Electrostatics of Micromesh Based Detectors

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Outline of the presentation

- Electrostatics of MPGDs and its relation to performance and optimization
- Available approaches for solving the electrostatic problem
- Brief introduction to BEM and the nearly exact BEM (neBEM)
- Application of neBEM for solving MPGD electrostatics
- Electrostatics of micromesh based detectors
- Integration of neBEM to the RD51 simulation framework
- Final remarks and future plan

We will try to illustrate both numerical and application aspects

Parameters affecting MPGD performance

Large number of design parameters affecting an equally large number of performance parameters. A representative set could be as follows:

Mesh geometry
Spacer geometry
Drift distance
Cell size

Applied voltages
Drift field
Amplification field
Resistive layer properties

Gas mixture

Efficiency
Count rate
Spatial resolution
Gain uniformity

Charging up
Occurrence and effect of sparks

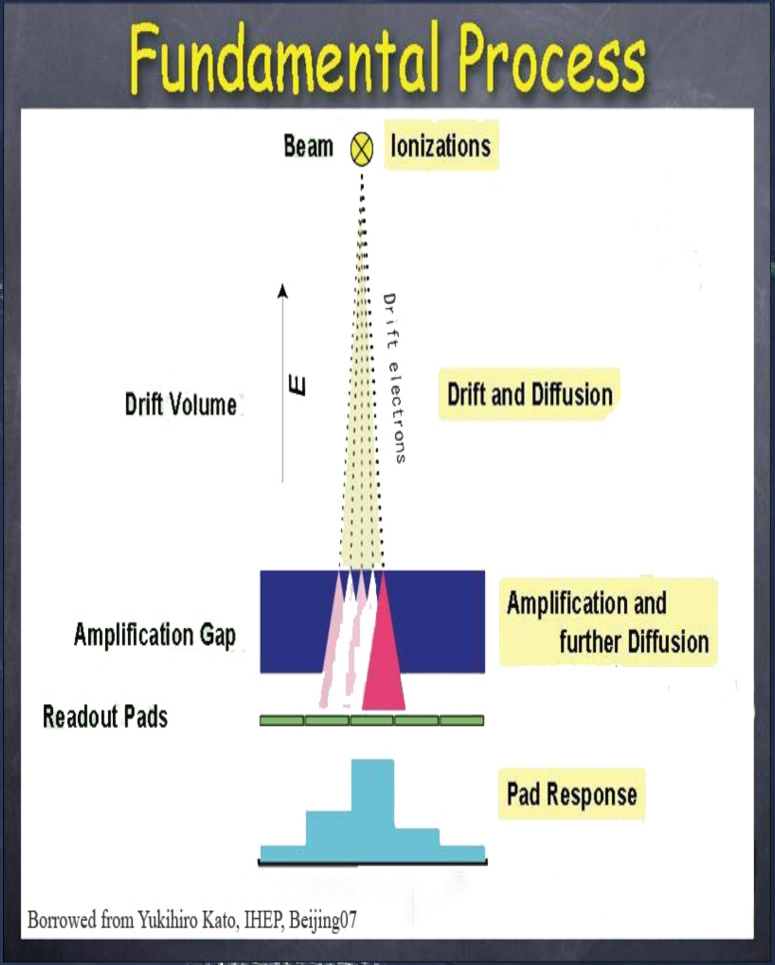
Cross-talk

Ease of fabrication
Mechanical strength

One way to interpret the performance and optimize the design of these complex devices is to use detailed and realistic numerical simulation.

Nuclear detector simulation

Long and winding road

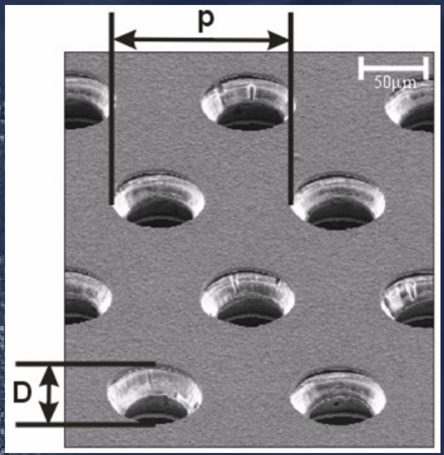


- Field Solver – commercial FEM packages (e.g., **MAXWELL**)
- Particle interaction to charge induction – **Garfield** framework
  - **Ionization:** energy loss through ionization of a particle crossing the gas and production of clusters - **HEED**
  - **Drift and Diffusion:** electron drift velocity and the longitudinal and transverse diffusion coefficients - **MAGBOLTZ**
  - **Amplification:** Townsend and attachment coefficients - **IMONTE**
  - **Charge induction**: Involves application of Reciprocity theorem (Shockley-Ramo's theorem), Particle drift, charge sharing (pad response function - PRF) - **GARFIELD**
- Signal generation and acquisition - **SPICE**

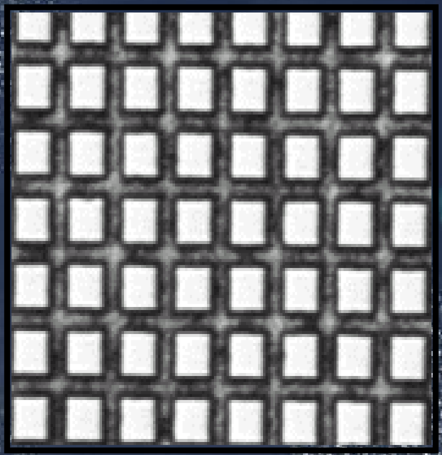
The Field Solver is crucial at every stage – Poisson equation

A Field Solver for Nuclear Detectors

Expected features



GEM Typical dimensions
Electrodes (5 µm thick)
Insulator (50 µm thick)
Hole size D ~ 60 µm
Pitch p ~ 140 µm
Induction gap: 1.0 mm,
Transfer gap: 1.5 mm



Micromegas dimensions
Mesh size: 50 µm
Micromesh sustained by
50 µm pillars

Some of the expected features are as follows

- Handle large variation in length scales (a micron to a meter)
- Make available, on demand, properties at arbitrary locations (near- and far-field)
- Model intricate geometrical features using triangular elements as and when needed
- Model multiple dielectric devices
- Model nearly degenerate (closely packed) surfaces
- Model space charge effects
- Model dynamic charging processes
- Compute field for the same geometry, but with different electric configuration repeatedly
- High computational efficiency – periodic structures

The de-facto standard FEM is unsatisfactory in dealing with 1., 2., 5., 6., 7. and 8. Hence, the search for a new tool.

The Poisson's equation

- Physical consequence of combining
  - A phenomenological law (inverse square laws, Fourier law in heat conduction, Darcy law in groundwater flow)
  - Conservation law (heat energy conservation, mass conservation)
- Primary variable (some scalar potential), P; material constant, m; Source, S

$$\nabla.(m\nabla P) = S$$

Heat transfer: temperature, thermal conductivity, heat source
Electrostatics: potential, dielectric constant, charge density
Magnetostatics: potential, permeability, charge density
Groundwater flow: piezometric head, permeability, recharge
Ideal fluid flow: stream function, density, source
Torsion of members with constant cross-section: stress, shear modulus, angle of twist
Transverse deflection of elastic members: deflection, tension, transverse load
Many more …

Arguably, the most important equation in classical physics!

