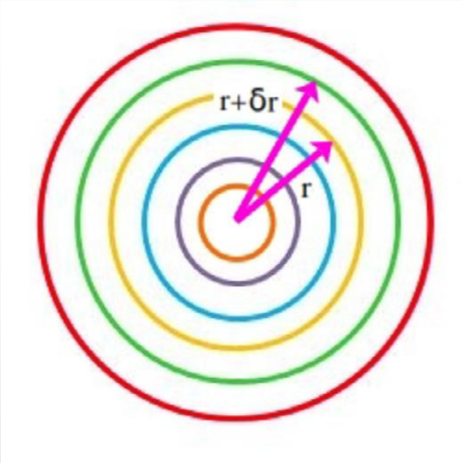
- Considering each and every charge individually is extremely difficult.
- Several representations of the space charge were tried:
  - rings with image charges
  - lines with image charges

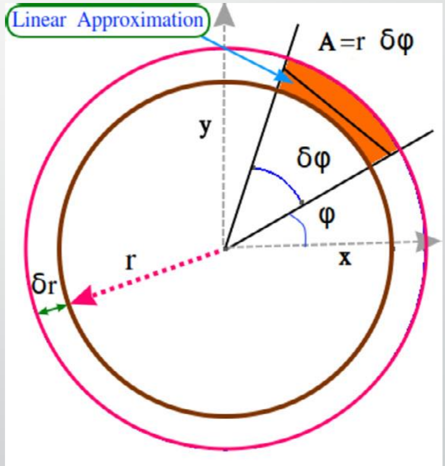


Electron cloud



Ion cloud



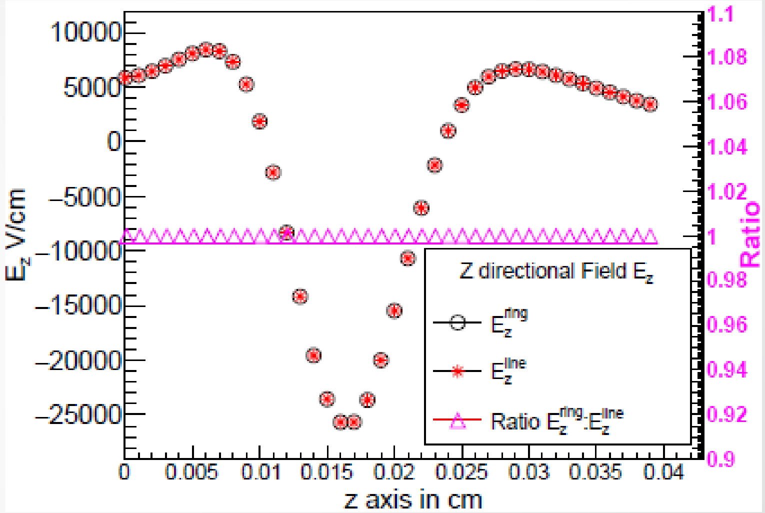


Parallelization of Garfield++ and neBEM to simulate space-charge effects in RPCs, Dey et al., CPC, https://doi.org/10.1016/j.cpc.2023.108944

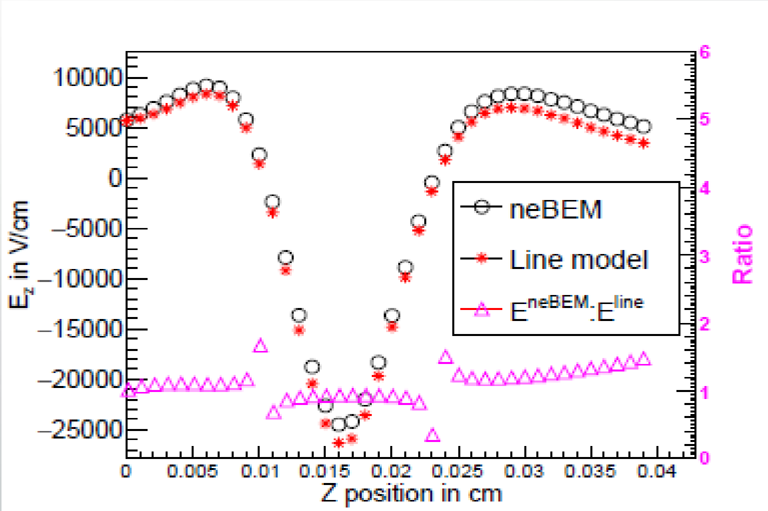
Numerical study of effects of electrode parameters and image charge on the electric field configuration of RPCs, Dey et al, JINST, https://doi.org/10.1088/1748-0221/17/04/P04015

Performance of these representations

- Results from ring and line were compared.
  - No differences observed in this case
  - Can be quite different if the avalanche is not symmetric in θ.

