GEM detector simulation for the configuration of the upcoming BM@N Run

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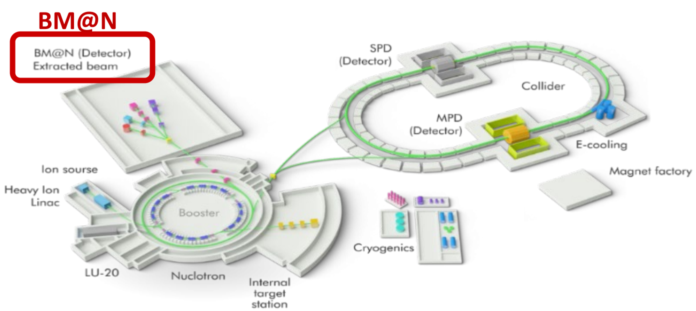
BM@N experiment

BM@N (**B**aryonic **M**atter at **N**uclotron) is the first stage experiment at the accelerator complex of NICA

This is a fixed target experiment aimed to study interactions of relativistic heavy ion beams with a fixed target



NICA (Nuclotron-based Ion Collider fAcility) accelerator complex located at Joint Institute for Nuclear Research in Dubna

At this moment, **seven BM@N RUNs** have already been carried out since 2015:

RUN 1-2-3-4 (2015)
beam: deuteron; target: C, Cu

RUN 5
beam: deuteron; target: CH2, C, Cu, Pb

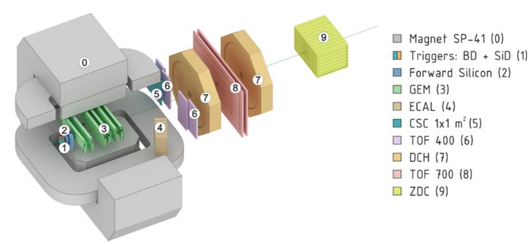
RUN 6 (2017)
beam: deuteron, C; target: CH2, C, Al, Cu, Pb

RUN 7 (2018)
beam: Ar, Kr; target: C, Al, Cu, Pb

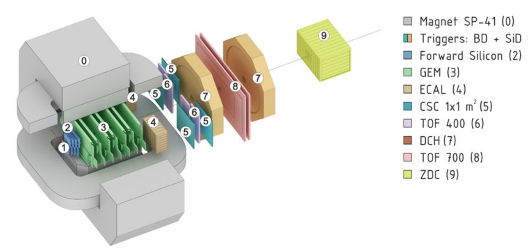
RUN 8 (2022)
beam: Ar, Xe; target: CsI

The detector setup of BM@N consists of:

1. **Tracking system**:
   - Forward Silicon (*Semiconductor Silicon Modules*)
   - GEM (*Gas Electron Multipliers*)
   - CSC (*Cathode Strip Chambers*)
   - DCH (*Drift Chambers*)
2. **Particle identification system**:
   - TOF-400 (*First Time-of-Flight detector*)
   - TOF-700 (*Second Time-of-Flight detector*)
3. **Other detector systems:**
   - Triggers system
   - ECAL (*Electromagnetic Calorimeter*)
   - ZDC (*Zero Degree Calorimeter*)



*BM@N setup for the previous **RUN-7** configuration (spring 2018)*

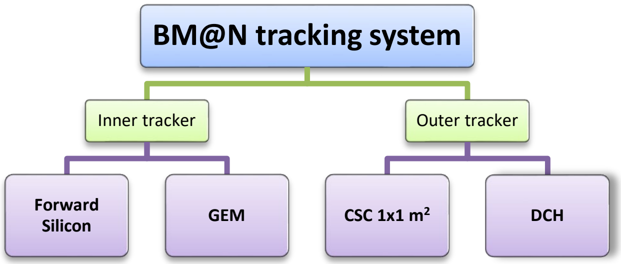


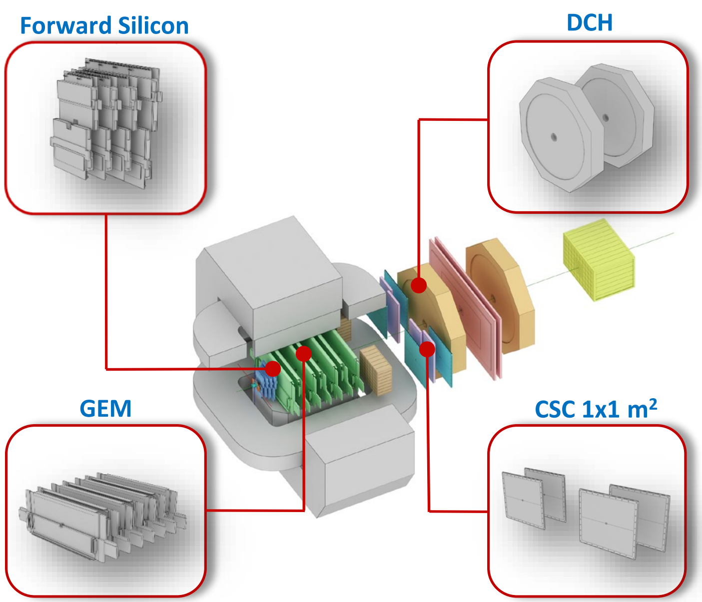
*BM@N setup for the next **RUN-8** configuration (autumn 2022)*

BM@N tracking system

Tracking system of the BM@N setup consists of high-precision coordinate detectors for charged particle track registration

The tracking system is subdivided into the **inner** and **outer** trackers.
The inner tracker includes detectors located inside the magnet, the outer – outside

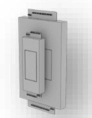
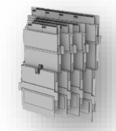
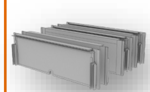
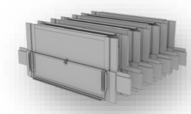
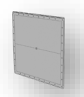
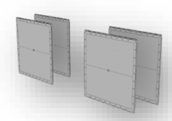
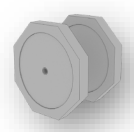
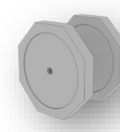




Tracking detectors of the BM@N setup for RUN-8

BM@N tracking detectors for RUN-8:

- **Forward Silicon** detector (8 half-planes)
- **GEM** detector (14 half-planes)
- **CSC** detector (4 small planes of 1x1 m^2)
- **DCH** detector (2 chambers)

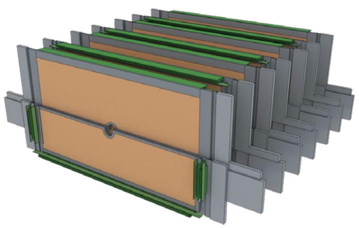
Detector	RUN-7	RUN-8	Features
Fwd Si			**RUN-7**: 2 stations (14 Si-modules) **RUN-8**: 4 stations (48 Si-modules)
GEM			**RUN-7**: 6 stations (6 half-planes) **RUN-8**: 7 stations (14 half-planes)
CSC			**RUN-7**: 1 chamber (1x1 m^2) **RUN-8**: 4 chambers (1x1 m^2)
DCH			**RUN-7**: 2 DCH chambers **RUN-8**: 2 DCH chambers (nothing changed)

Upgrade of the tracking detectors after the transition from RUN-7 to RUN-8

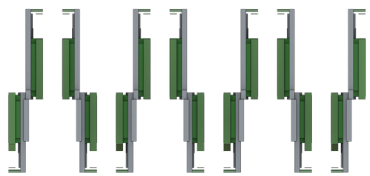
GEM detector

GEM (**G**as **E**lectron **M**ultipliers) – microstrip coordinate detector of the central tracker of the BM@N setup. It consists of gaseous chambers with electron multiplier system inside.

The configuration of this detectors for the future RUN-8 comprises **seven stations** located inside the magnet along the beam axis.

