Overview of simulation activities at SINP and future prospects

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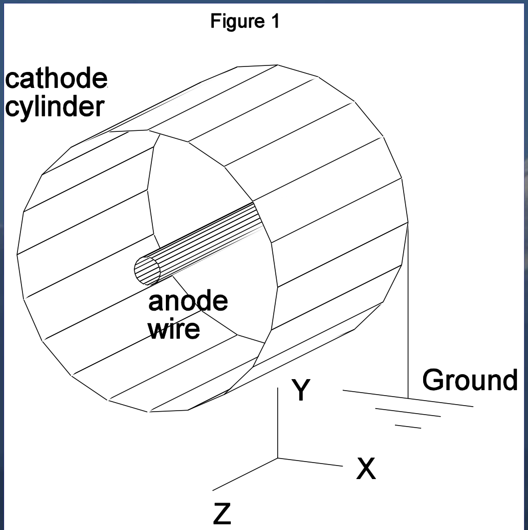
on behalf of the SINP team

First Collaboration meeting of the DRD1 Collaboration
29 January 2024 to 2 February 2024 at CERN

Outline of the presentation

- Simulation of gaseous ionization detectors at SINP - more or less, a chronological view.
- Ongoing activities
- Future projections

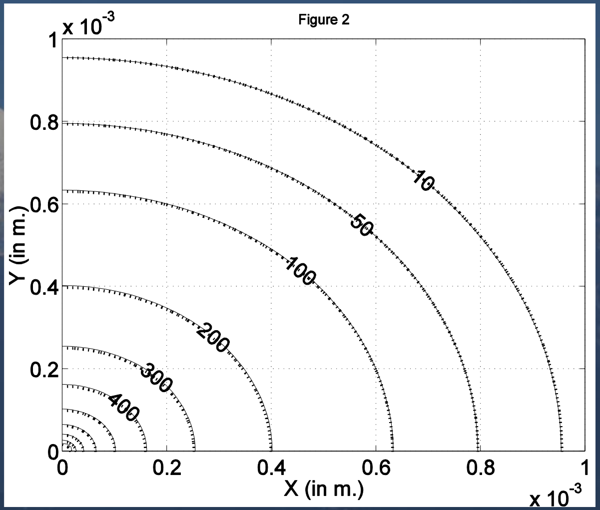
Initial attempts: a cylindrical proportional counter



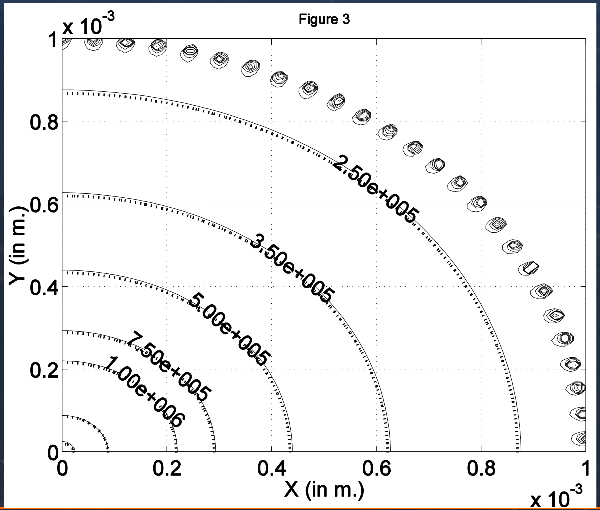
Geometry of a cylindrical proportional counter

Collocation BEM

Acceptable potential



Field values not acceptable



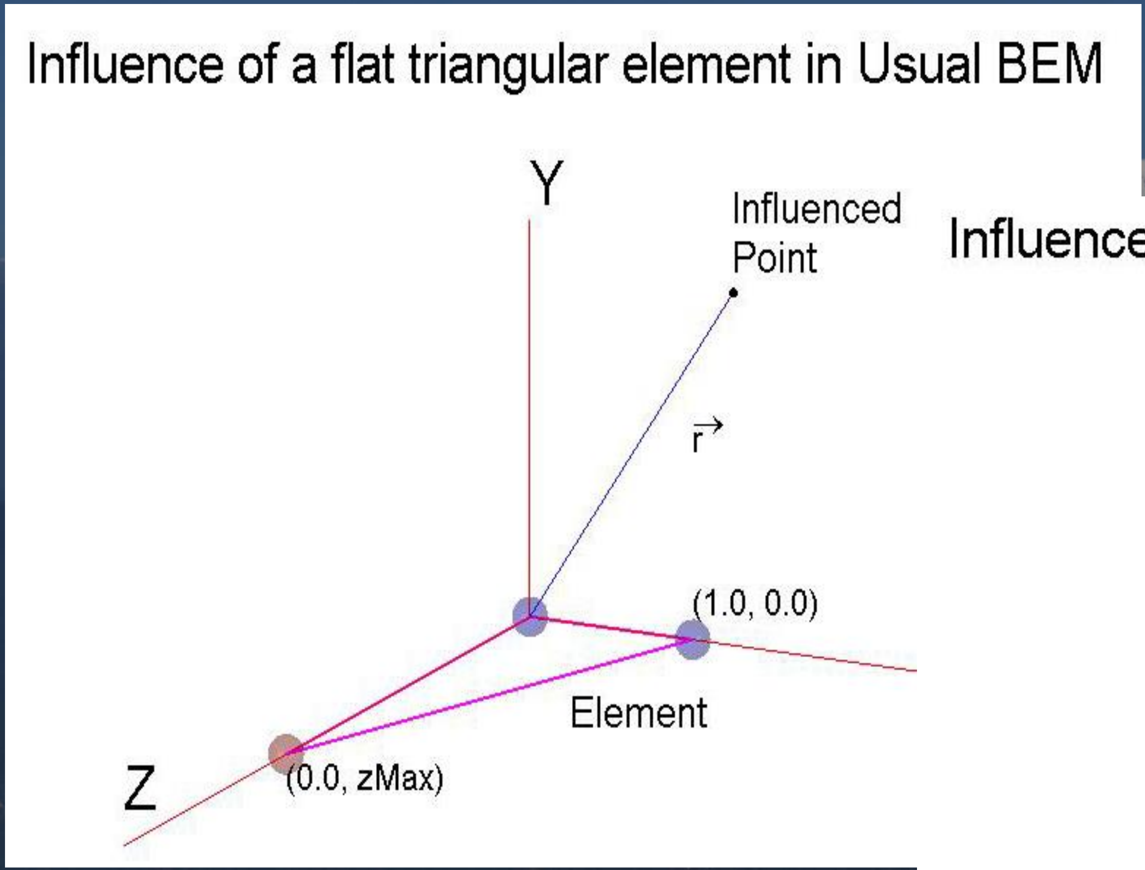
Edge effects studied, thanks to numerical implementation

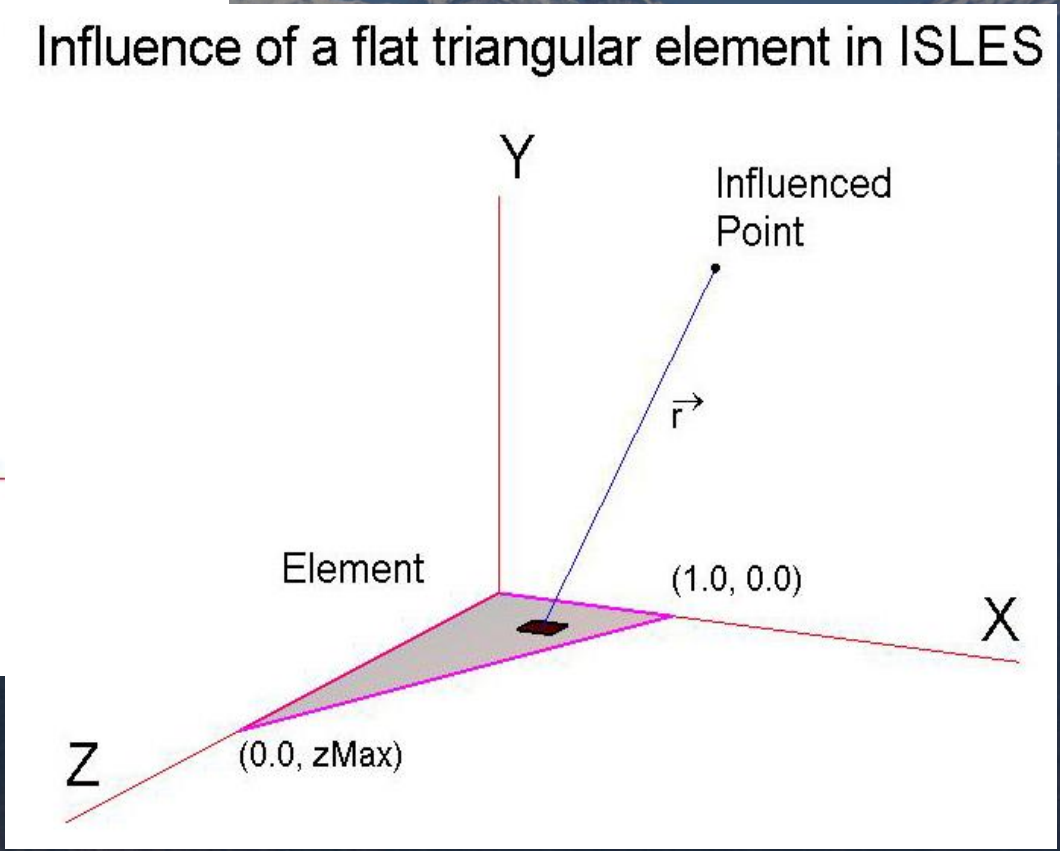
The collocation BEM model found not good enough even for a very simple geometry!

doi:10.1109/TNS.2006.872634

Search for a better solution

nodal versus distributed

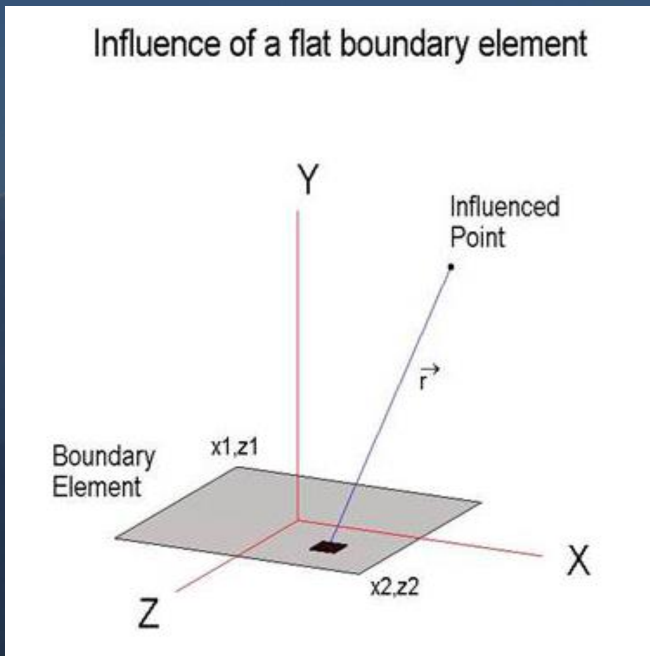




Foundation expressions of ISLES

Inverse Square Law Exact Solutions

Rectangular element



$$\Phi(X,Y,Z)=\int_{x1}^{x2}\int_{z1}^{z2}\frac{dxdz}{\sqrt{(X-x)^2+(Y-y)^2+(Z-z)^2}}$$

$$\Phi(X,Y,Z)=\frac{1}{2}\times\left\{\begin{aligned}&2\times(X|Z|x_i|z_j)\times\ln\left(\frac{D_{i,j}-(X|Z-x_i|z_j)}{D_{m,n}-(X|Z-x_m|z_n)}\right)\\&+iS_j|Y|\times\left[\tanh^{-1}\left(\frac{R_j-iI_i}{D_{i,j}|Z-z_j|}\right)-\tanh^{-1}\left(\frac{R_j+iI_i}{D_{i,j}|Z-z_j|}\right)\right]\end{aligned}\right\}-2\pi Y$$

4 log terms

4+4 complex $\tanh^{-1}$ terms

$$D_{i,j}=\sqrt{(X-x_i)^2+Y^2+(Z-z_j)^2}$$
$$R_i=Y^2+(Z-z_i)^2$$
$$I_i=(X-x_i)|Y|$$
$$S_i=Sign(Z-z_i)$$

May need translation and vector rotation

Value of multiple dependent on strength of source and other physical consideration

doi:10.1016/j.enganabound.2006.03.002

Foundation expressions of ISLES

$$F_X(X,Y,Z) = \ln\left(\frac{D_{i,j} - (Z - z_j)}{D_{m,n} - (Z - z_n)}\right)$$

2 terms

$$F_Y(X,Y,Z) = -\frac{i}{2}Sign(Y) \times \left\{ \begin{array}{l} S_j \tanh^{-1}\left(\frac{R_j + iI_i}{D_{i,j}|Z - z_j|}\right) \\ +S_j \tanh^{-1}\left(\frac{R_j - iI_i}{D_{i,j}|Z - z_j|}\right) \end{array} \right\} + C$$