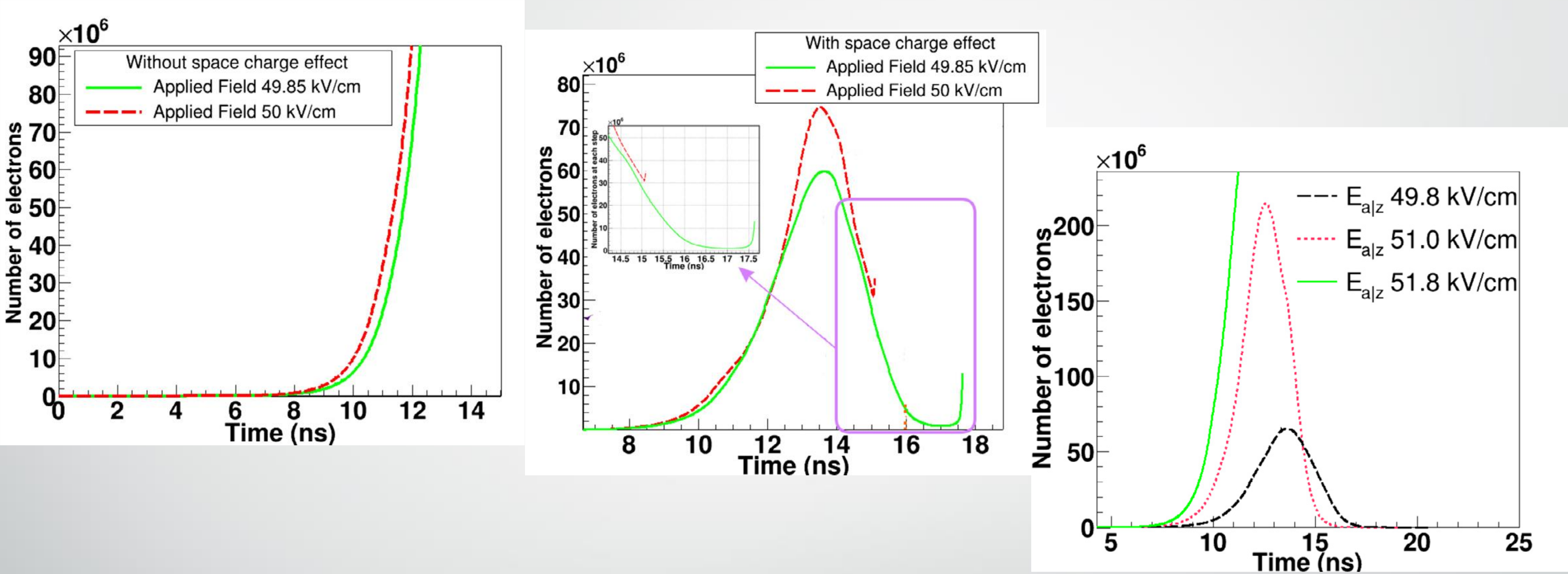


- Results were also compared with already existing line representation of neBEM
  - Good overall agreement



Numerical study of space charge electric field inside Resistive Plate Chamber, Dey et al, JINST, https://doi.org/10.1088/1748-0221/15/11/C11005

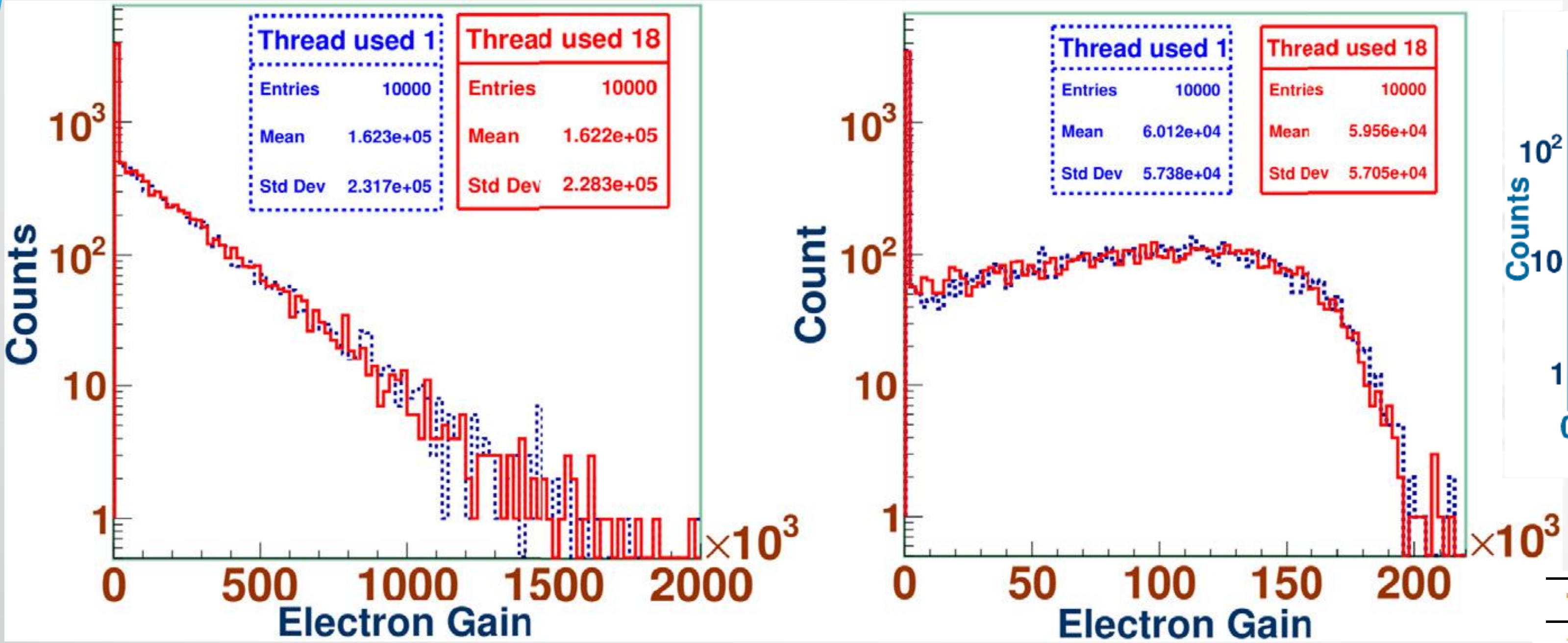
Effect of space charge in an RPC

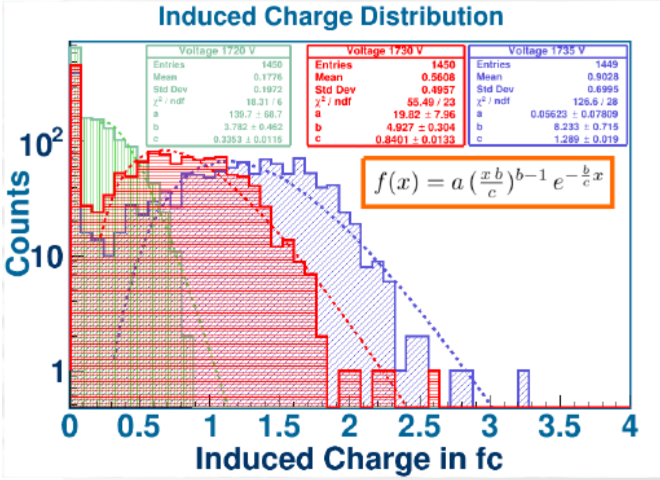


Variation of number of electrons with time steps of the avalanche for electric fields of 49.85 kV/cm, and 50 kV/cm, (a) without space-charge effect, (b) with space-charge effect, (c) considering negative ions .

