RD51 COLLABORATION MEETING - 22ND TO 26TH JUNE 2020

Charging-up simulations

for GEM, THGEM and Micromegas

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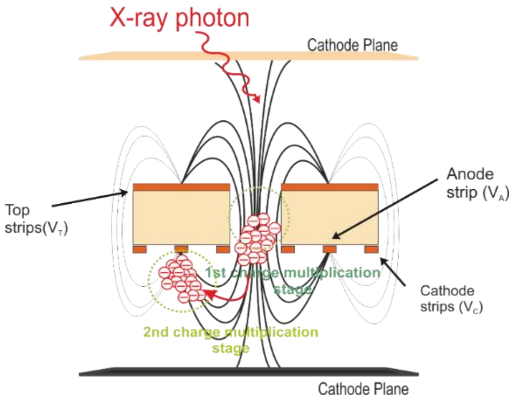
Outline

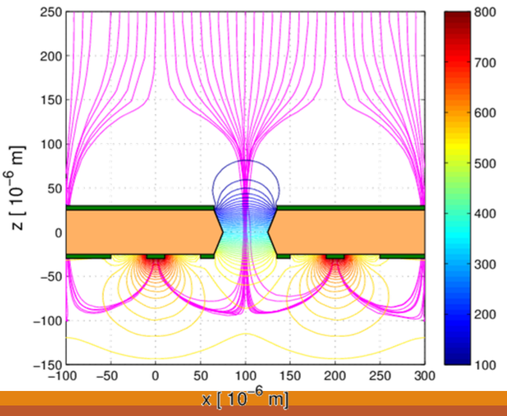
- Background
- Simulations software in MPGDs
- Building the Electrostatic field maps
- Particle transport using Garfield++ (GEM, THGEM and Micromegas)
- Some examples (explaining differences between simulation and measurements, gain evolution over time)
- Main conclusions

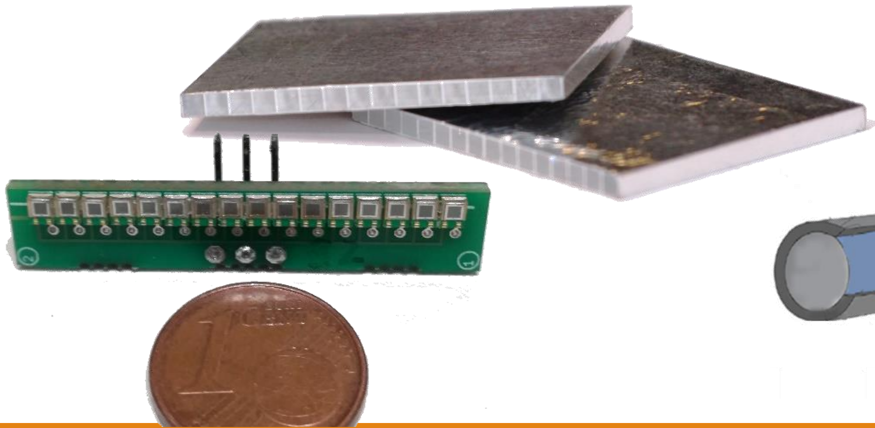
Investigation group – DRIM University of Aveiro (PT)

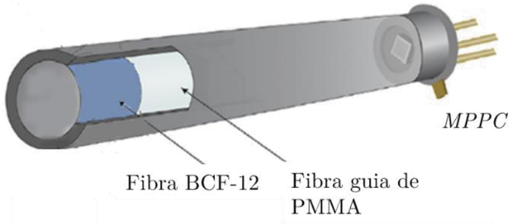
Deteção de **R**adiação e **I**magiologia **M**édica - Radiation detection and Medical Imaging

- Medical Physics (CT, PET, easyPET);
- Physics Instrumentation;
- Applied Physics
- Strong research in new systems and devices with application in Medical Physics / Biomedical Engineering





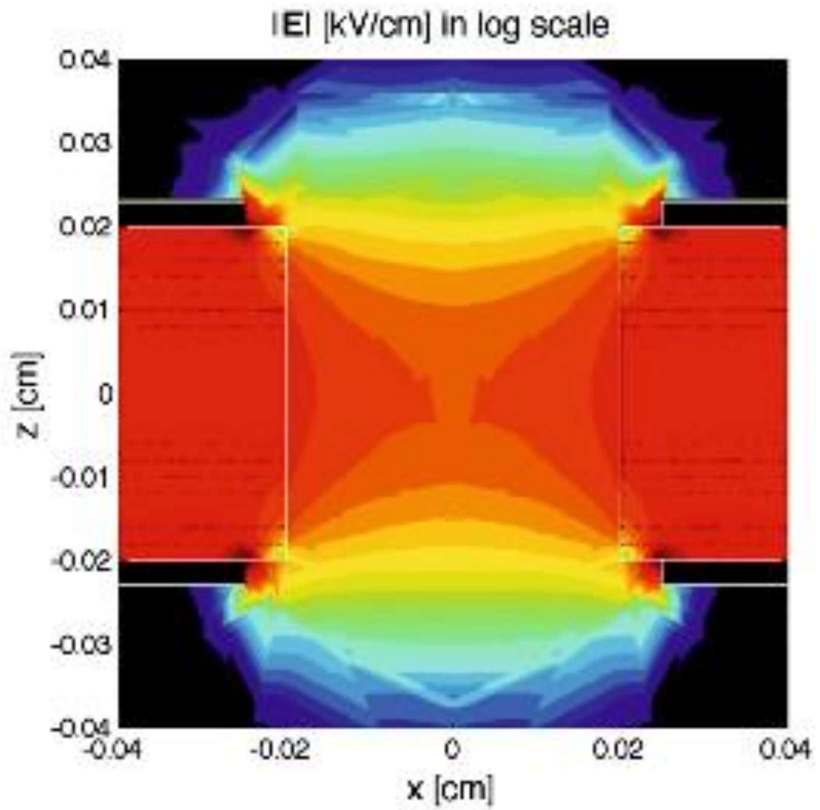




Background

Typical MPGDs simulations rely in two types of calculations:

- **Electrostatic fields (FEM calculations)**

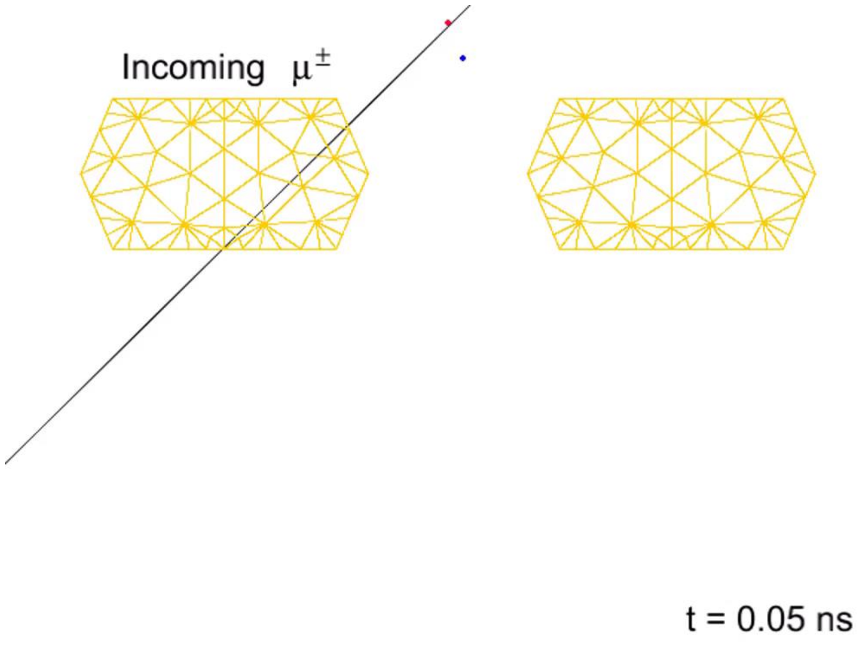


Correia et al, GEM Electrostatic Field Map
MPGD CB Zaragoza 2013

Background

Typical MPGDs simulations rely in two types of calculations:

- Electrostatic fields (FEM calculations)
- **Particle transport in gaseous or liquid materials**

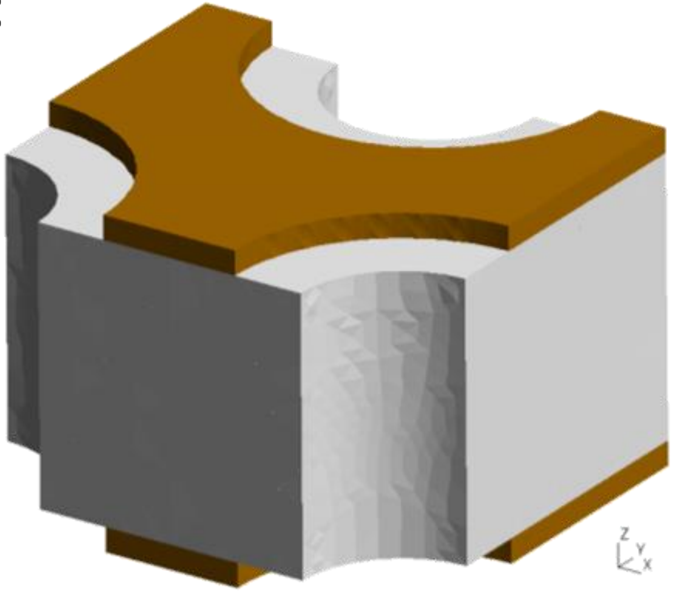


Dildick et al, MPGD CB CERN 2011

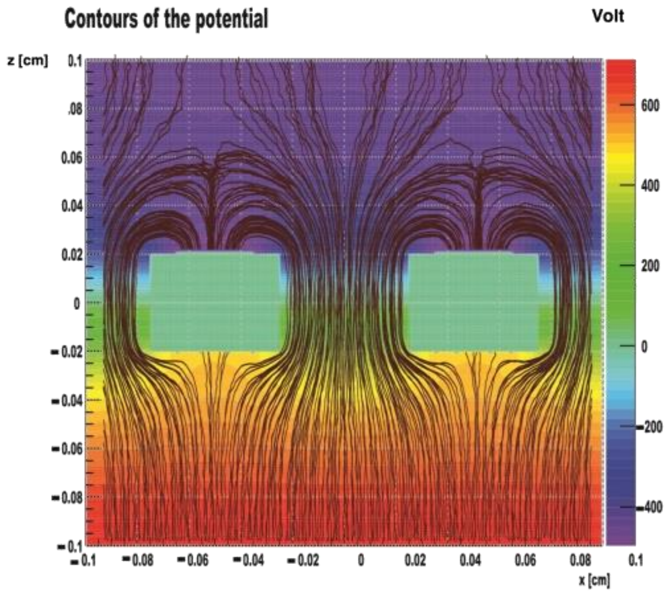
Electrostatic fields

The calculation of the Electrostatic Field Maps, needed for the calculations of the particle's trajectories in the detector medium, are often based in Finite Element Methods software:

- Ansys
- ELMER+GMSH
- Synopsys Sentaurus
- COMSOL
- neBEM
- CST Studio
- …



Josh Renner - THGEM cell from "Open-source finite-element field calculations with Elmer and Gmsh"

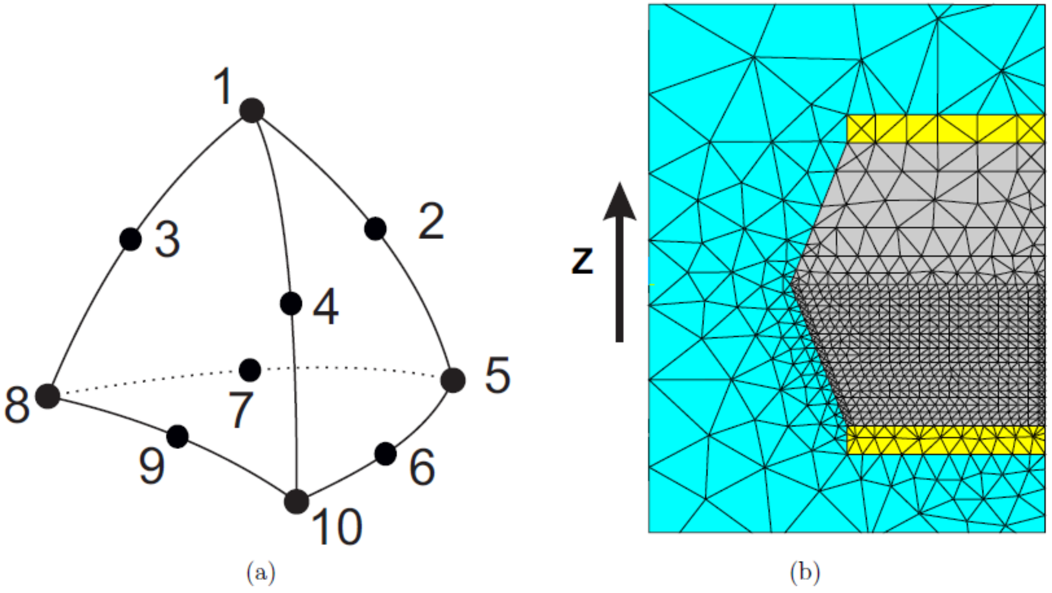


THGEM. Potential map and field lines.

Check yesterday hands-on with Josh **Link**

Using Ansys

- Based in Finite Element methods
- Potential is calculated for specific points in space, and interpolated for the remaining
- Can be accessed from Lxplus (Cern accounts)



Ansys SOLID123 typical element. These elements fill the space and the electric potential is calculated in each node. Needs bondary conditions (usually the potential applied to electrodes. B) Example of a GEM mesh simulation using SOLID123 elements.