Solve $\nabla.(m\nabla P) = S$

BEM

- ✓ Reduced dimension
- ✓ Accurate for both potential and its gradient

- x Complex numerics
- x Numerical boundary layer
- x Numerical and physical singularities

Analytic

- ✓ Exact
- ✓ Simple interpretation

- x Restricted
- x 2D geometry
- x Small set of geo-metries

FEM / FDM

- ✓ Nearly arbitrary geometry
- ✓ Flexible

- x Interpolation for non-nodal points
- x Field values liable to be inaccurate
- x Difficulty in unbounded domains

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BEM Basics

Green's identities ⇒ Boundary Integral Equations

Potential *u* at any point *y* in the domain *V* enclosed by a surface *S* is given by

$$u(y) = \int_S U(x,y)q(x)dS(x) - \int_S Q(x,y)u(x)dS(x) + \int_V U(x,y)b(x)dV(x)$$

where *y* is in *V*, *u* is the potential function, $q = u_{,n}$, the normal derivative of *u* on the boundary, *b(x)* is the body source, *y* is the load point and *x*, the field point. *U* and *Q* are fundamental solutions

$$U_{2D} = (1/2\pi)\ln(r),\ U_{3D} = 1/(4\pi r),\ Q = -(1/2\pi\alpha r^{\alpha})\, r_{,n}$$

$\alpha = 1$ for 2D and 2 for 3D. Distance from *y* to *x* is *r*, n_i denotes the components of the outward normal vector of the boundary.

2D Case	3D Case	r = 0	r -▷ 0, r≠ 0
ln(r)	1/r	Weak singularity	Nearly weak singularity
1/r	$1/r^2$	Strong singularity	Nearly strong singularity
$1/r^2$	$1/r^3$	Hyper singularity	Nearly hyper-singularity

Solution of 3D Poisson's Equation using BEM

- Numerical implementation of boundary integral equations (BIE) based on Green's function by discretization of boundary.
- Boundary elements endowed with distribution of sources, doublets, dipoles, vortices.

Electrostatics BIE

$$\Phi(\vec{r}) = \int_S G(\vec{r}, \vec{r}')\rho(\vec{r}')dS'$$

Potential at r

Charge density at r'

Green's function

$$G(\vec{r}, \vec{r}') = \frac{1}{4\pi\varepsilon|\vec{r} - \vec{r}'|}$$

ε - permittivity of medium

discretization

$$[A]\{\rho\} = \{\Phi\}$$

Influence Coefficient Matrix

$$\{\rho\} = [A]^{-1}\{\Phi\}$$

Accuracy depends critically on the estimation of [A], in turn, the integration of G, which involves singularities when r → r'.

Most BEM solvers fail here.

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Conventional BEM

Major Approximations

- Singularities modeled by a sum of known basis functions with constant unknown coefficients.
- The strengths of the singularities solved depending upon the boundary conditions, modeled by shape functions.

Numerical boundary layer

Difficulties in modeling physical singularities

- geometric singularity
- boundary condition singularity

Constant element approach

Singularities assumed to be concentrated at centroids of the elements, except for special cases such as self influence.

Boundary conditions are satisfied at the same nodal points.

Present Approach

Analytic expressions of potential and force field at any arbitrary location due to a uniform distribution of source on flat *rectangular* and *triangular* elements. Using these two types of elements, surfaces of any 3D geometry can be discretized.

Restatement of the approximations

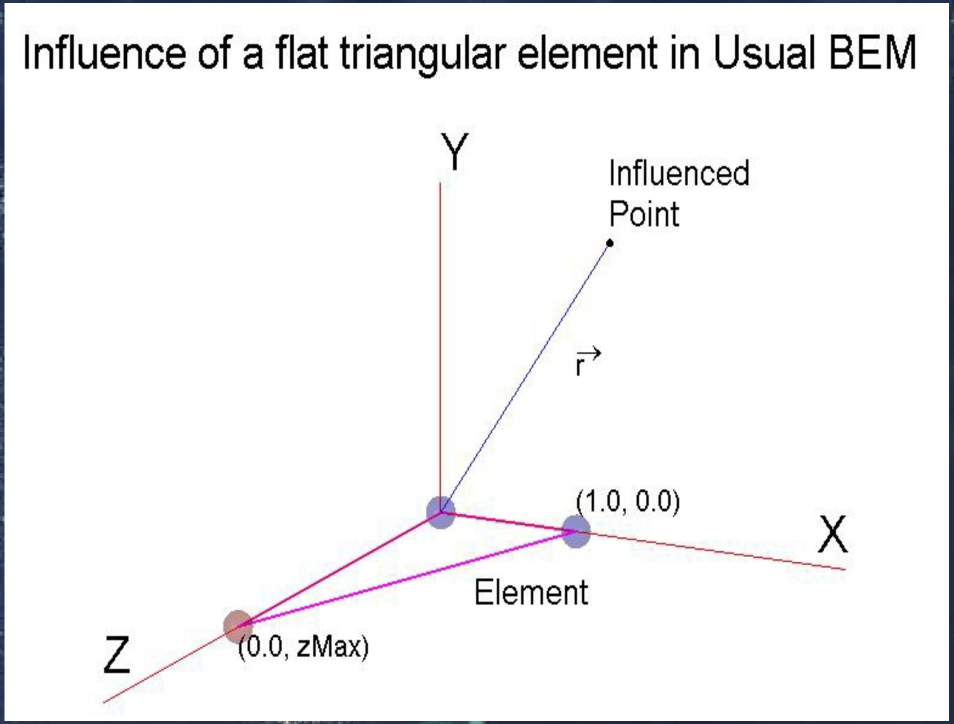
- Singularities distributed uniformly on the surface of boundary elements
- Strength of the singularity changes from element to element.
- Strengths of the singularities solved depending upon the boundary conditions, modeled by the shape functions

neBEM Formalism

Foundation expressions of the neBEM formalism are analytic and closed-form
They are valid for the complete physical domain

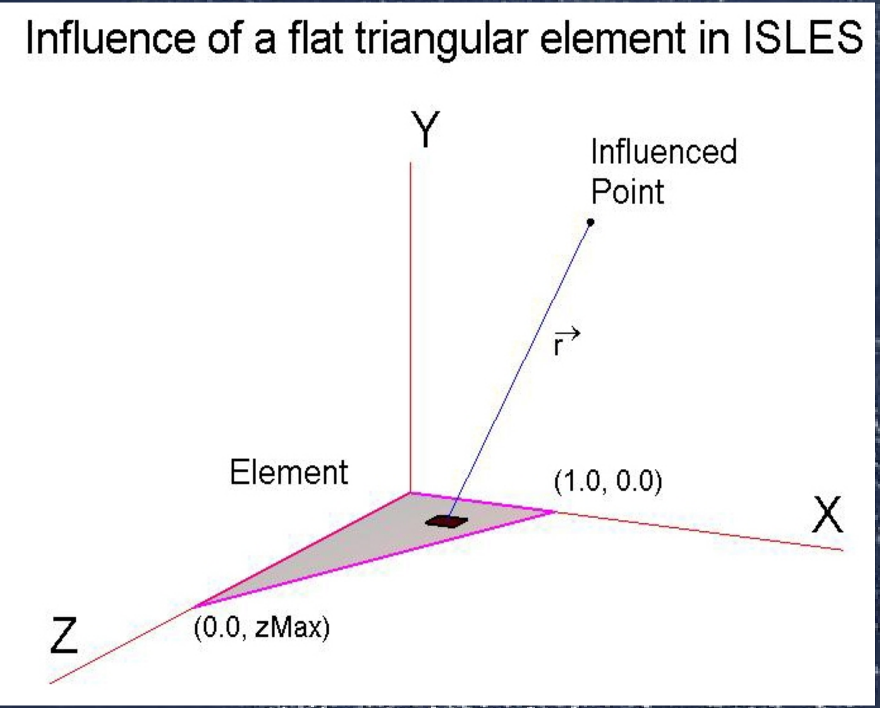
Contrast of approaches

Conventional BEM (nodal) versus nearly exact BEM (distributed)



Conventionally, charges are assumed to be concentrated at *nodes*. This is convenient since the preceding integration is avoided. Introduces large errors in the near field.