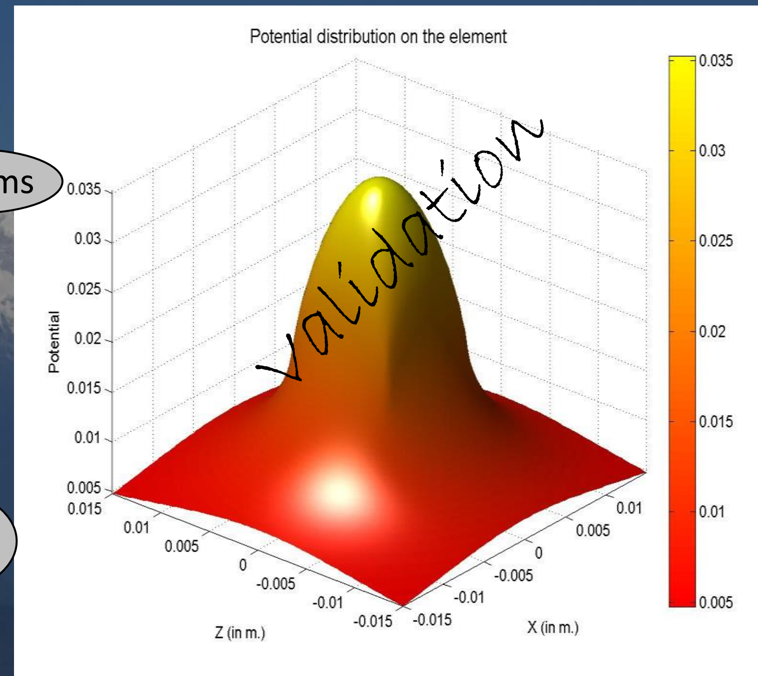
4+4 terms

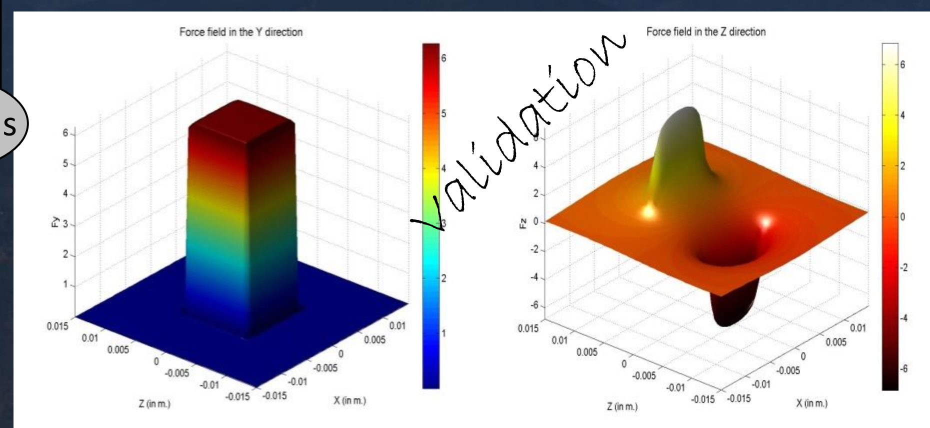
$$F_Z(X,Y,Z) = \ln\left(\frac{D_{i,j} - (X - x_i)}{D_{m,n} - (X - x_m)}\right)$$

2 terms

C is a constant of integration

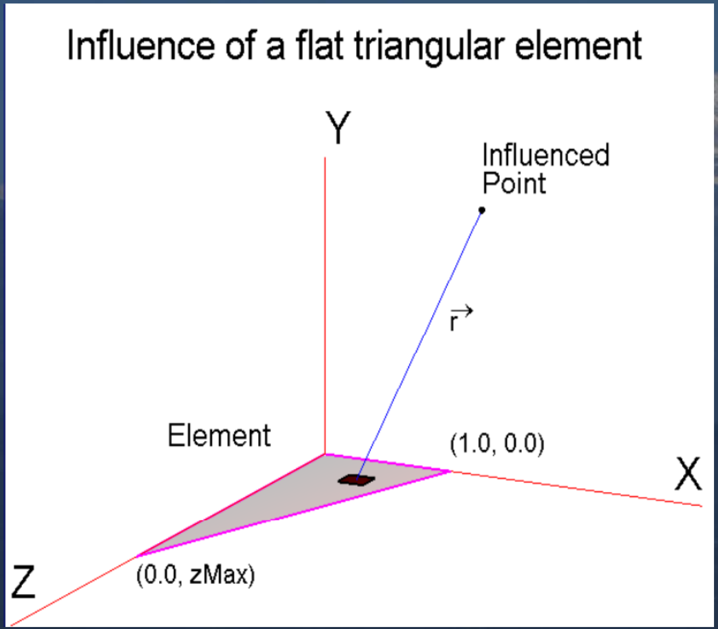
$$C = \begin{cases} 0, & \text{If outside XZ extent of element} \\ 2\pi, & \text{If } Y > 0 \\ -2\pi, & \text{If } Y < 0 \end{cases}$$





Foundation expressions of ISLES

Triangular element



$$\Phi(X,Y,Z) = \int_0^1 \int_0^{z(x)} \frac{dx\,dz}{\sqrt{(X-x)^2 + (Y-y)^2 + (Z-z)^2}}$$

$$\begin{aligned}\Phi = \frac{1}{2}\Bigg(& (z_M Y^2 - XG)(LP_1 + LM_1 - LP_2 - LM_2) \\ & + \mathrm{i}|Y|(z_M X + G)(LP_1 - LM_1 - LP_2 + LM_2) \\ & - S_1 X\left(\tanh^{-1}\left(\frac{R_1 + \mathrm{i}I_1}{D_{11}|Z|}\right) + \tanh^{-1}\left(\frac{R_1 - \mathrm{i}I_1}{D_{11}|Z|}\right)\right. \\ & \left. - \tanh^{-1}\left(\frac{R_1 + \mathrm{i}I_2}{D_{21}|Z|}\right) - \tanh^{-1}\left(\frac{R_1 - \mathrm{i}I_2}{D_{21}|Z|}\right)\right) \\ & + \mathrm{i}S_1|Y|\left(\tanh^{-1}\left(\frac{R_1 + \mathrm{i}I_1}{D_{11}|Z|}\right) - \tanh^{-1}\left(\frac{R_1 - \mathrm{i}I_1}{D_{11}|Z|}\right)\right. \\ & \left. - \tanh^{-1}\left(\frac{R_1 + \mathrm{i}I_2}{D_{21}|Z|}\right) + \tanh^{-1}\left(\frac{R_1 - \mathrm{i}I_2}{D_{21}|Z|}\right)\right) \\ & + \frac{2G}{\sqrt{1+z_M^2}} \log\left(\frac{\sqrt{1+z_M^2}\,D_{12} - E_1}{\sqrt{1+z_M^2}\,D_{21} - E_2}\right) \\ & + 2Z \log\left(\frac{D_{21} - X + 1}{D_{11} - X}\right)\Bigg) + C\end{aligned}$$

Similar expressions as for rectangular elements but much longer with larger number of definitions and constants of integration.

Please note the integration limits: while any length is allowed in one co-ordinate, the other can be varied from 0 to 1, only.

May need translation, vector rotation and simple scalar scaling

doi: 10.1016/j.enganabound.2008.06.003

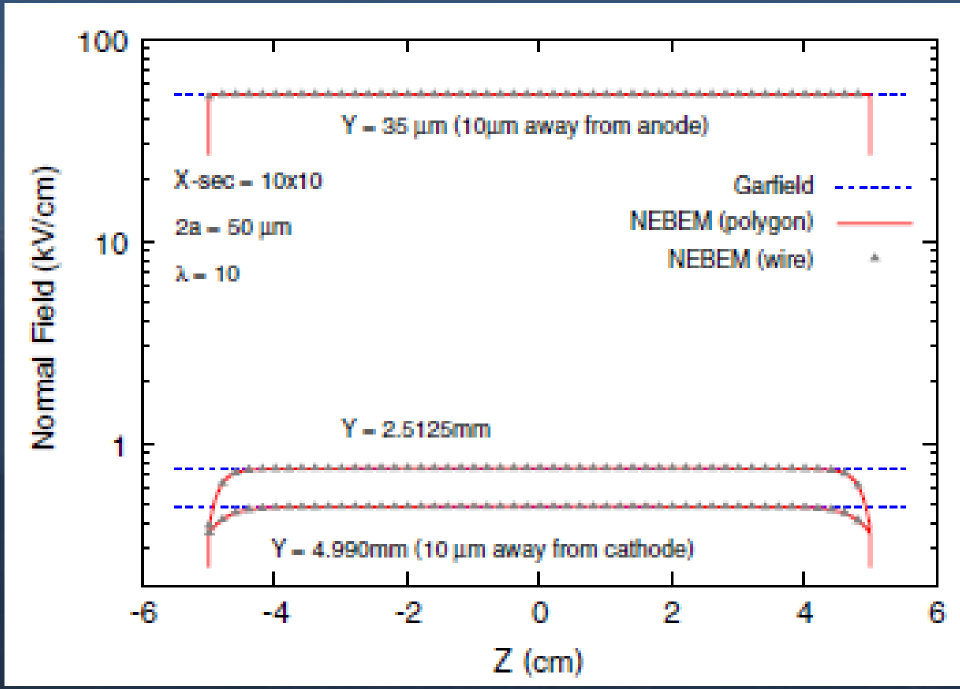
nearly exact BEM (neBEM)

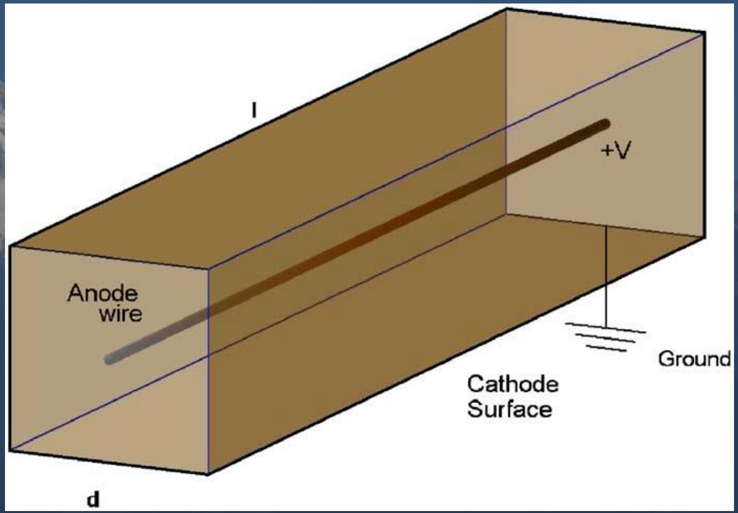
- A new set of closed-form exact solutions for precise estimation of potential and flux due to singularities (sources, sinks, doublets etc) uniformly distributed over rectangular and triangular elements has been found. Functions for wire, ring and disc elements have also been tested. These have evolved into a C library, namely ISLES.

- Based on this library, the neBEM (nearly exact Boundary Element Method) solver has been developed to solve problems of interest in science and engineering

Wire chamber

Fields Very close to the wire of an Iarocci tube





Axial deviation of normal electric field at the mid-plane of an Iarocci chamber with cross-section 10mm × 10mm.

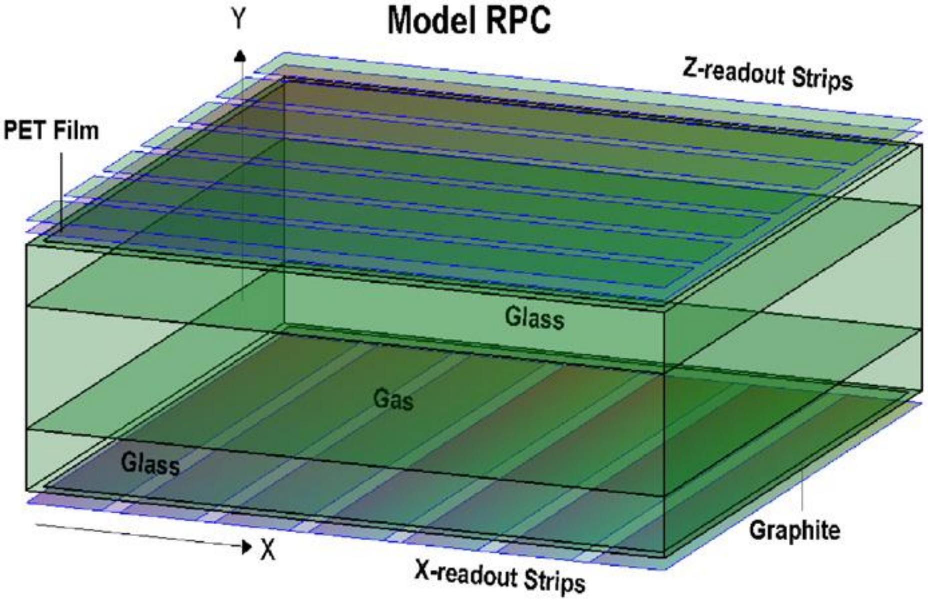
Two different models of wire have been considered

- Despite the proximity of the top line to the wire surface, the normal electric field is found to be completely free from jaggedness or oscillations.