Source: RD51 simulation school - Modeling the GEM Efield using finite elements
Studies in gaseous radiation detectors: GEM, THGEM and Compton camera

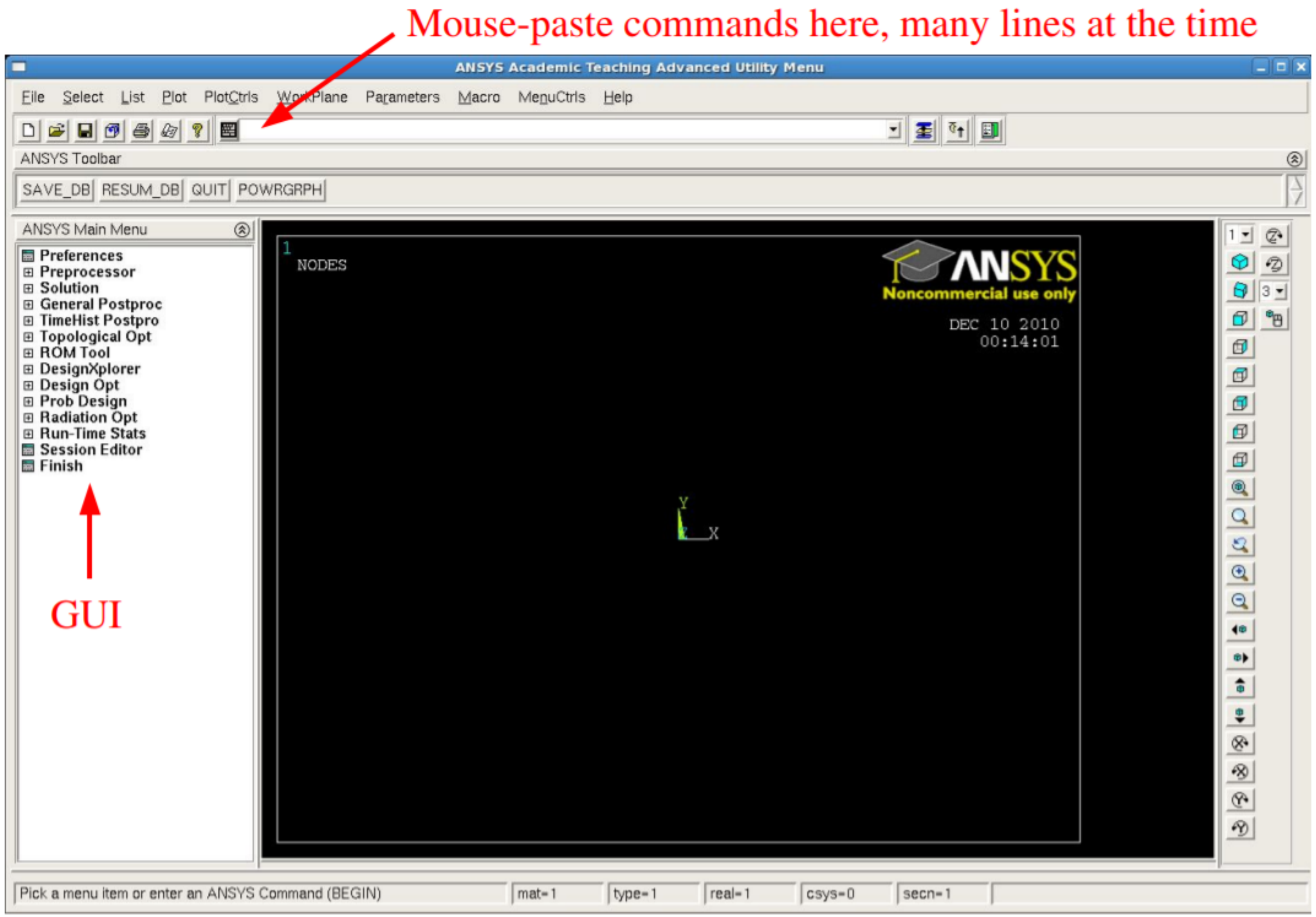
Using Ansys by GUI

Users can do simulations by:

- **User Interface** (not so user friendly…)

  Usually, the UI is preferred during the geometry development

- A **script (text) file**



Source: [RD51 simulation school - Modeling the GEM Efield using finite elements]

Using Ansys by script

- The scripting method is used when an established geometry is already available and only simulations parameters are to be studied
- Examples:
  - Electrode voltages
  - Drift fields
  - Geometry dimensions
  - Material Properties
  - Charge in insulators

```
! Material properties
MP,PERX,1,1e10   ! Metal Permittivity
MP,RSVX,1,0.0    ! Metal Resistivity
MP,PERX,2,1.0    ! Gas Permittivity
MP,PERX,3,3.9    ! Permittivity of kapton

! Construct the GEM
pitch =  0.140   ! Distance between holes, in mm
kapton = 0.05   ! Thickness of the kapton layer, in mm
metal =  0.005   ! Thickness of the metal layers, in mm
outdia = 0.07   ! Hole outer diameter, in mm
middia = 0.05   ! Hole diameter in the centre, in mm
drift =  1.0     ! Position of the drift plane in mm
induct = -1.0    ! Position of the induction plane in mm
rim =    0.07   ! Rim diameter, in mm
v = 350     ! Voltage difference across the GEM
e_d = 200        ! Electric field between drift plane and upper metal (abs,V/mm)
e_i = 300        ! Electric field between lower metal and inductive plane (abs,V/mm)
unit = 1000      ! Units: 1000 for mm, 100 for cm, 1 for m
pi = 3.14159265  ! pi
qe = 1.60217646e-19      ! Electron charge [C]
n = 24         ! Number of slices

! Make the plastic (1-n), lower metal (n+1), upper metal (n+2) and gas (n+3)
*do, i, 1, n-4
*if, i,lt,21,then
    BLOCK, 0, pitch/2, 0, sqrt(3)*pitch/2, -kapton/2+(i-1)*(kapton/2)/(n-4), -kapton/2+
*endif
```

Using Ansys

- Output files are:
  - ELIST.lis
  - MPLIST.lis
  - NLIST.lis
  - PRNSOL.lis

```
LIST MATERIALS        1  TO        3  BY        1
 PROPERTY= ALL

MATERIAL NUMBER       1

     TEMP          RSVX
                 0.000000

     TEMP          PERX
               0.1000000E+11
```

```
NODE          X                    Y                    Z
      1   0.700000000000E-01   0.00000000000       -0.250000000000E-01
      2   0.700000000000E-01  0.862435565298E-01  -0.250000000000E-01
      3   0.340000000000E-01   0.00000000000       -0.225000000000E-01
      4   0.700000000000E-01   0.00000000000       -0.225000000000E-01
      5   0.700000000000E-01  0.867435565298E-01  -0.237500000000E-01
```

These files contain information about the materials, elements, nodes and the correspondent potential solution obtained

```
***** POST1 NODAL DEGREE OF FREEDOM LISTING *****

LOAD STEP=     1  SUBSTEP=     1
 TIME=    1.0000      LOAD CASE=   0

  NODE       VOLT
     1   175.00
     2   175.00
     3   144.97
     4   157.43
     5   157.40
```

Particle transport in MPGDs

- Within the MPGD community, the software used for simulating microscopic drift of charged particles in gaseous or liquid volumes is **Garfield**:
  - **Garfield** (Fortran version developed by Rob Veenhof, last update 2010)
  - **Garfield++** (C++ version) currently maintained by a collaboration headed by Heinrich Schindler - https://garfieldpp.web.cern.ch/garfieldpp/

Interfaces with other software:

- **Heed** (for simulation of primary ionizing particles patterns)
- **Magboltz** (for computing electron transport and avalanches)
- **GEANT4** (integration with larger experiments at CERN)
- **Field maps calculators**

Garfield++

- Documentation available: User Guide
- For simple geometries, where electric field can be calculated analytically, geometries and medium parameters are enough for avalanches simulations
- However, for most cases the field maps needs to be calculated previously (either in ANSYS, ELMER, COMSOL, ….).

Gain stability over time

- Environmental factors can affect the avalanche gain - temperature, pressure, gas purity, irradiation rate – probably not so interesting to simulate.

- Some works focused on gain variations due to **insulator charging-up** in MPGDs
  - M. Alfosi et al, NIMA 2012 "Simulation of the dielectric charging-up effect in a GEM detector"
  - Correia et al, JINST 2014 "A dynamic method for charging-up calculations: the case of GEM"
  - S. Dalla Torre JINST 2015 "The gain in Thick GEM multipliers and its time-evolution"
  - Correia et al, JINST 2018 "Simulation of gain stability of THGEM gas-avalanche particle detectors"
  - M. Pitt et al, JINST 2018 "Measurements of charging-up processes in THGEM-based particle detectors"
  - P. Hauer et al, NIMA 2020 "Measurements of the charging-up effect in Gas Electron Multipliers"
  - G. Song et al, JINST 2020 "A fast simulation method for THGEM charging-up study"
  - V. Kumar et al, Arxiv 2020 "Studies on charging-up of single Gas Electron Multiplier" and yesterday talk (link)
  - M. Chargnyshova et al, Fusion Enginnerging and Design 2020 "Effect of charging-up and regular usage on performance of the triple GEM detector to be employed for plasma radiation monitoring"

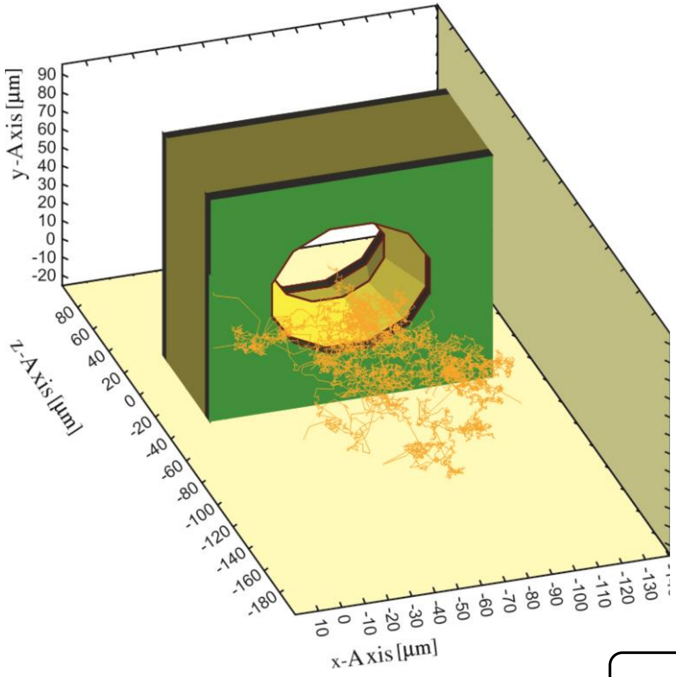
- **Discharges** are also known to change gain behavior on MPGDs and have also been investigated (I will not develop this topic on this talk):
  - P. Fonte et al "The physics of streamers and discharges" 2nd RD51 Collaboration Meeting
  - F. Resnati "Modelling of dynamic and transient behaviours of gaseous detectors", RD-51 Open Lectures 2017

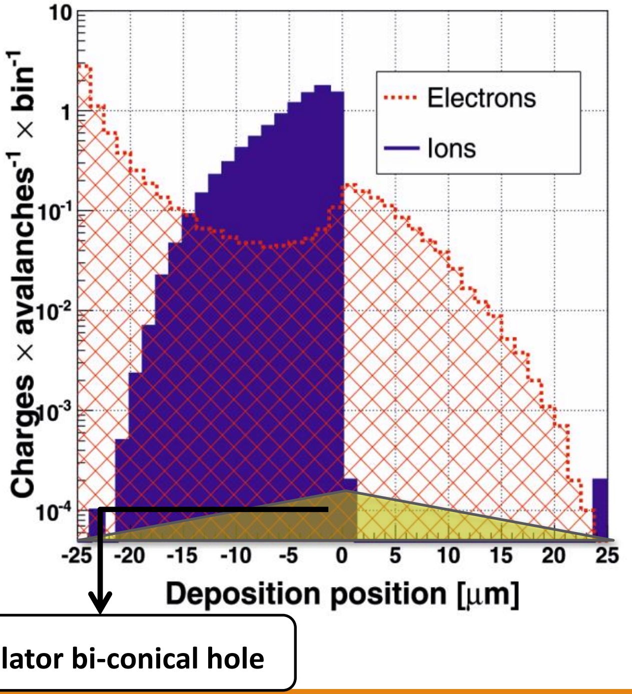
Charging-up effect

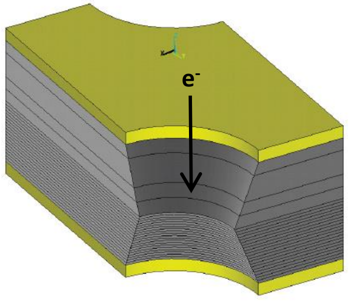
If you ask google about **charging up**…

Charging-up effect GEM

- During avalanche amplification, charges can stop their drift on the insulator surface.
- Electrostatic calculations done with Ansys, and drift of charges with GARFIELD
- The deposition pattern of electrons and ions is not equal nor constant in the hole surface (z coordinate)







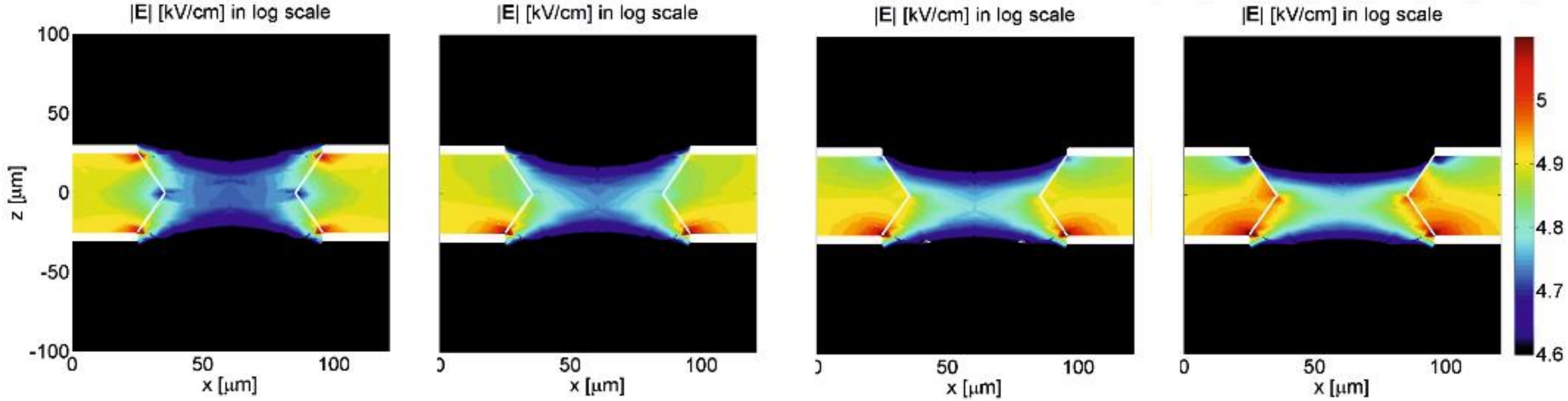
(a) GEM unity cell.