Parallelization of Garfield++ and neBEM to simulate space-charge effects in RPCs, Dey et al., CPC, https://doi.org/10.1016/j.cpc.2023.108944

Effect on gain distribution





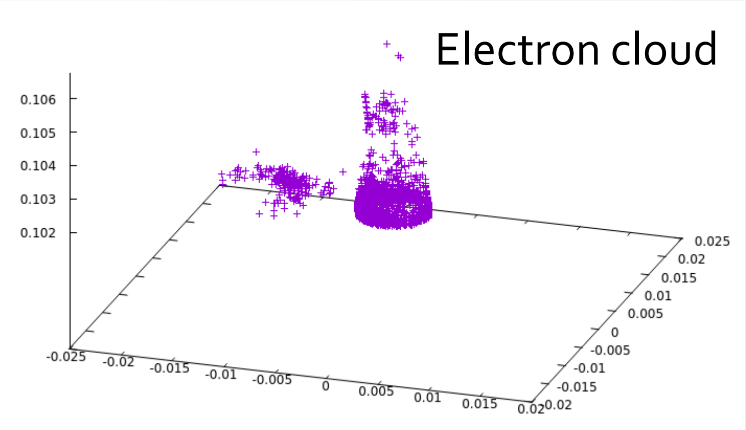
Voltage (V)	a	b	c (fc)
1720	139.7 ± 68.7	3.8 ± 0.5	0.34 ± 0.01
1730	19.8 ± 7.9	4.9 ± 0.3	0.8 ± 0.01
1735	0.06 ± 0.07	8.2 ± 0.7	1.3 ± 0.02

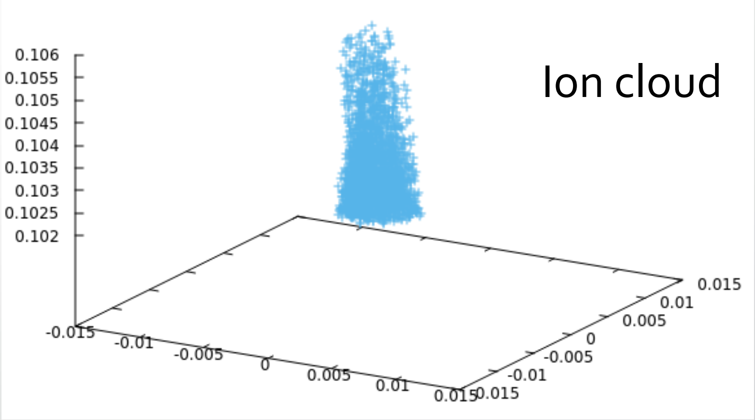
Distribution of electron gain for 10^4 avalanches (a) without space-charge effect, and (b)with space-charge effect.

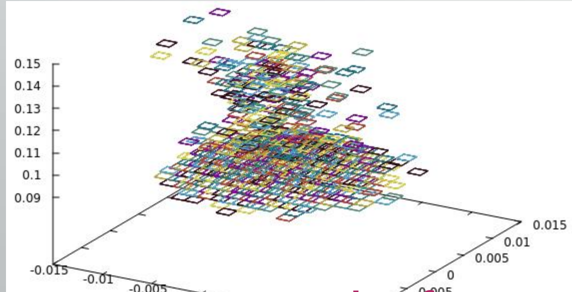
Parallelization of Garfield++ and neBEM to simulate space-charge effects in RPCs, Dey et al., CPC, https://doi.org/10.1016/j.cpc.2023.108944

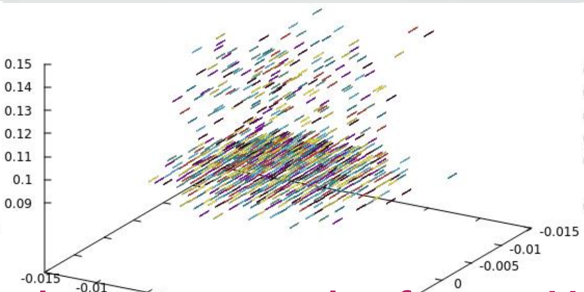
Space charge in GEM – particle model

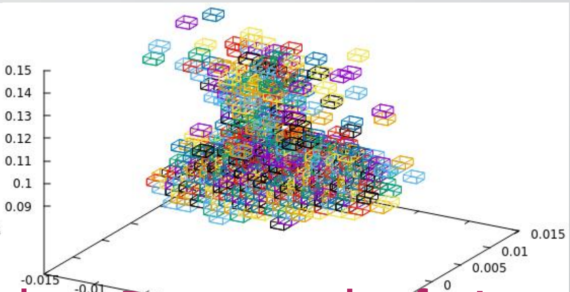
- Existing:
  - point
  - line
  - ring
  - area
  - volume (point in cell – PIC)
- Future:
  - disc (formulation available; long expressions, but doable)
  - volume (???)