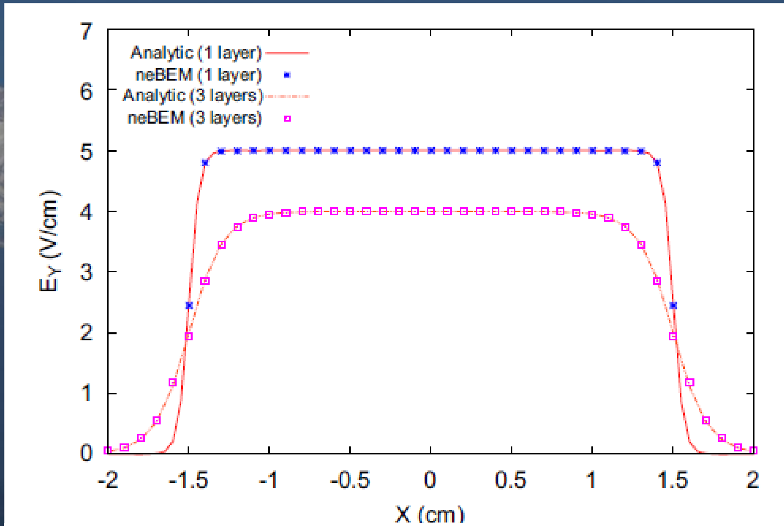
doi:10.1016/j.nima.2006.06.035

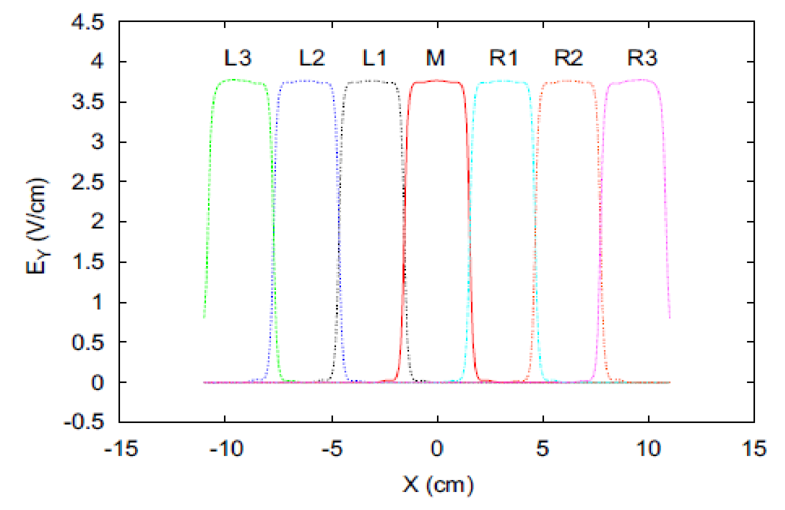
Resistive plate chambers

Number of thin dielectric layers



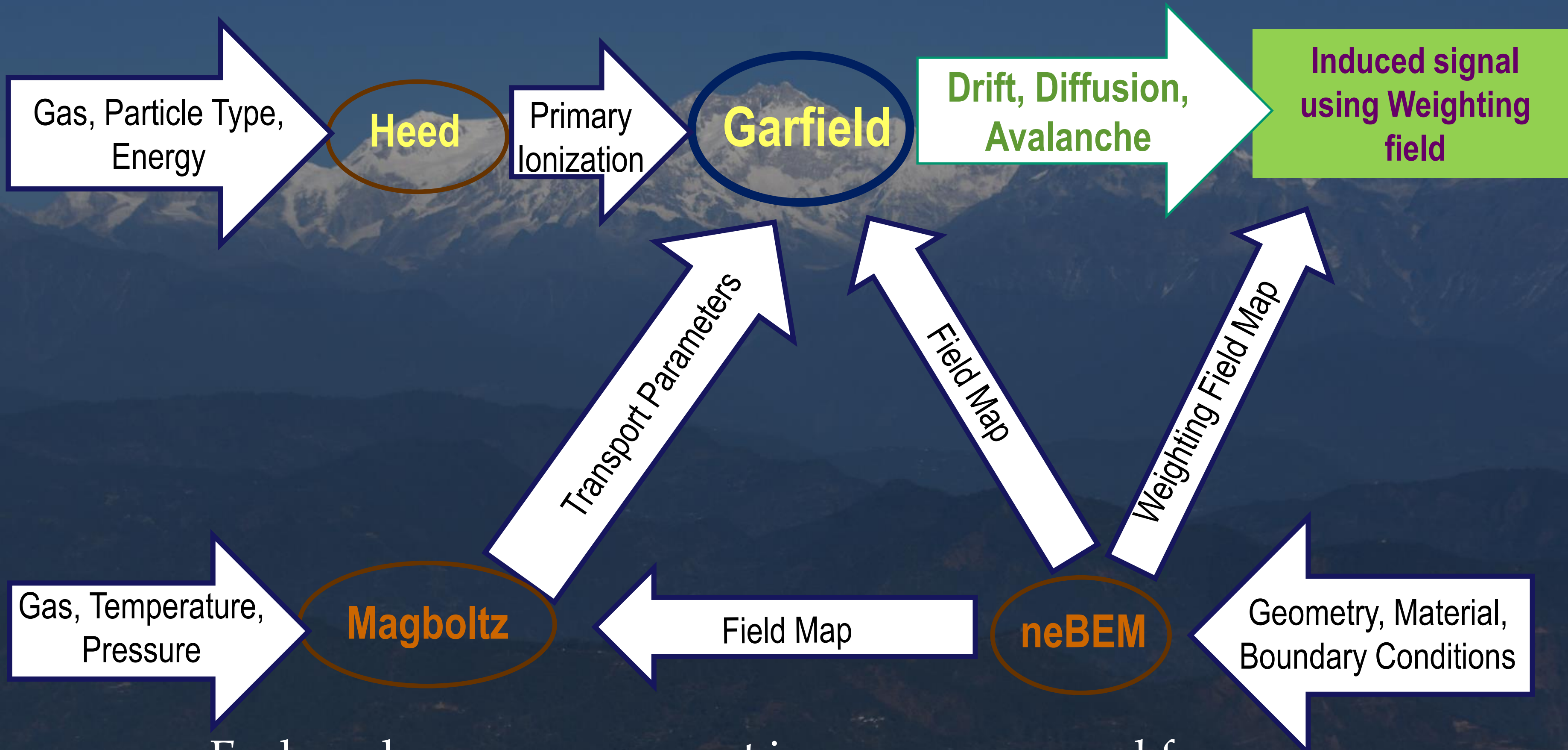
Strip width: 3.0cm, Strip length: 50.0cm
Layer height: 2.0mm
Layer-3 permittivity (ε_r): 7.75 (~glass)
Layer-2 (middle) permittivity (ε_r): 1.000513 (~Argon)
Successful validation with Riegler et al.





doi: 10.1016/j.nima.2008.07.033

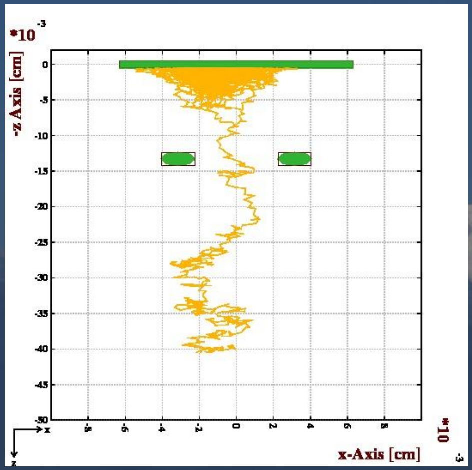
Simulation framework in 2009

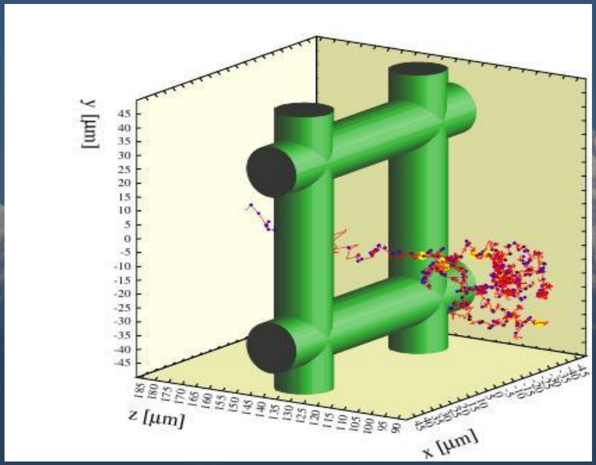


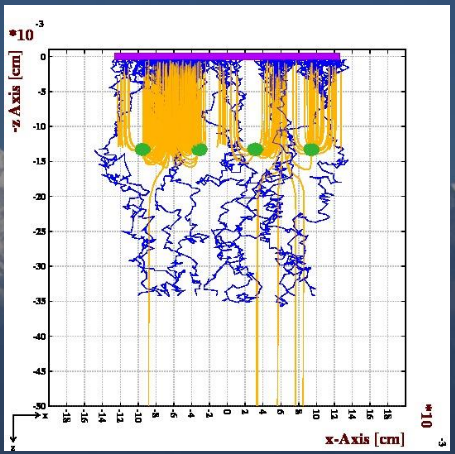
Each and every component is open-source and free

Garfield: garfield.web.cern.ch, Heed: heed.web.cern.ch,
Magboltz: magboltz.web.cern.ch, neBEM: nebem.web.cern.ch

Simulation of Micromegas

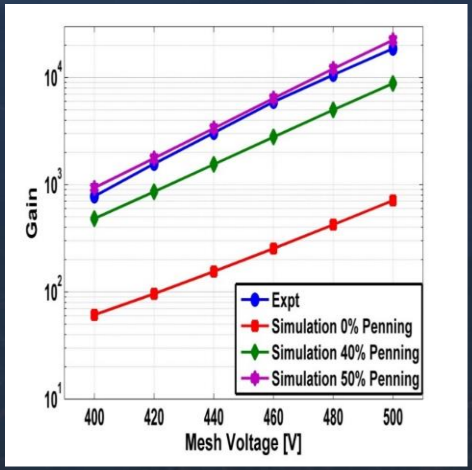


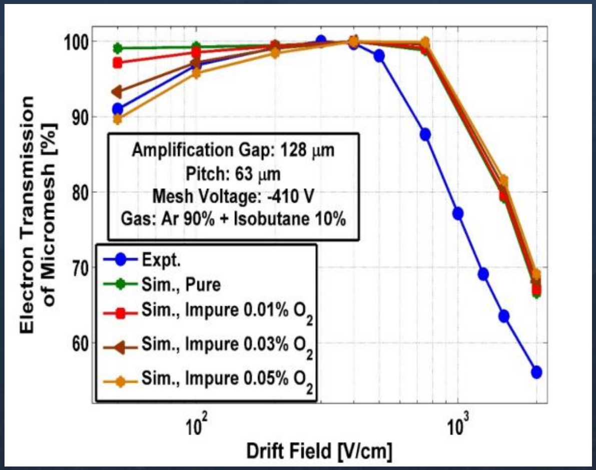


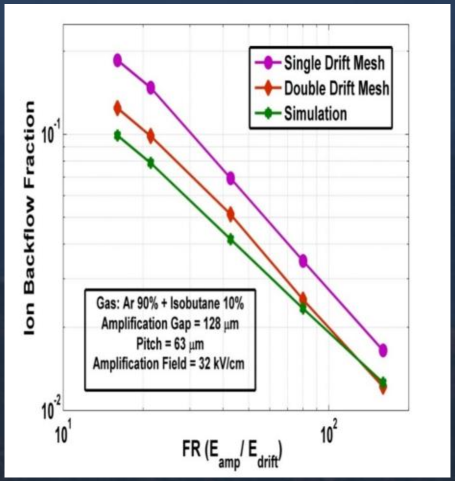


1) Gain, energy resolution
2) Transparency
3) Ion back-flow

Several other …

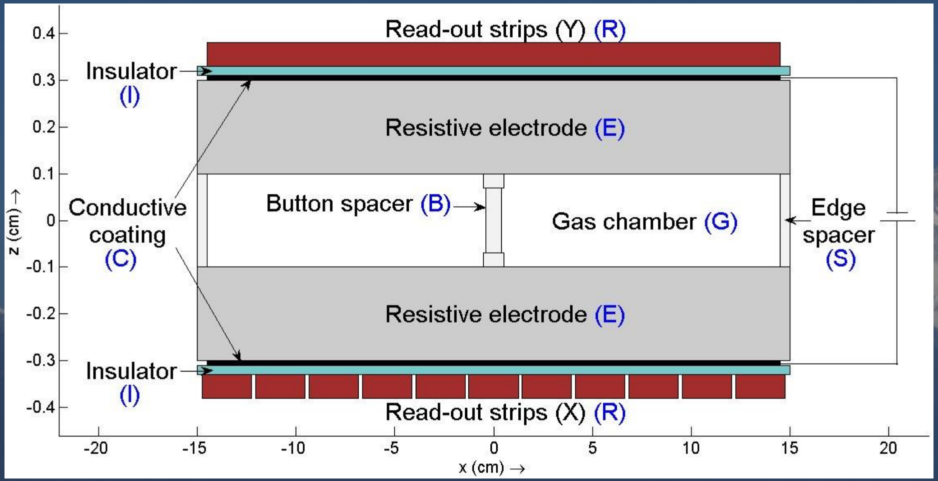


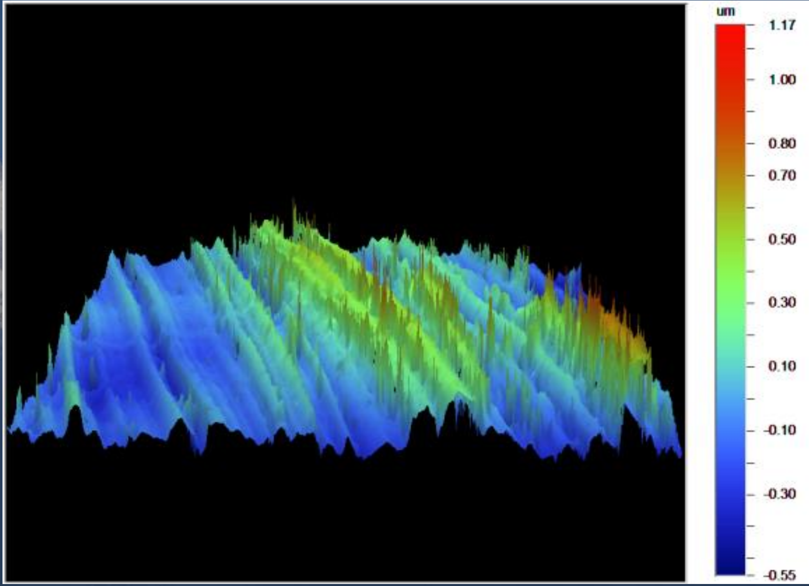


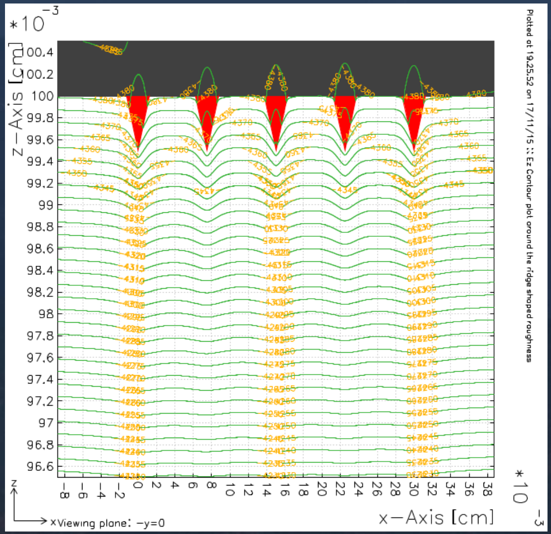


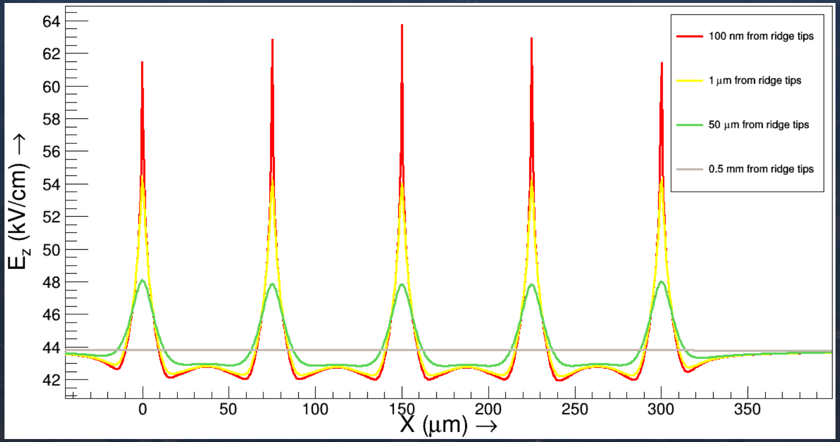
doi: 10.1016/j.nima.2010.07.026
doi: 10.1088/1748-0221/6/06/P06011 (2011)
doi:10.1088/1748-0221/10/09/P09017 (2015)
doi: 10.1016/j.nima.2017.04.031

