Software development for Monte-Carlo simulation and hit-reconstruction for tracking detectors in the next runs of the BM@N experiment in 2021-2022

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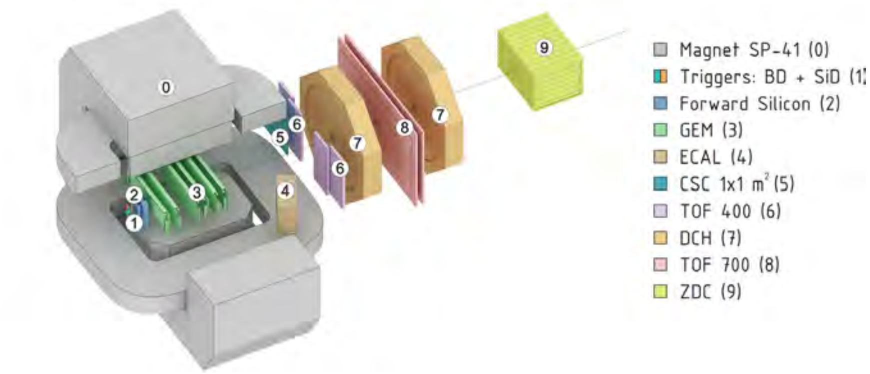
Talk topics:

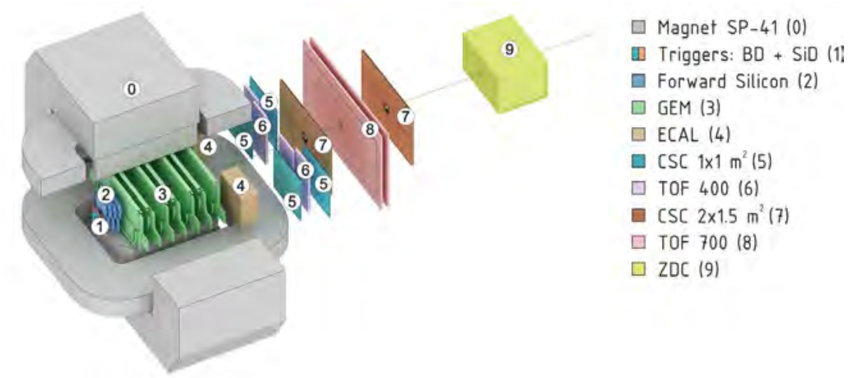
- ❑ BM@N setup for RUN-7 and RUN-8
- ❑ Tracking system of the BM@N setup for RUN-8:
- ❑ Tracking detectors: steps of simulation and reconstruction
- ❑ Description of tracking detectors
    - Forward Silicon
    - GEM
    - CSC
- ❑ Monte-Carlo simulation
- ❑ Hit reconstruction
- ❑ Structure of software for tracking detectors

BM@N setup: configurations

BM@N (**B**aryonic **M**atter at **N**uclotron) is a fixed target experiment aimed to study dense baryonic matter on heavy-ion collisions.



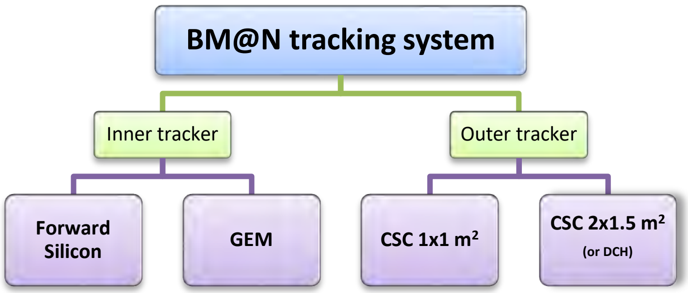
Previous configuration of the BM@N setup in the spring of 2018 (RUN-7)

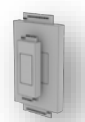
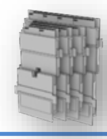
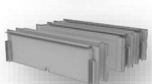
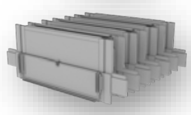
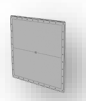
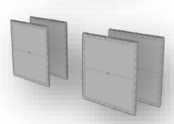
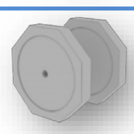
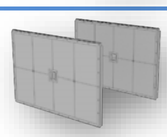


Future full configuration of the BM@N setup planned to be carried out in the spring of 2022 (RUN-8)

BM@N tracking system

The complete tracking system of the BM@N setup is divided into the **inner** and **outer** trackers:

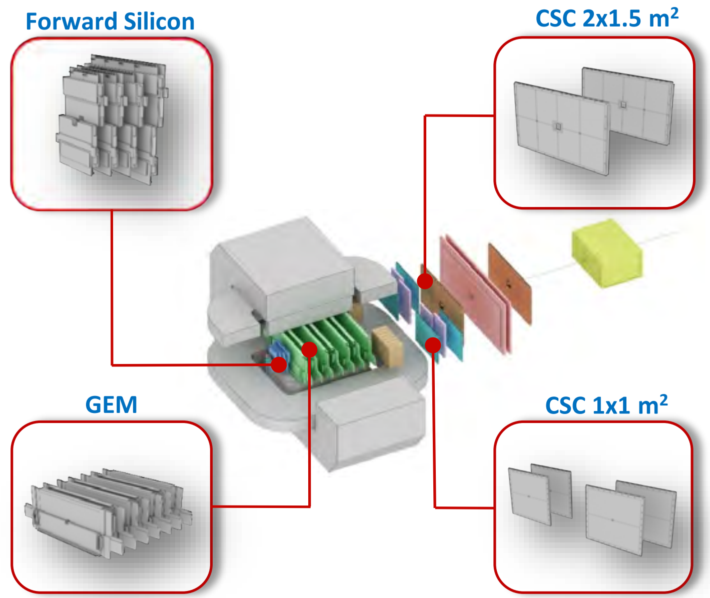


Detector	RUN-7	RUN-8	Features
Fwd Si			**RUN-7**: 2 stations (14 Si-modules) **RUN-8**: 4 station (64 Si-modules)
GEM			**RUN-7**: 6 stations (6 half-planes) **RUN-8**: 7 stations (14 half-planes)
CSC			**RUN-7**: 1 station (1x1 m^2) **RUN-8**: 4 stations (1x1 m^2)
DCH->CSC			**RUN-7**: 2 DCH chambers **RUN-8**: 2 CSC stations (2x1.5 m^2)

Upgrade of the BM@N tracking system in transition from RUN-7 to RUN-8

BM@N tracker consists of the following components:

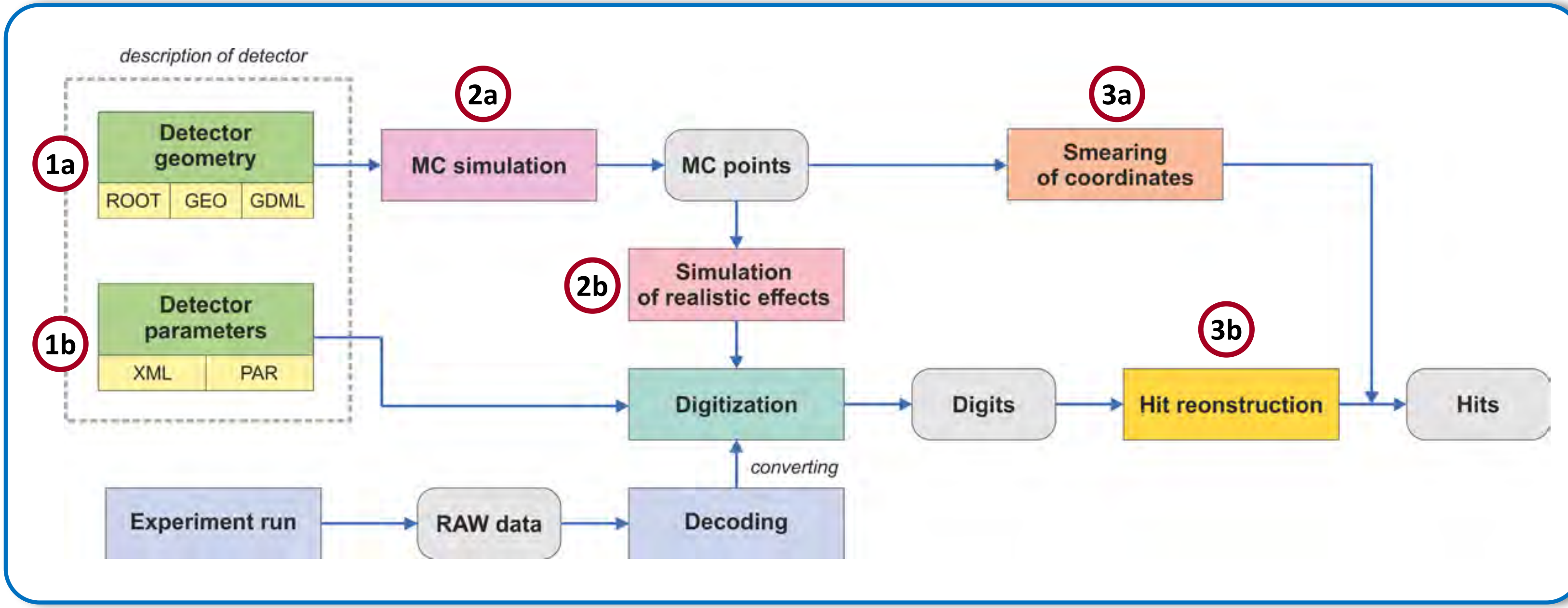
- **Forward Silicon** detector (8 half-planes)
- **GEM** detector (14 half-planes)
- **CSC** detector (4 planes of 1x1 m^2)
- **CSC** detector (2 planes of 2x1.5 m^2) *as a replacement for DCH*



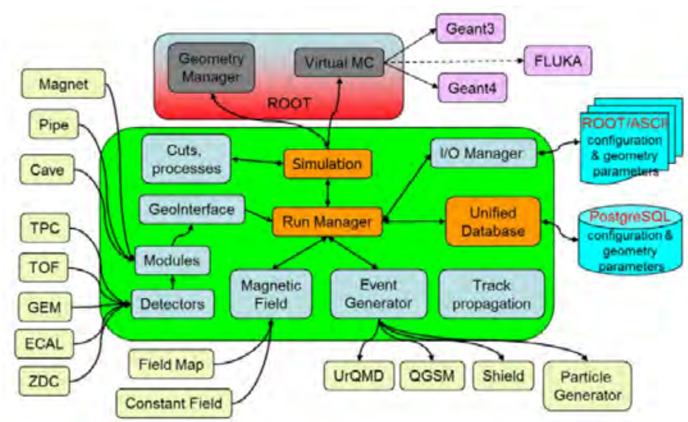
Tracking detectors of the BM@N setup in the future configuration (RUN-8)

Tracking detectors: steps of simulation and reconstruction

Scheme of the main steps of simulation and reconstruction for tracking detectors in the BmnRoot