- VGEM=400V
- Ar 70% CO_2 30%
- 50 µm and 70 µm of int. and ext. diameter.
- Pitch 140 µm
- 760torr 293K
- Insulator 50 µm

Charging-up: Electric field evolution

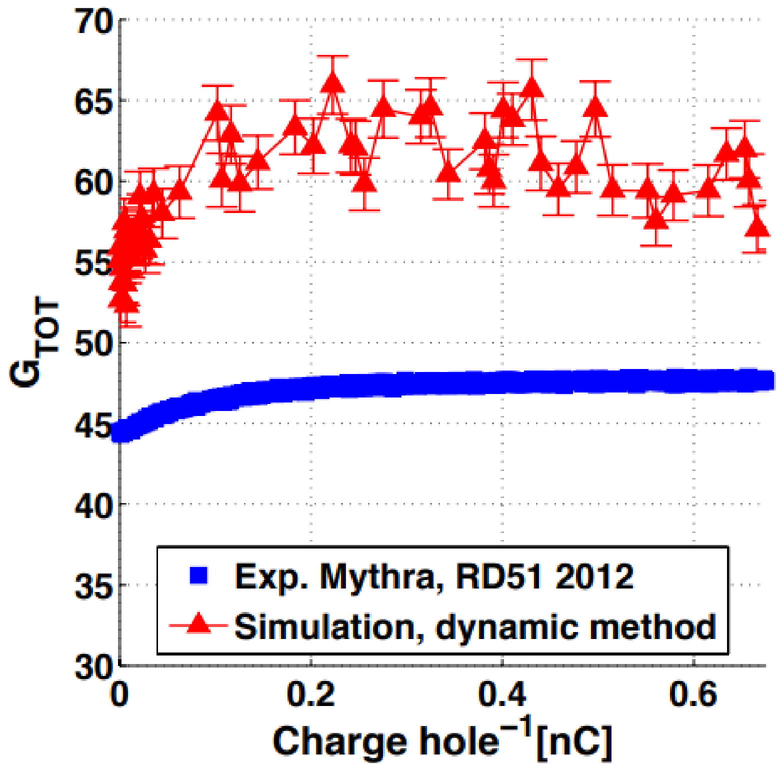
- Electric field values are shown in logarithm scale, to emphasis the variations in the hole region.
- Field increases near bottom electrodes and inside the hole - gain increase
- Also decreases near the top electron.

https://garfieldpp.web.cern.ch/garfieldpp/examples/gemcharging/

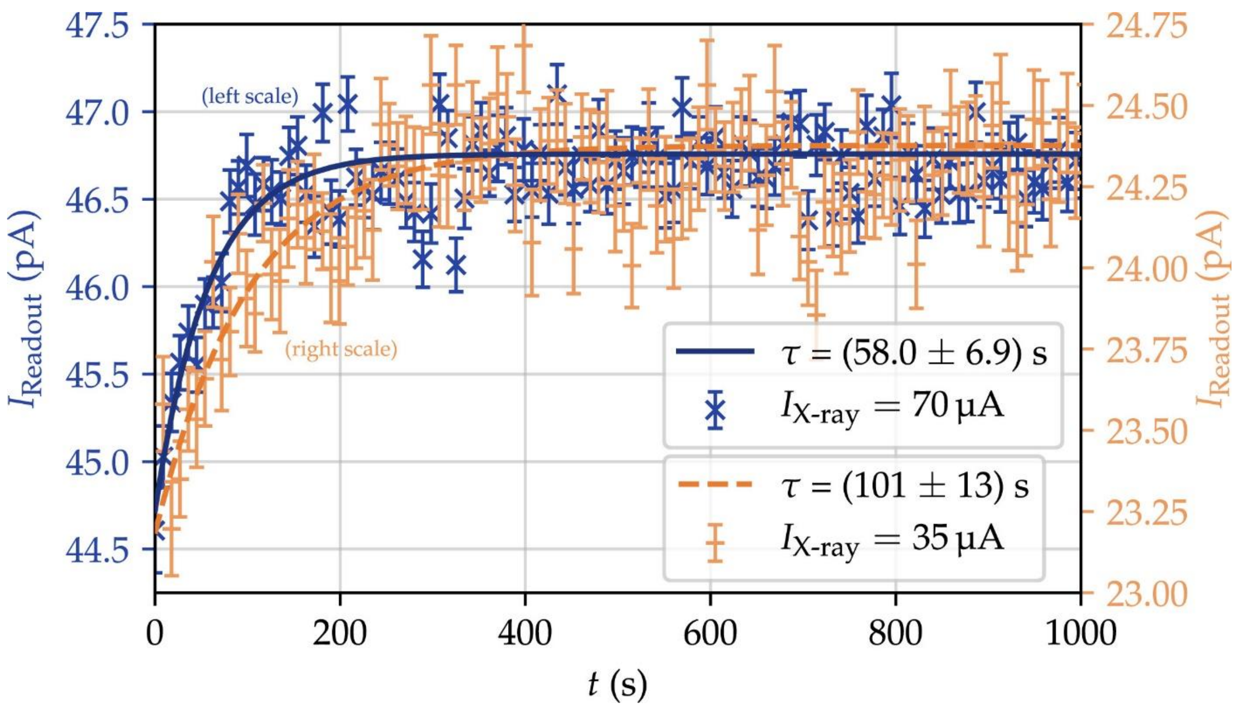


Without charging-up. **After $3x10^6$ avalanches.** **After $6x10^6$ avalanches.** **After $10x10^6$ avalanches.**

Gain stability over time: GEM



Correia et al, JINST 2014 "A dynamic method for charging-up calculations: the case of GEM"

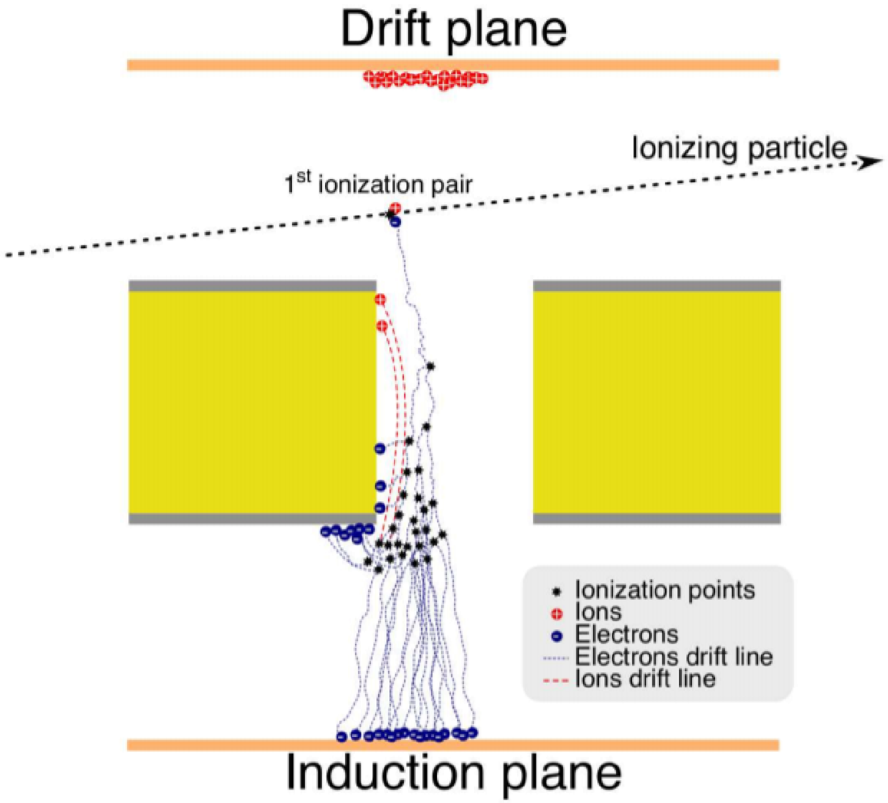


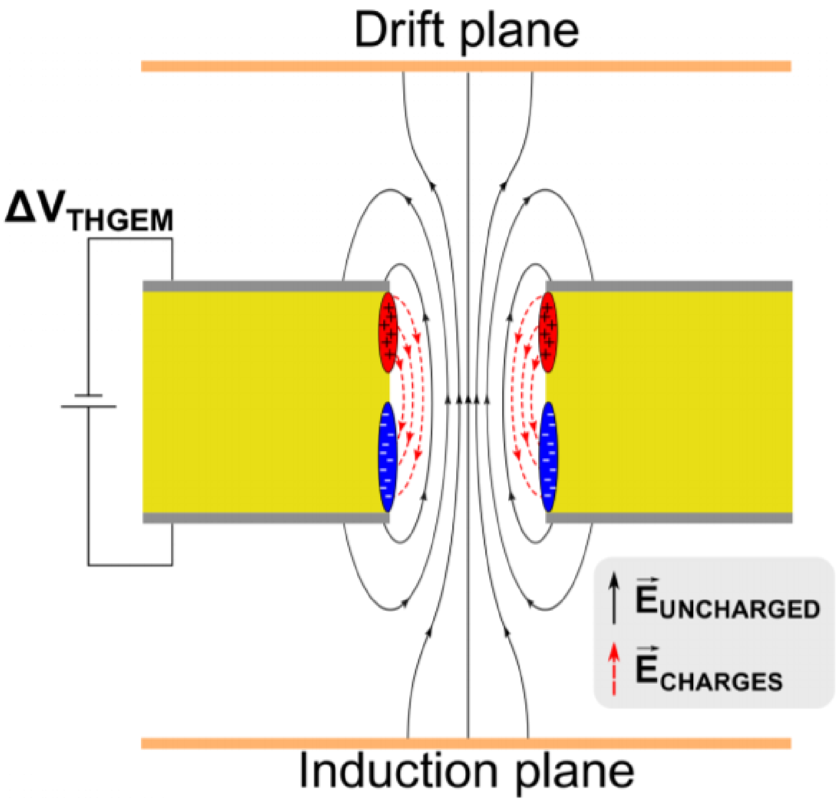
P. Hauer et al, NIMA 2020 "Measurements of the charging-up effect in Gas Electron Multipliers"

Calculation Algorithm

- Insulator charging-up during avalanches:

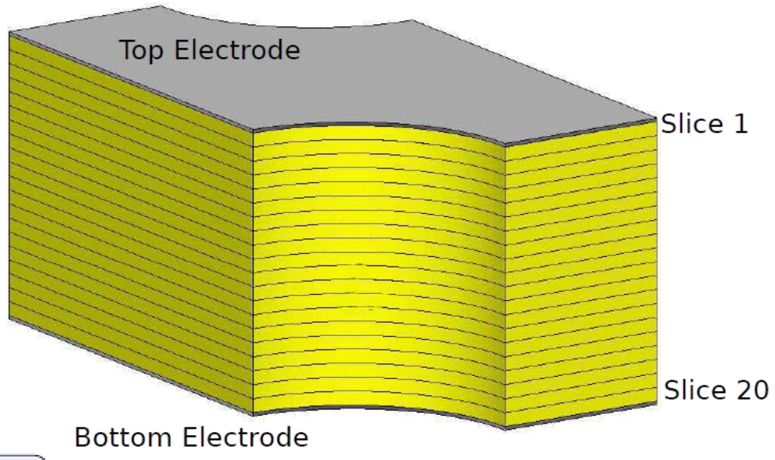
Correia et al, JINST 2018 "Simulation of gain stability of THGEM gas-avalanche particle detectors