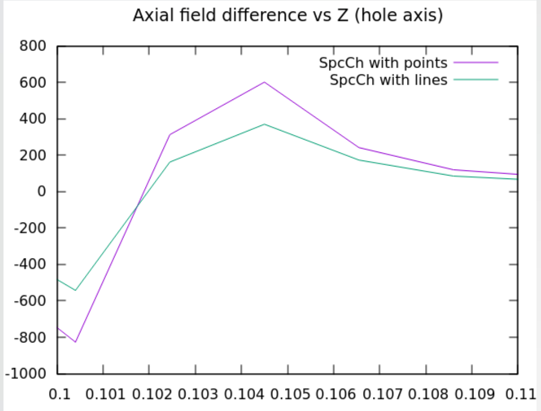

Area Representation for Ions

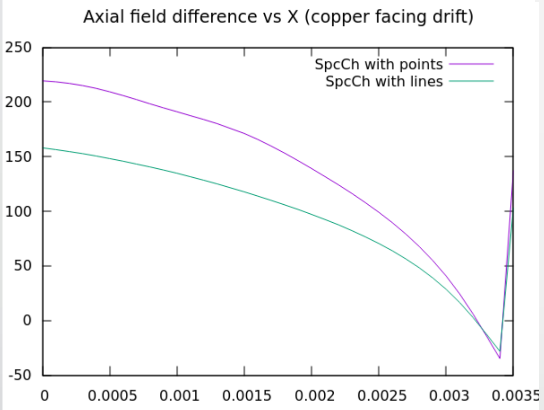

Line Representation for Ions

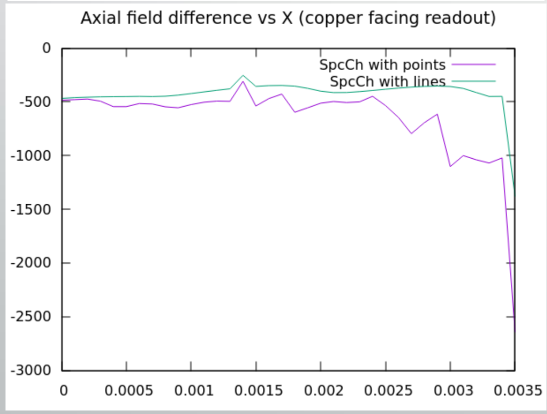

Volume Representation for Ions

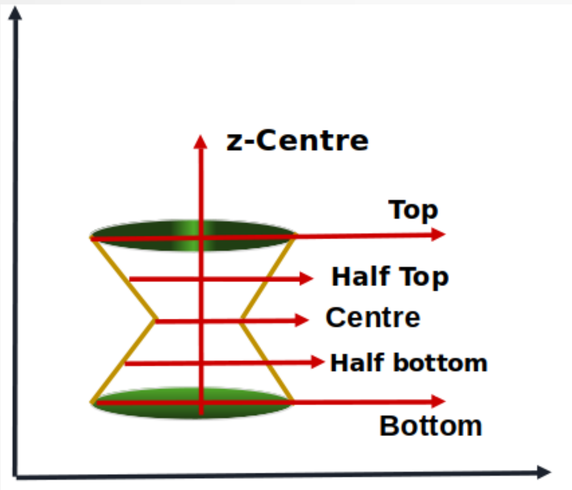
Different field lines

Particle model



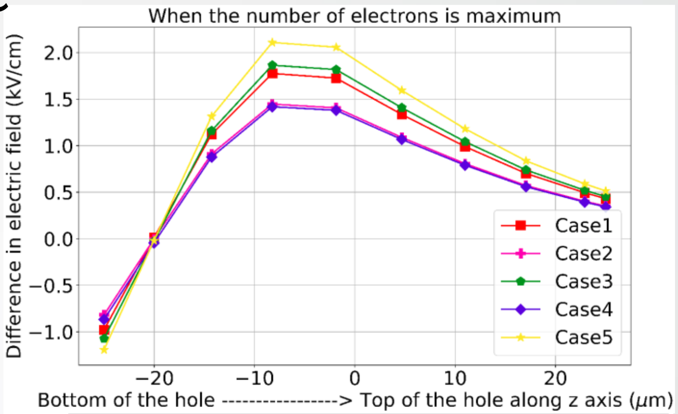


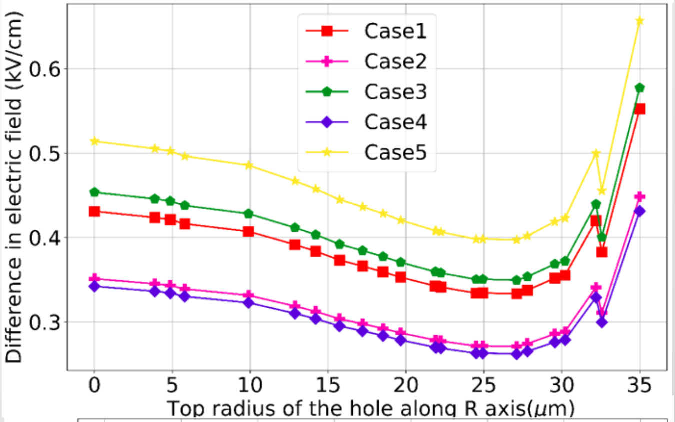


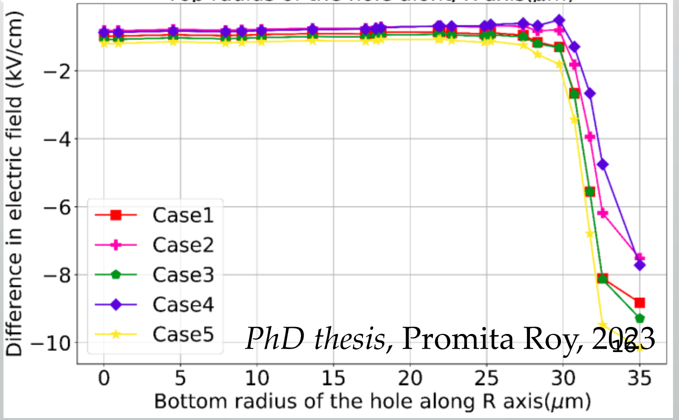


Field values are compared for lines indicated above (not all are shown)