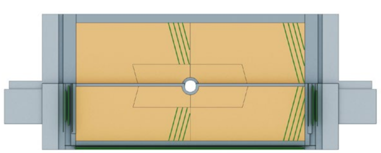


Configuration of the GEM detector for the first physics run in 2022 (RUN-8)

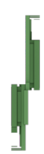


Side view

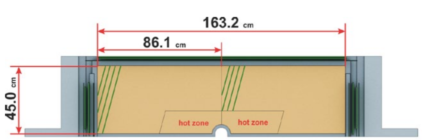
Each station is combined by two half-plane: upper and lower



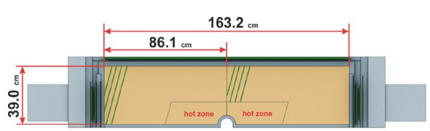
Single GEM station



Side view



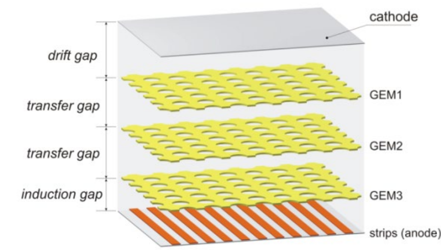
Upper half-plane



Lower half-plane

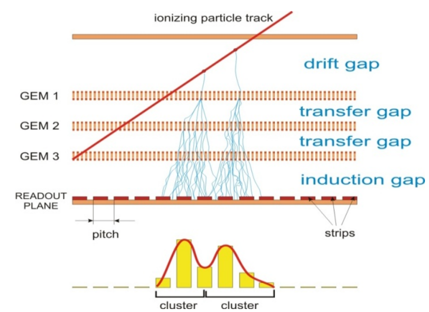
GEM structure

The detector chamber used in BM@N has three cascaded GEM foils, separated by gas gaps, and a two-dimensional projective readout on anode strips



Working principle

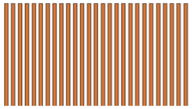
- **Gas ionization**
- **Electron multiplication**
- **Charge collection**



Signal formation in a GEM chamber:

1. A particle passes through the detector and ionizes gas molecules, producing electron-ion pairs. Positive ions and electrons drift to the cathode and to the anode, respectively
2. Primary electrons, passing through amplifying GEM cascades, gain their kinetic energy and enable secondary ionization. As a result of it is a lot of secondary electrons (electron avalanches). Amplification is about $10^4 – 10^5$.
3. Being collected on the anode, electrons form clusters on strip layers.

GEM readout



Layer of straight strips

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Layer of inclined strips

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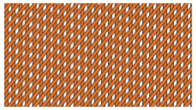
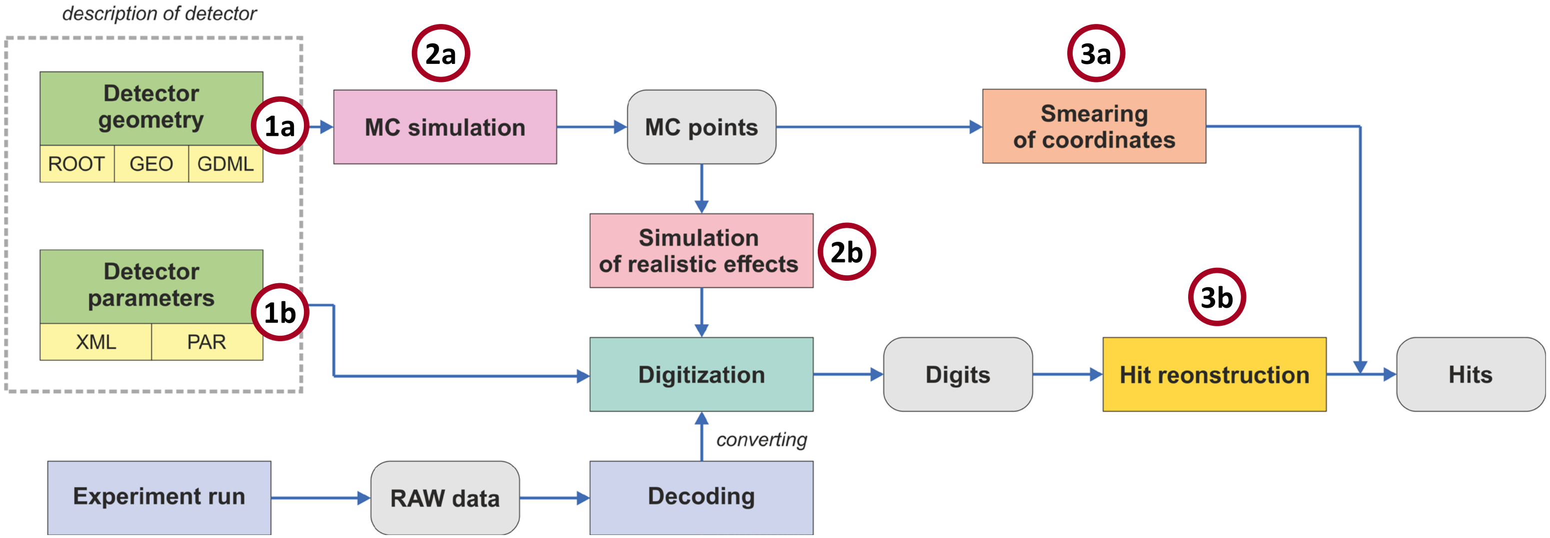


2D Strip readout

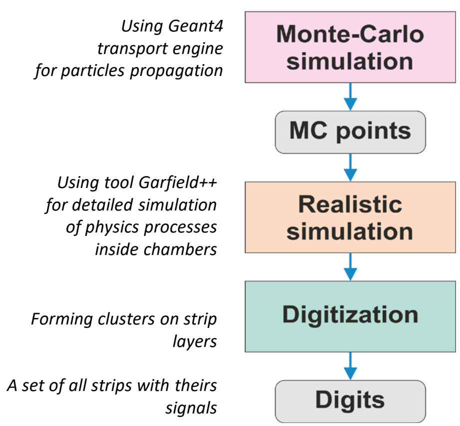
Readout plane is formed by two sets of anode strips (layers)

BM@N GEM simulation



Basic stages of data processing for GEM detector in BmnRoot

1. **Complete description of a detector**:
   a) Description of detector geometry (ROOT files)
   b) Description of detector parameters (XML files)
2. **Simulation**:
   a) Monte-Carlo simulation
   b) Simulation of realistic effects
3. **Procedures of getting "hits"**:
   a) Smearing Monte-Carlo points (hit producing)
   b) Hit reconstruction from "digits":
      - Realistic simulation + digitization
      - RAW experimental data + digitization



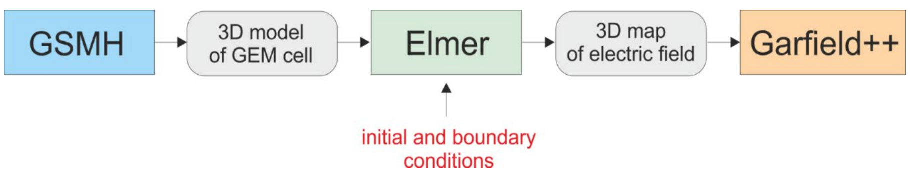
Complete simulation for GEM comprises the following stages:

1. Monte-Carlo simulation (getting MC-points by using Geant4)
2. Realistic simulation (taking into account the signal formation features)
3. "Digitization" (forming 'digits' as signal on the strips)

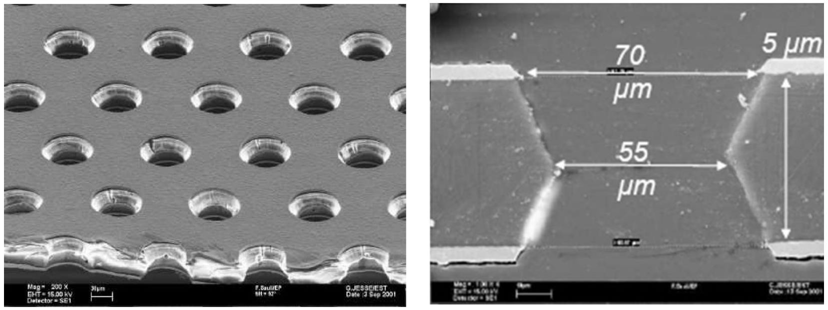
BM@N GEM: tools for electric field calculation