Roughness in RPCs





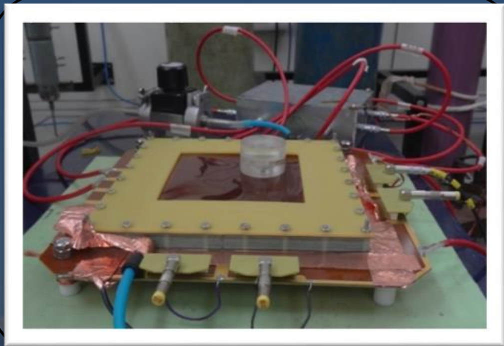


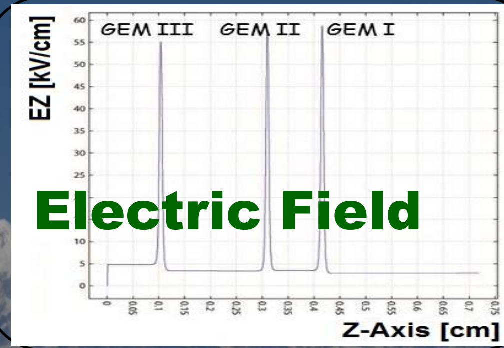


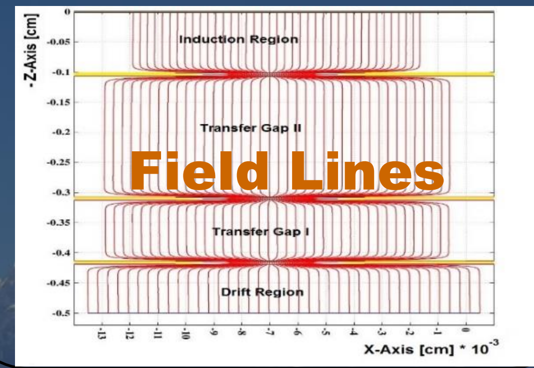
doi: 10.1088/1748-0221/7/11/T11027 (2012)

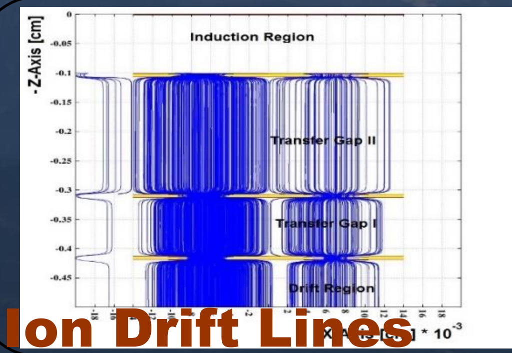
doi:10.1088/1748-0221/11/06/C06010 (2016)

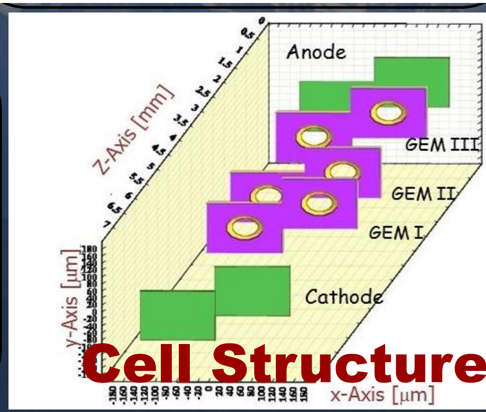
Triple GEM @ CMS

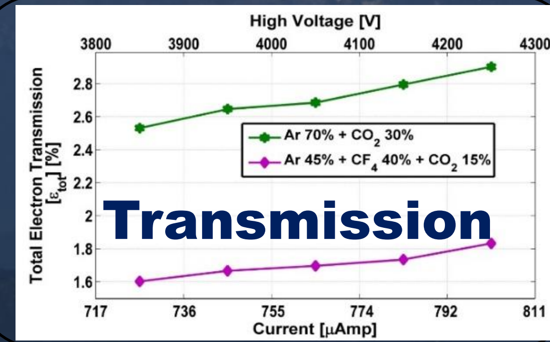


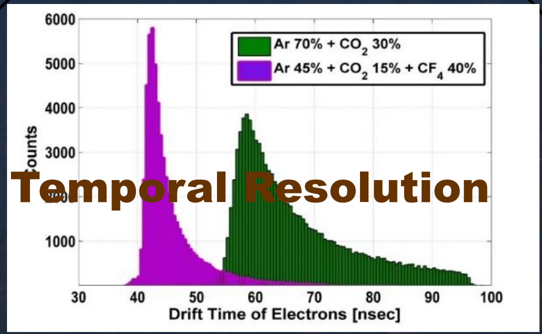


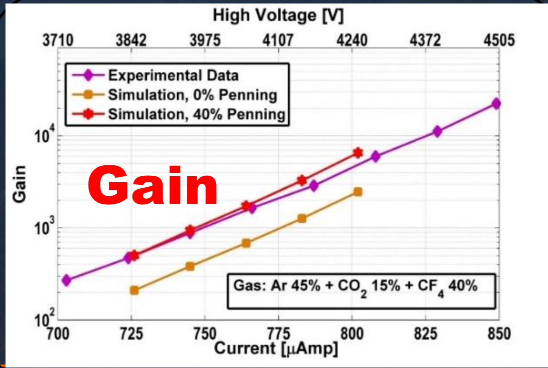


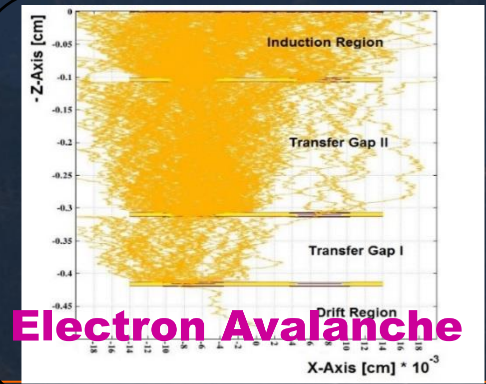








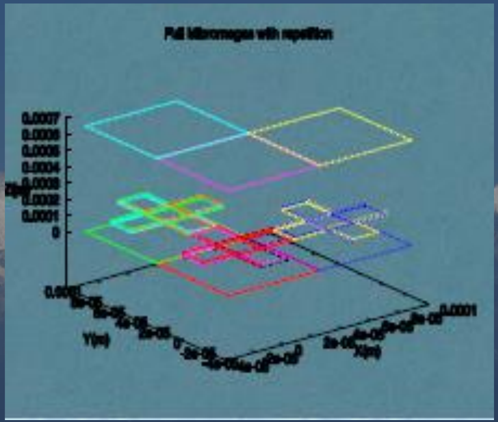


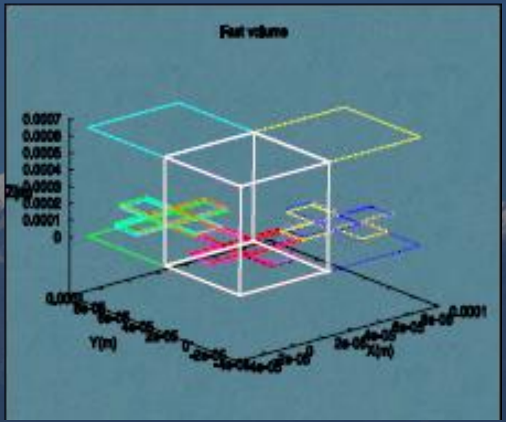


doi: 10.1088/1742-6596/759/1/012071 (2016)
doi: 10.1016/j.nima.2017.06.054

Fast Volume

- Typical problem related to MPGD
  - Hundreds of primitives, thousands of elements and hundreds of repetitions.
- Time to estimate potential and electric field at each point is significant.
- Complex processes such as avalanche, Monte-Carlo tracking and Micro-Tracking take enormous amount of time.
- Way out is to use pre-computed values of potential and field at large number of nodal points in a set of suitable volumes.
- These, so called Fast Volumes, are chosen such that they can be repeated to represent any region of a given device and simple trilinear interpolation is used to find the properties at non-nodal points.

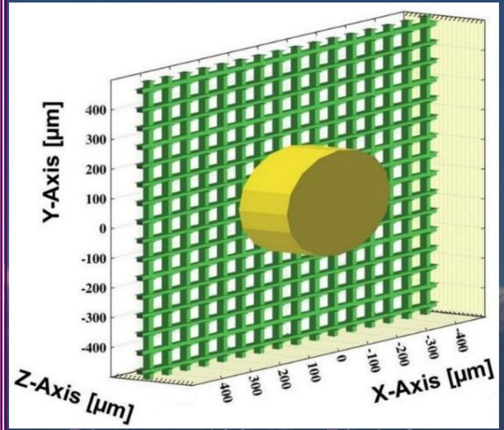




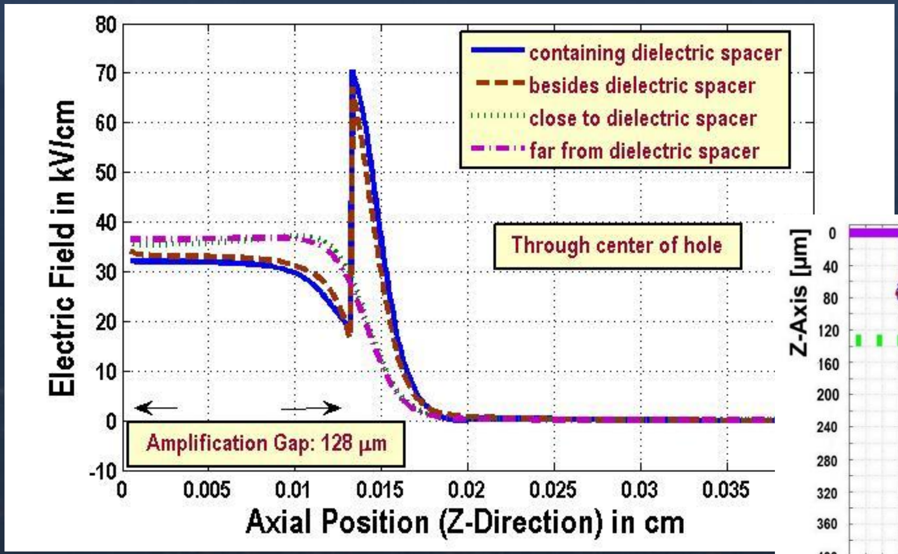
Effect of using Fast Volume		
Computation time	Without FastVol	With FastVol
Charge density	15s	5m16s (includes calculation of FastVol)
Field map	6m33s	1s (error 0.3%)
Ten drift lines	7m54s	2s
Number of avalanche electrons	712	726
Hundred avalanches	3 days	21s

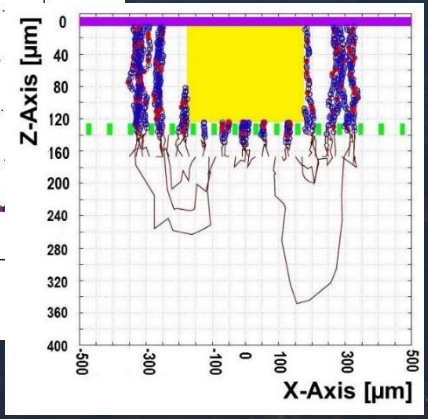
Effect of Spacer

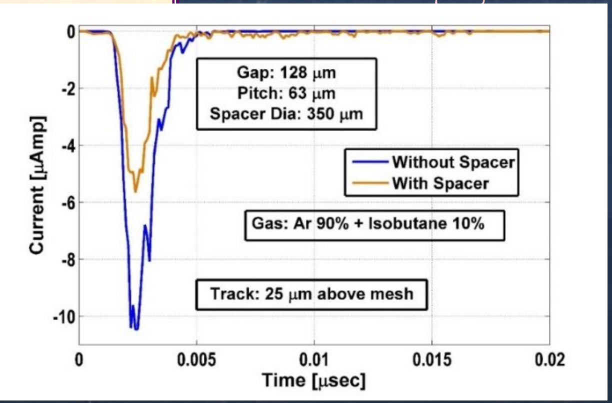
- ✓ Spacers cause significant perturbation resulting in increased field values, particularly in the regions where cylinders touch the mesh
- ✓ Electron drift lines get distorted near the spacer, some electrons are lost on it, resulting in a reduced gain
- ✓ Due to the reduced gain, electron signal strength gets affected significantly, the signal profile consists of a long tail resulting from the distorted drift
- ✓ Due to the dead regions introduced by the spacer, the readout pads below or close to the spacers are found to be affected which leads to inefficiencies in track reconstruction

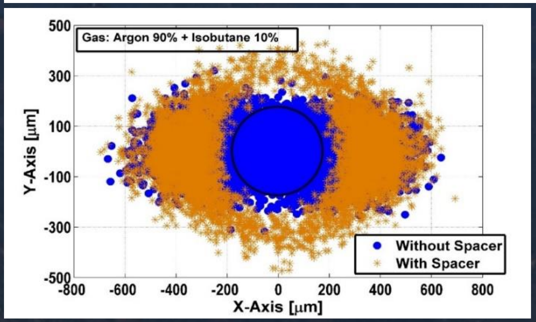


Diameter 400 μm, Pitch 2 mm









doi: 10.1016/j.nima.2015.04.051

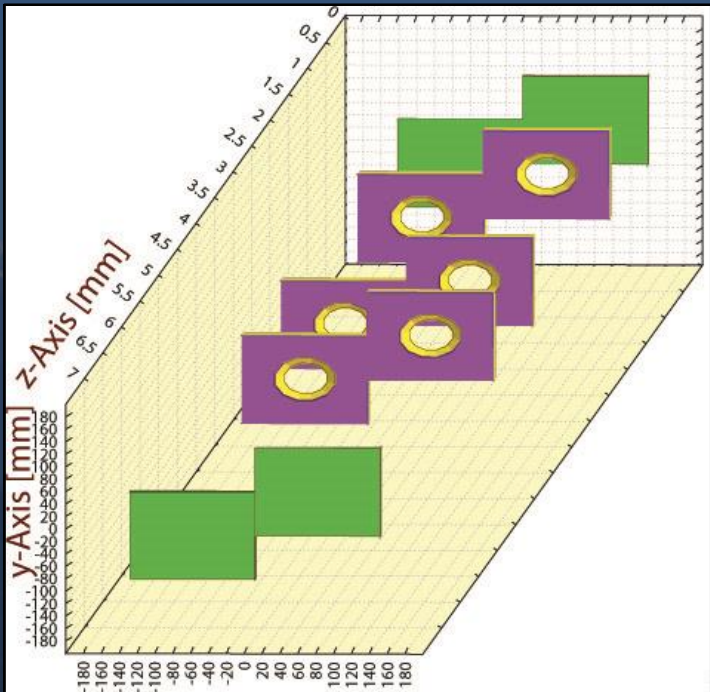
OpenMP code parallelization

- Open Multi-Processing (OpenMP): an Application Programming Interface (API).
- Supports multi-platform shared memory multiprocessor programming in C, C++ and Fortran on most processor architectures and operating systems.
- Consists of a set of compiler directives, library routines and environment variables that influence run-time behavior.