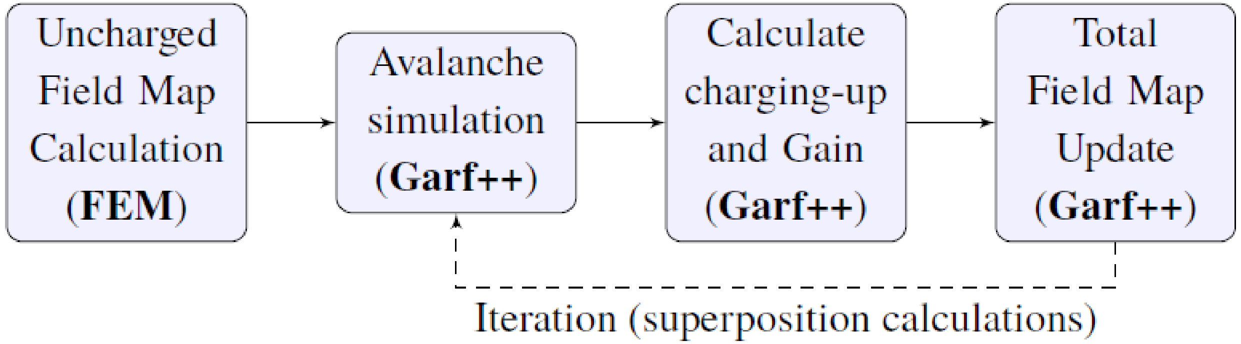




Calculation Algorithm

- Insulator charging-up during avalanches – The **algorithm**
- Starting point – Few initial field maps:
  - 1 for voltage applied to electrodes (*Uncharged* field map)
  - *N* for the insulator surfaces, divided in thin slices.
- Algorithm runs **entirely** inside Garfield++ (https://github.com/pmcorreia/Garfpp-chargingup and "How charging up affects THGEM detectors gain")

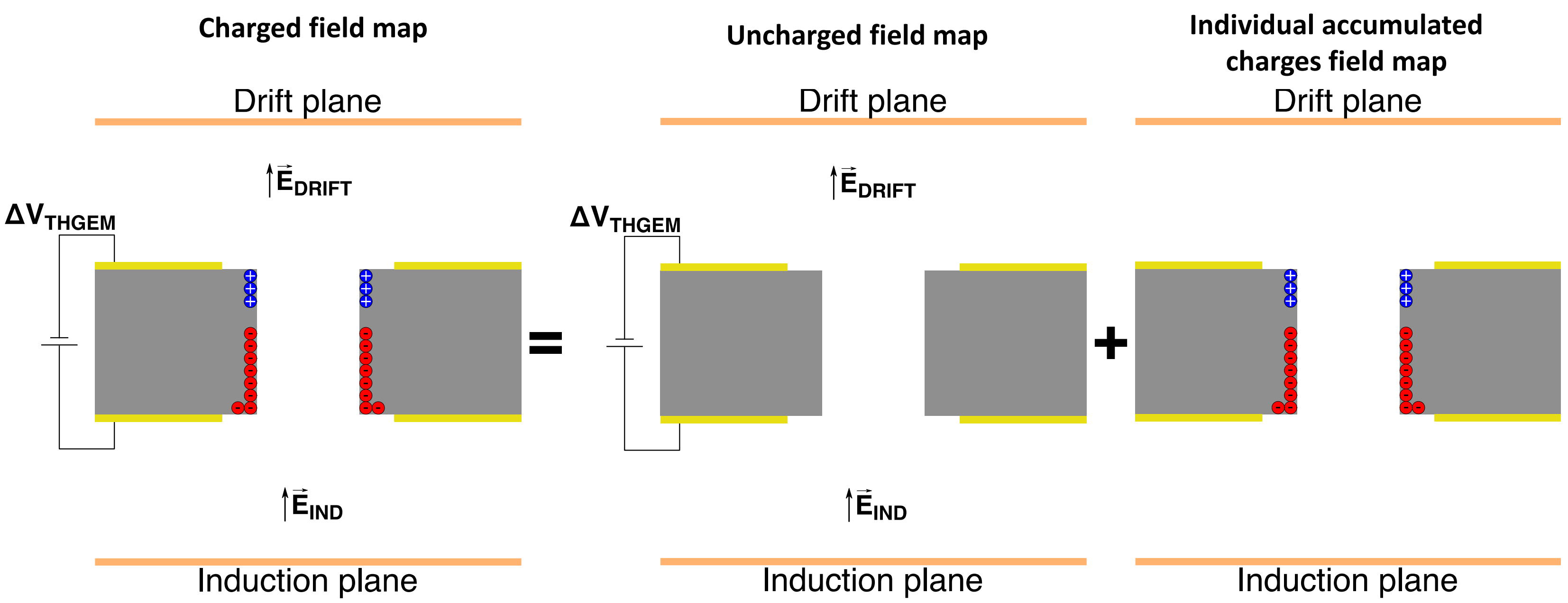


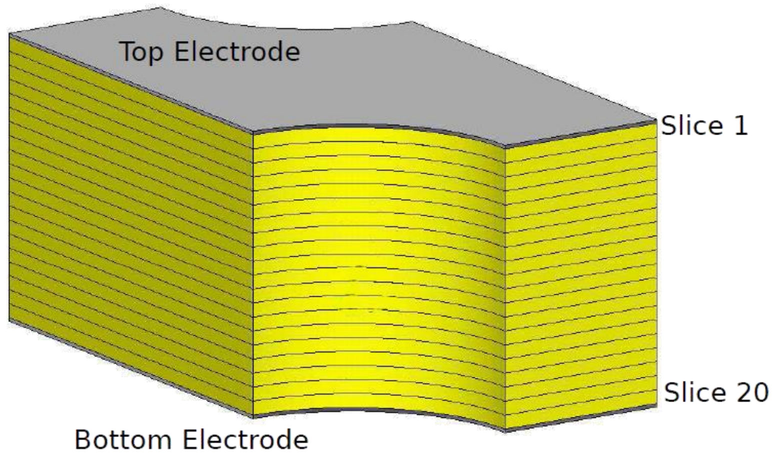


Gain stability over time: THGEM

- Insulator charging-up during avalanches – The **algorithm**

$$V(charges, i) = V\ (uncharged, i) + N\ \times s \times V(j, i)$$



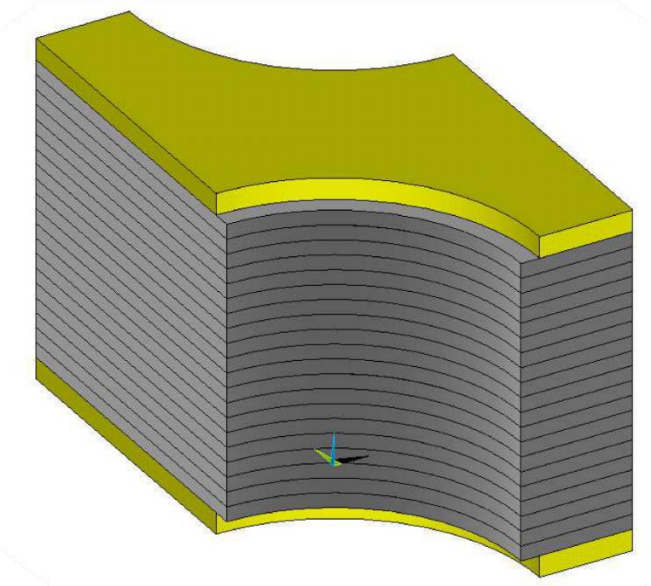


$\boldsymbol{V(j, i)}$ is the electric potential on node i due to the presence of a unitary charge in the surface of slice j

$\boldsymbol{N}$ is the number of accumulated charges on a given surface and iteration

$\boldsymbol{s}$ is a speed-up parameter for convergence

Principle of superposition



```
PRNSOL_700V.lis
PRNSOL_750V.lis
PRNSOL_800V.lis
PRNSOL_900V.lis
PRNSOL_slice10.lis
PRNSOL_slice11.lis
PRNSOL_slice12.lis
PRNSOL_slice13.lis
PRNSOL_slice14.lis
PRNSOL_slice15.lis
PRNSOL_slice16.lis
PRNSOL_slice17.lis
PRNSOL_slice18.lis
PRNSOL_slice19.lis
PRNSOL_slice1.lis
PRNSOL_slice20.lis
PRNSOL_slice2.lis
PRNSOL_slice3.lis
PRNSOL_slice4.lis
PRNSOL_slice5.lis
PRNSOL_slice6.lis
PRNSOL_slice7.lis
PRNSOL_slice8.lis
PRNSOL_slice9.lis
PRNSOL_sliceRimBottom.lis
PRNSOL_sliceRimTop.lis
```

- Ex: Thick-GEM, insulator with 20 slices
- For each voltage between electrodes, field map is calculated as usually (without charging-up)
- For each slice, the field map correspondent to 1 electron accumulated on the correspondent slice surface is calculated
- 22 field maps due to charges + 1 (at least) potential field map are needed for full simulation

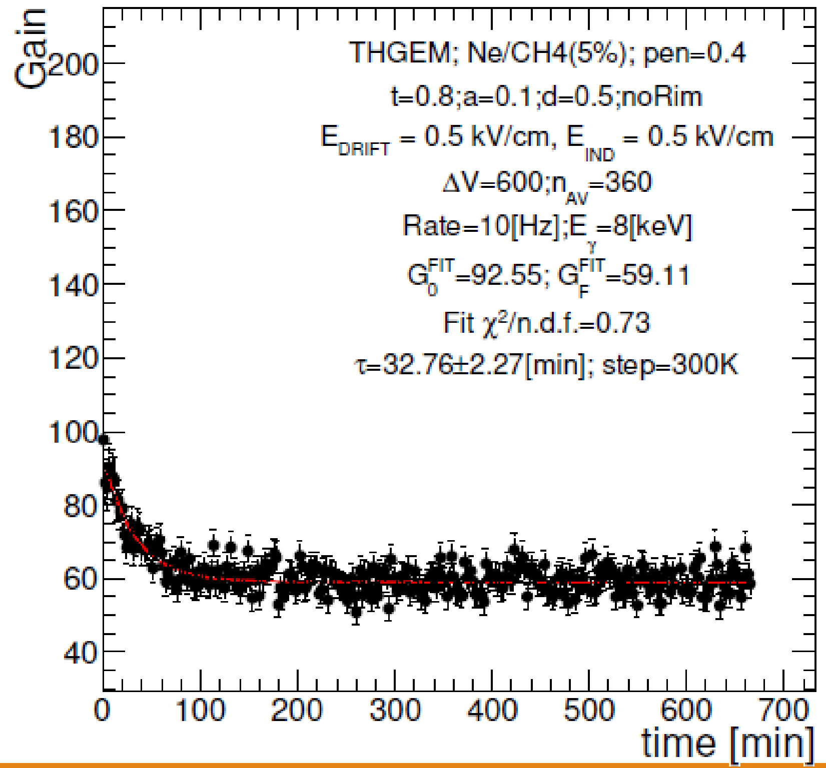
Garfield++ Method

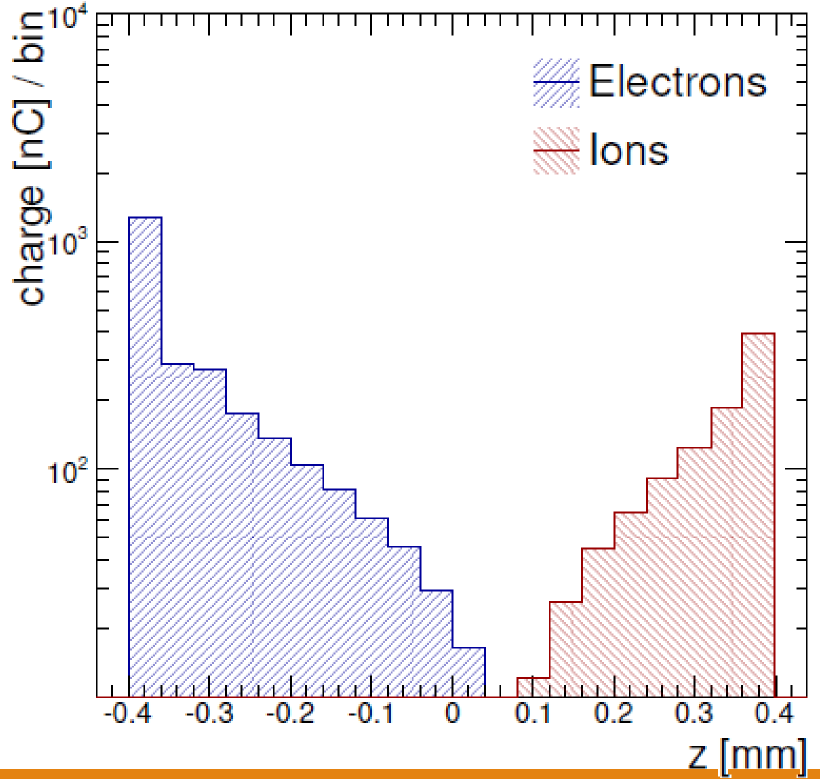
- A new Garfield++ class has been developed (~500 lines of code, up to now).
- Responsible to find the field maps (only **ANSYS** at the moment)
- Writes a temporary field map depending on the number of accumulated charges for each iteration
- It allows restart simulation at a specific iteration if previous field maps are stored
- (code for demonstration only)

```
#include "ChargingUpAnsys.hh"

using namespace std;
using namespace Garfield;
int main(int argc, char * argv[]) {
    double ChargesVector[ nSlices ];

    //(...);

    ChargingUpAnsys file(mapfilesdir, nSlices, ChargesVector, gasstr, vgem, npe);
    if (!file.checkSlicesFieldMaps()){
        std::cout<<"Error 1, files does not exist"<<endl;
        exit(0);
    }
    file.loadSlicesFieldMaps();


    double simulatedCharges[ nSlices ];

    //for loop over iterations
    // (...) after avalanches calculation and calculation of the
    // number of accumulated electrons+ions

    file.UpdateFieldMap(simulatedCharges);
    file.SaveKaptonChargesFile(iter);
    file.printCurrentCharges();
    //end of the for loop

}
```