Tools for electric field generation and detailed simulation for GEM:

- **GMSH** *(building the geometrical 3D model and mesh of the basic GEM cell)*
- **ELMER** *(calculating 3D map of electrostatic field)*
- **GARFIELD++** *(detailed simulation of physics processes inside the GEM chamber)*

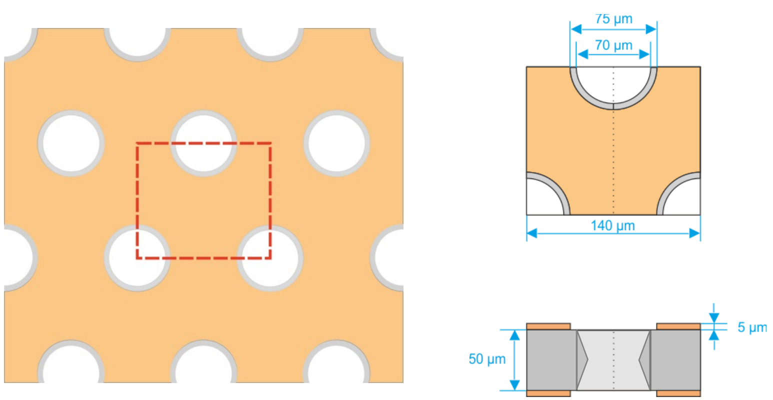


Stages of detailed simulation for the GEM detector



Microscopic pictures of the GEM foil and hole inside one

Before we can build the GEM foil structure we have to define a **periodic cell**



Basic parameters of the cell:

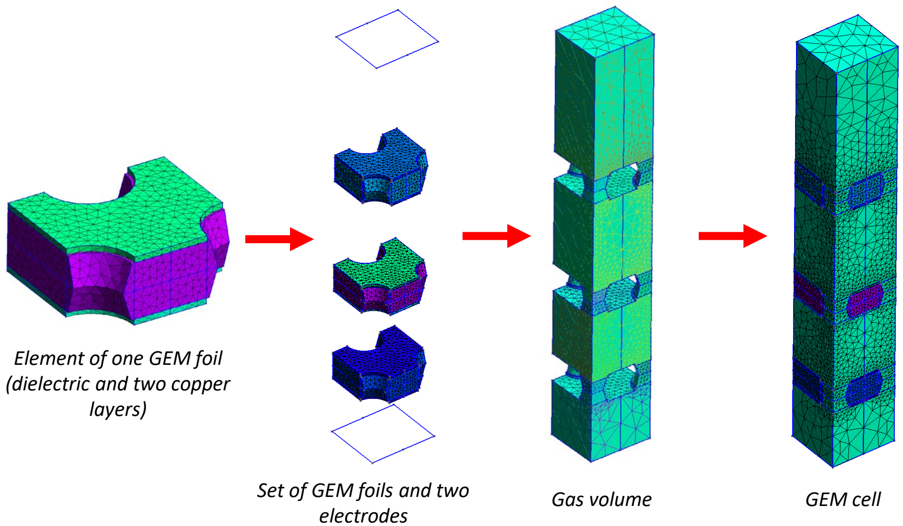
- outer diameter of dielectric hole: **70 µm** *(biconical)*
- inner diameter of dielectric hole: **55 µm** *(biconical)*
- diameter of electrode hole: **55 µm**

- thickness of dielectric: **50 µm**
- thickness of copper: **5 µm**

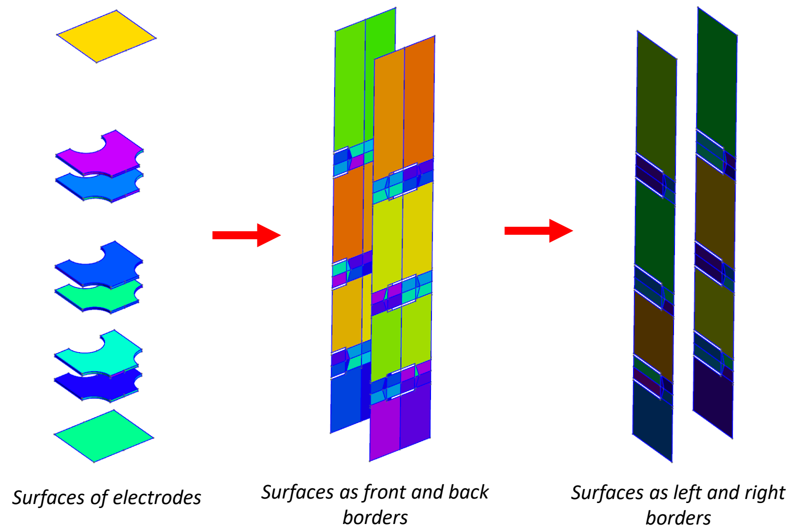
- material of dielectric: **kapton**
- material of electrode: **copper**

BM@N GEM: building GEM cell in GMSH

The mesh model of GEM in **GMSH** is a periodic cell, describing 3D structure of GEM chamber over the whole thickness (as sets of three gem cascades, two electrodes and gas volume)



Also we need to define all physical surfaces for all required elements (electrodes and borders)

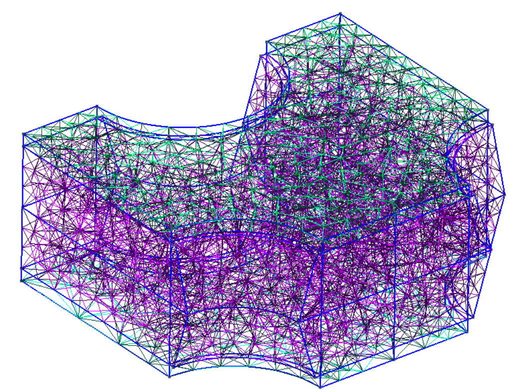


Stages of building GEM cell:

1. Creation of *.**geo**-file, containing the geometrical description of the model (manually in a text file or with visual 3D editor)
2. Generation 3D mesh (*.**msh**-file) based on geometrical description, using the command:

gmsh *filename*.geo -3 -order 2 -format msh2 -optimize_netgen

- -3 ↑ *three-dimensional mesh*
- -order 2 ↑ *mesh order*
- -format msh2 ↑ *output format*
- -optimize_netgen ↑ *enable mesh optimizer*



Generated mesh is filled with tetrahedral elements suitable for second-order interpolation that is supported by Garfield++

BM@N GEM: calculation electrostatic field in ELMER

There are two main components in **Elmer** that are used to calculate the electric fields based on the mesh created:

- **ElmerGrid** (converts the mesh of GMSH format to ElmerSolver format to perform calculations)
- **ElmerSolver** (performs the finite element calculation to obtain the electric potentials and fields)

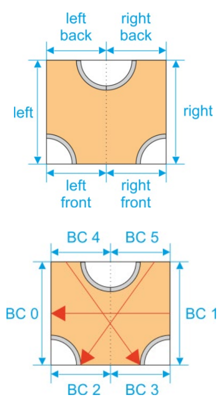
ElmerSolver tool

Before we can perform electrostatic field calculations we need to define parameters and initial/boundary conditions of bodies and materials in a solver input file (*.**sif**)

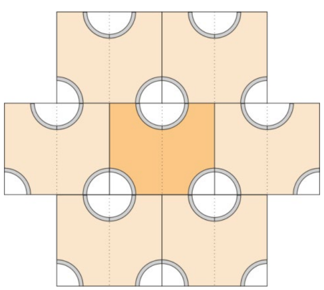
ElmerSolver *filename.sif*

Output: calculation results (*.**result** file) and data for the visualization of potentials and electrostatic fields (*.**ep** and ***.vtu** files**)**