Table 5.4: Computational time for calculation of potential and field map using code parallelization.

Problem specification	Thread 1	Thread 2	Thread 4	Thread 6	Thread 8
Number of elements = 3089 Periodicity = 40	140 min 23 sec	70 min 46 sec	35 min 36 sec	25 min 34 sec	22 min 13 sec
Number of elements = 3089 Periodicity = 24	75 min 47 sec	38 min 49 sec	19 min 32 sec	13min 25 sec	14 m 42 sec
Number of elements = 3089 Periodicity = 16	37 min 51 sec	19 min 37 sec	10 min 9 sec	7 min 18 sec	8 min 47 sec
Number of elements = 11345 Periodicity = 8	46 min 17 sec	24 min 22 sec	13 min 16 sec	9min 47sec	11 min 14 sec

Adaptive meshing



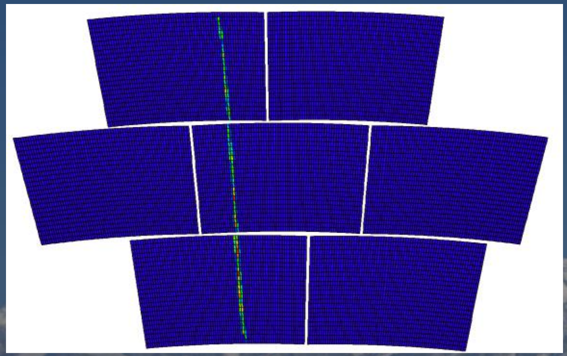
Triple GEM repetitions in X and Y: ~100

The question is:
Can we ignore the variation of charge density on a virtual GEM that is far away from the base device?

Computational time for calculation of charge density, potential and field map with and without AM and estimates of resulting error			
PrimAfter	Charge density	Potential and field	Error
0	3m25s	141m2s	
2	4m42s	27m69s	0.5%
5	4m27s	52m56s	0.3%
10	3m26s	71m28s	0.1%

Foil thickness : 50 μm
Copper thickness : 5 μm
Hole dia (outer) : 70 μm
Hole dia (inner) : 50 μm
Hole pitch : 140 μm
Configuration : 3:1:2:1 (mm)

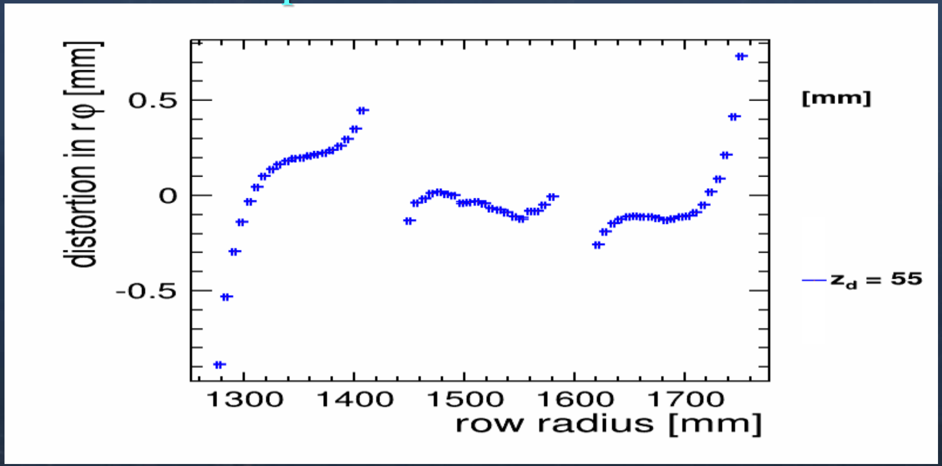
Distortion in Micromegas based TPC @ILC



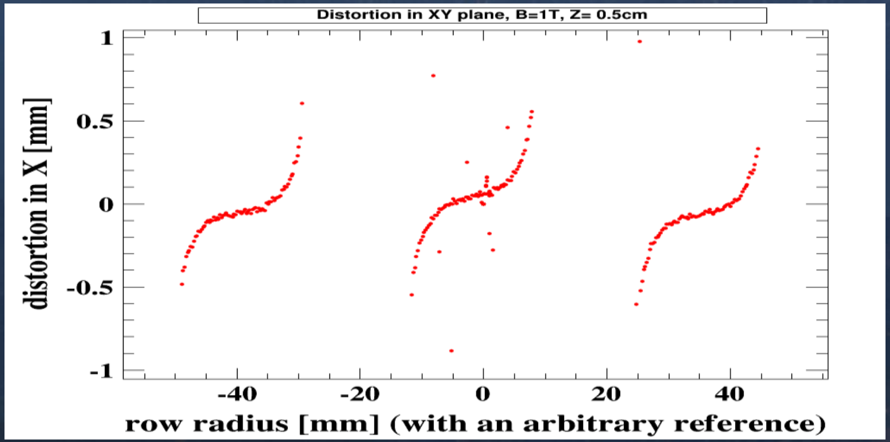
All modules are identical keystone shaped.
Gap between the modules = 3 mm

A resistive MM module for the LPTPC

- Module size: 22 cm × 17 cm
- Readout: 1726 pads, 24 rows
- Pad size: ˜3 mm × 7 mm



Distortion as observed in *Experiment*
At B=1T. Track is a 5 GeV electron beam.
Correction for the misalignment of the modules is not done here.

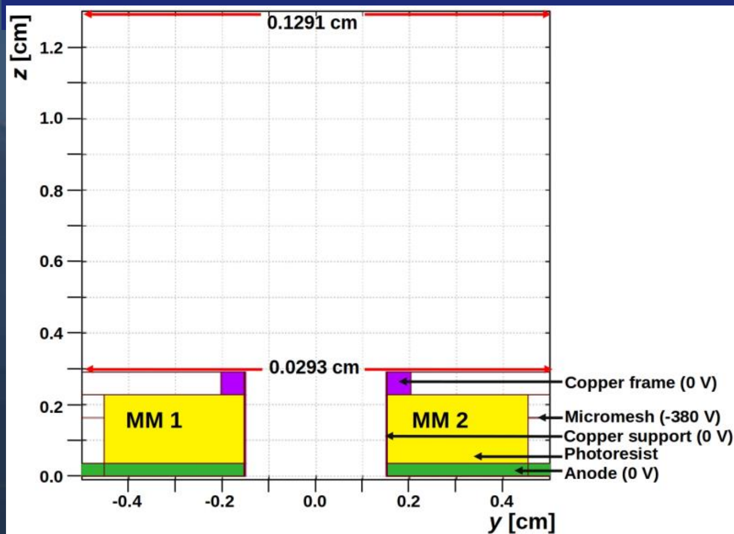


Distortion as obtained from *Simulation*
at B=1T. The track consists of of 457 equidistant primary electrons.
Result is averaged over 50 tracks.

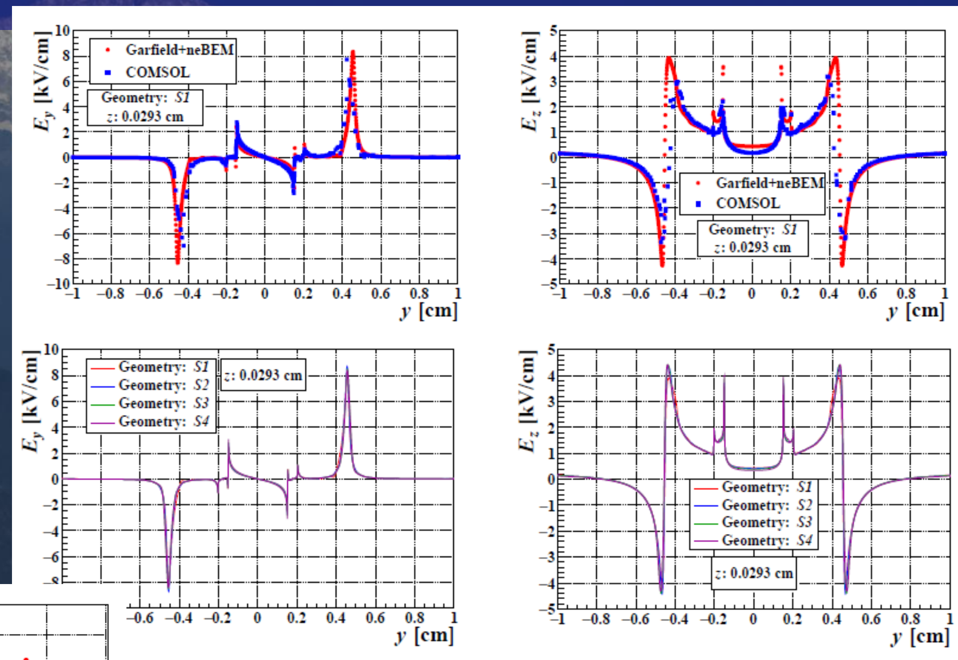
Field non-uniformity and distortion

- Extremely difficult problem from the point of view of field solutions:
  - The component lengths span over several orders of magnitude. For example, length of a module is 22 cm whereas the copper frame width is 30 μm (7000:1). The situation is even worse if the entire device is considered.

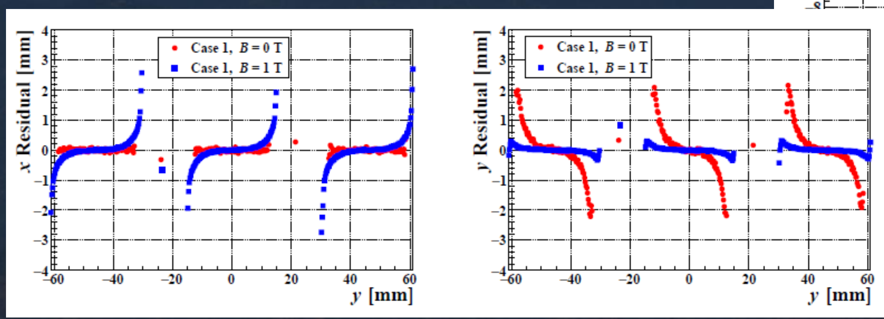
(a)



(b)



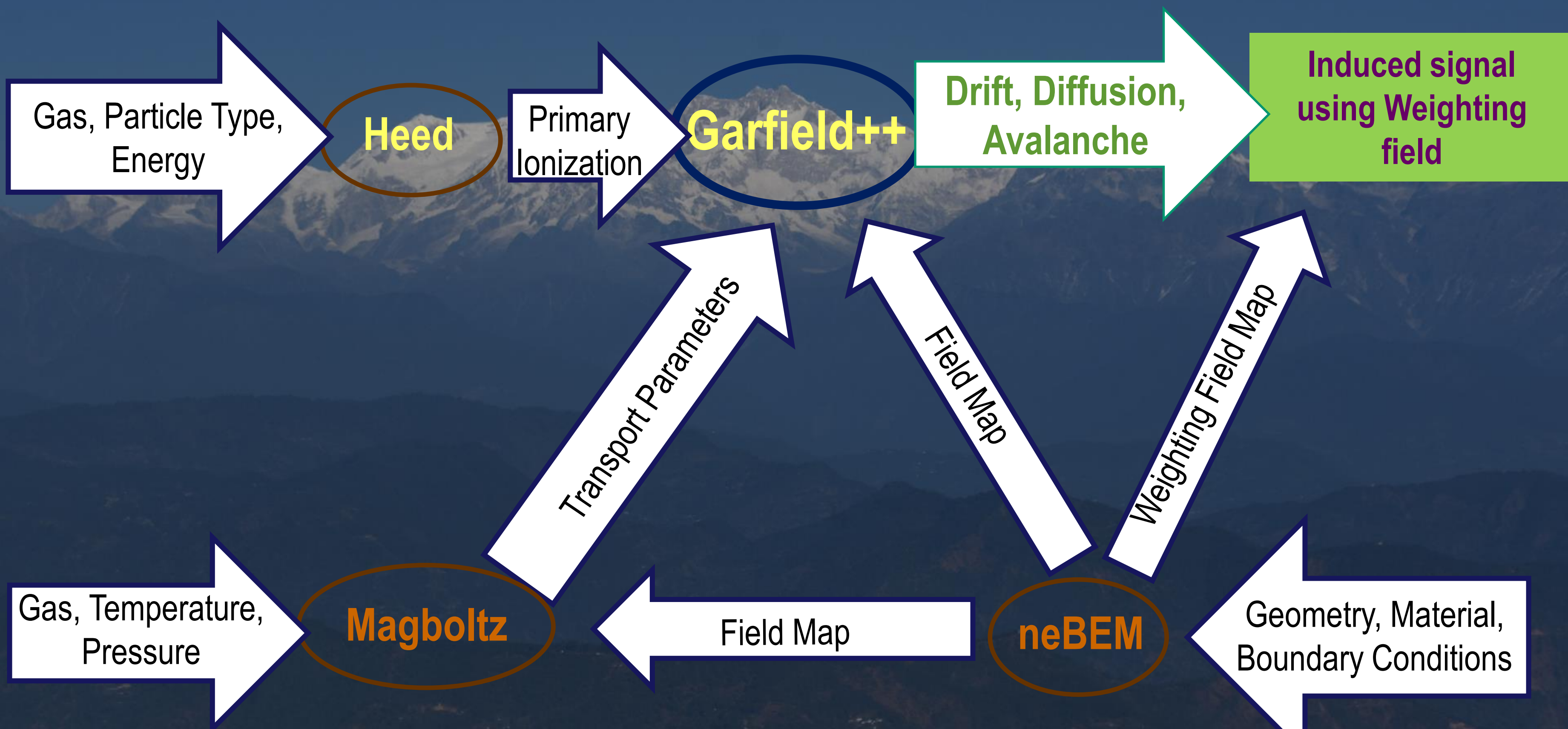
(c)