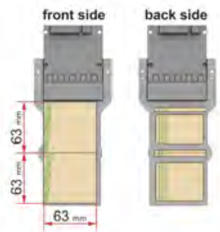
1. **Complete description of a detector**:
   a) Description of detector geometry (ROOT files)
   b) Description of detector parameters (XML files)
2. **Simulation**:
   a) Monte-Carlo simulation
   b) Simulation of realistic effects
3. **Procedures of getting "hits"**:
   a) Smearing Monte-Carlo points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



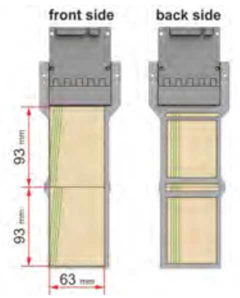
Structure of the BmnRoot framework

Forward Silicon detector

Forward Si is a silicon based semi-conductor detector consisting of Si-modules. There are two types of these modules: standard with sensor sizes of **63x126** mm^2 and long with sensor sizes of **63x186** mm^2



*Standard Si-module with sensor **63x126** mm^2*

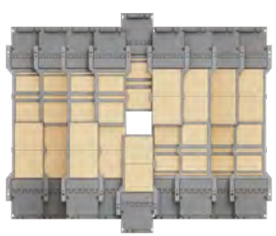


*Long Si-module with sensor **63x186** mm^2*

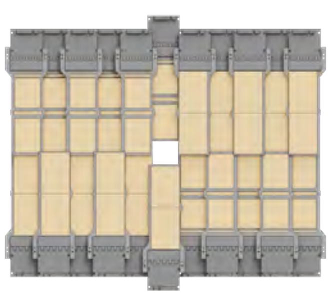
Si-modules are combined into **4 stations** of 10, 14, 18 and 22 modules (64 modules in total)

Station 1:
10 Si-modules of 63x126 mm^2

Station 2:
14 Si-modules of 63x126 mm^2

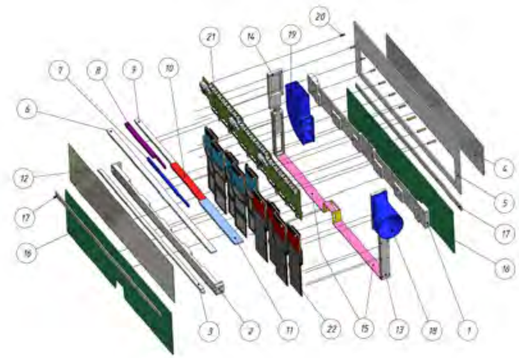


Station 3:
18 Si-modules of 63x126 mm^2



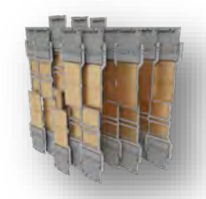
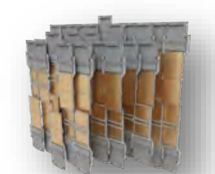
Station 4:
22 Si-modules of 63x126 mm^2

Then the Si-modules combined together are put into an air-cooled housing which comprises different components of various materials



Scheme of one half-plane (a half station) of the forward Silicon detector

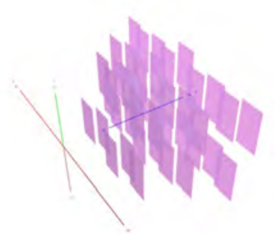
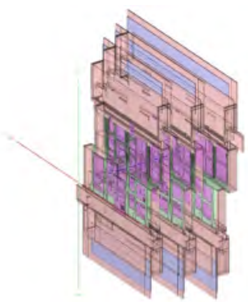
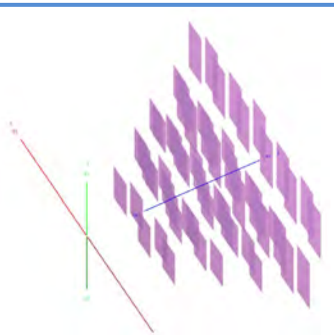
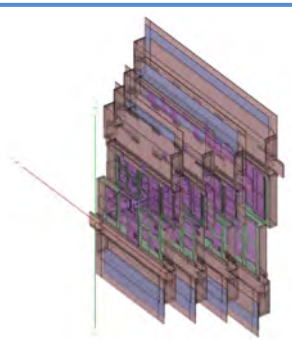
At this moment there are two versions of the configuration for the Forward Silicon detector for the future RUN-8

1st configuration (realistic)	 *3 stations (or 6 half-planes)*	 *42 Si-modules in the configuration*
2nd configuration (optimistic)	 *4 stations (or 8 half-planes)*	 *64 Si-modules in the configuration*

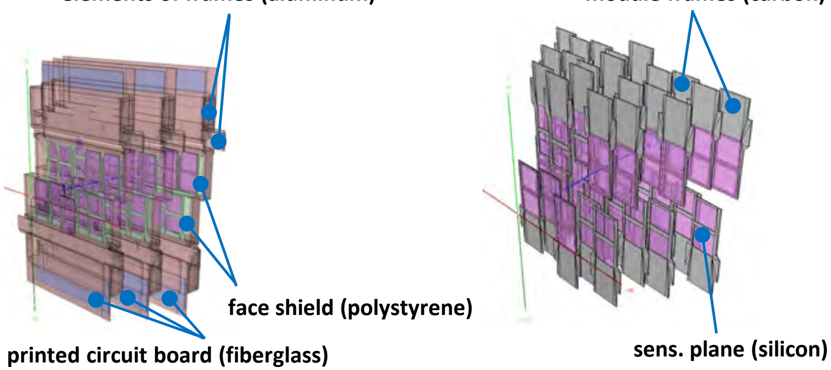
Forward Silicon detector: ROOT geometry

There are two versions of ROOT geometry for each configuration of the Forward Silicon detector: **simplified** and **detailed**.