For calculations we need to correctly define mesh as a periodic cell with 6 borders at which to apply proper boundary conditions



Boundary conditions at borders of the cell



Logical assembly of GEM cells

ElmerGrid tool

Converting 3D mesh model of the GEM cell (gmsh format) to ElmerSolver format, using the command:

ElmerGrid 14 2 *filename*.msh -autoclean

input file format (14) — *output file format* (2) — *re-index physical elements* (-autoclean)

List of input and output formats for ElmerGrid tool:

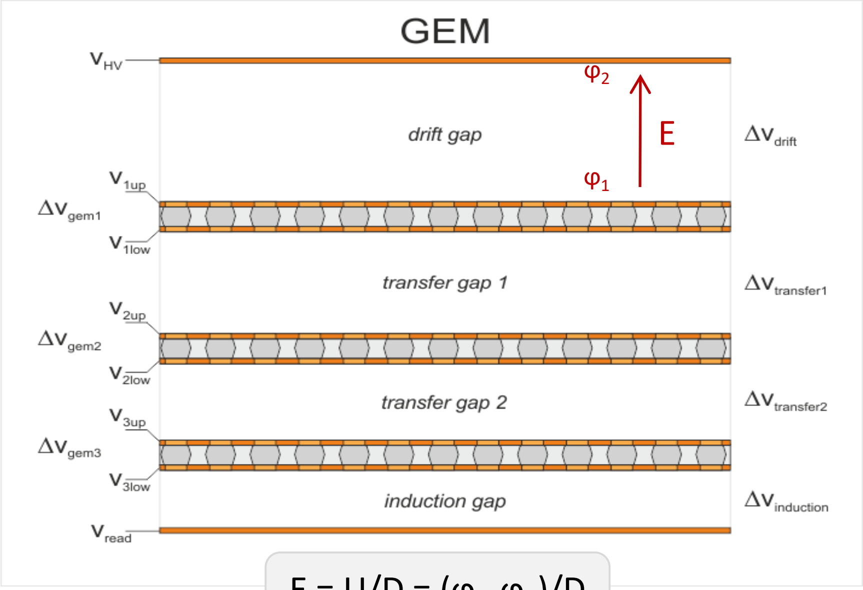
```
The first parameter defines the input file format:
1)  .grd       : Elmergrid file format
2)  .mesh.*    : Elmer input format
3)  .ep        : Elmer output format
4)  .ansys     : Ansys input format
5)  .inp       : Abaqus input format by Ideas
6)  .fil       : Abaqus output format
7)  .FDNEUT    : Gambit (Fidap) neutral file
8)  .unv       : Universal mesh file format
9)  .mphtxt    : Comsol Multiphysics mesh format
10) .dat       : Fieldview format
11) .node,.ele: Triangle 2D mesh format
12) .mesh      : Medit mesh format
13) .msh       : GID mesh format
14) .msh       : Gmsh mesh format
15) .ep.i      : Partitioned ElmerPost format

The second parameter defines the output file format:
1)  .grd       : ElmerGrid file format
2)  .mesh.*    : ElmerSolver format (also partitioned
3)  .ep        : ElmerPost format
4)  .msh       : Gmsh mesh format
5)  .vtu       : VTK ascii XML format
```

Output: full information about a mesh model, describing in files:

- **mesh.header**
- **mesh.nodes**
- **mesh.elements**
- **mesh.boundary**

BM@N GEM: parameters of GEM detector for RUN-8



$$E = U/D = (\varphi_1 - \varphi_2)/D$$

The electrostatic field map was calculated based on the given parameters for RUN-8 configuration:

E-field in gas gaps:

E_{drift} = 1.76 kV/cm
E_{trans1} = 2.27 kV/cm
E_{trans2} = 3.25 kV/cm
E_{induct} = 3.75 kV/cm

Thicknesses of gaps:

D_{drift} = 0.3 cm
D_{trans1} = 0.25 cm
D_{trans2} = 0.20 cm
D_{induct} = 0.15 cm

Voltages:

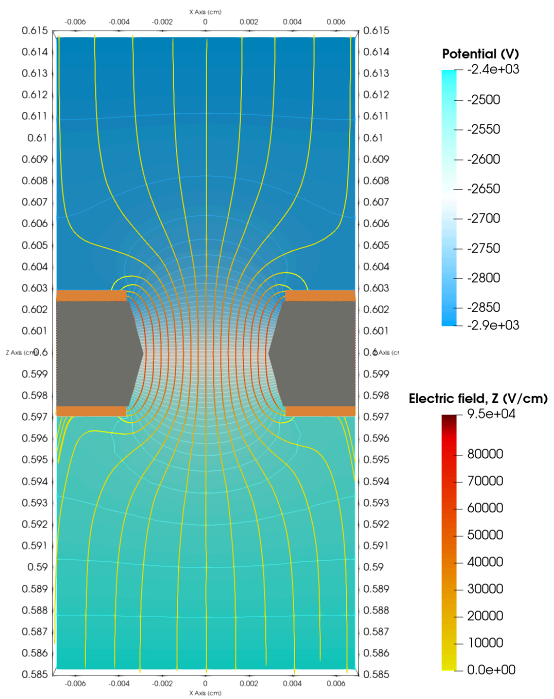
ΔV_{drift} = 528.1 V
ΔV_{trans1} = 567.0 V
ΔV_{trans2} = 649.3 V
ΔV_{induct} = 562.7 V

ΔV_{gem1} = 354.9 V
ΔV_{gem2} = 337.6 V
ΔV_{gem3} = 320.3 V

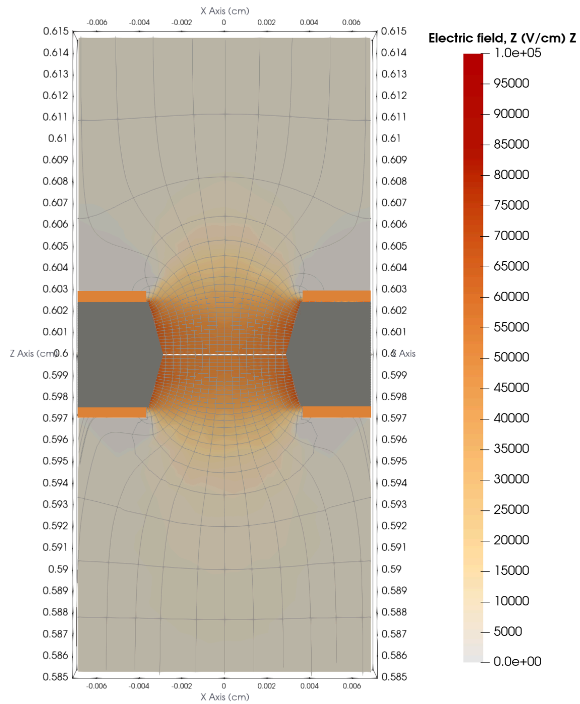
Potentials:

V_{HV} = -3319.9 V
V_{1up} = -2791.8 V
V_{1low} = -2436.9 V
V_{2up} = -1869.9 V
V_{2low} = -1532.3 V
V_{3up} = -883.0 V
V_{3low} = -562.7 V
V_{read} = 0.0 V

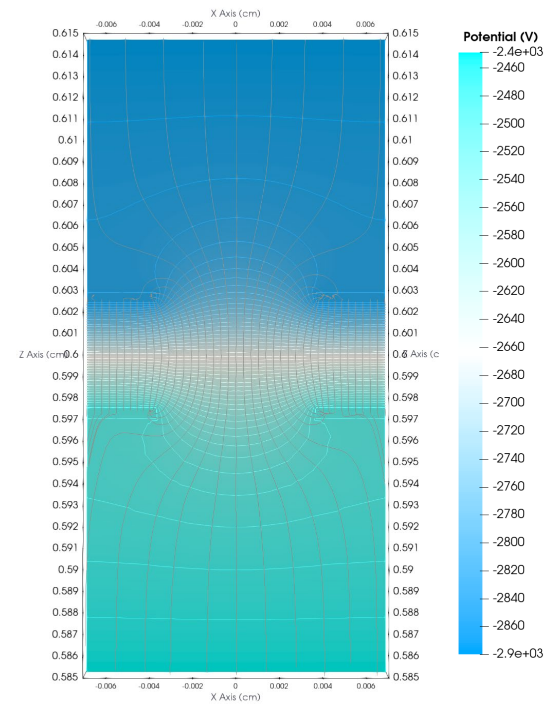
BM@N GEM: electric field calculation



Equipotential and electric field lines
(GEM hole, GEM1 = 0.6 cm)