We have derived exact expressions for the integration of G and its derivative for uniform charge *distributions* over triangular and rectangular elements



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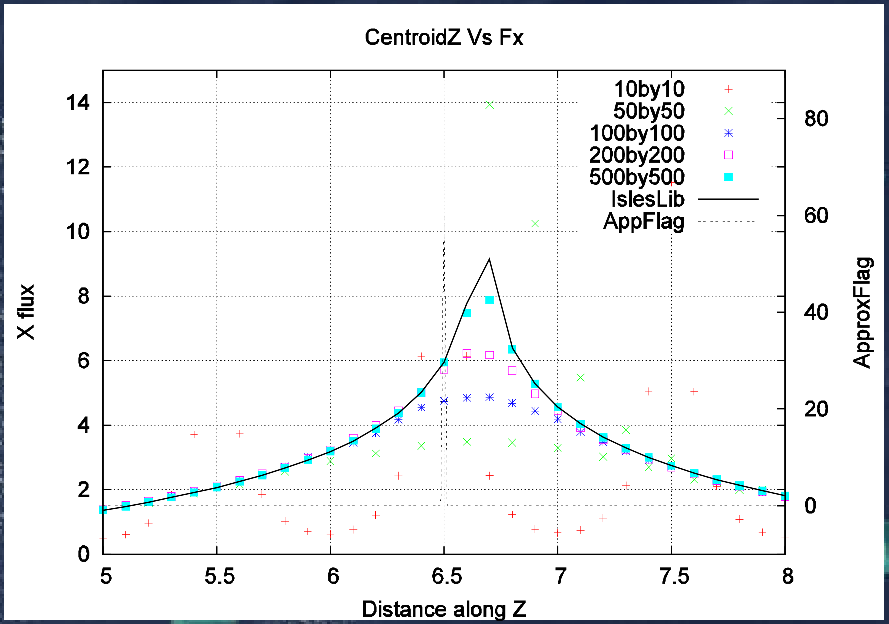
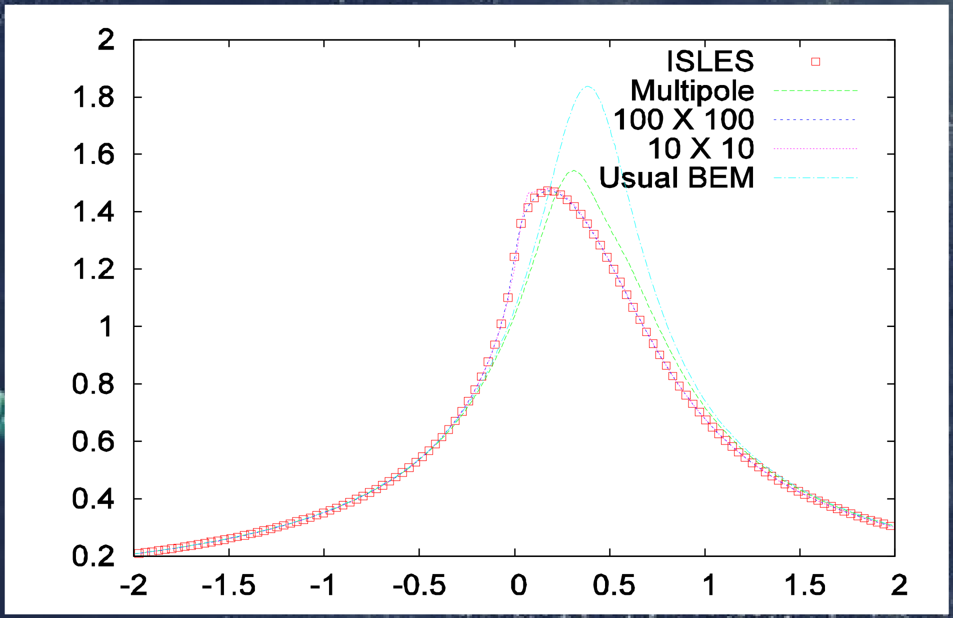
Precision in flux computation

comparison with quadrature and multipole expansions

zMax = 10.0





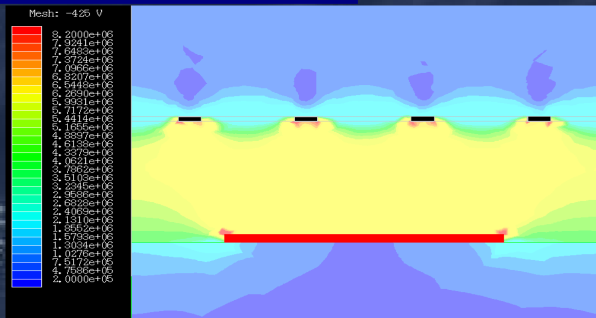
Quadrature with even the highest discretization fails!

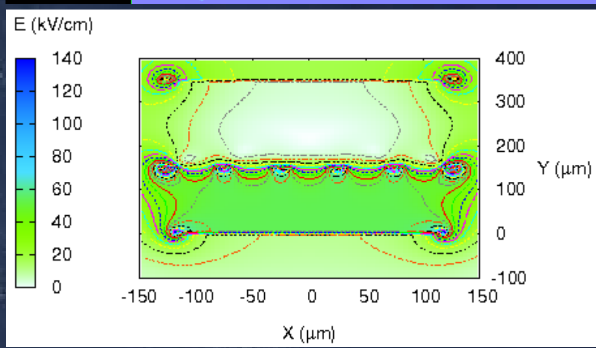
Comparison of flux along a line parallel to Z axis passing through barycenter

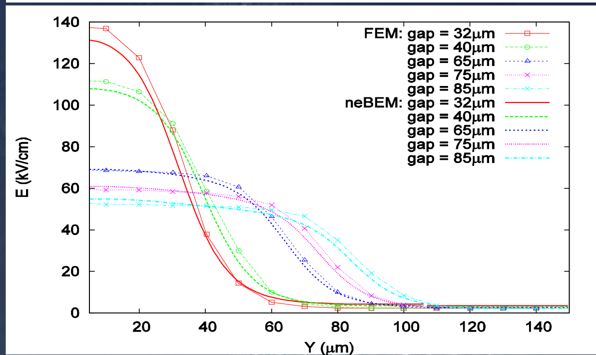
The quadrupole results are far from precise; quadrature needs very fine discretization