- **Basic ROOT geometry** consists of only sensor elements without any passive materials.
- **Detailed ROOT geometry** completely describes the detector including passive elements such as electronics, housing and supporting components.

Configuration	Basic ROOT geometry	Detailed ROOT geometry
1st configuration	 *42 Si-modules*	 *3 stations (or 6 half-planes)*
2nd configuration	 *64 Si-modules*	 *4 stations (or 8 half-planes)*

Adding passive elements to the geometry allows us to take into account detector materials which affect the passage of particles trough matter. This, in turn, improves the accuracy of the Monte-Carlo simulation.



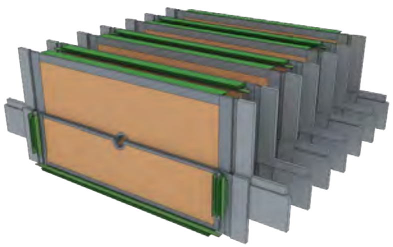
Materials of some elements of the Forward Silicon detector

The present geometry was prepared in according to the drawings and schemes provided by the detector group

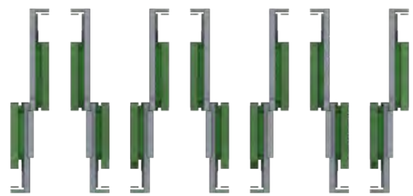
GEM detector

GEM (**G**as **E**lectron **M**ultiplier) is a gaseous detector with micro-strip readout. Its configuration for RUN-8 comprises seven stations located inside the magnet along the beam axis.

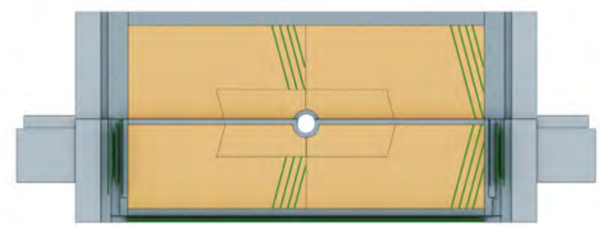
Each station in the configuration RUN-8 is combined from two half-planes: upper and lower. These half-planes are joined together to form an XY plane.



GEMs for RUN-8



GEMs for RUN-8 (side view)

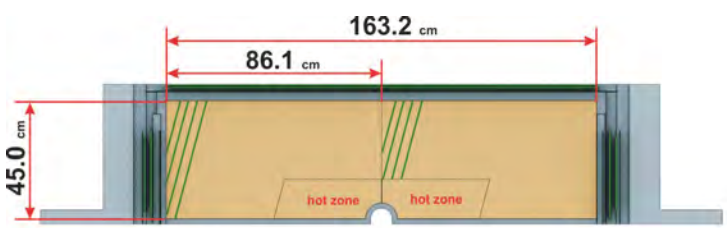


1st GEM station

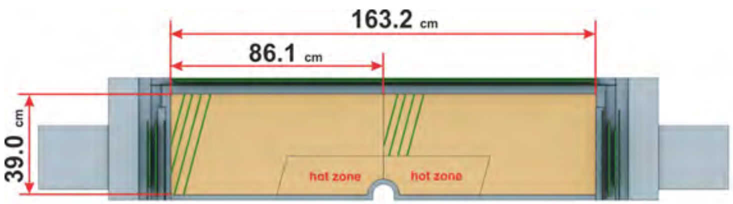
1st GEM station (side view)

Upper and lower half-planes have different sizes of their sensitive areas:

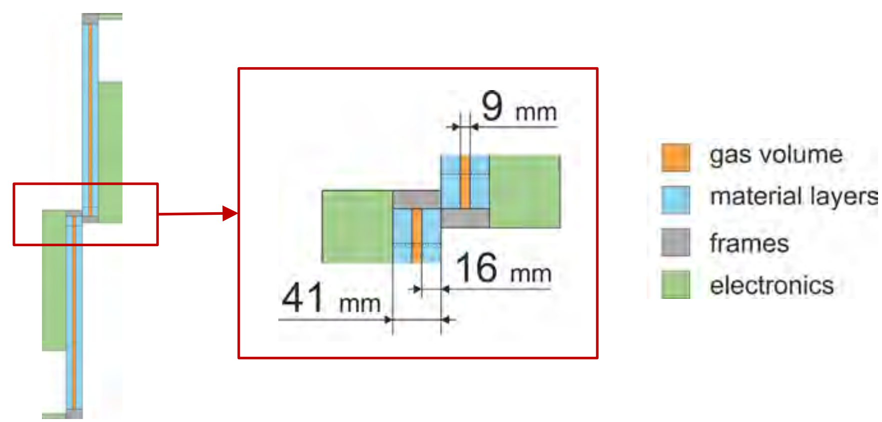
- Upper half-plane sensor: **163x45** cm
- Lower half-plane sensor: **163x39** cm



Upper half-plane



Lower half-plane

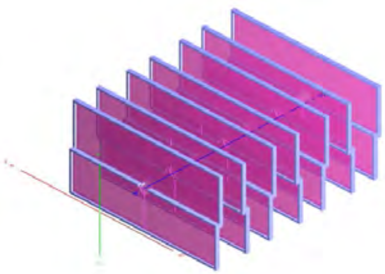


Scheme of joining two half-planes together in a station (side view)