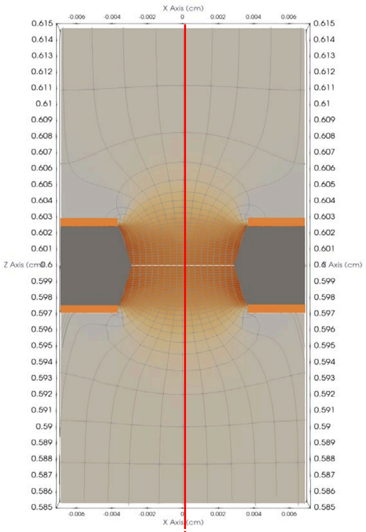


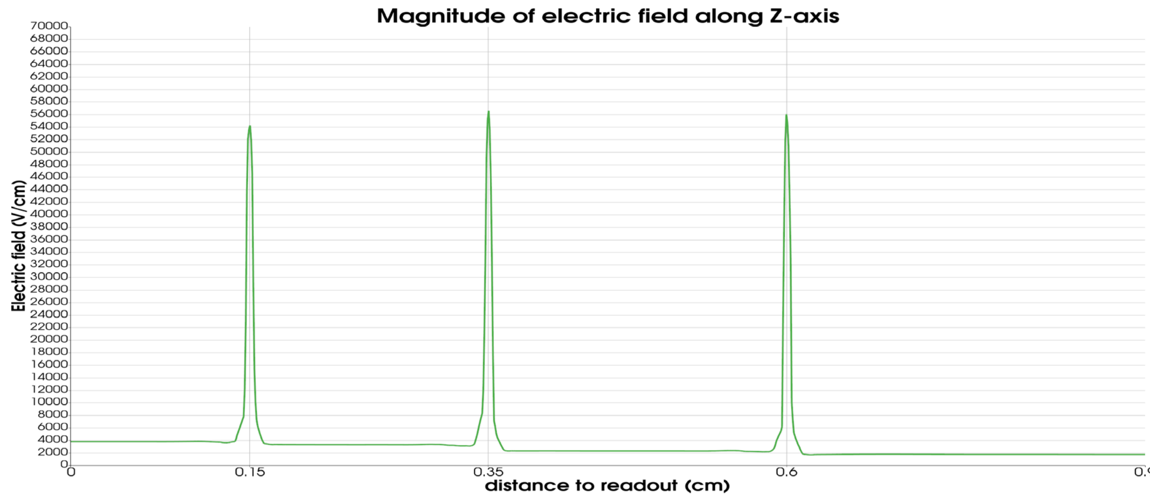
Electric field intensity
(GEM hole, GEM1 = 0.6 cm)



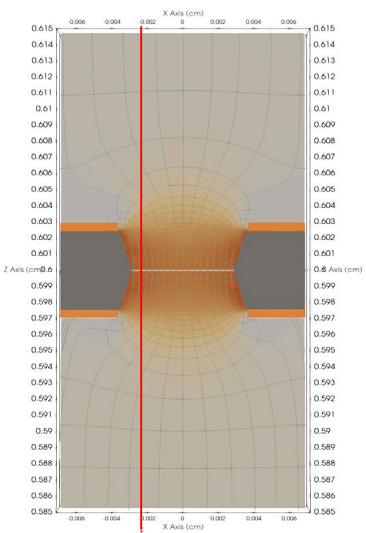
Electric potential
(GEM hole, GEM1 = 0.6 cm)

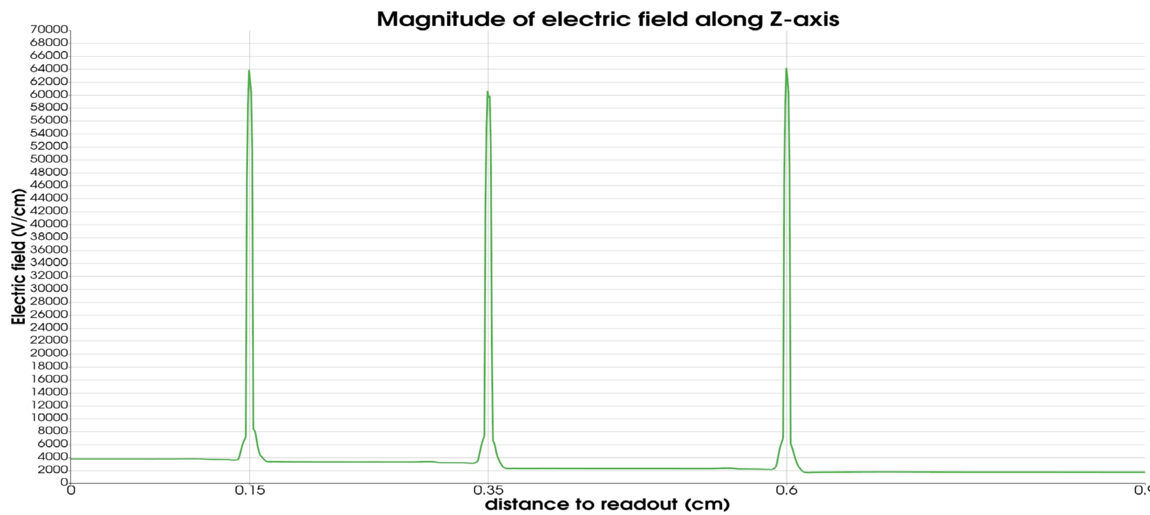
BM@N GEM: electric field magnitude





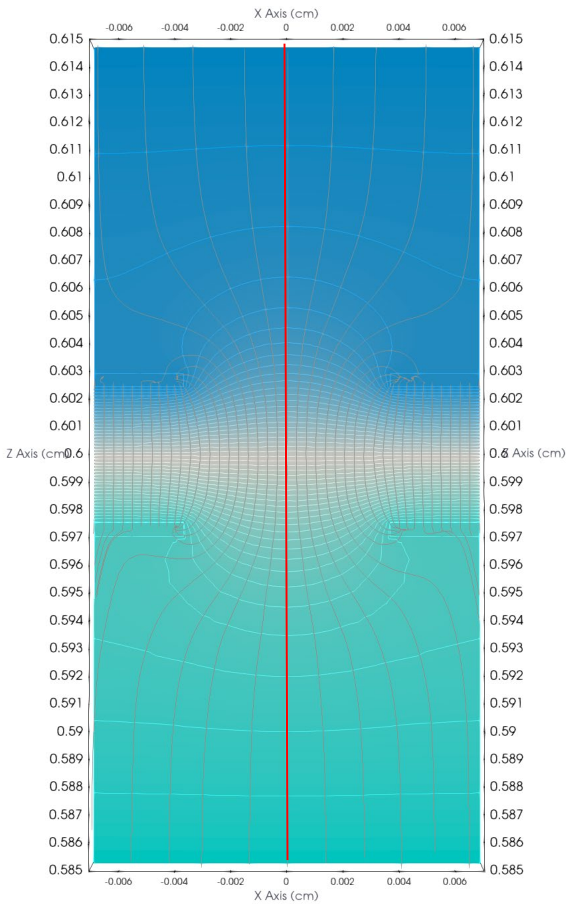
Electric field magnitude along the line through the center of the holes in the whole thickness of GEM