Gain stability over time: THGEM

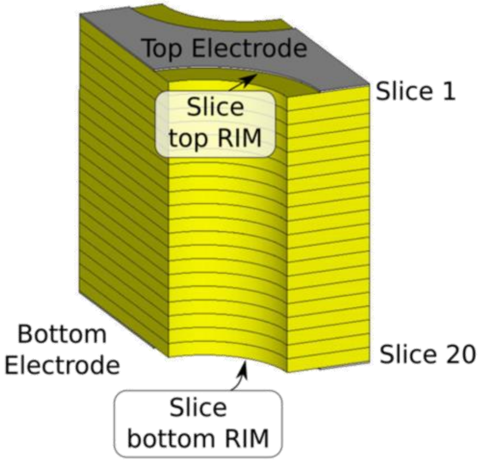
- Typical results (for THGEM without RIM): Gain drops and stabilizes after few minutes to few hours – **fast component**.
- Charge accumulation on the surface holes is not symmetric (neither constant during iterations)



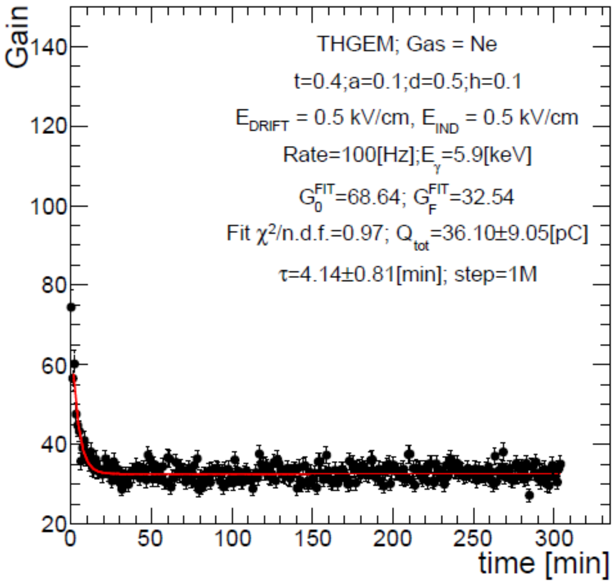


Gain stability over time: THGEM

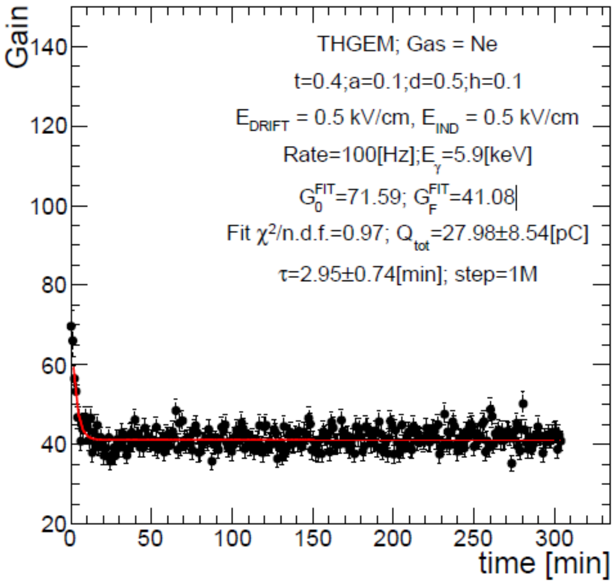
- Now considering the charge on the RIM (M. Pitt et al, JINST 2018 "[Measurements of charging-up processes in THGEM-based particle detectors]" - **Longer component appears, apparently due to TOP RIM charge accumulation.**
- Defined Total charge (Q_{tot}) as the charge accumulated during relaxation period.



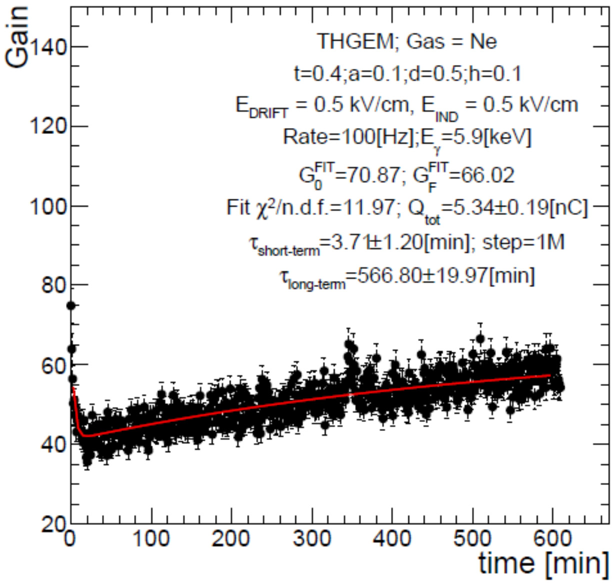
None of the RIMs charged up



Only BOT RIM charged up

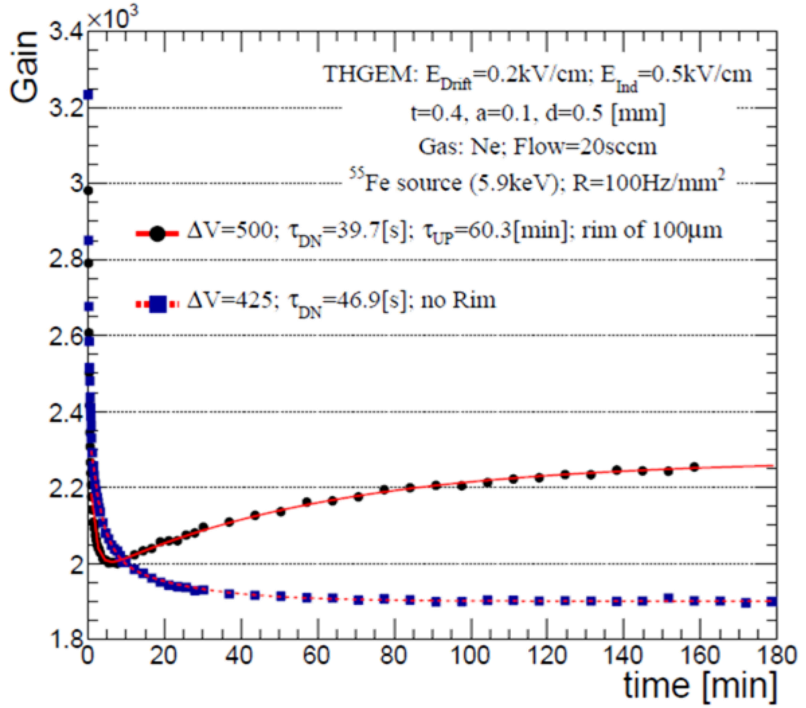


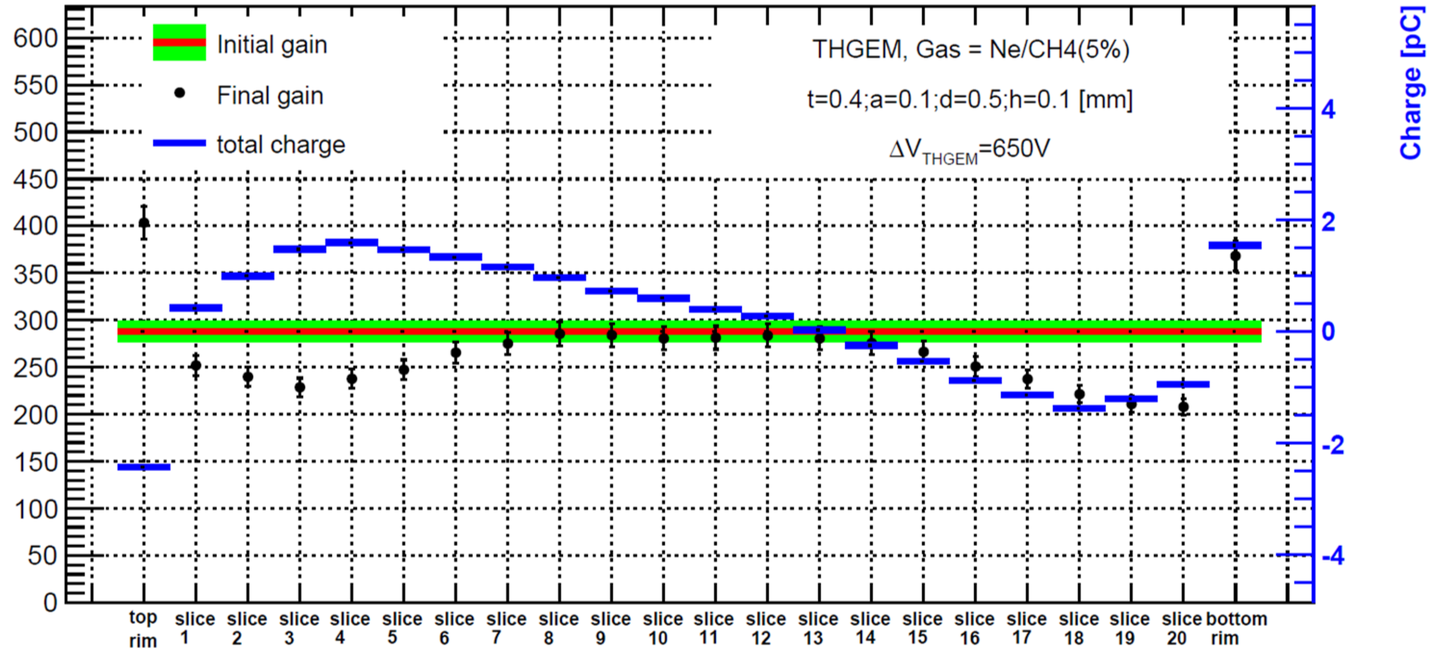
Both RIMs charged up



Gain stability over time: THGEM

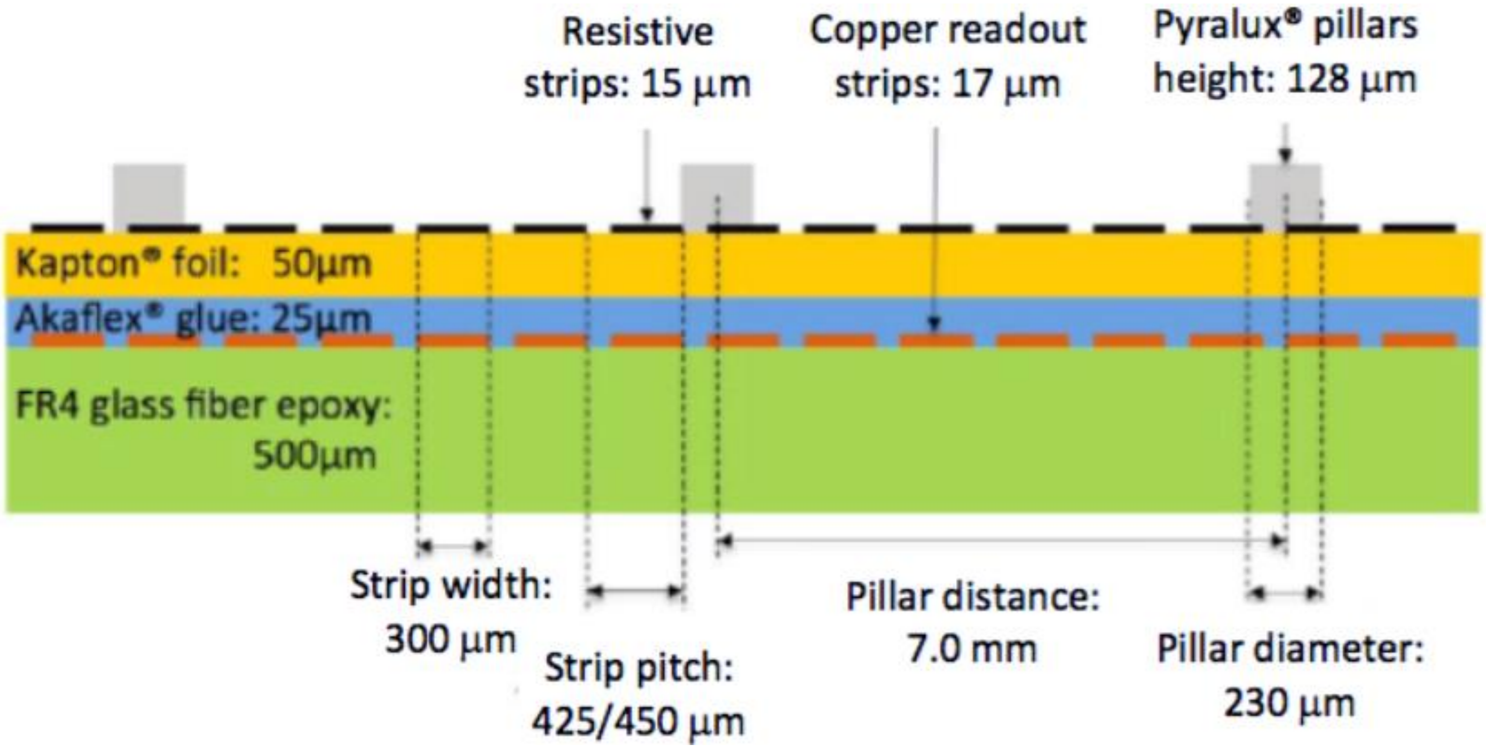
- Now considering the charge on the RIM (M. Pitt et al, JINST 2018 "[Measurements of charging-up processes in THGEM-based particle detectors]" - Comparison between **No RIM** and **100 µm RIM (left)** and effect on the gain due to the **accumulated charge on each insulator slice** (right).