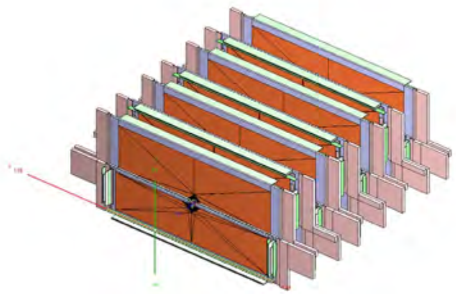
GEM detector: ROOT geometry

Two versions of ROOT geometry of the GEM detector have been prepared for the next RUN-8 configuration:

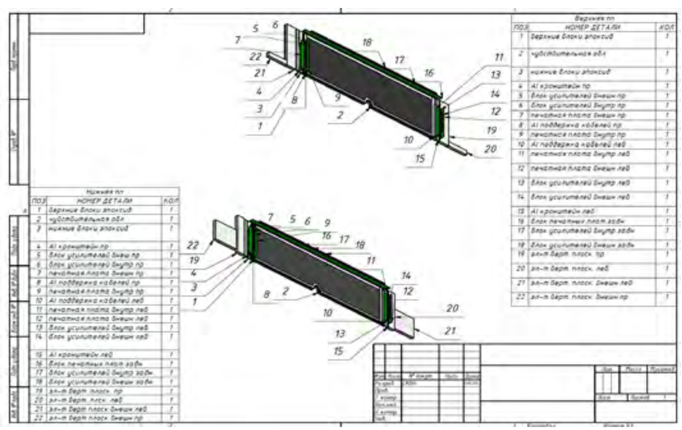
- **Basic ROOT geometry** comprises 14 sensitive volumes with simplified frames around each one.
- **Detailed ROOT geometry** completely describes the detector including passive elements such as electronics, housing and supporting components.



Basic ROOT geometry of the GEM detector



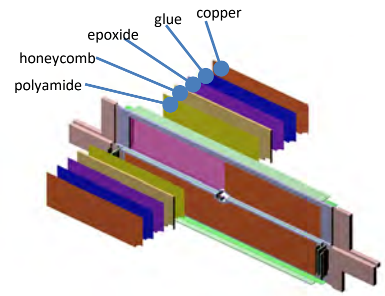
Detailed ROOT geometry of the GEM detector



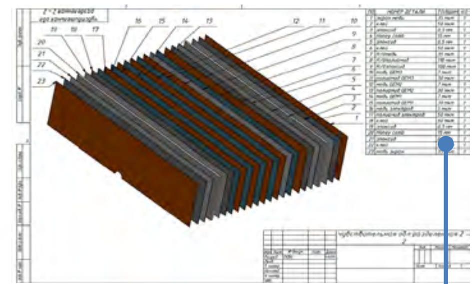
Geometry of the GEM detector was created in accordance with detailed drawings prepared by the GEM group

Sensitive area of a GEM chamber:

Each active zone in a GEM chamber has a multi-layer structure. A layer has the following properties: thickness, material type and other characteristics which are taken into account in the Monte-Carlo simulation process.



Multi-layer structure of a GEM chamber (ROOT-geometry)



Scheme of layers in a half-plane (prepared by the GEM group)

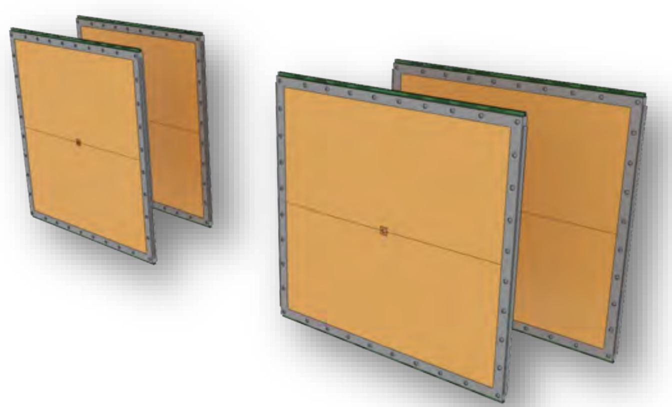
copper: 35µm + 35µm + 7µm + 7µm + 7µm + 5µm + 35µm = **131µm**
glue: 50µm + 50µm +50µm + 50µm = **200µm**
epoxide: 0.5mm + 0.5mm + 100µm + 0.5mm + 0.5mm = **2.1mm**
honeycomb: 15mm + 15mm = **30mm**
polyamide: 110µm + 30µm + 30µm + 30µm + 50µm = **250µm**

layer	material	density [g/cm-3]	thickness (X) [cm]	X0 [cm]	X/X0 [%]
gas	ArC_4H_{10} (80/20)	0.002	0.9	12343	0.0073
copper	copper	8.96	0.0131	1.435	0.9129
glue	acrylic glue	1.25	0.02	32.1603	0.0622
epoxide	polyurethane	1.8	0.21	22.5351	0.9319
honeycomb	nomex aramid honeycomb	0.048	2.86	755.397	0.3786
polyamide	polyamide	1.14	0.025	36.4052	0.0687

Properties of layers

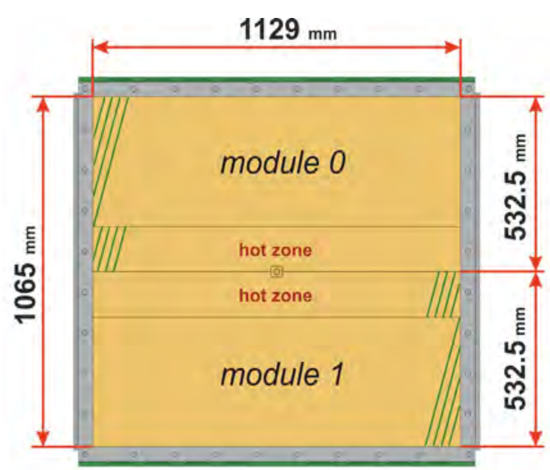
CSC detector

CSC (**C**athode **S**trip **C**hamber) is a gaseous detector with micro-strip readout. It is comprised in the outer tracking system of the BM@N setup. The configuration of this detector for RUN-8 consists of four stations located behind the magnet.