Hydrodynamic model



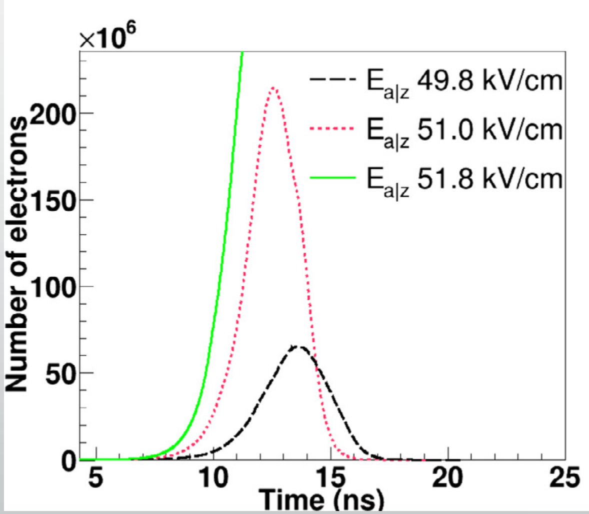




PhD thesis, Promita Roy, 2023

Section 3: Discharge simulation

- Occurrence of discharges / streamers are considered disruptive
- The detector can go blind for a short period of time
- Detector aging can occur
- Detector can get damaged beyond repair
- Electronics can get damaged
- Very, very complex phenomena

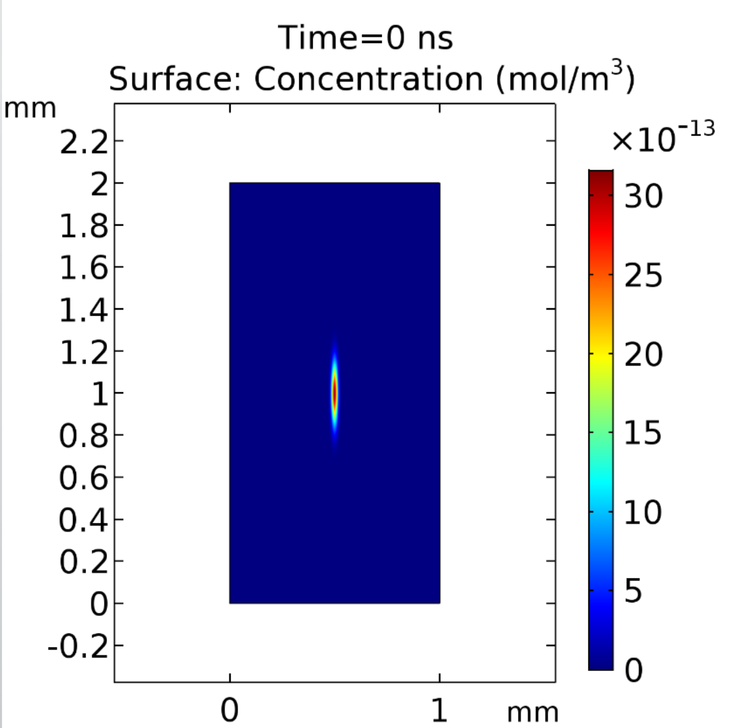


<u>Difficulties with particle model</u>

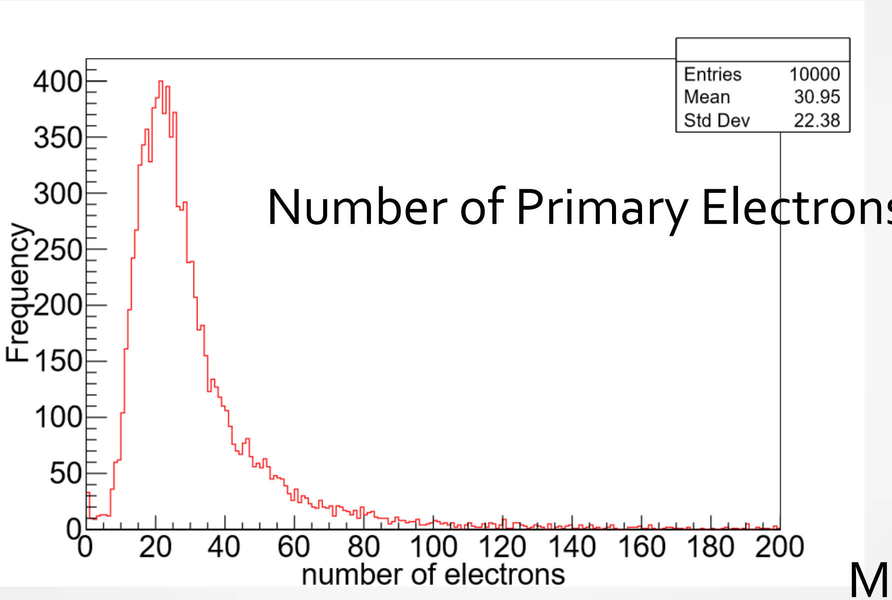
- Large number of charged particles
- PIC is a possibility, but beyond that …
- Extremely time-taking computation even after using simple representation such as lines.
- As discussed earlier, some progress has been made for RPCs.
- The number of charged particles considered in these simulations has been ~10^6.