Electrostatics of MPGDs

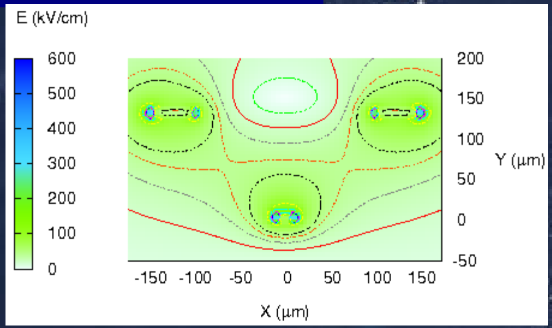
Micromegas

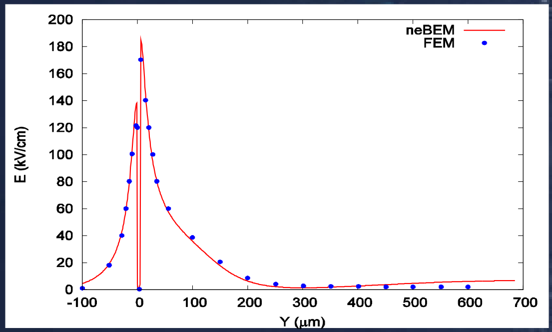


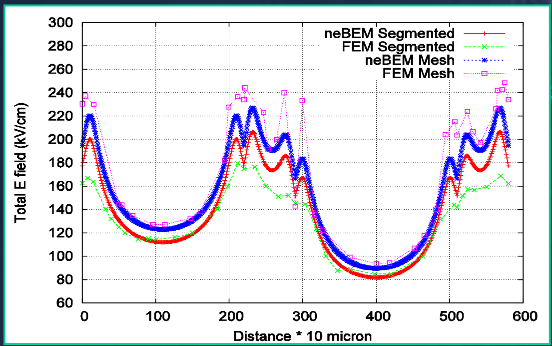




Micro-Wire





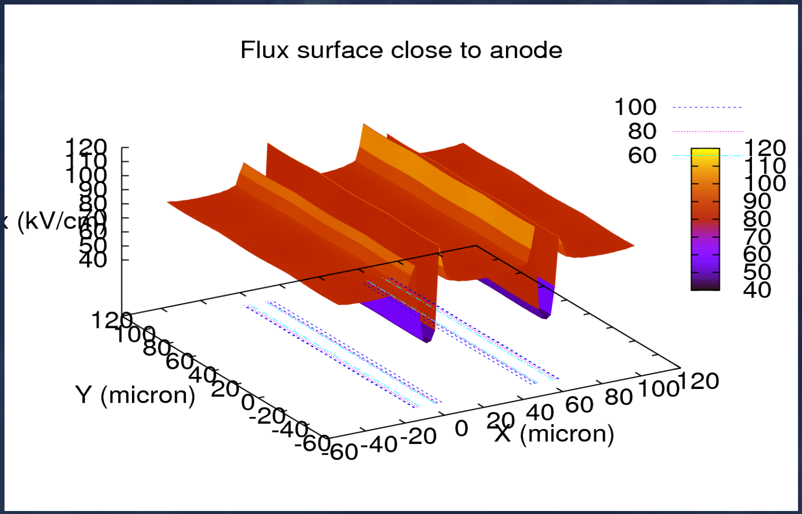


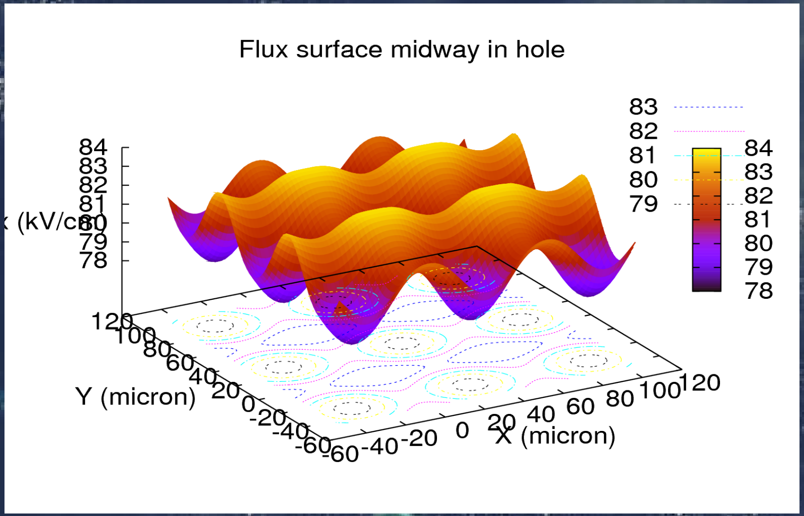
Theoretical considerations imply better performance by the neBEM solver which solves for the charge density on boundary elements rather than potential at a pre-fixed set of nodal points.

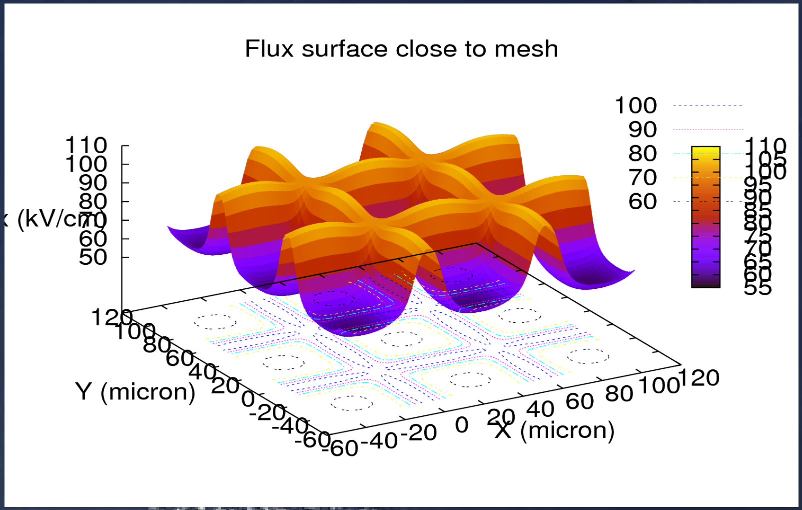
Numerical comparisons
1) neBEM results are as accurate as FEM results in the far-field
2) In the near-field, neBEM performs better than FEM
3) No artificial truncation of open domain is necessary while using neBEM

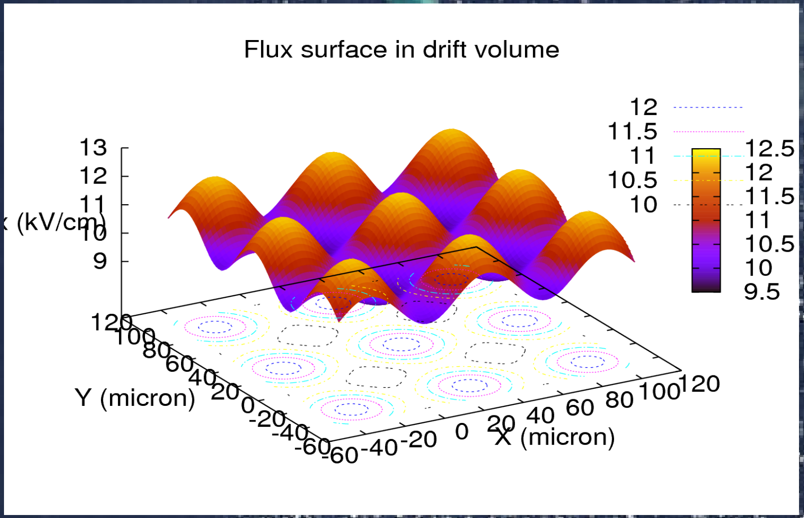
Flux surfaces in a micromesh device

Hole size 50 micron, pitch 60 micron and gap 50 micron; grid @ -400V, drift plane @ 16mm, -3800V