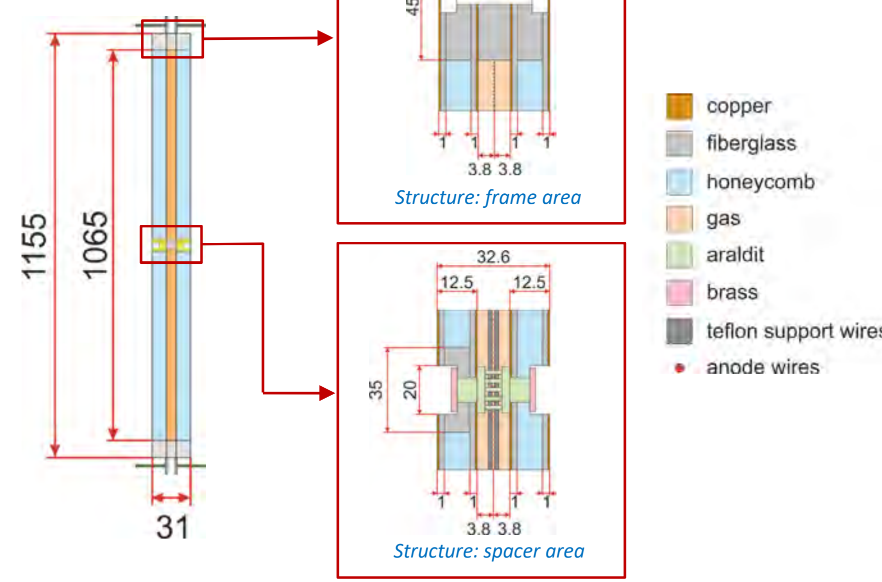
CSC chambers for RUN-8

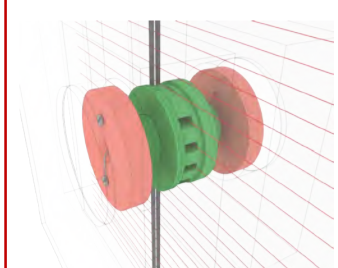
Each chamber has sensitive area with sizes of **1129x1065** mm^2.



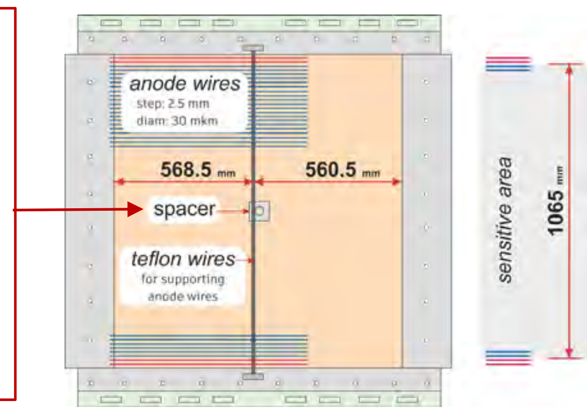
Structure of a CSC chamber :

CSC chamber (side view)





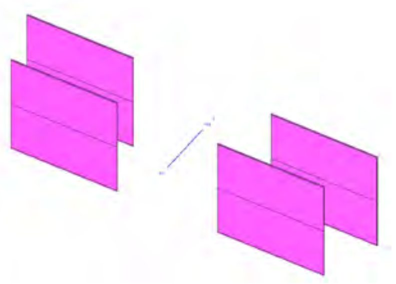
Spacer for supporting a fixed distance between two cathode plates



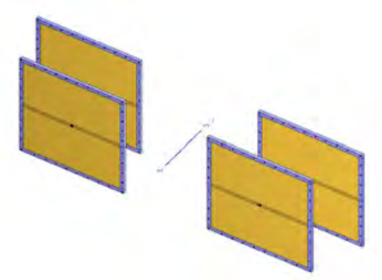
CSC detector: ROOT geometry

As well as for others tracking detector there are two versions of ROOT geometry of the CSC detector which have been prepared for the forthcoming RUN-8:

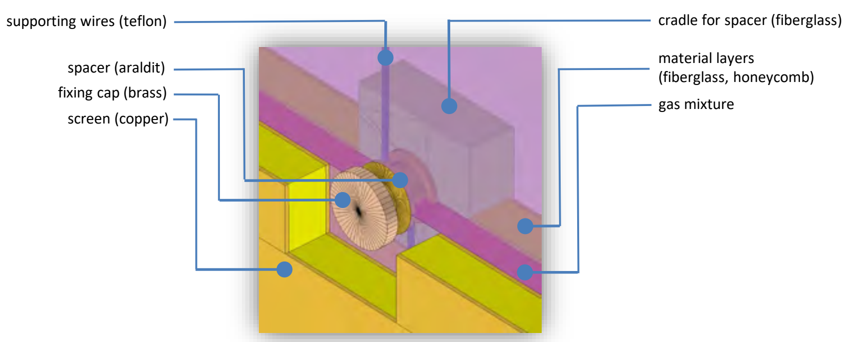
- **Basic ROOT geometry** is four sensitive volumes filled with an active gas mixture (without any frames)
- **Detailed ROOT geometry** includes, in addition to gas volumes, passive elements, such as frames, material layers and other constructive components