Resistive Micromegas

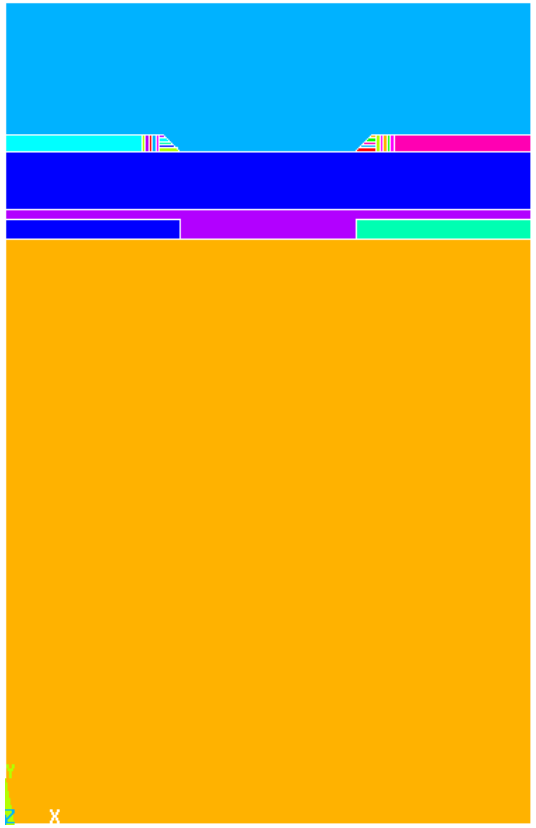
Layout of the Micromegas

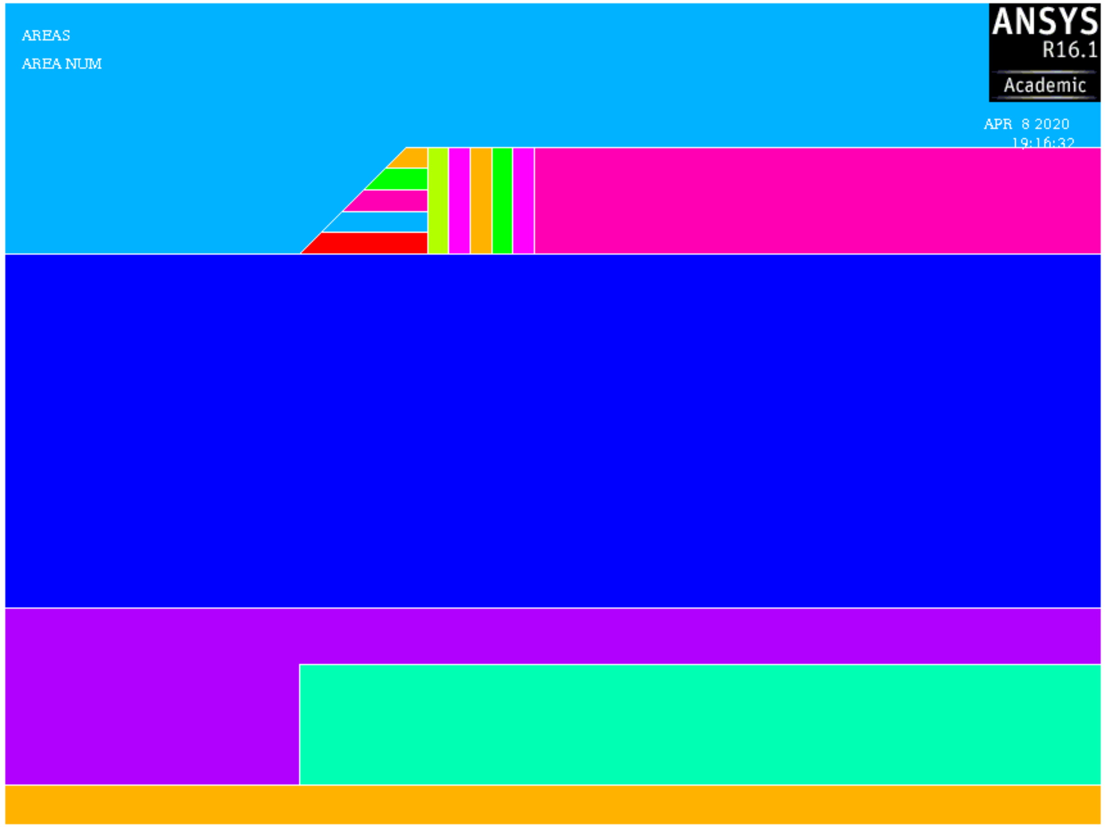


mesh,
0V
500 V,
Ag paste
connection
0V

G. Sekhniaidze 2017 JINST 12 C03020.

Layout of the elements





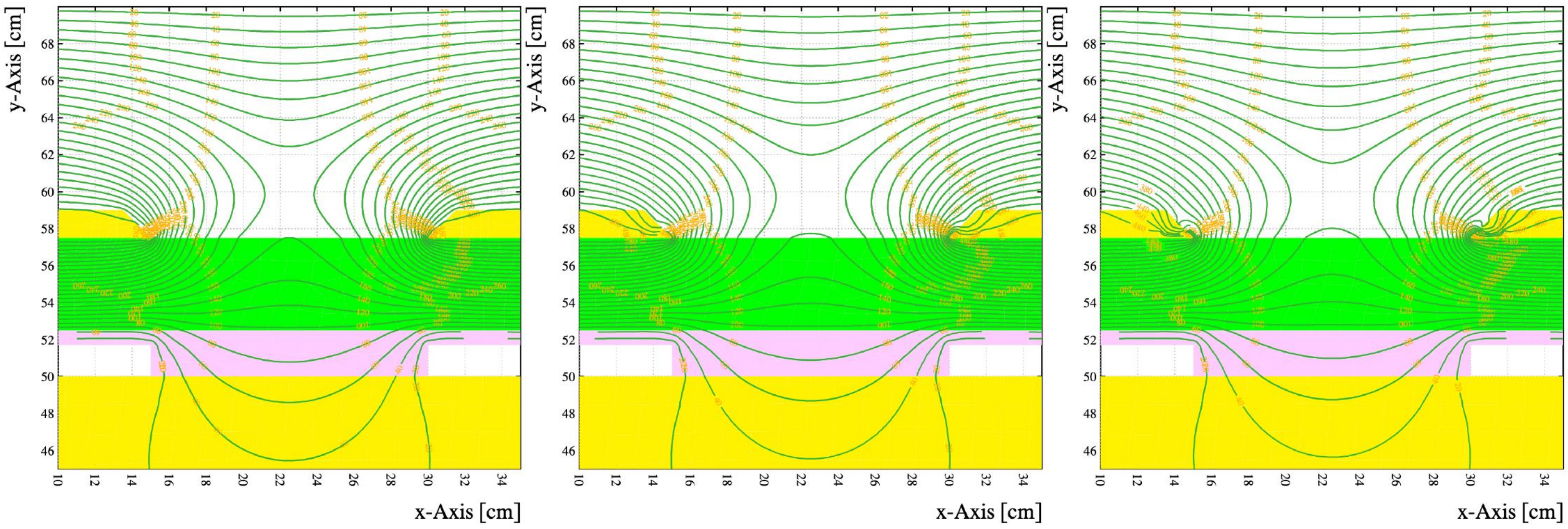
Plots and calculations: ANSYS 16.1

Iterations

- As for GEM charging-up:
  - avalanche charge accumulation is counted on surfaces
  - surface charge is injected in the model
  - field is re-computed
  - avalanches are run
  - electrons on the surfaces are counted