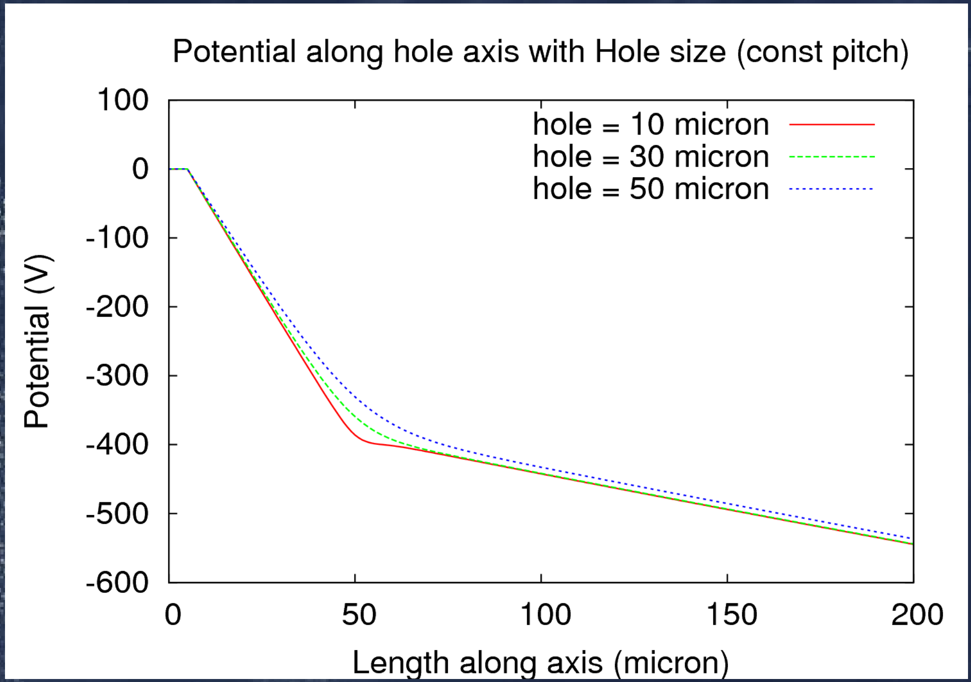


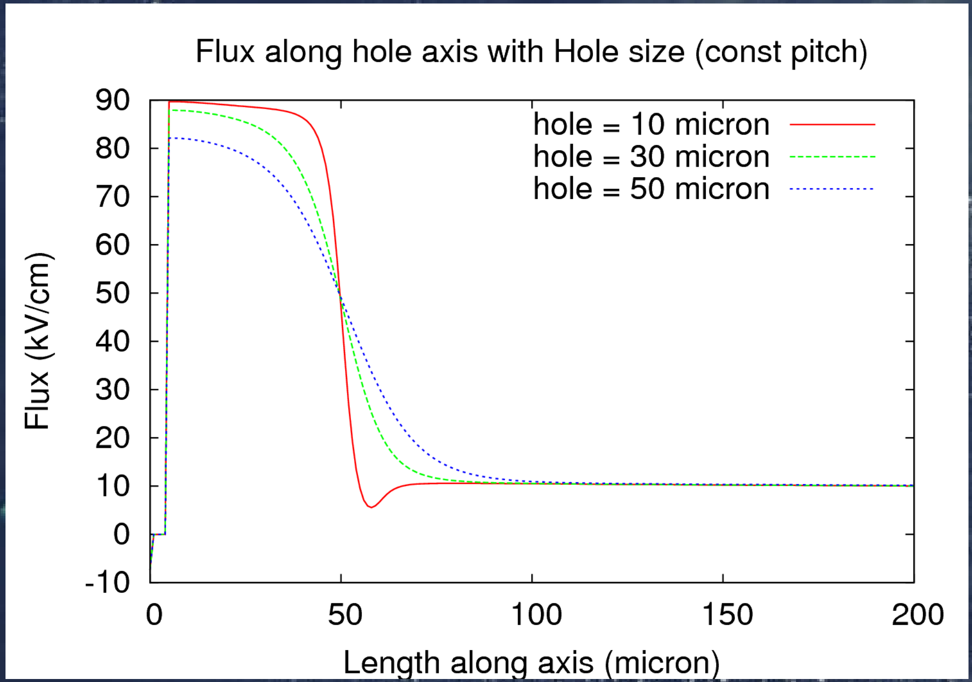






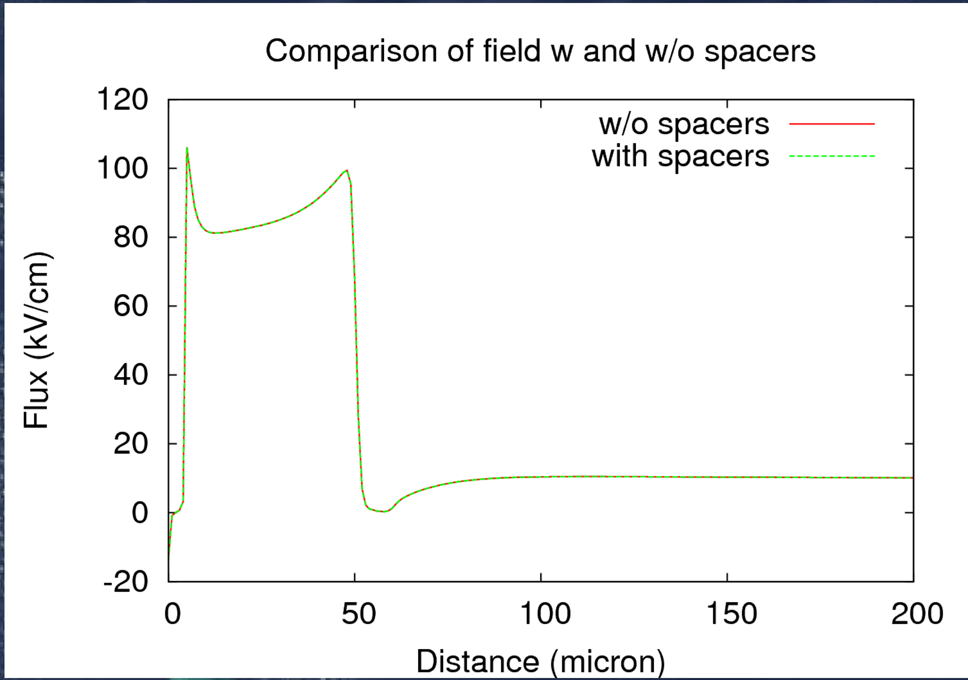
Special attention - Effect of the variation of hole size