Basic ROOT geometry of the CSC detector



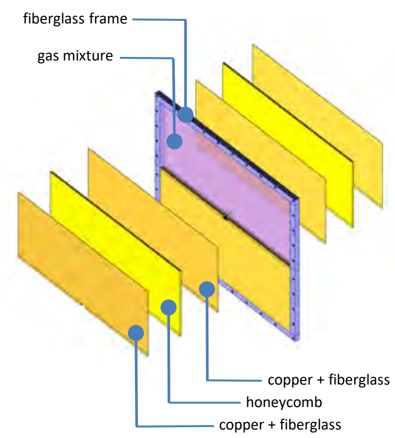
Detailed ROOT geometry of the CSC detector



Spacer, as an example of a passive element, was implemented in the ROOT geometry of the CSC chamber

Sensitive area of a CSC chamber:

Each active zone in a GEM chamber has a multi-layer structure. A layer has the following properties: thickness, material type and other characteristics which are taken into account in the Monte-Carlo simulation process.



Multi-layer structurer of a CSC chamber

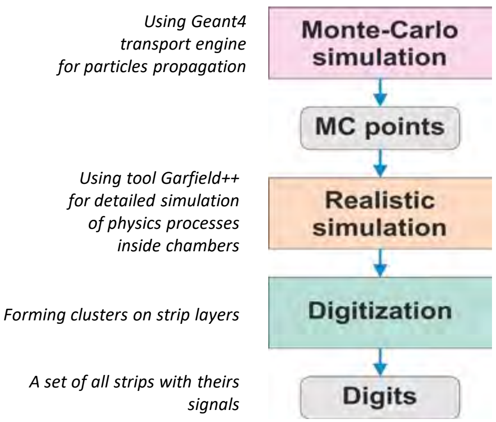
gas mixture: 3 mm + 3 mm = **6 mm**
copper: 35 µm + 35 µm + 35 µm + 35 µm = **140 µm**
fiberglass: 0.965 mm + 0.965 mm + 0.965 mm + 0.965 mm = **3.86 mm**
honeycomb: 10.5 mm + 10.5 mm = **21 mm**

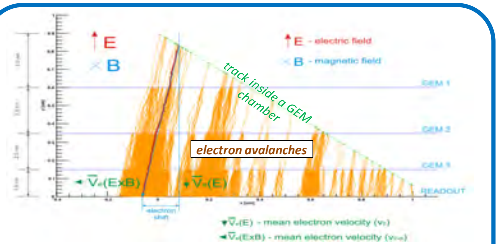
layer	material	density [g/cm-3]	thickness (X) [cm]	X0 [cm]	X/X0 [%]
gas mixture	ArC_4H_{10} (75/25)	0.002	0.76	11579.9	0.0066
copper	copper	8.96	0.014	1.435	0.9896
fiberglass	fiberglass	1.9	0.386	18.411	2.0977
honeycomb	nomex aramid honeycomb	0.048	2.1	755.397	0.2780

Properties of layers

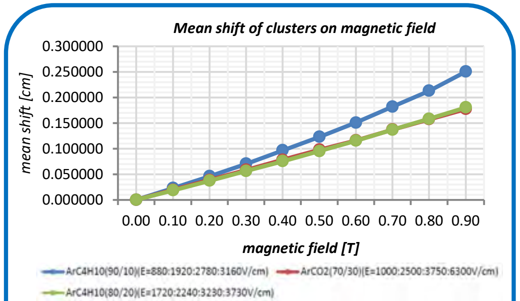
Tracking detectors: simulation

Stages of simulation for the BM@N tracking detectors:



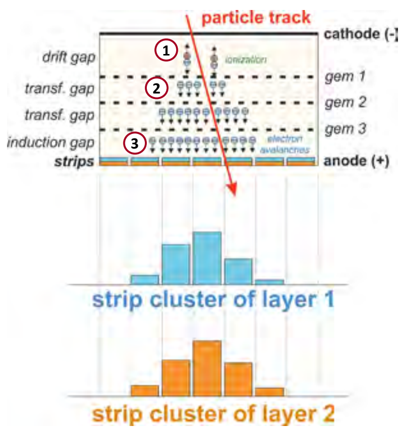


Example of detailed simulation of one particle inside a GEM chamber using ***Garfield++***



Example of dependency of mean cluster shift on magnetic field for various gas mixtures in a GEM chamber (from Garfield++)

Signal formation on readout layers (strips) in various types of the tracking detectors:

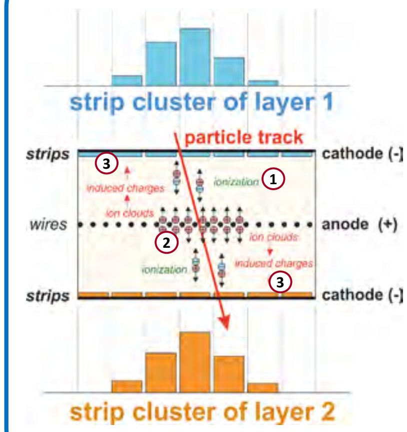


Signal formation in a GEM chamber:

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 each strip layer.