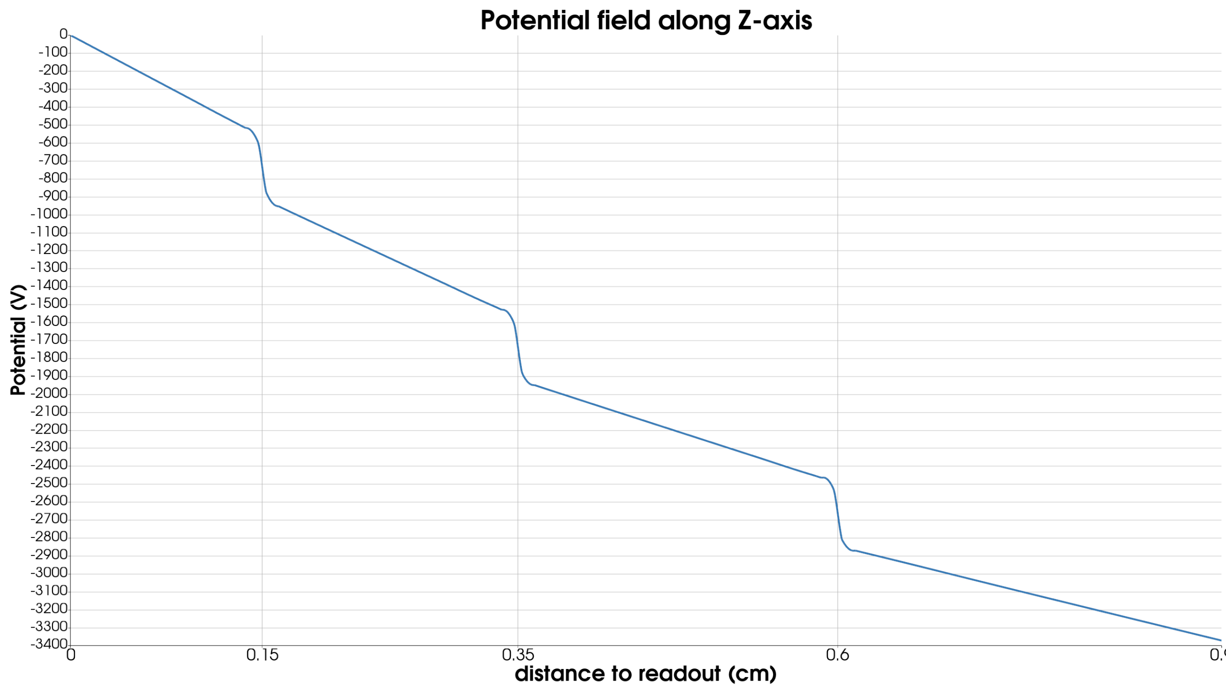




Electric field magnitude along the line through the holes with 25 μm shift from the whole thickness of GEM

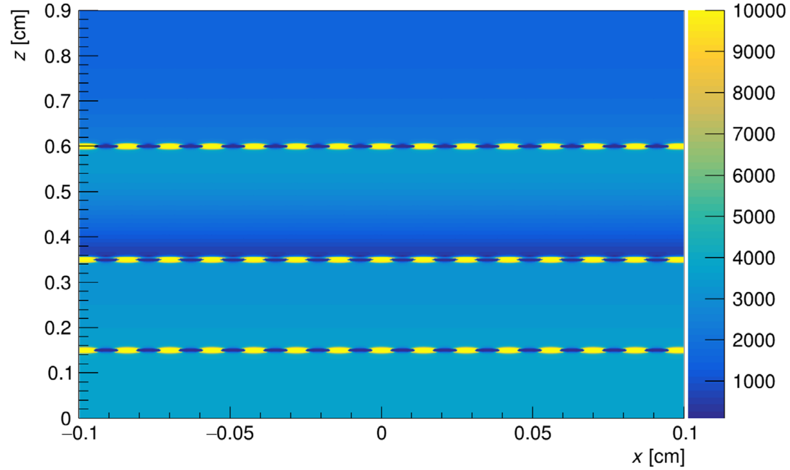
BM@N GEM: electric potential magnitude



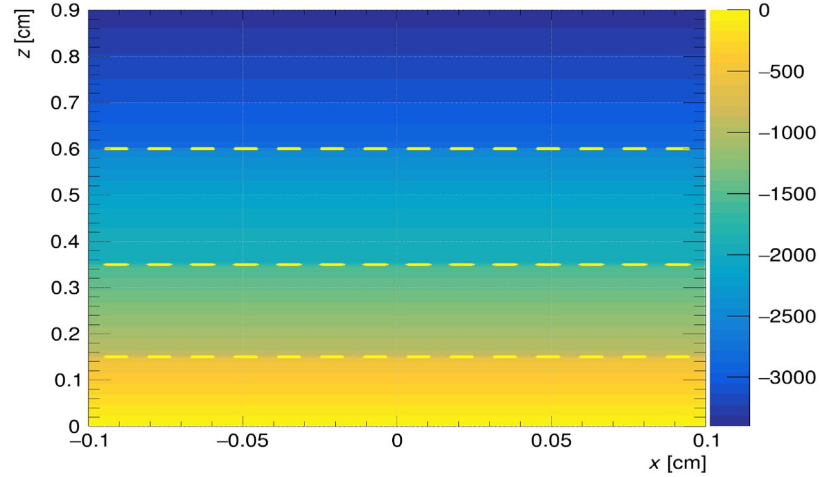


Electric potential magnitude along the line through the center of the holes in the whole thickness of GEM

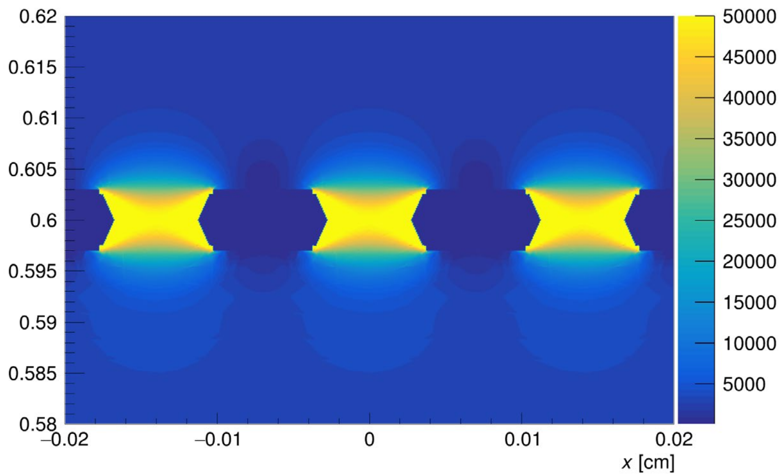
BM@N GEM: electric field map in Garfield++



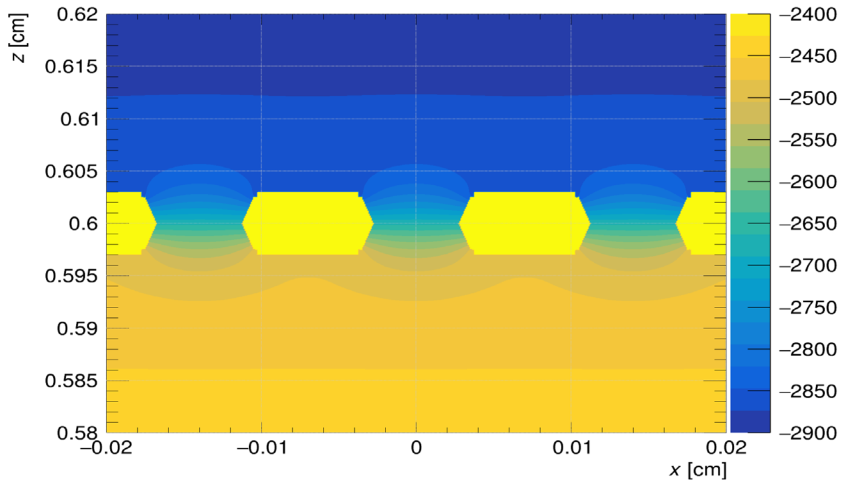
Electric field map throughout the thickness of GEM (Garfield++ visualization)