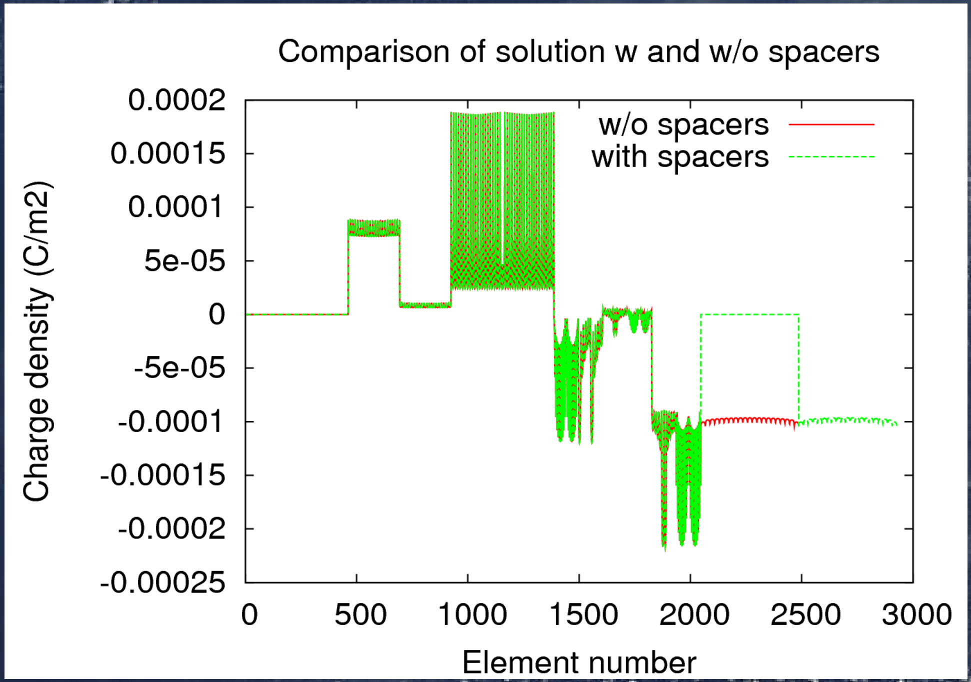




1. The pitch was kept constant (60 micron). The anode was also kept unchanged.
2. The potential is closer to parallel plate case for the smaller hole size - naturally.
3. Although the field is larger for the smaller hole size, it falls off more rapidly
4. The data has been generated for points one micron apart – the smooth variation usually observed in analytical solutions is typical of BEM, especially neBEM

The effect of pillars / spacers

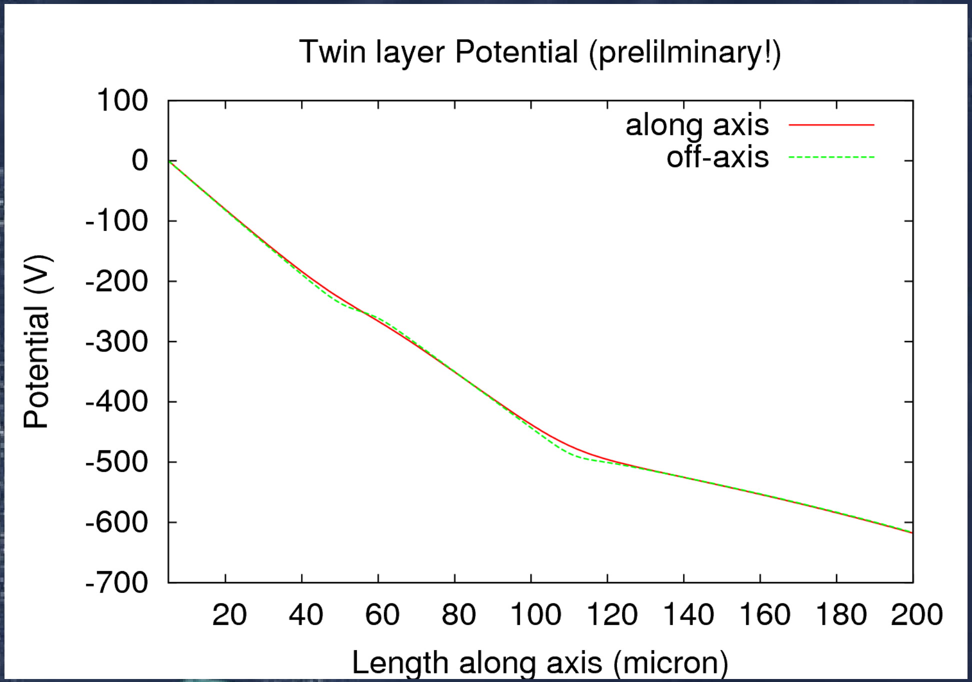


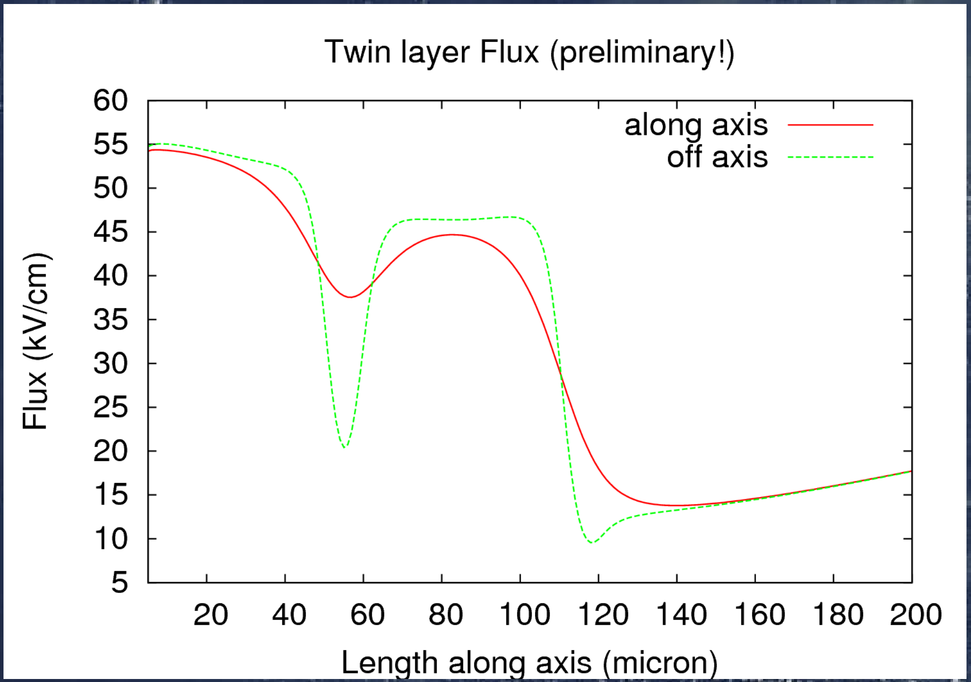


For the 50 micron hole device discussed in the earlier pages.

1. The pillars are assumed to match the mesh crossings – 10 micron cross-section
2. There is no difference that seems to be able to affect the performance
3. The reason is reflected in the charge density plot where we can see that the amount of charge on the spacer material is negligible