RPC streamers using hydrodynamic model

Inclusion of Primary Electrons

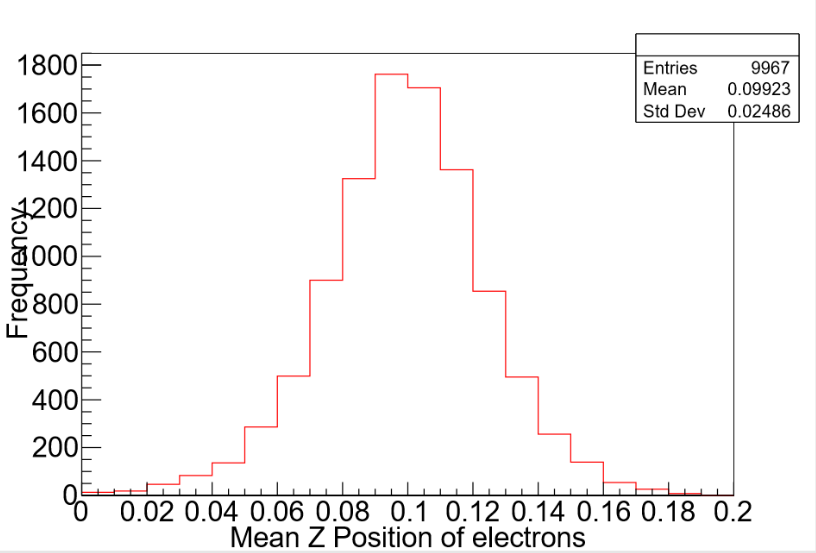


Initial Electron Distribution
No. of electrons = 10
σ_x = 0.01 mm, σ_y = 0.1 mm



Number of Primary Electrons

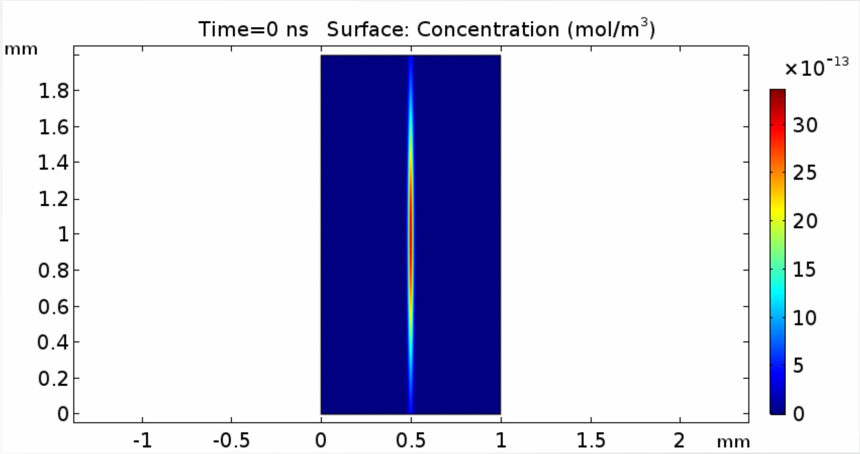
Mean Z Position of Electrons



Study of streamer development in Resistive Plate Chamber, Datta et al., JINST, https://10.1088/1748-0221/15/12/C12006

Streamer Probability

- In simulation, use different number of primaries for each voltage. Find out whether streamer occurs, which is defined by the situation that the electrons have reached the cathode.
- Find out the probability of occurrence of that number of electrons from the HEED primary electron information. Add up the probabilities.
- For experiment, first find out whether more than one pulse has come or not, if yes then whether the amount of charge is more than 20 pC or not, which is equivalent to Raether Limit.



Scope of improvement in simulation

1. Carry out 3D computation

2. Improve the relative tolerance in computation (currently at 0.01).

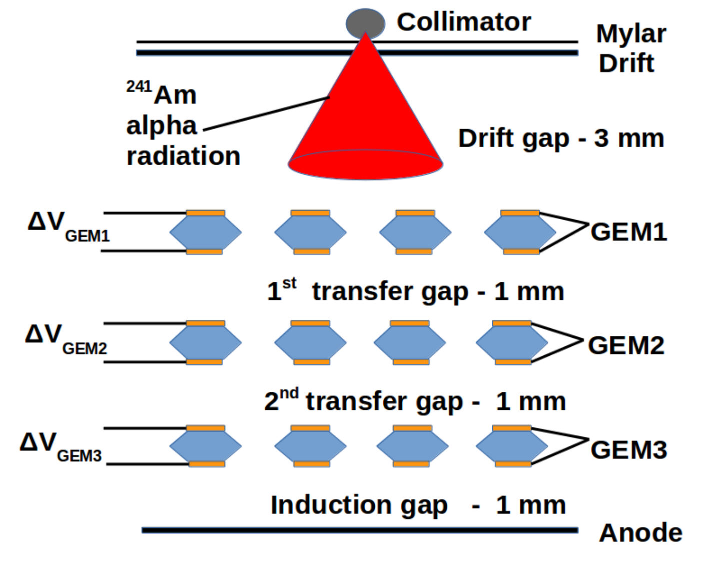
3. The initial position of the electron distribution was taken at the middle of the whole gap. But there is a distribution of that. So error due to the initial position will affect the result.

4. While calculating the streamer probability we have divided the number of events which will give streamer by the total number of events simulated in HEED. Fluctuation in the latter that will also add up in the error.

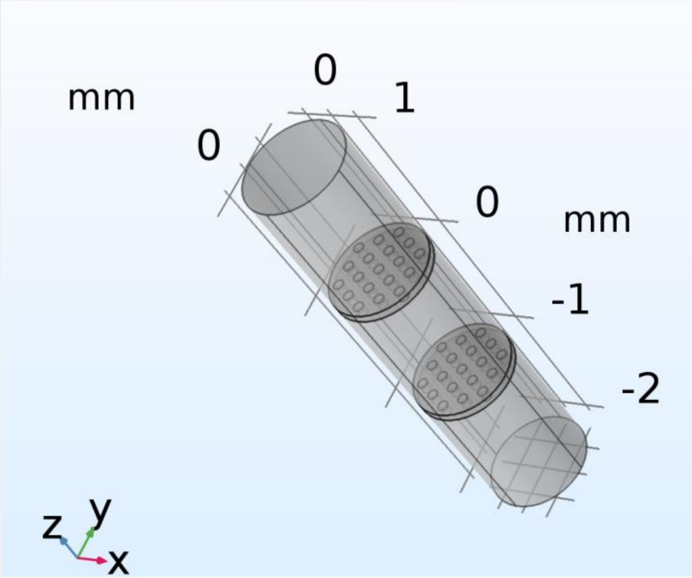
Streamer simulated

Voltage (in V)	From experiment	From simulation
9400	0.00087 +/- 0.00011	0.008
9600	0.00091 +/- 0.00015	0.008
9800	0.00411 +/- 0.00181	0.0135
10000	0.02681 +/- 0.00052	0.0224