For the B = 0 T case, distortion in both the cases are found to be around 0.5 mm, while for the B = 1 T case, the distortions are around 2 mm. Thus, the estimates are qualitatively and quantitatively comparable to the experimental results.

doi: 10.1088/1748-0221/15/07/P07030 (2020)

RD51 simulation framework in 2018



Each and every component is open-source and free

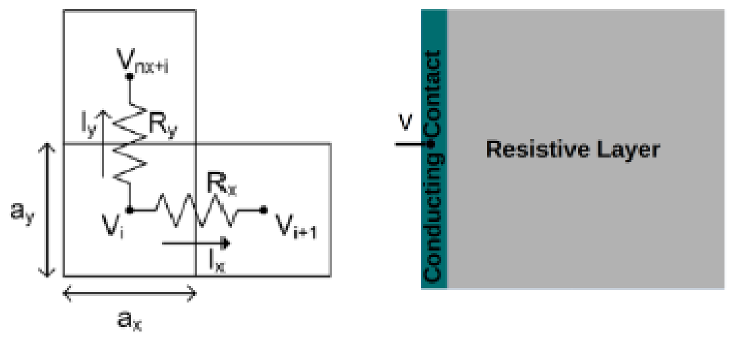
Garfield++: garfieldpp.web.cern.ch, Heed: heed.web.cern.ch,
Magboltz: magboltz.web.cern.ch, neBEM: nebem.web.cern.ch

Ongoing work

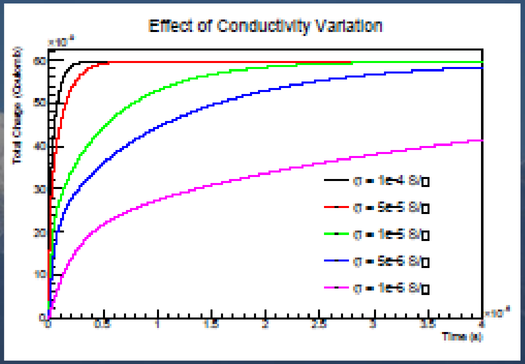
- Charge transport in resistive layers
- Space charge effects in general, and also in TPCs / ATTPCs
- Charging up effects in relevant detectors
- Avalanche to streamer transition
- Discharge probability estimation

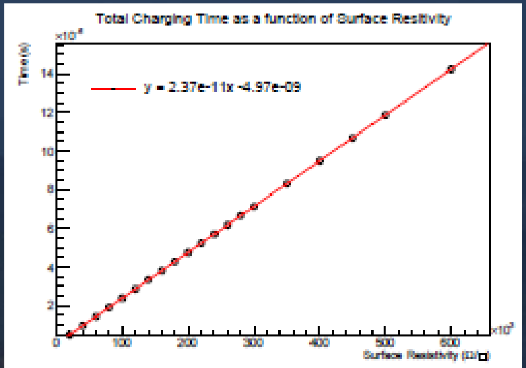
Next several slides borrowed from presentation by Purba Bhattacharya et al. in "Aging and Stability Conference" at CERN during November 2023.

Charge transport in a resistive layer



$$R_x = (\rho_s \times a_x)/a_y$$
$$R_y = (\rho_s \times a_y)/a_x$$
$$I_{x_i} = (V_i - V_{i+1})/R_x$$
$$I_{y_i} = (V_i - V_{n_x+i})/R_y$$
$$\Delta q = I \times \Delta t$$

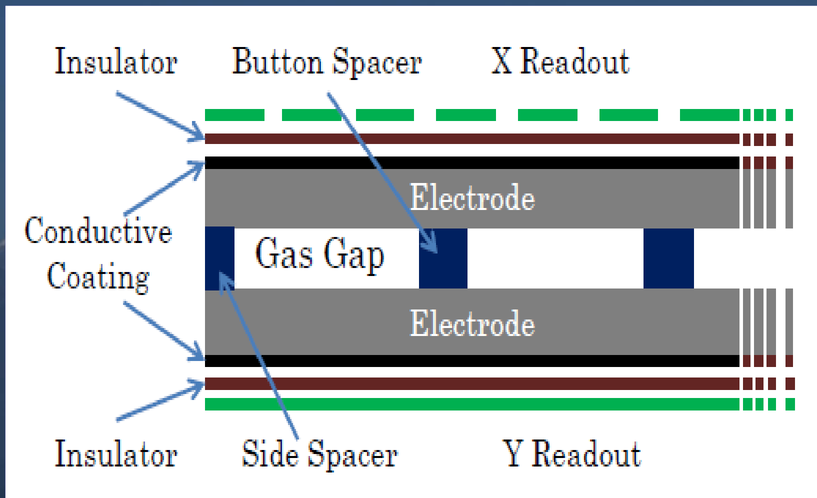


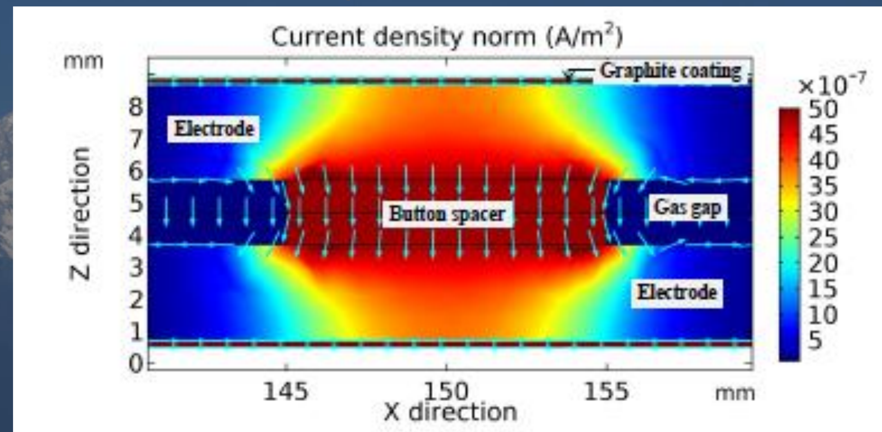


1) Finite-Difference-Time-Domain (FDTD) approach.
2) Not very precise, but produces reasonable results without demanding very high-end computing infrastructure.
3) Can be easily coupled with neBEM.

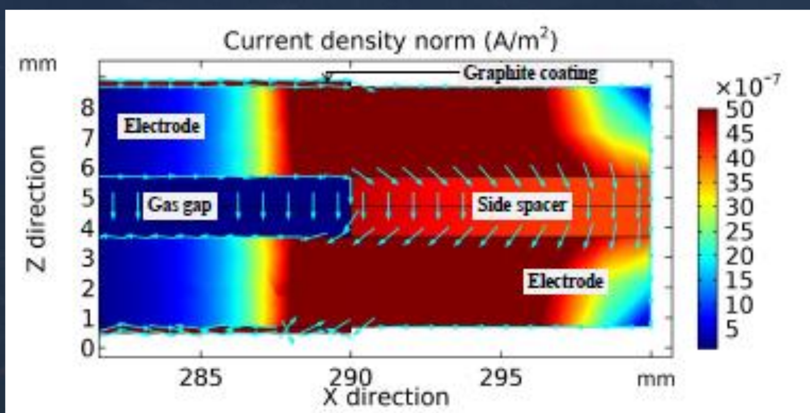
Current through resistive layers

RPC material studies using Comsol

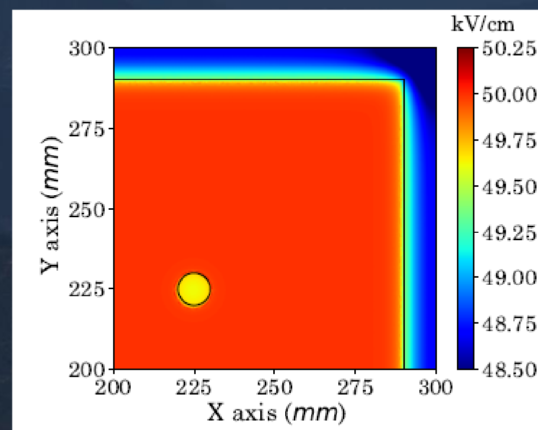




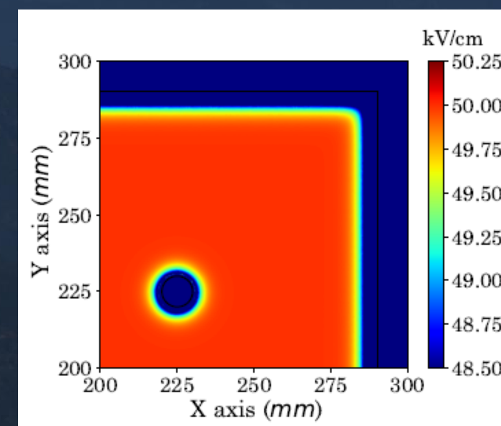
(a) Dark current in the button spacers.



(b) Dark current in the side spacer.



(a) Ratio of ρ_{spacer} to $\rho_{electrode}$ = 10^3.



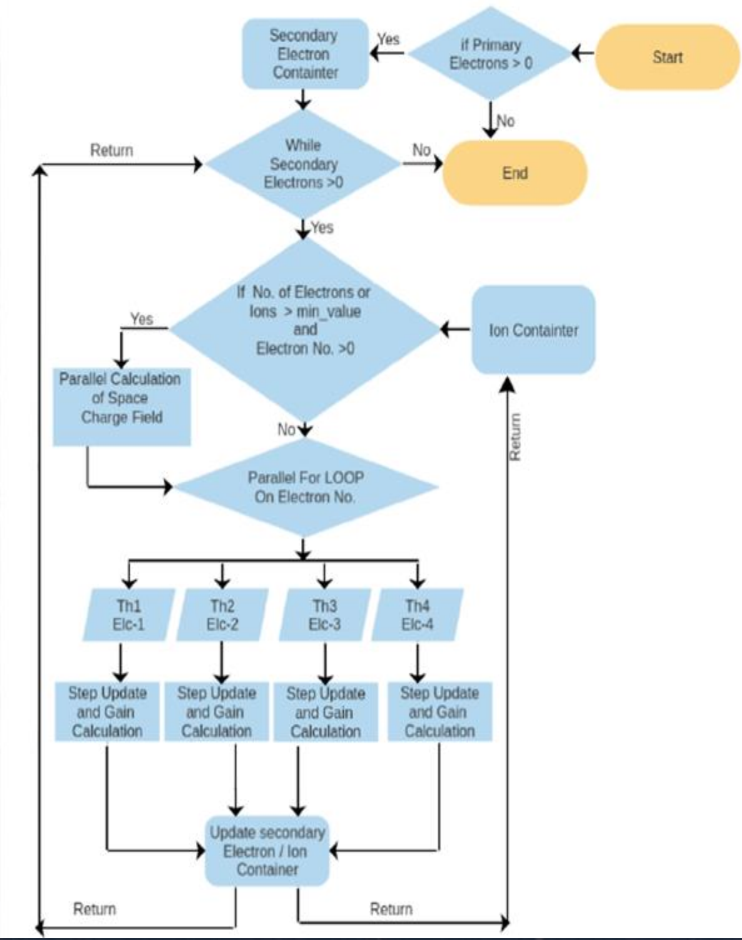
(b) Ratio of ρ_{spacer} to $\rho_{electrode}$ = 10.

Studies on electrical properties of Resistive Plate Chamber (RPC), Subhendu Das et al., JINST 17 P09041, doi: 10.1088/1748-0221/17/09/P09041

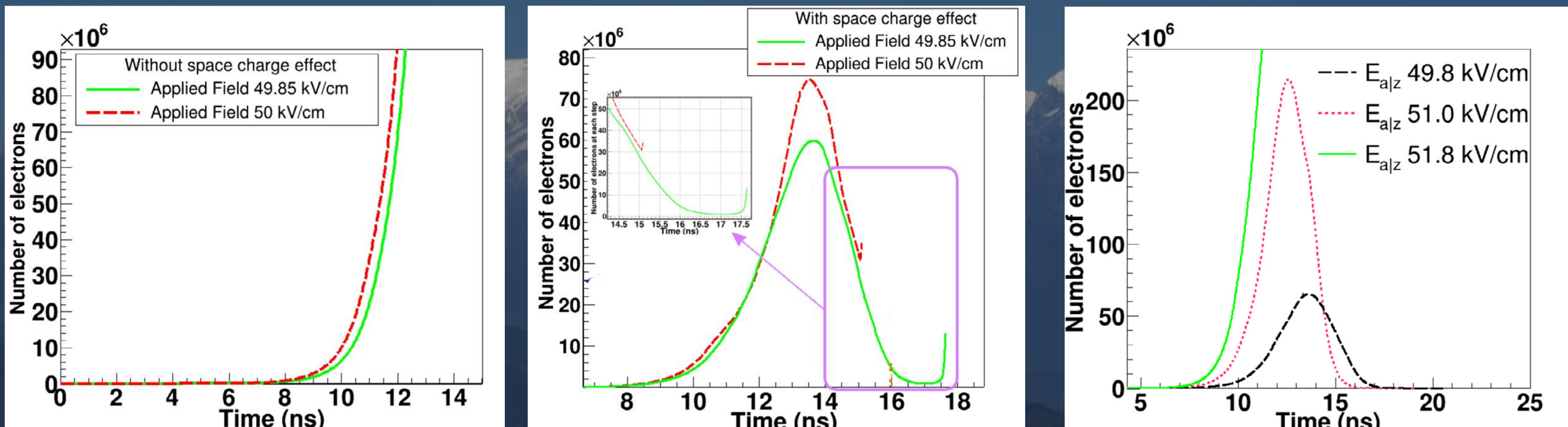
RPC space charge using particle model

- 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.