Field shape changes while charging

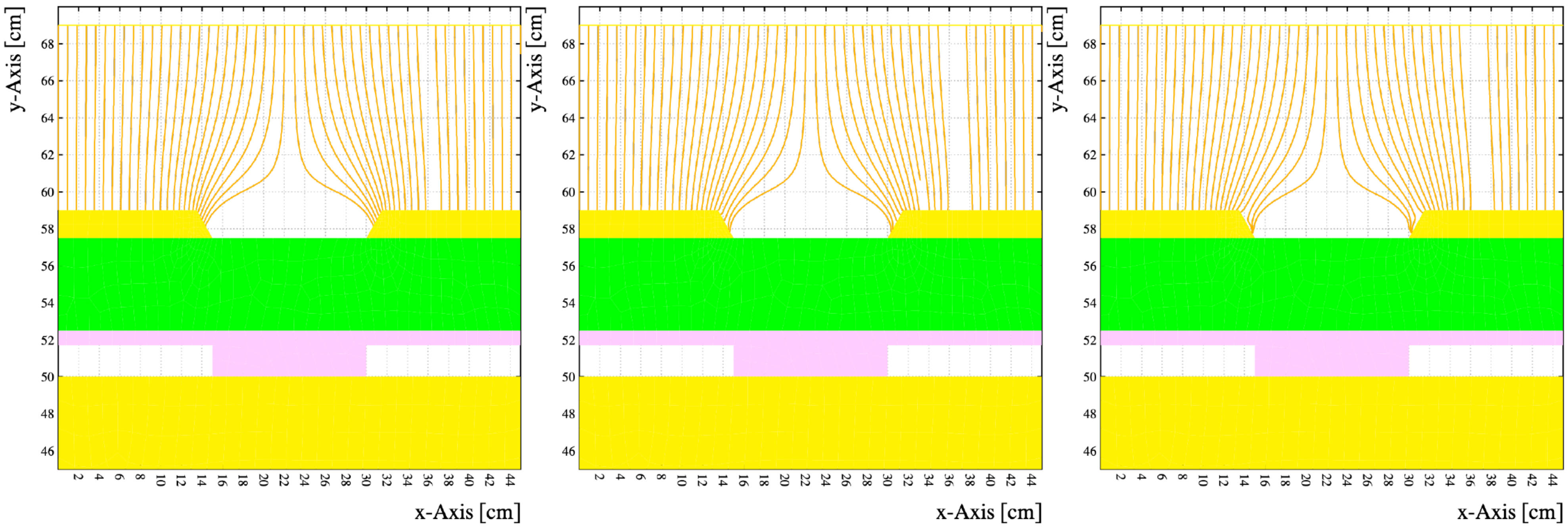
- Potential contours



Initial Iteration 5 Iteration 10

Field shape changes while charging

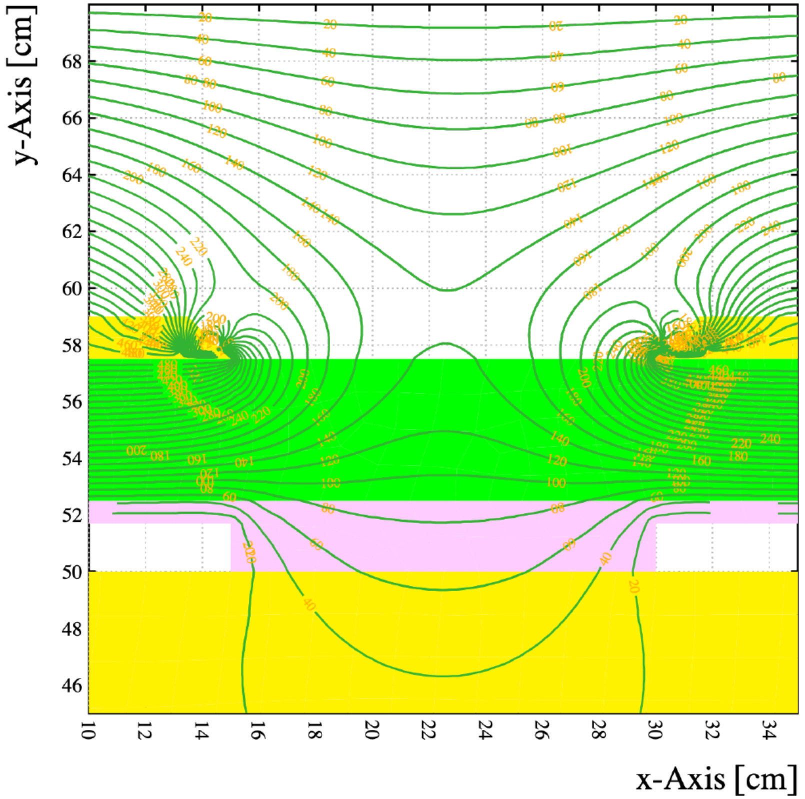
- Electric field

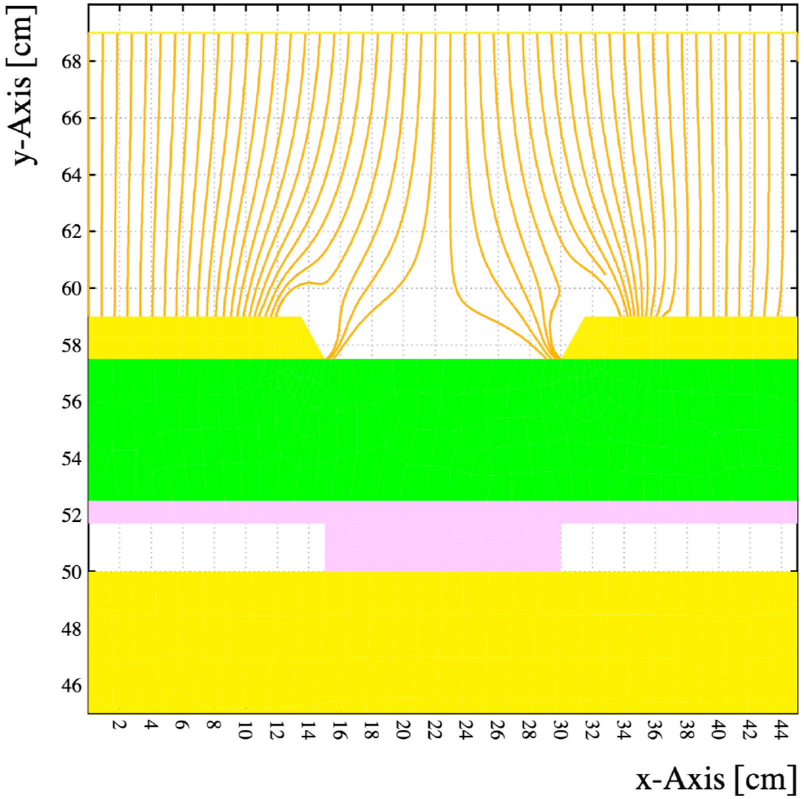


Initial | Iteration 5 | Iteration 10

Field shape changes while charging

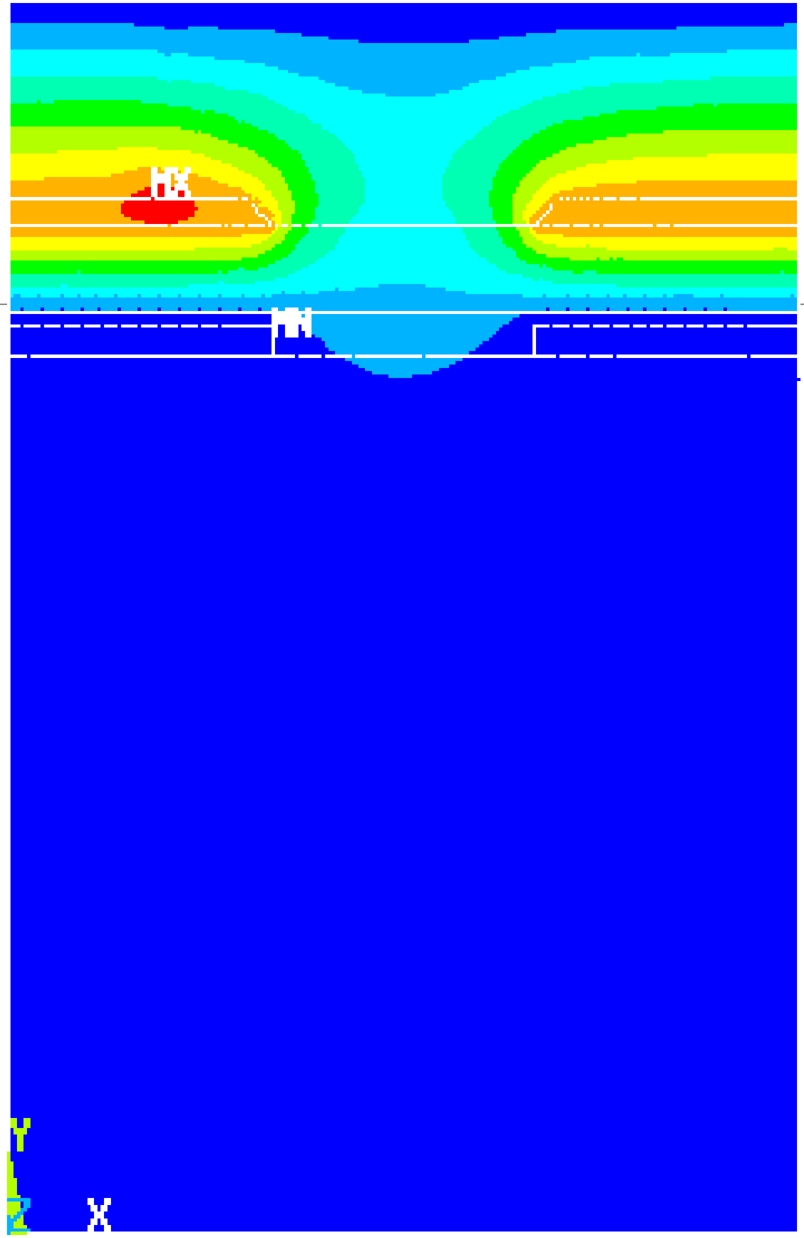
- After 100 iterations, contours and electric field





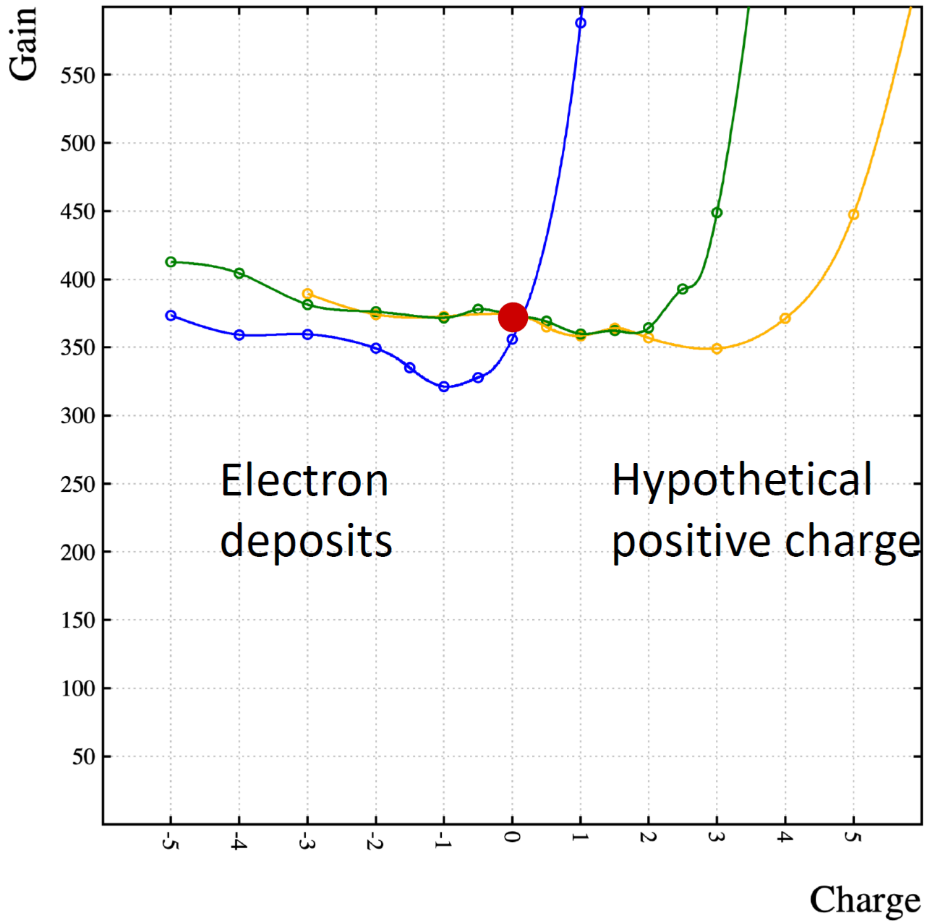
Charged strip

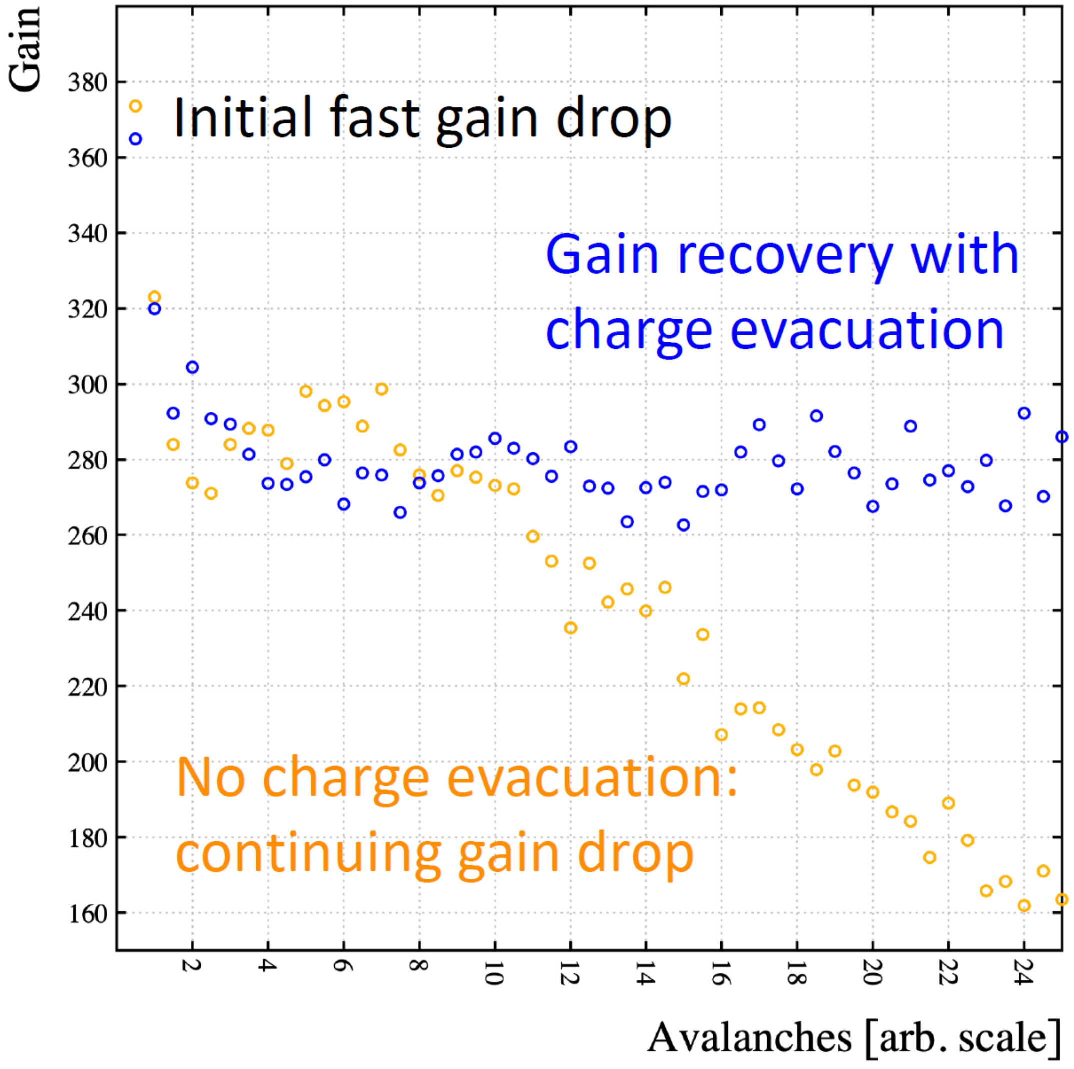
- strip: 31
- charge: -1.5 10^{-10}



Influence of surface charge on gain

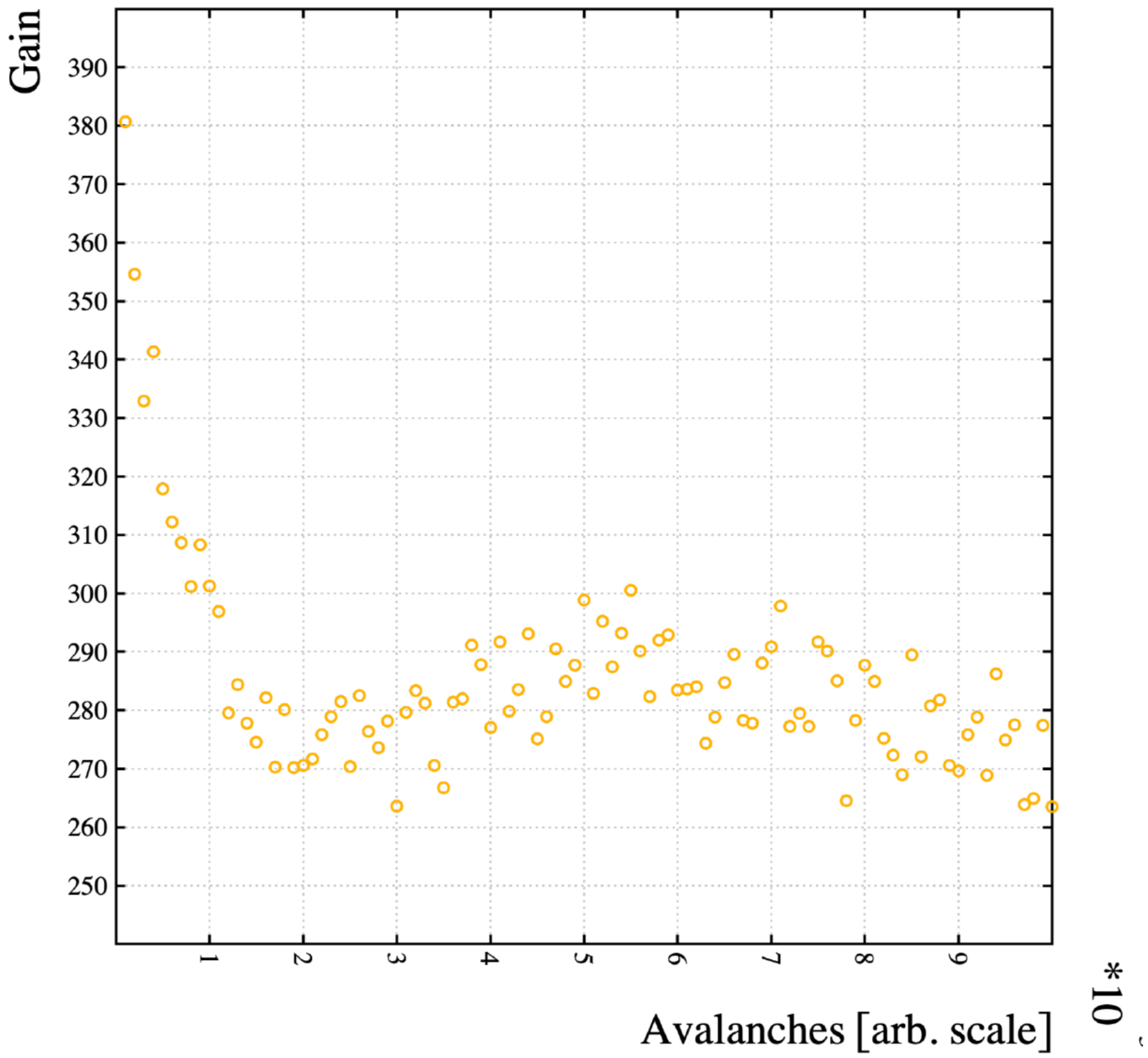
- Read-out strips:
- orange: 31
- green: 36
- blue: 44