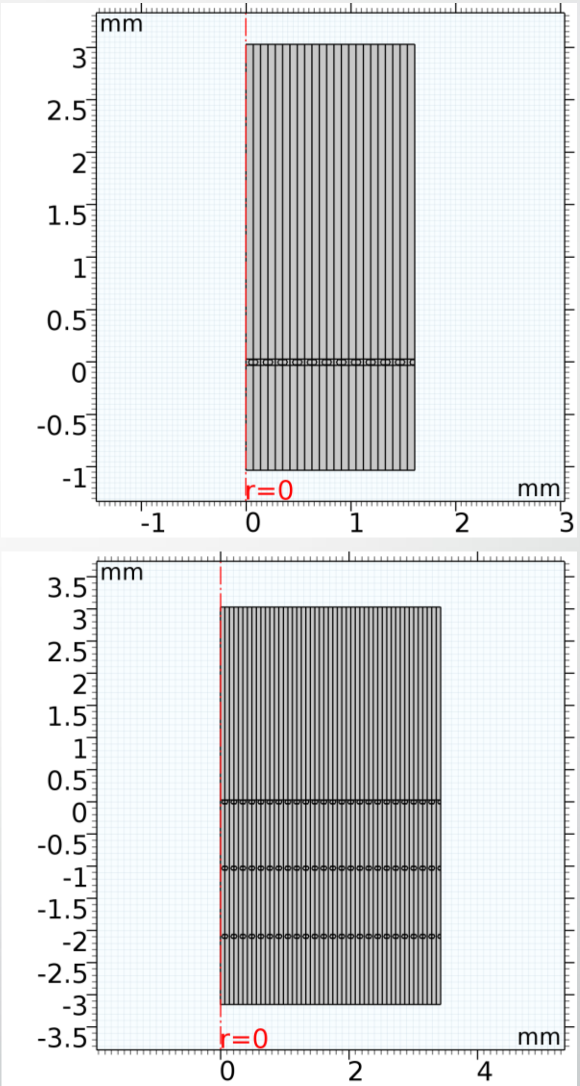
GEM



Experimental setup



3D model

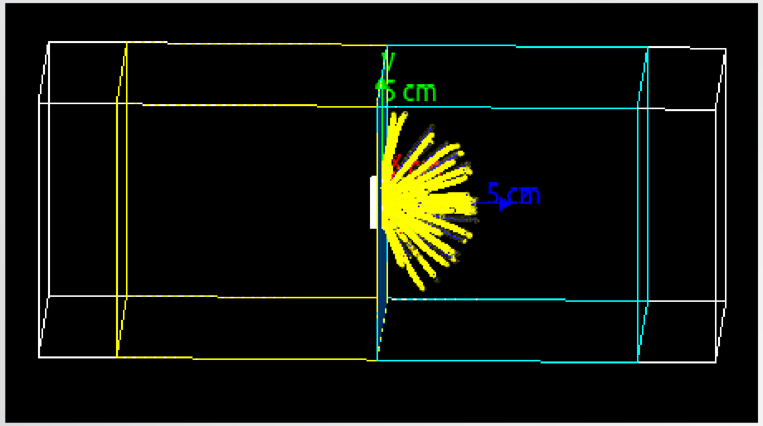


Axis-symmetric model (incorporating appropriate corrections)

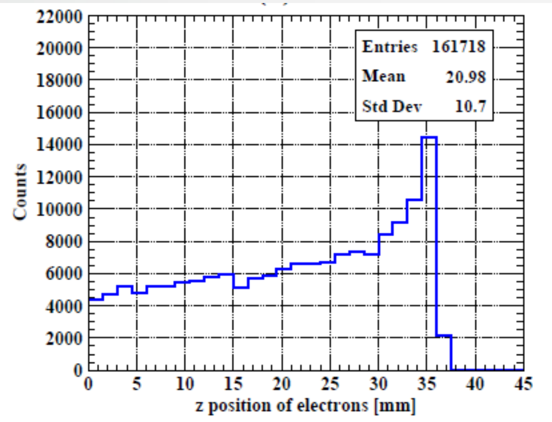
Fast simulation of avalanche and streamer in GEM detector using hydrodynamic approach, Rout et al., JINST, https://doi.org/10.1088/1748-0221/16/02/P02018

Numerical estimation of discharge probability in GEM-based detectors, Rout et al., JINST, https://doi.org/10.1088/1748-0221/16/09/P09001

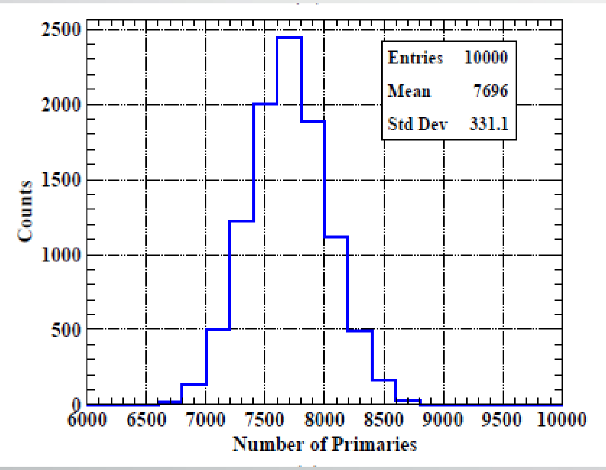
Introduce some effects of statistical processes



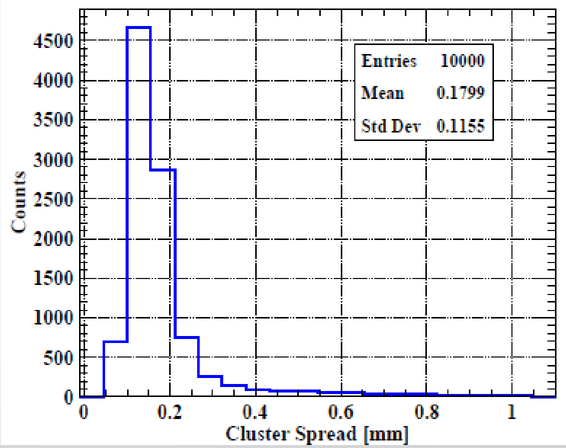
(a)



(b)



(c)



(d)

(a) Geant4 display of the collimated alpha tracks with an angle of +-30 in Ar-CO2 (70–30) gas volume.