Flow of algorithm of pAvalancheMC



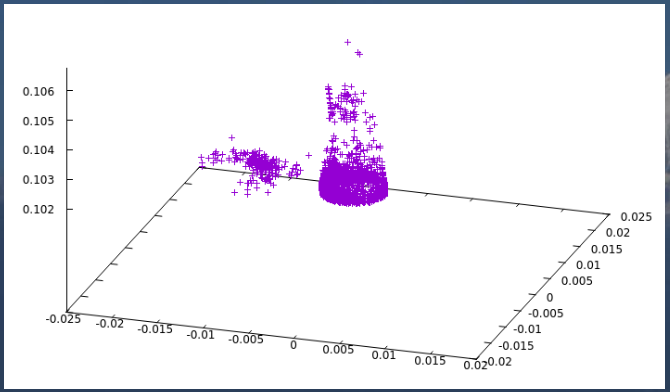
Effect of space charge in an RPC

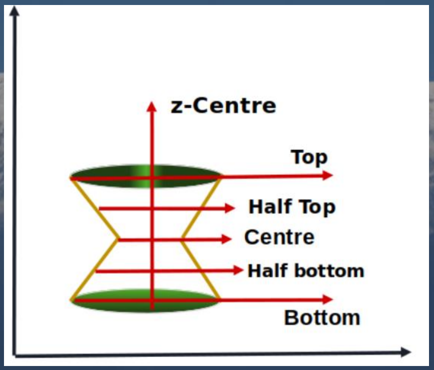


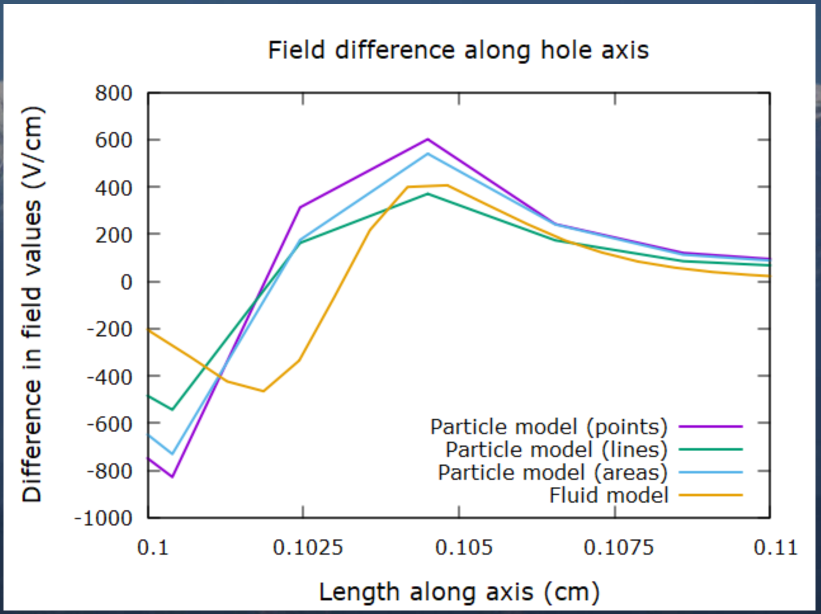
Variation of number of electrons with time steps of the avalanche for electric fields of 49.85 kV/cm, and 50 kV/cm, (a) without space-charge effect, (b) with space-charge effect, (c) considering negative ions.

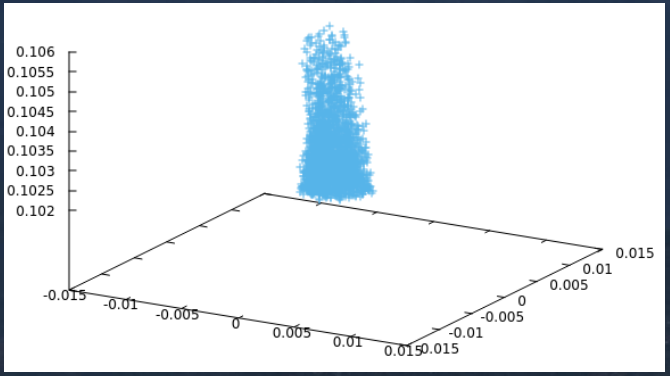
Parallelization of Garfield++ and neBEM to simulate space-charge effects in RPCs, Dey et al., CPC, https://doi.org/10.1016/j.cpc.2023.108944

Space charge in GEM
particle (Garfield++) and fluid (Comsol) models



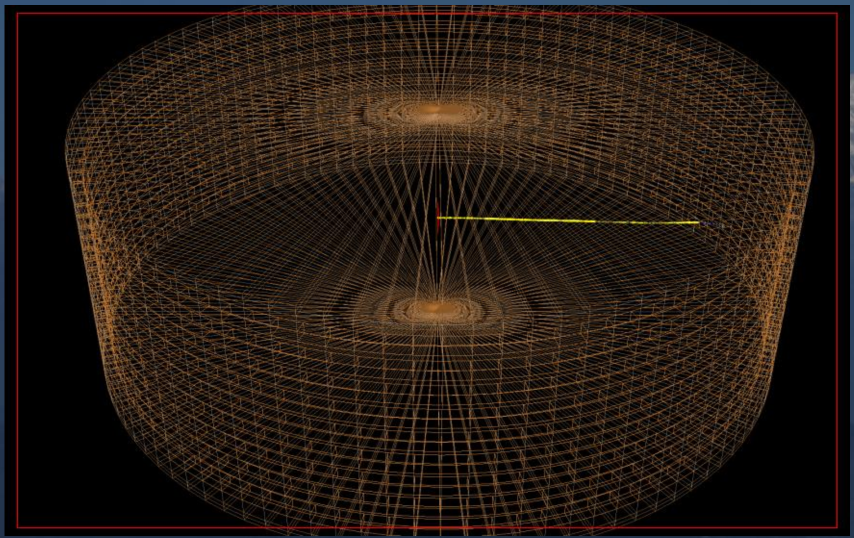


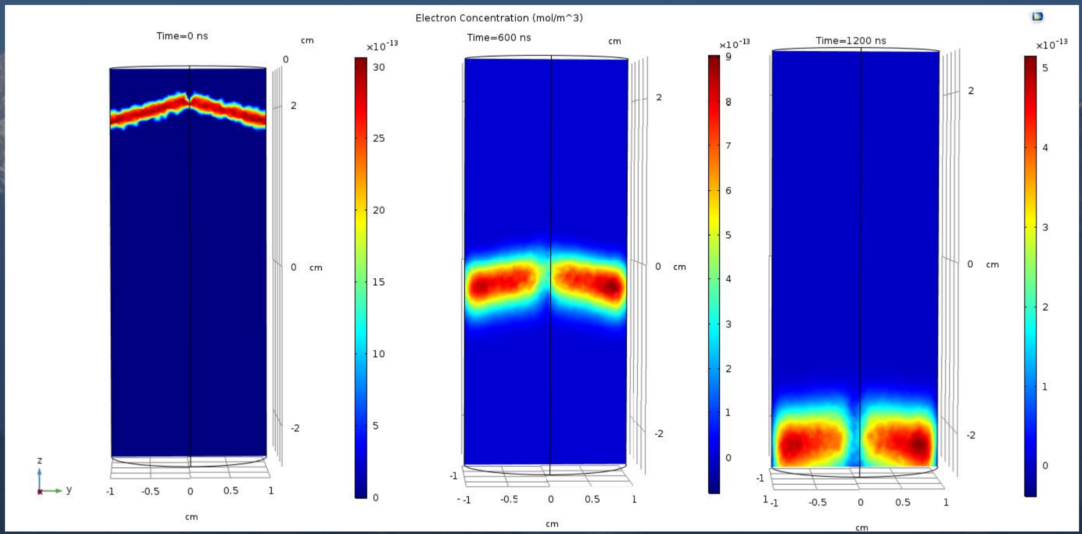




- All the models produce similar estimates.
- This is despite very different mathematical models used in particle and fluid models.
- Different particle models agree with each other.

Space charge effects in an ATTPC

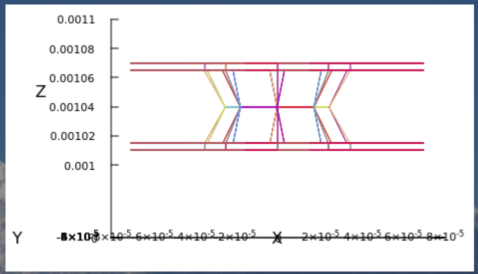




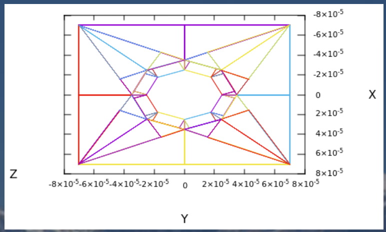
Preliminary studies:
1) α-track in an ATTPC
2) Primary ionization information obtained using Geant4
3) Space charge due to an earlier event distorts tracks in subsequent events.

Charging up in GEM
particle model

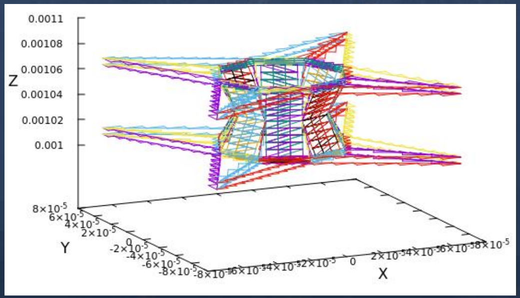
- Algo 1: Use end-points provided by Garfield++
  - Consider the ending point of charged particles. Garfield++ tries to terminate a drift line close to the boundary.
- Algo 2: Assign surface charge densities to elements
  - Identify the element on which the charged particles falls. Add all the charged 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.



Side view

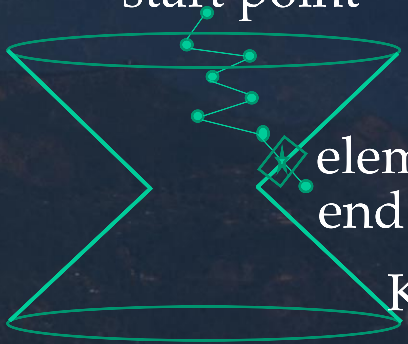


Top view



Some elements representing a GEM hole

start point

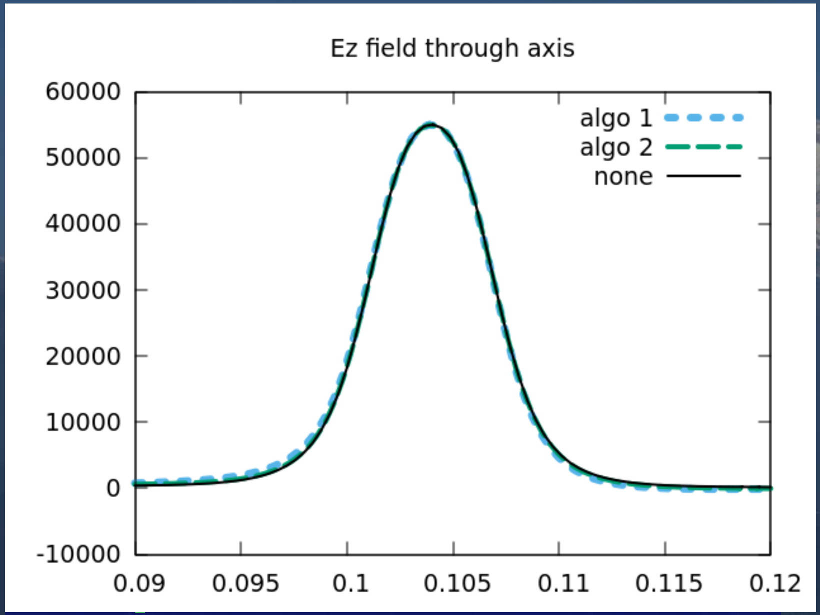


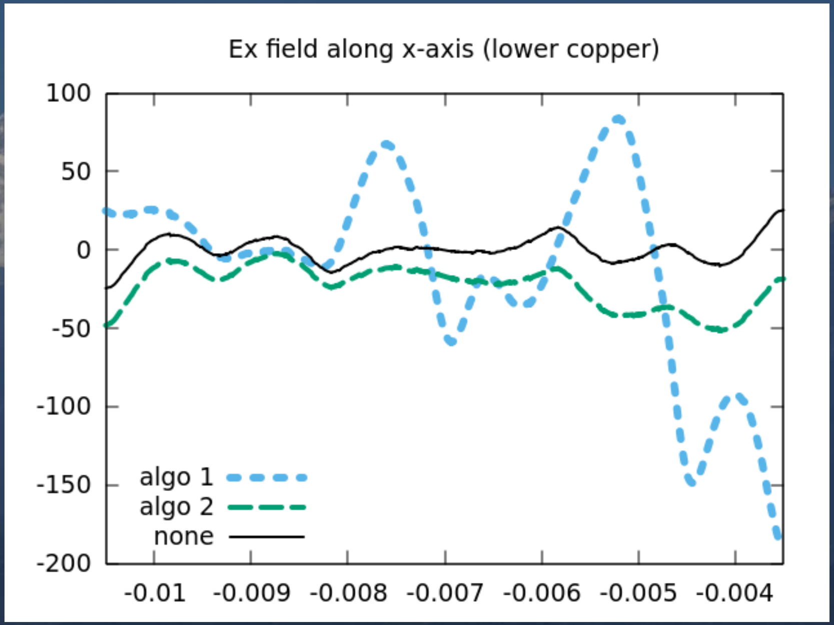
element

end point

Kapton

Effects of charging up





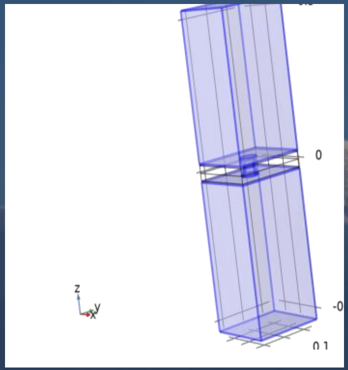
Points to be noted:

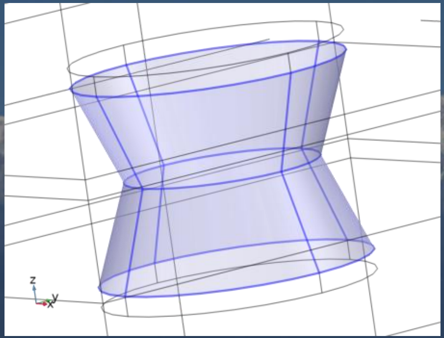
- Number of charge deposited per element has wide variation – no circular symmetry for one event.
- The symmetry may be regained due to overlap of a large number of events.
- Accumulation due to large number of events need to be considered.