Potential map throughout the thickness of GEM (Garfield++ visualization)



Electric field map near the holes of GEM (Garfield++ visualization)

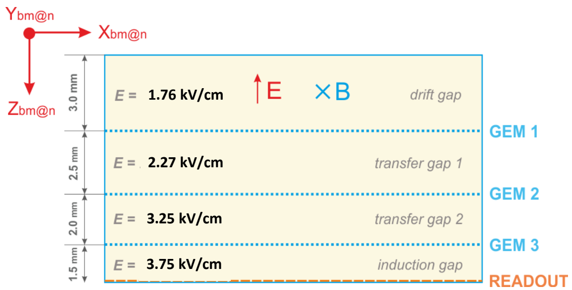


Potential map near the holes of GEM (Garfield++ visualization)

BM@N GEM: avalanche simulation in Garfield++

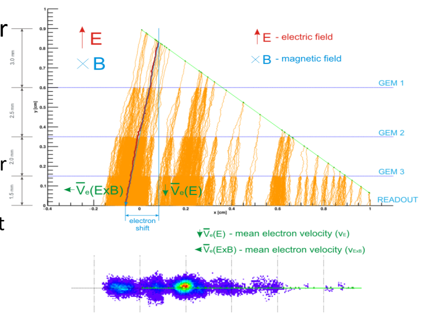
Input for electron avalanche simulation in Garfield++

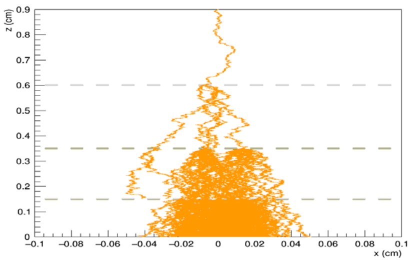
- Electrostatic field map calculated by Elmer FEM tools
- Gas mixture: **ArC_4H_{10}** (80:20)
- Magnetic field in the range **0 – 0.9** T



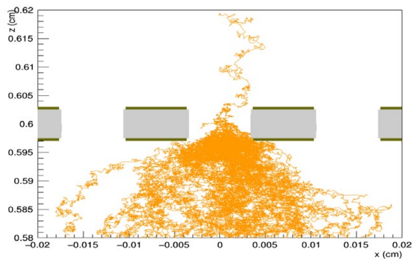
We use Garfield++ for detailed simulation of physics processes in our GEM chamber:

1. Gas ionization by a charged particle.
2. Electron drift to an anode readout (under electric field influence)
3. Electron avalanches production (as result of multiplication in GEM holes)
4. Electron shift (under the Lorentz force influence in mag. field)





Electron avalanche production in our triple GEM



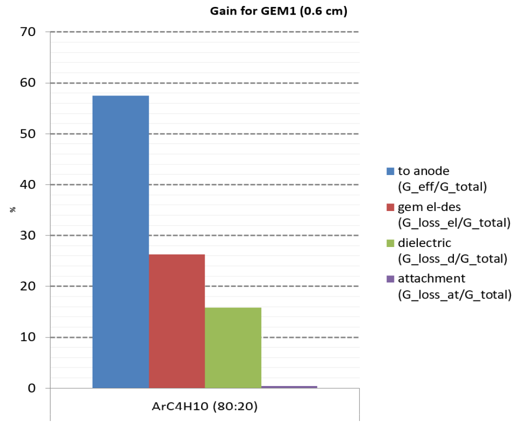
Electron avalanche production from one ionizing electron in a hole (GEM-1 0.6 cm readout)

Secondary electron production in GEM (statistics)

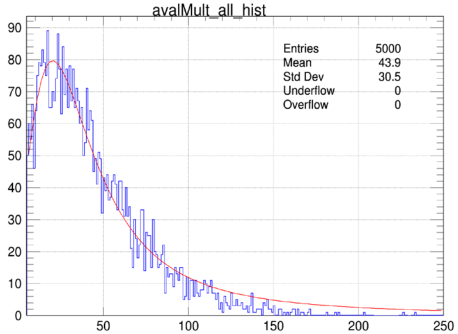
Total amount of electrons, prodused as a result of secondary inonization under the influence of strong electric field in gem holes, determine a **total gain**

The part of an electron avalanche is collected by GEM electrodes and dielectrics (**electron loss**)

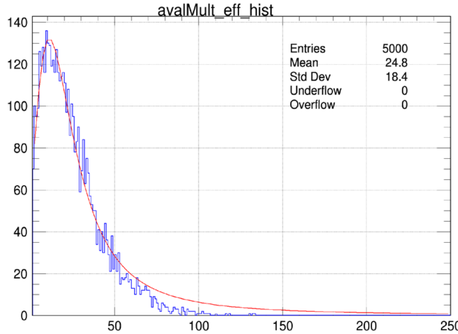
Electrons, passed to the anode, form a signal. Their amount determines an **effective gain**



The relative proportions of all secondary electrons from one primary electrons for our input characteristics of GEM (gem1, 0.6 cm)



The distribution of all produced electrons



The distribution of produced electrons that form a signal

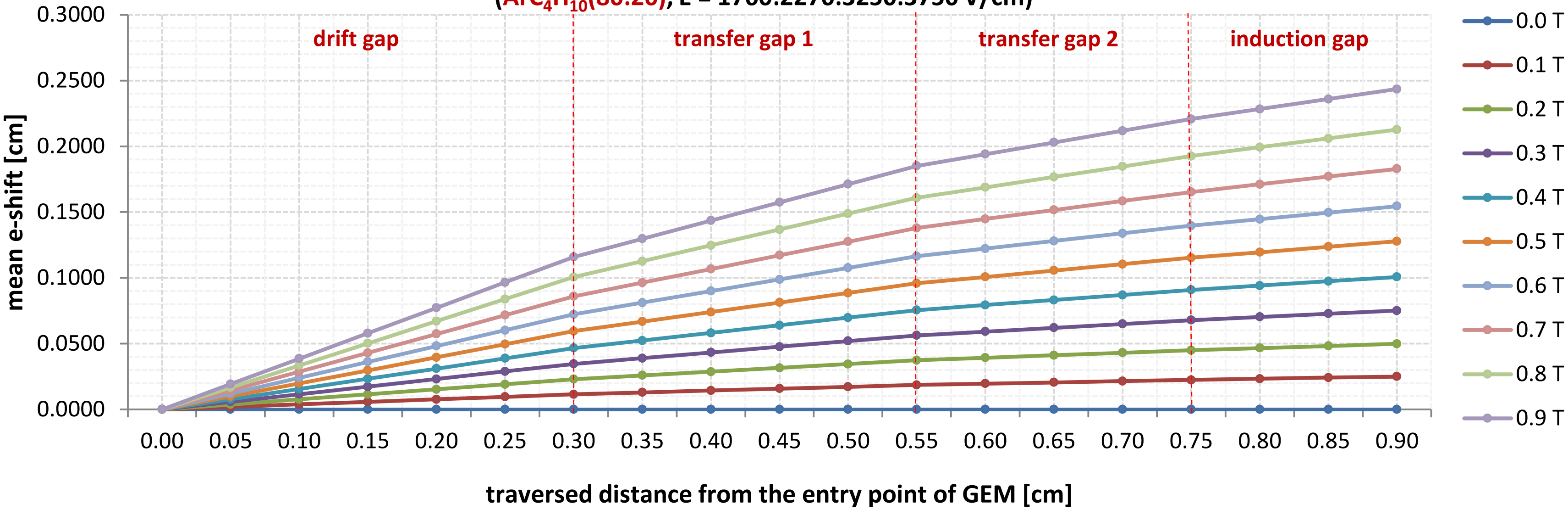
BM@N GEM: electron shift in magnetic field

BMN GEM: mean electron shift in mag. field (ArC_4H_{10}(80:20), E = 1760:2270:3250:3750 V/cm)