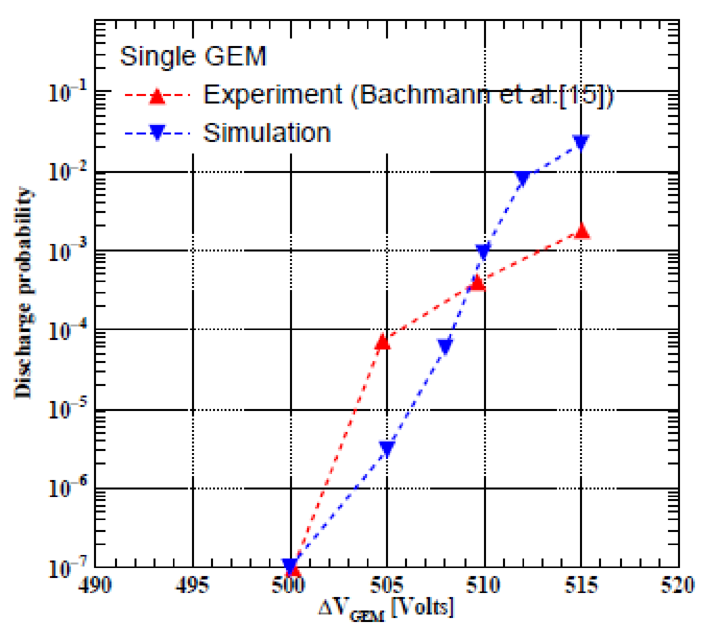
(b) z position of primary electrons in an event.

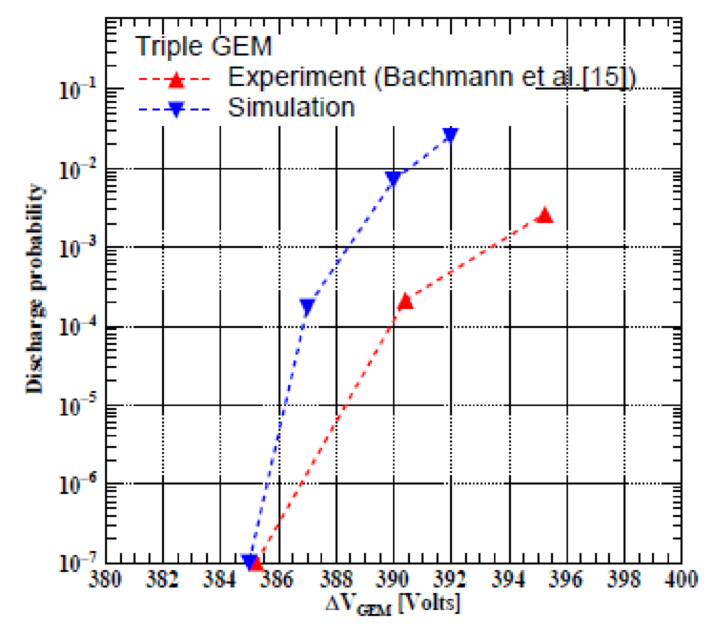
(c) Distribution of number of primaries within 3mm gas gap for 10000 events.

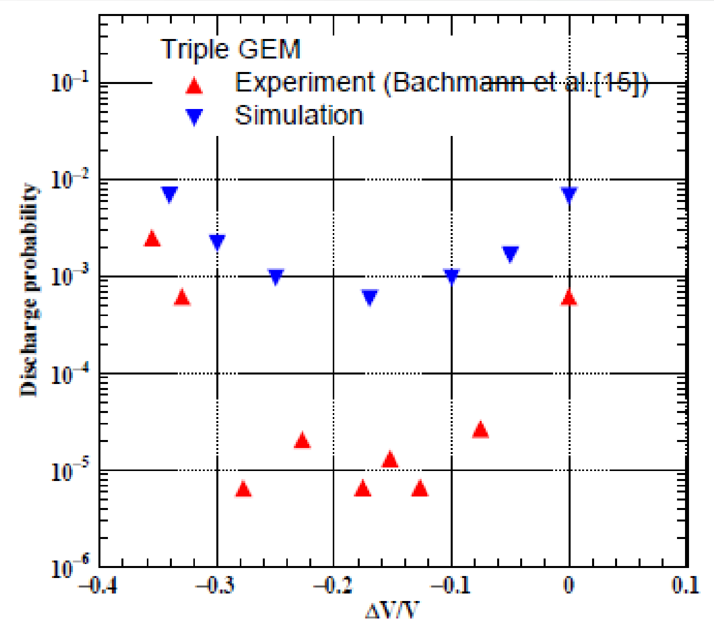
(d) Cluster spread distribution in 3mm gas gap for 10000 events.

Ref:
[1] S. Bachmann et al., *Discharge mechanisms and their prevention in the gas electron multiplier (GEM)*, *Nucl. Instrum. Meth. A* **479** (2002) 294
[2] P. Gasik, A. Mathis, L. Fabbietti and J. Margutti, *Charge density as a driving factor of discharge formation in GEM-based detectors*, *Nucl. Instrum. Meth. A* **870** (2017) 116

Discharge probabilities







- Comparison of discharge probability estimates in single GEM
- Comparison of discharge probability estimates in triple GEM
- Comparison of discharge probability estimates with asymmetric distribution of voltages

Discharge mechanisms and their prevention in the gas electron multiplier (GEM), Bachmann et al., Nucl. Instrum. Meth. A 479 (2002) 294.

Conclusion and future directions

- Ionization detector simulation is in a very interesting and rapidly evolving phase.
- Several complex phenomena are being addressed with reasonable success.
- Both particle and hydrodynamic models are found to be useful.
- Ouroboros BEM has already successfully implement GPU computation for Garfield++. Similar efforts for neBEM will be taken up.

Collaborators

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  - Nayana Majumdar
  - Prasant Kumar Rout
  - Promita Roy
  - Rob Veenhof
  - Supratik Mukhopadhyay
  - Tanay Dey
  - Vishal Kumar
- The entire RD51 community

THANK YOU