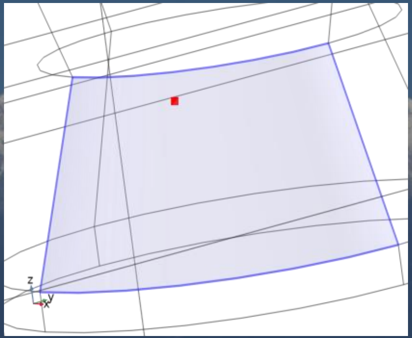
Charging up in GEM

fluid model using Comsol

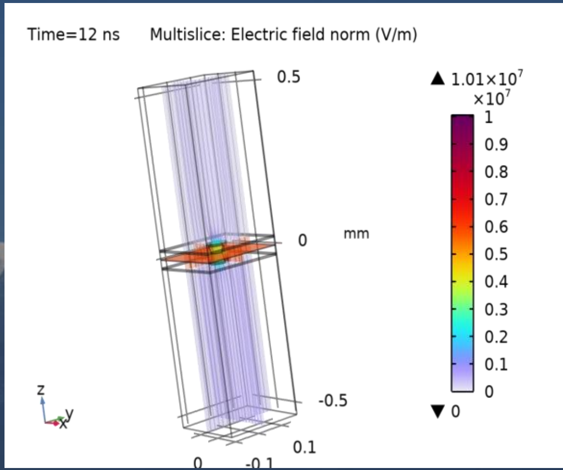
$$\frac{\partial \rho_s}{\partial t} = \mathbf{n}\cdot\mathbf{J}_i + \mathbf{n}\cdot\mathbf{J}_e$$

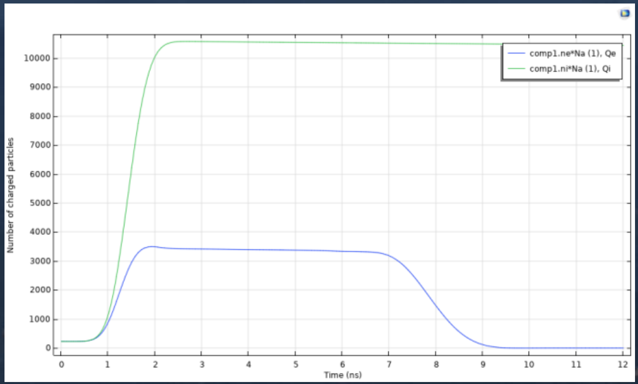


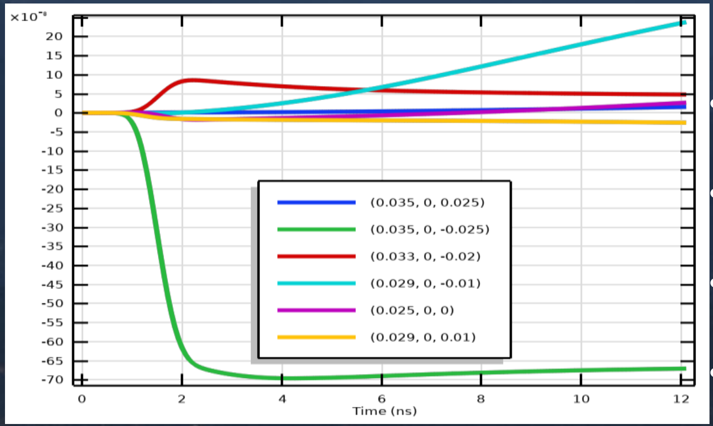




$$-\mathbf{n}\cdot(\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$$





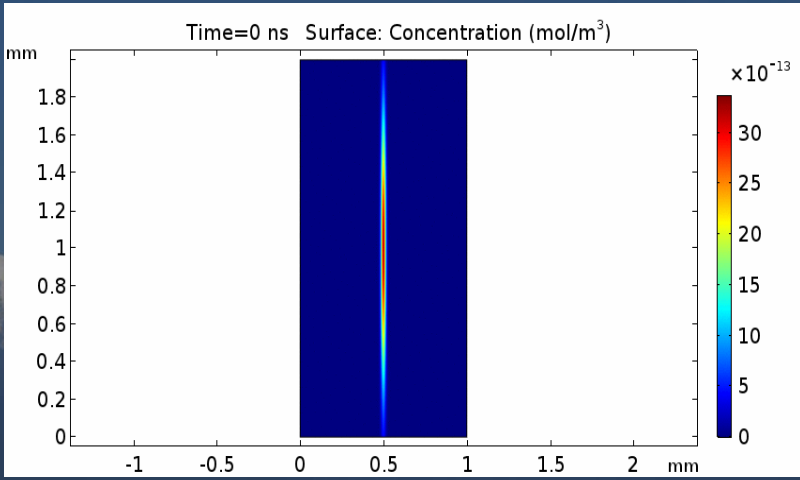


- Charge is accumulated more towards the induction / transfer volume.
- Hardly any charge is found on surface towards drift volume.
- More negative charges towards induction / transfer volume.
- Some positive charges around the middle of the hole.
- Note that only collection is simulated at present.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

This will, hopefully, also lead us to a long term model

Streamer Probability in RPC

fluid model (Comsol)



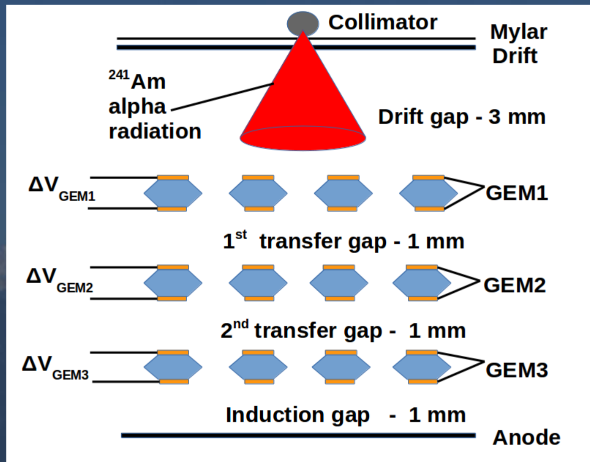
Simulated streamer

1) 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.
2) Find out the probability of occurrence of that number of electrons from the HEED primary electron information. Add up the probabilities.
3) 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.

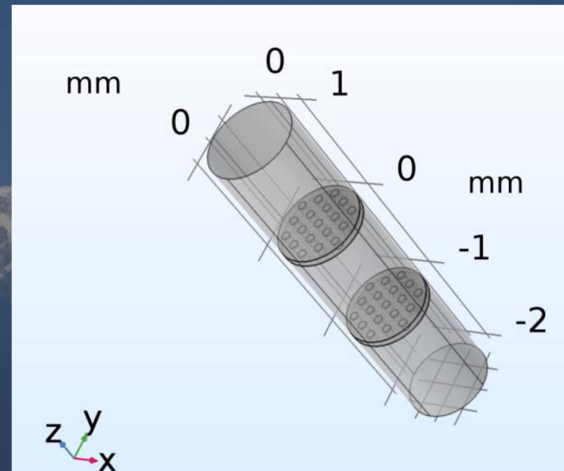
Voltage (in V)	From experiment	From simulation
9400	0.00087 +/- 0.00011	0.008
9600	0.00091 +/- 0.00015	0.008
9800	0.00411 +/- 0.00181	0.0135
10000	0.02681 +/- 0.00052	0.0224

Study of streamer development in resistive plate chamber, J.Datta et al., JINST 15 C12006 (Decmber 18, 2020), doi: 10.1088/1748-0221/15/12/C12006

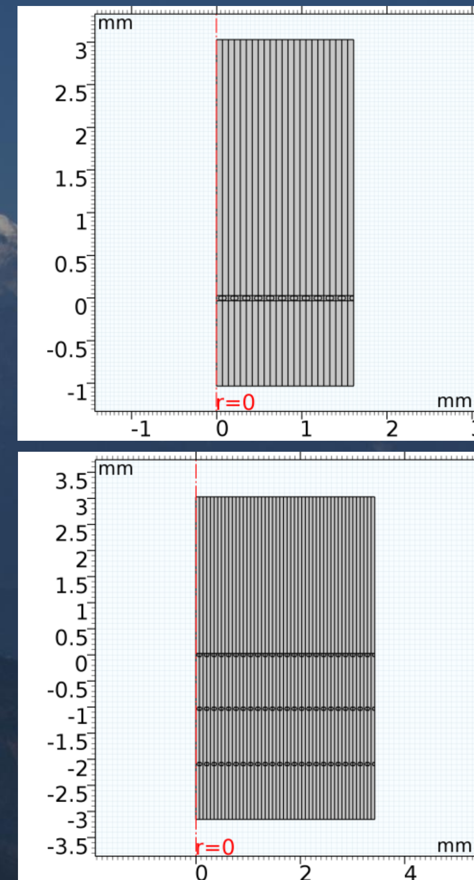
Avalanche to streamer transition in GEM



Experimental setup



3D model in Comsol

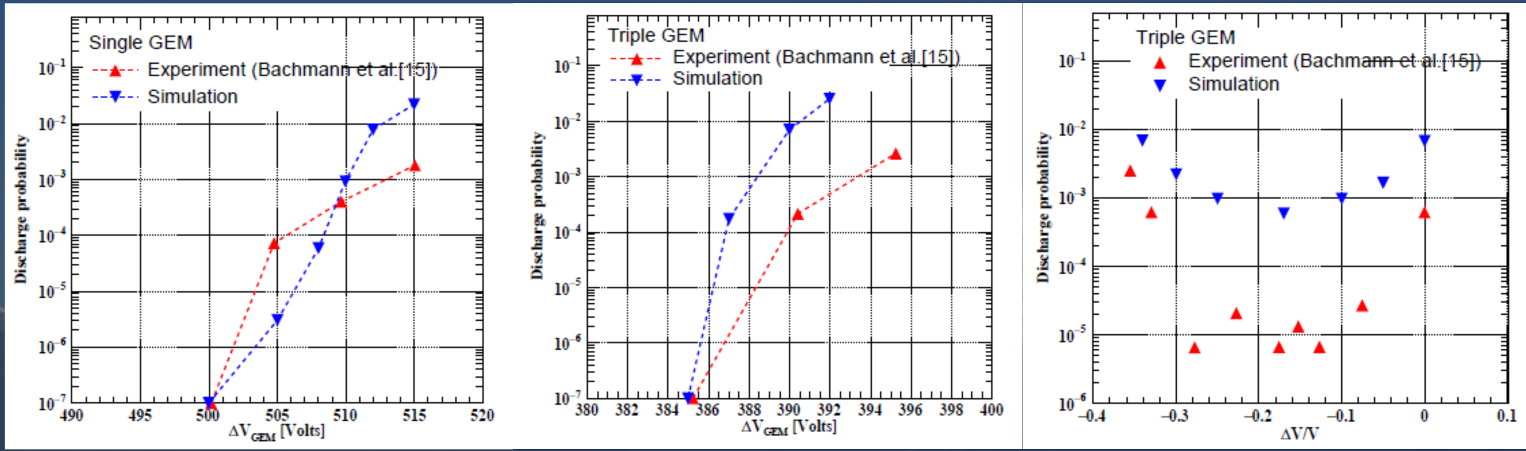


Axis-symmetric model (incorporating appropriate corrections)

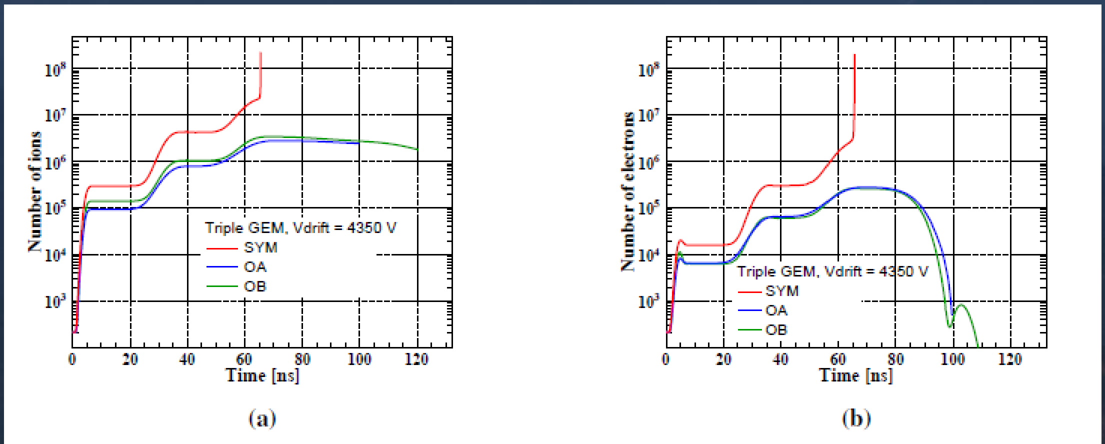
Fast simulation of avalanche and streamer in GEM detector using hydrodynamic approach, Rout et al., JINST, https://doi.org/10.1088/1748-0221/16/02/P02018

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

Discharge probability in GEM



1) Comparison of discharge probability estimates in single GEM
2) Comparison of discharge probability estimates in triple GEM
3) Comparison of discharge probability estimates with asymmetric distribution of voltages



Simulated transition from avalanche to streamer modes for SYM configuration in Triple GEM: (a) evolution of number of ions and (b) evolution of number of electrons. The avalanche mode is maintained for OA and OB configurations at this drift voltage.

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

Charge sharing in single and double GEMs, Promita Roy et al., JINST, Volume 16, C05001 (4 May 2021)
doi: 10.1088/1748-0221/16/05/C05001

Future plans

- The ongoing set of activities need to be further validated and implemented into Garfield++ in a user-friendly manner.
- Attempt to model some amount of (plasma?) chemistry leading to aging.

- Device specification and mesh generation have been implemented in a rather simple manner; rigorous but user-friendly implementation is a necessity.

- Implementation of better algorithms to handle these huge and dense matrices can make wonders, complex and transcendental functions also may benefit.
- Computational effort should be optimized – use of symmetry, adaptive mesh generation can help reducing the computational expenses by a significant amount.
- Parallel computation, GPU computation can help the overall detailed simulation.

The TEAM @ SINP

- Deb Sankar Bhattacharya
- Purba Bhattacharya
- Sudeb Bhattacharya
- Tanay Dey
- Jaydeep Dutta
- Abhik Jash
- Anil Kumar
- Vishal Kumar
- Mohammed Salim
- Muzamil Ahmad Teli
- Nayana Majumdar
- Sandip Sarkar
- Supratik Mukhopadhyay
- Pralay Das
- Prasant Kumar Rout
- Project students
- Promita Roy
- Saikat Ghosh
- Shubhabrata Dutta
- Sridhar Tripathy
- Subhendu Das

Beyond SINP: Rob Veenhof, Heinrich Schindler and members of the RD51 collaboration

The names are not in any particular order.

This has been a huge team effort. I just hope that I have not missed anybody. If I have, I surely owe an unconditional apology!

Thank you all!