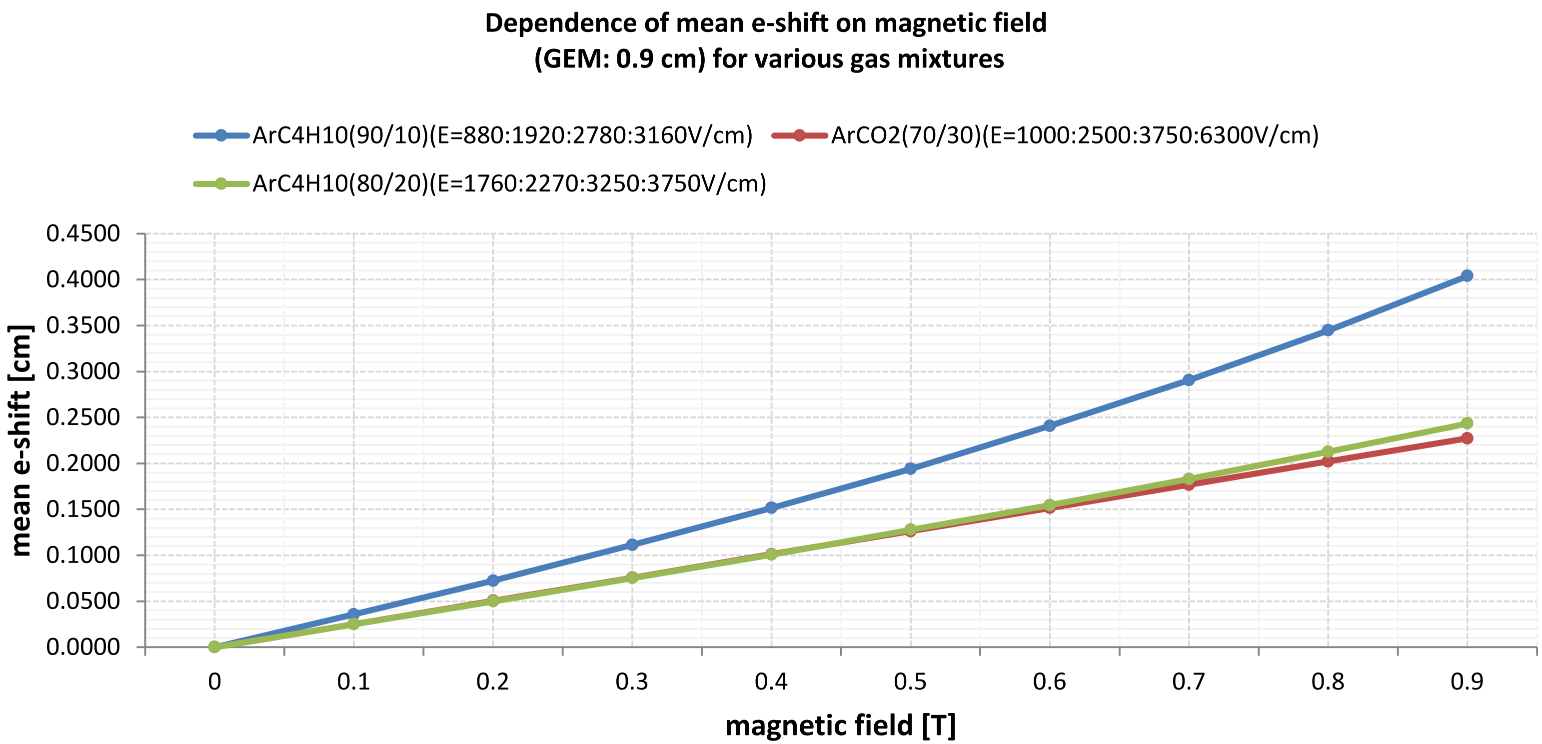
	traversed distance from the entry point of GEM, cm																		
B-field[by], T	***0.00***	***0.05***	***0.10***	***0.15***	***0.20***	***0.25***	***0.30***	***0.35***	***0.40***	***0.45***	***0.50***	***0.55***	***0.60***	***0.65***	***0.70***	***0.75***	***0.80***	***0.85***	***0.90***
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1	0.0000	0.0019	0.0038	0.0058	0.0077	0.0096	0.0115	0.0130	0.0144	0.0158	0.0172	0.0187	0.0196	0.0206	0.0215	0.0225	0.0233	0.0242	0.0250
0.2	0.0000	0.0038	0.0077	0.0115	0.0153	0.0191	0.0229	0.0258	0.0287	0.0316	0.0345	0.0374	0.0393	0.0412	0.0431	0.0450	0.0466	0.0483	0.0499
0.3	0.0000	0.0058	0.0116	0.0173	0.0231	0.0289	0.0346	0.0390	0.0433	0.0476	0.0520	0.0563	0.0592	0.0621	0.0650	0.0679	0.0703	0.0727	0.0752
0.4	0.0000	0.0078	0.0155	0.0233	0.0311	0.0388	0.0466	0.0524	0.0582	0.0639	0.0697	0.0755	0.0793	0.0832	0.0870	0.0909	0.0941	0.0974	0.1007
0.5	0.0000	0.0099	0.0198	0.0297	0.0397	0.0496	0.0595	0.0668	0.0740	0.0813	0.0886	0.0959	0.1007	0.1056	0.1105	0.1153	0.1195	0.1237	0.1278
0.6	0.0000	0.0120	0.0241	0.0361	0.0482	0.0602	0.0723	0.0811	0.0900	0.0988	0.1076	0.1165	0.1223	0.1281	0.1339	0.1396	0.1446	0.1496	0.1545
0.7	0.0000	0.0143	0.0287	0.0430	0.0573	0.0717	0.0860	0.0964	0.1068	0.1172	0.1275	0.1379	0.1448	0.1516	0.1584	0.1653	0.1711	0.1770	0.1829
0.8	0.0000	0.0168	0.0335	0.0503	0.0670	0.0838	0.1006	0.1126	0.1247	0.1368	0.1488	0.1609	0.1688	0.1767	0.1846	0.1925	0.1992	0.2059	0.2126
0.9	0.0000	0.0193	0.0386	0.0579	0.0772	0.0965	0.1159	0.1297	0.1436	0.1574	0.1713	0.1851	0.1940	0.2029	0.2118	0.2207	0.2283	0.2359	0.2435

drift gap *(0.3 cm)* — **transfer gap 1** *(0.25 cm)* — **transfer gap 2** *(0.2 cm)* — **induction gap** *(0.2 cm)*

Dependence of mean e-shift on traversed distance from the entry point of GEM for various magnetic fields (ArC_4H_{10}(80:20), E = 1760:2270:3250:3750 V/cm)



BM@N GEM: electron shift in magnetic field



total mean e-shift throughout the whole thickness of GEM (0.9 cm), cm

	E=880:..V/cm	*E=1000:..V/cm*	*E=1760:..V/cm*
B-field[by], T	**ArC_4H_{10}(90/10)**	**$ArCO_2$(70/30)**	**ArC_4H_{10}(80/20)**
0	0.0000	0.0000	0.0000
0.1	0.0356	0.0251	0.0250
0.2	0.0722	0.0505	0.0499
0.3	0.1112	0.0755	0.0752
0.4	0.1514	0.1011	0.1007
0.5	0.1939	0.1262	0.1278
0.6	0.2408	0.1515	0.1545
0.7	0.2906	0.1767	0.1829
0.8	0.3447	0.2021	0.2126
0.9	0.4038	0.2273	0.2435

Summary

- Electrostatic field map was calculated for relevant parameters of GEMs for the future run of the BM@N experiment (GMSH + ELMER tools)

- Detailed simulation of triple GEMs based on this field map and various magnetic field ranges was performed (Garfield++ tool)

- Some dependencies and distributions were obtained from the detailed simulation to be used in the further simulation procedures that take into account the realistic signal formation

Thank you for your attention…