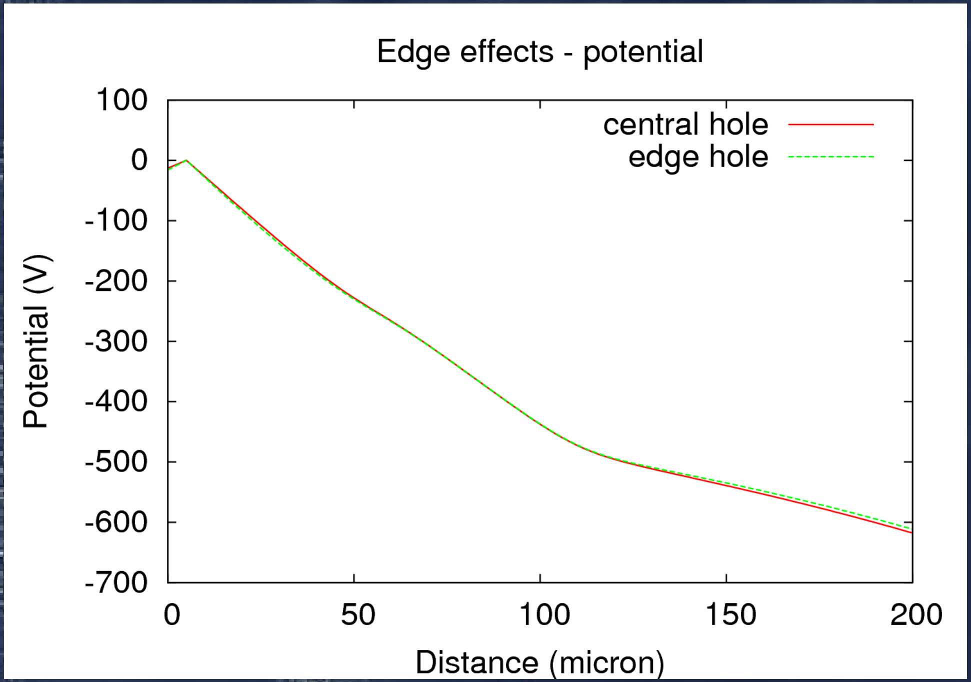
Twin layer micromegas

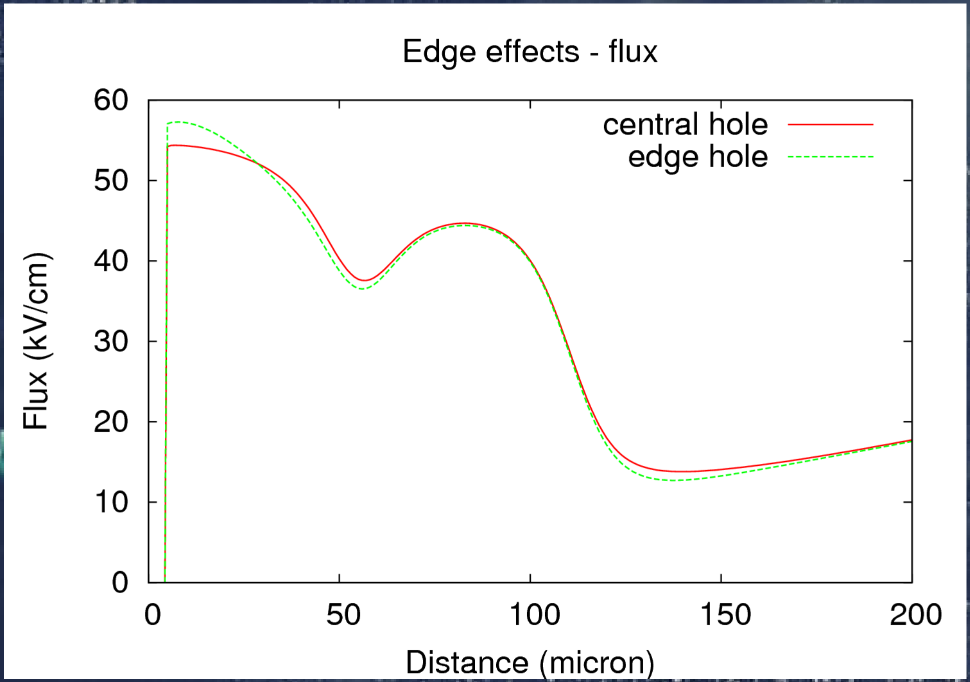




1. Please note that the results are preliminary in nature!
2. Both amplification gaps are 50 micron; Voltages -250V and -500V
3. The general trend is intuitive – no big surprise around
4. With some patience, it should be easy to make amends to the curious flux shape
5. For this calculation, we did not use periodicity - ~13000 elements – four hours on blade server!
6. But, the important point is, it can be done, if necessary - for example, if you are studying edge effects

The importance of edge effects





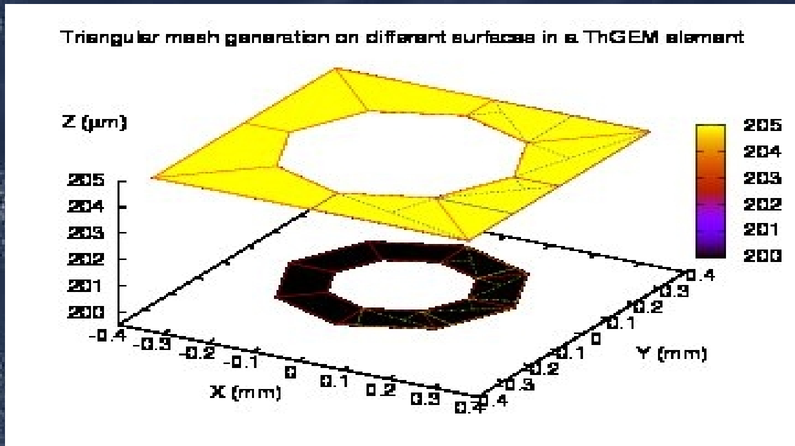
Please note the preliminary nature of these results

1. Not much difference in potential

2. Flux, however, shows significant differences, especially in the first amplification gap

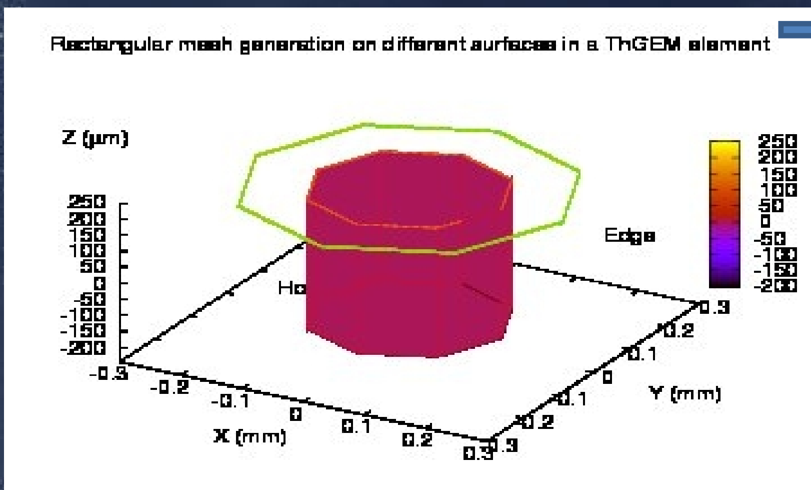
How do we go about it?

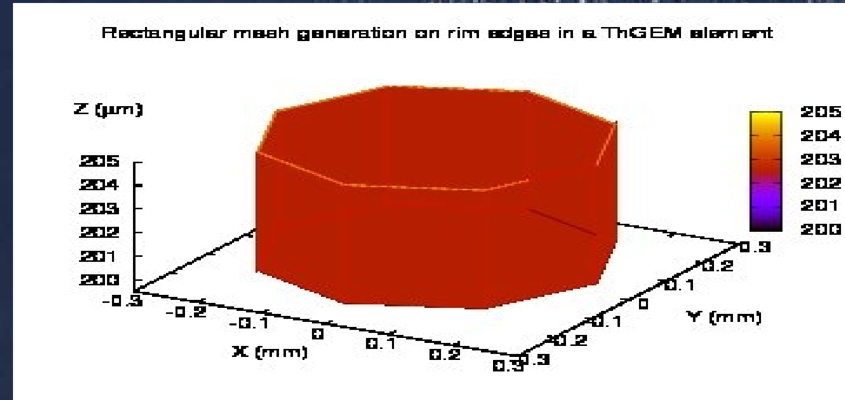
Example analysis of a ThGEM



Preprocess :

- Device definition using various primitives / surfaces
- Discretization of primitives into triangular or rectangular elements
- Preparation of input files for neBEM with geometrical and electrical parameters of the elements





Interfaces – available, under development and planned

1. neBEM is written as a tool-kit – the user can supply one driver routine and one interface routine. They can be together, but is more convenient kept apart.