Iterative charge accumulation

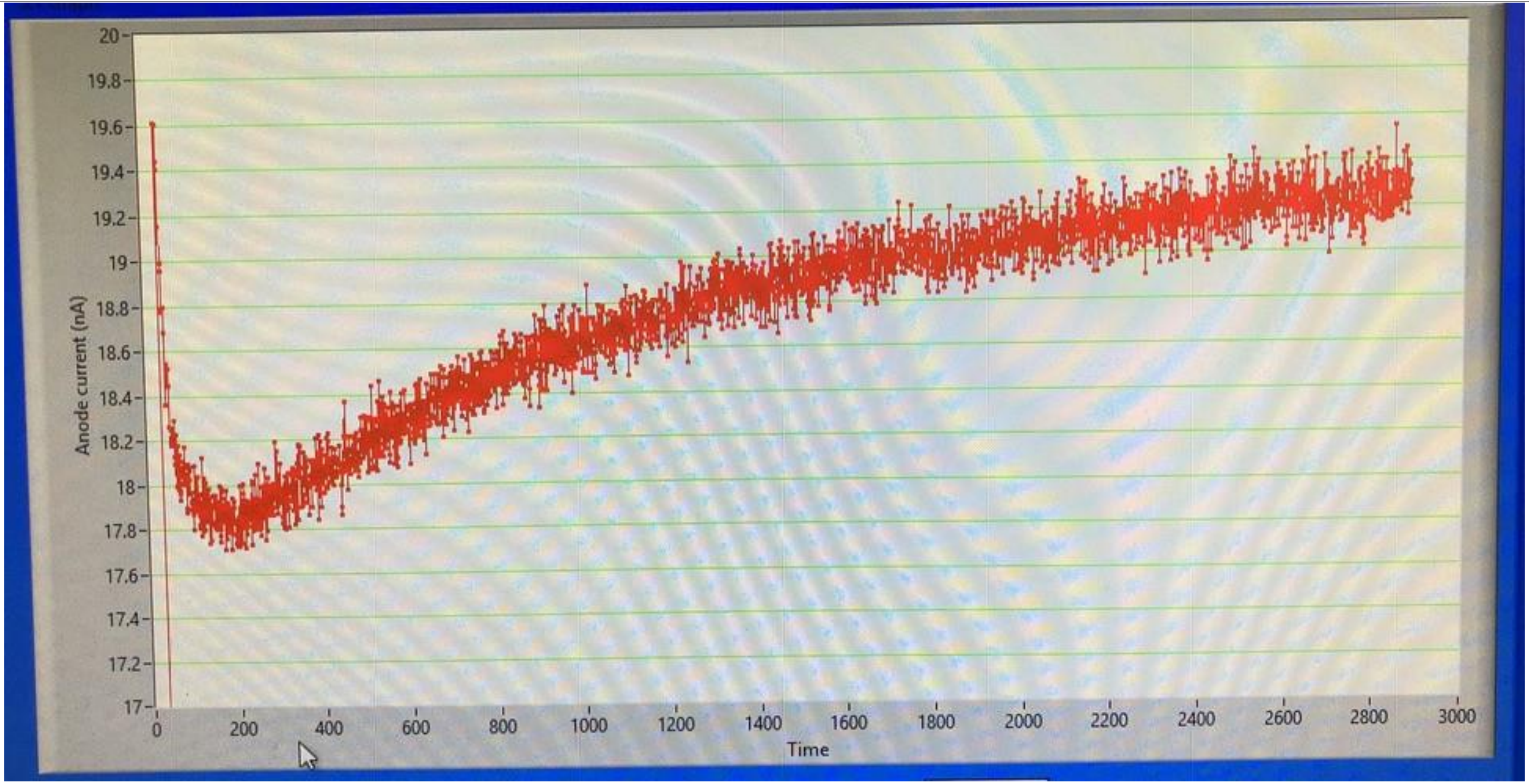
- Fast initial drop due to electron accumulation;
- overshoot & recovery;
- no charge evacuation:
- continuing gain drop;
- with charge evacuation:
- gain stabilises at a lower level than the uncharged MM.
- 500 avalanches between field calculations.



Finer step iteration

- 100 avalanches between field calculations.
- Average of 10 sequences.

Measurements (from Jérôme Samarati)



Main conclusions

- Simulation of MPGDs have been an important tool in the design and understanding of the detectors.
- Often rely in the use of **Garfield/Garfield++** interfaced with other software.
- Gain variation over time due to charging-up simulation can be simulated and match experimental results, quantitatively (eg for THGEMs):
  - Accumulated charge Q_{tot} needed for stabilization increases with the decrease of insulator thickness or increase of V_{THGEM} – usually within few minutes to hours.
  - RIMs play an important rule in the effect, specially the TOP RIM responsible for a **long term component** of the gain variation, while the BOTTOM RIM **increases** the total gain.
- These studies didn't consider charges **flow in the insulator surface and bulk**, neither **insulator polarization** due to potential applied to electrodes - should be related with even longer components of gain variation (**up to days**) **– Needs to be addressed by simulations!**
- Code speed up also not discussed here – parallelization of algorithms and/or use of GPU can be the future.

Acknowledgments

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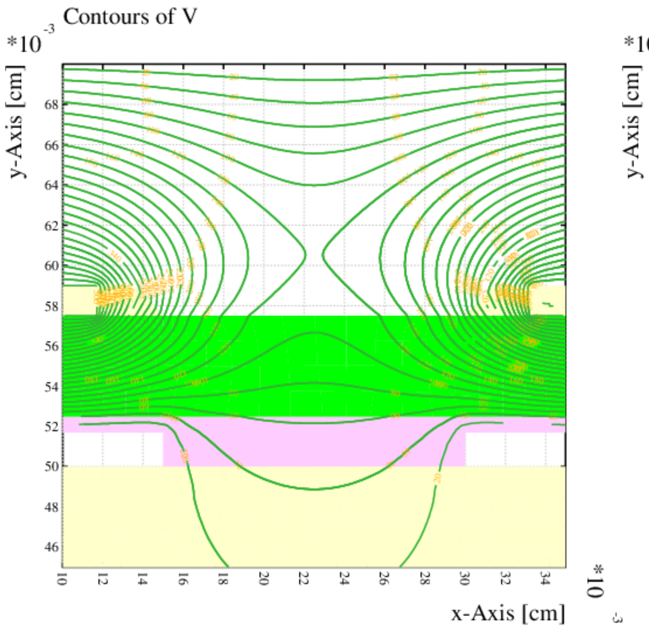
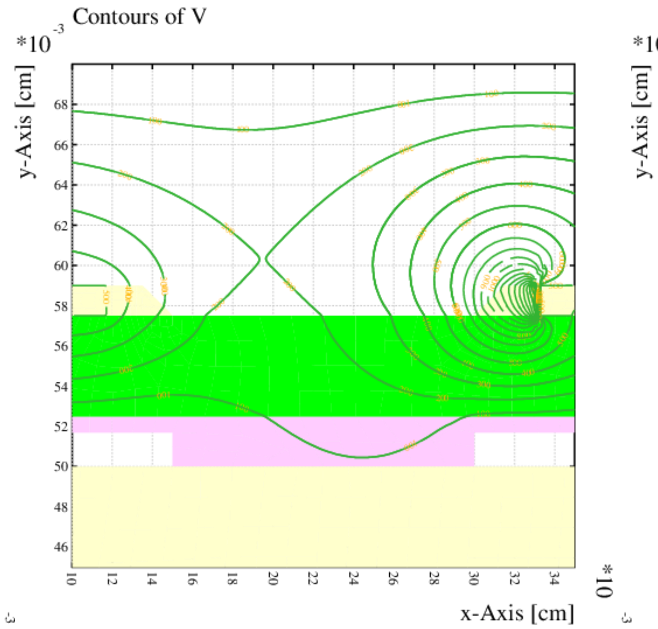
Not used

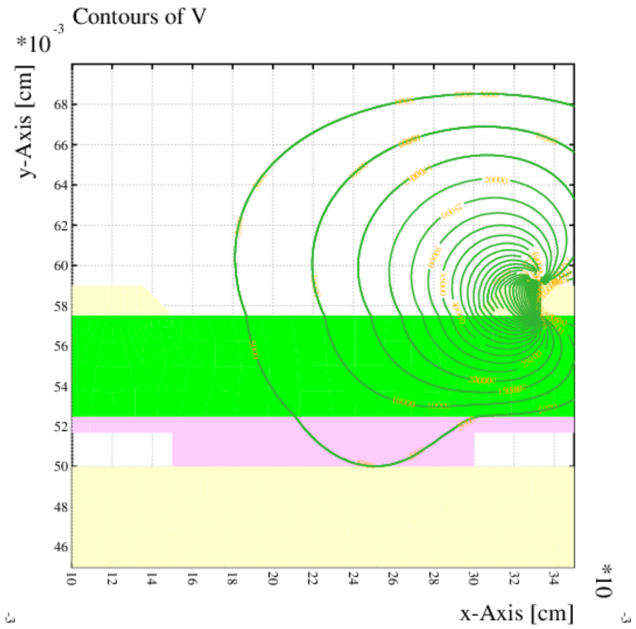
Equipotentials



q = 0

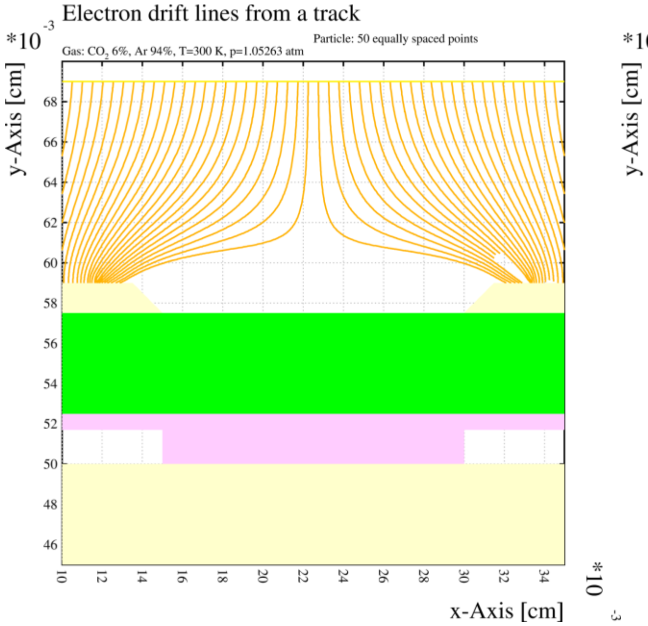


$q = 10^{-8}$

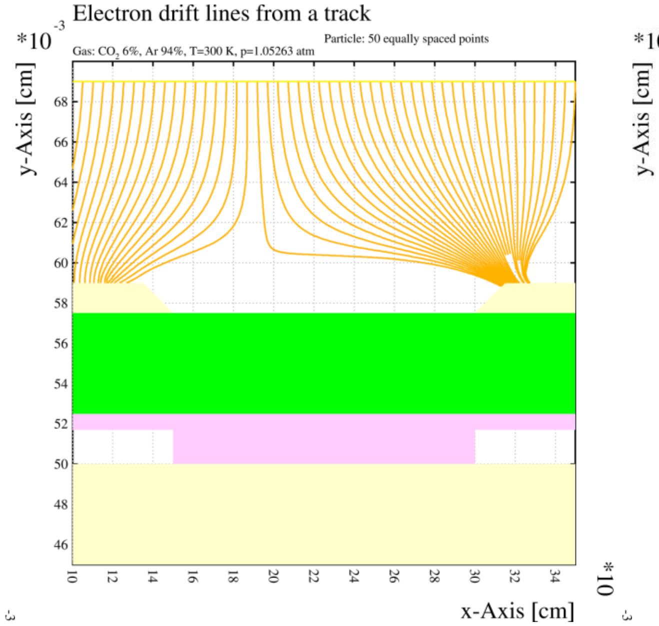


$q = 10^{-6}$

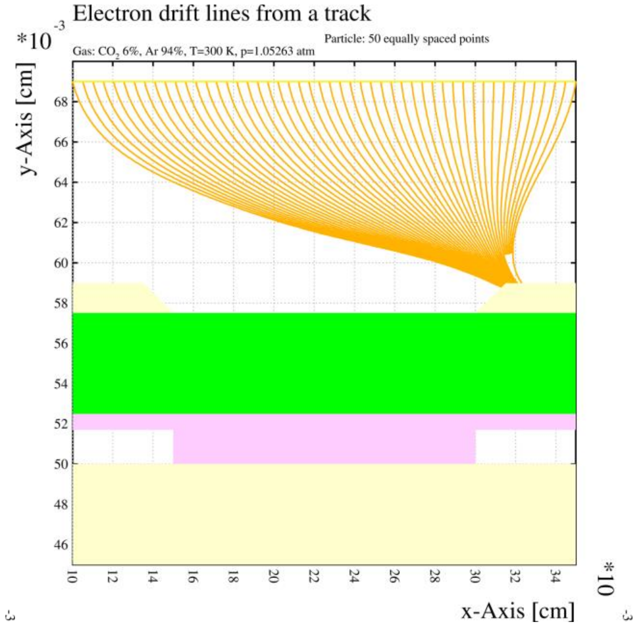
Drift paths



q = 0



$q = 10^{-8}$



$q = 10^{-6}$