2. Several examples are available – the results presented here constitute a part of the repertoire

3. Setting up the device geometry is the main challenge. It can be done using a stand-alone code.

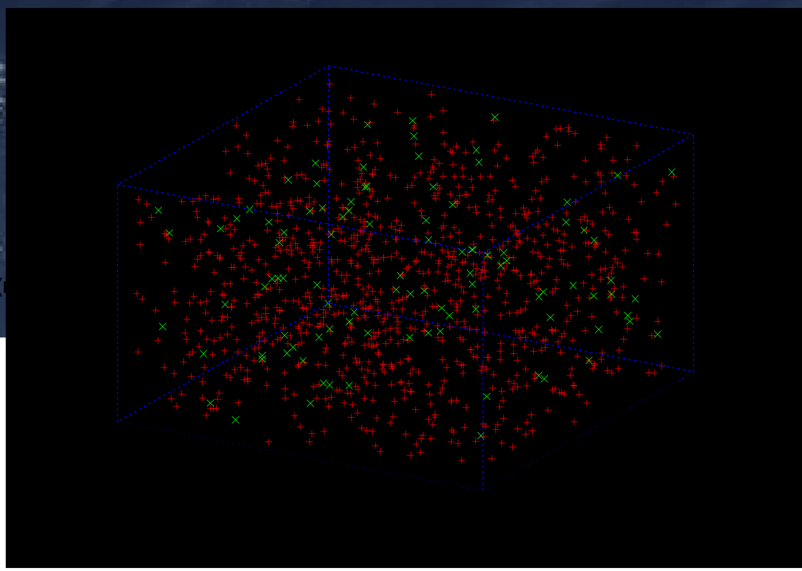
4. The code has an interface (already working, thanks to Rob!) with Garfield.

5. Simple device geometries can now also be set up using ROOT

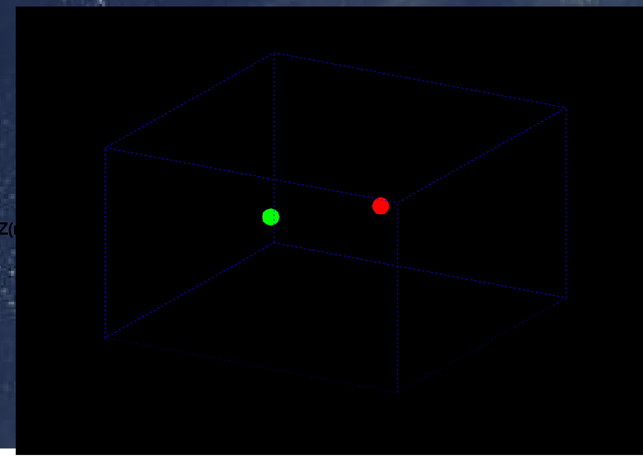
6. It is possible to use experimentally measured device geometry and use it to estimate the (hopefully more realistic) electrostatic configuration.

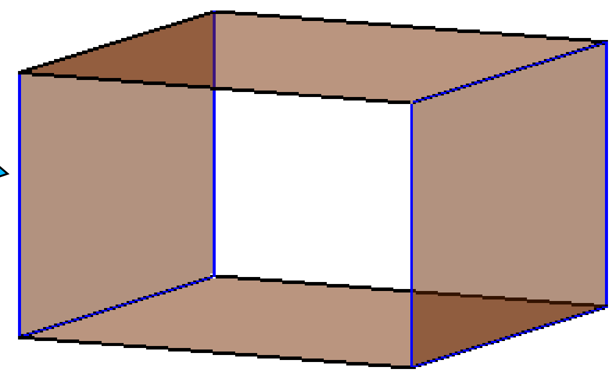
Particles on Surface (ParSue)

An improved model to represent space charge



PIC





Possible only through the use of neBEM formalism

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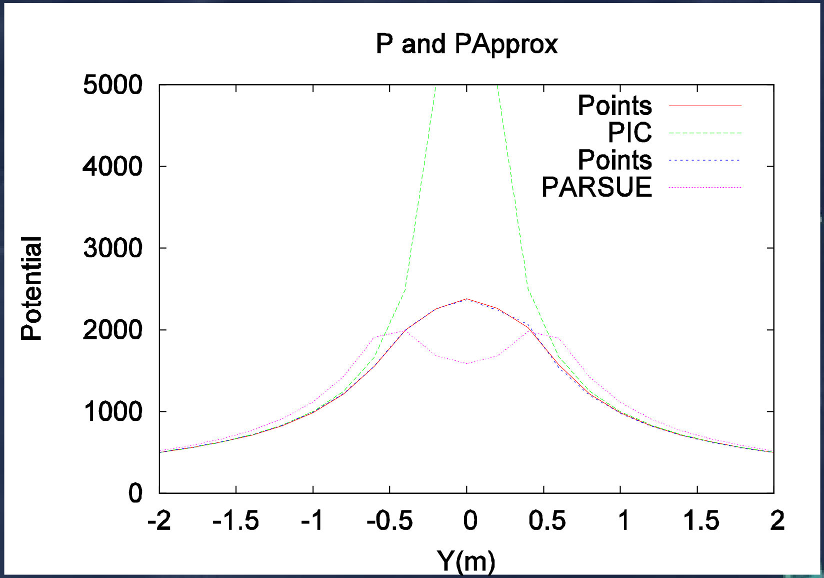
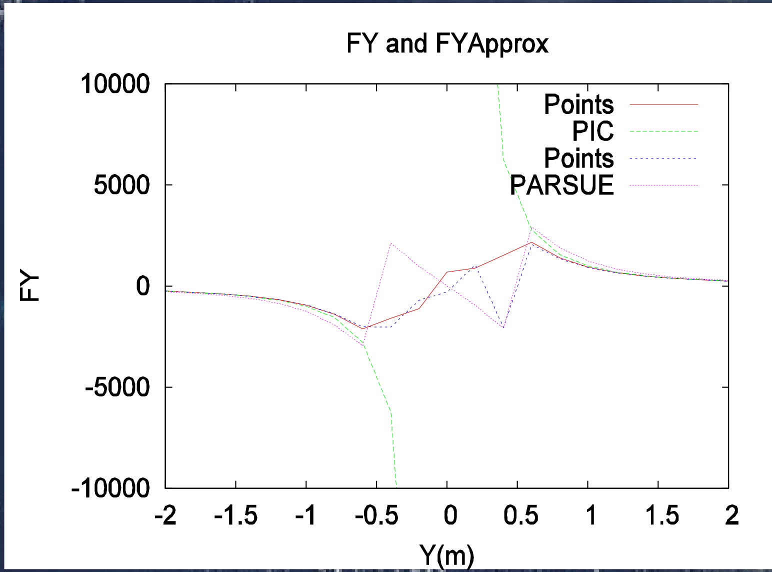
Space charge

Particles on Surface (ParSue)





- Both potential and field within the cell has been estimated far more accurately by ParSue than the PIC

PARticles on SUrfacE (PARSUE) seems to be the new model to pursue!!

RPC 2007;NIMA

Conclusions and future plans

- neBEM can provide us with one of the important missing pieces in the projected simulation framework
- Written in a toolkit fashion, it is available for users to be used in a stand-alone fashion, or interfaced / integrated with other codes
- Present version seem to provide us with reliable and precise estimation of electrostatic configuration
- Efficiency issues need to be resolved – especially those related to the evaluation of the foundation expressions near branch-cuts
- Dynamics charging is an issue that can be tackled using the same formulation in a quasi-static fashion - needs lot of work though
- Space charge can be modeled in a more accurate fashion using ParSue – proof-of-concept seems to be successful. Needs implementation
- Magnetostatics is another aspect that should be easily tackled using a similar formulation
- Documentation is in a very bad shape – we plan to put good effort into this within the coming couple of weeks

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Thank you!