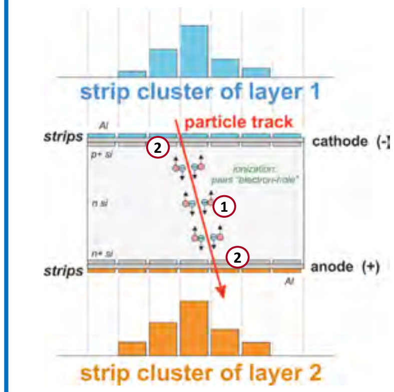


Signal formation in a Cathode Strip chamber:

1. When a particle passes through the active gas volume of the detector, it produces ionization (electron-ion pairs) along its trajectory.

2. Primary electrons drift towards the nearest anode wire, where avalanche take place. The resulting ion cloud induces a charge distribution on the cathodes close to the avalanche location by capacitive coupling.

3. Strips are used to sample the charge induced on the cathode planes. The relative values of the induced charges on the strips determine the position of the charged particle passing through the detector.



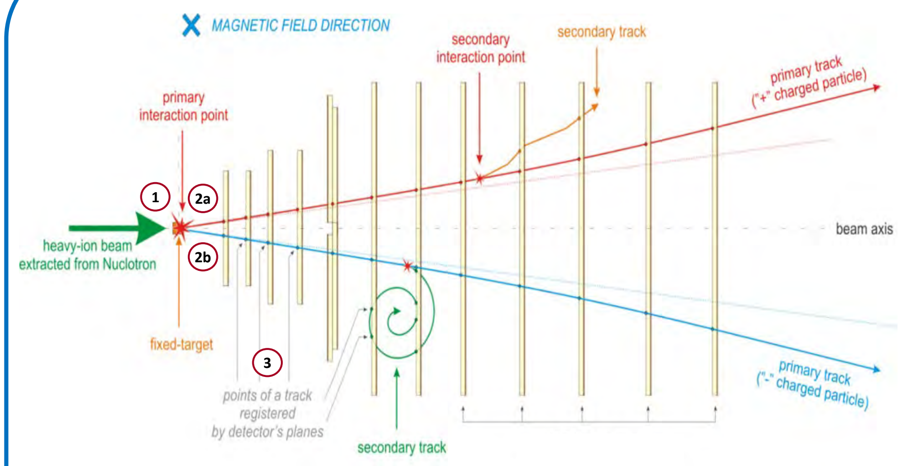
Signal formation in a Silicon module:

1. A particle, passing through the detector medium, produces electron-hole pairs.

2. Then mobile carriers (electrons and holes) drift to the electrodes, generating a current signal on the readout planes.

Tracking detectors: hit reconstruction

Scheme of registering particles by planes of tracking detector:

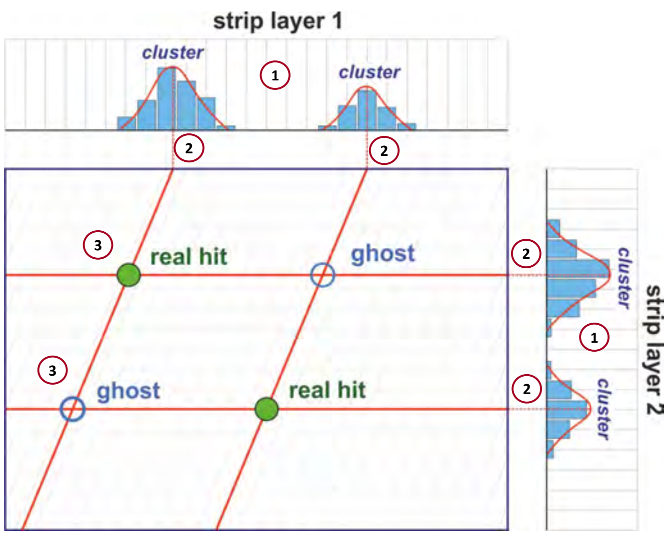


1. A heavy-ion beam, extracted from Nuclotron, collides with a fixed target.

2. As a result of this primary interaction is various particles. Their flying directions depend on their charge and a magnetic field which the detector located in (due to the Lorentz force).

3. Passing through the detecting planes, a particle leaves a "trace" (signal) on each of them. Our purpose is to reconstruct a spatial point, called "hit", which this particle passed through. A set of these hits from one particle defines its trajectory.

Hit reconstruction procedure for micro-strip readout:



1. There is a set of digits for one event (signals on strips for each layer). We find clusters of strips and estimate their parameters.

2. We find weighted position of each cluster to collapse lighted strips into one average-weighted strip.

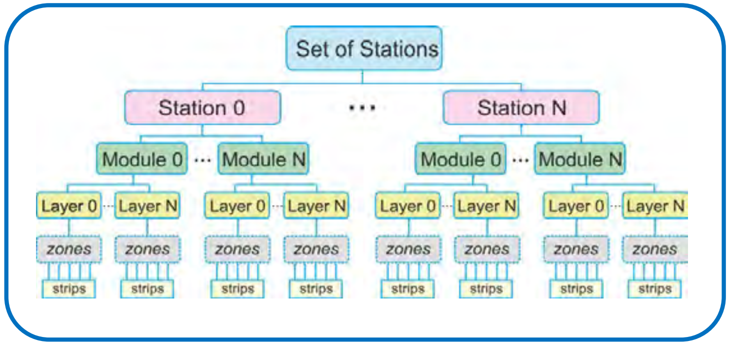
3. Crossing these strips of one layer with another, we get intersections, where one part of them are hits from real particles and another – "ghosts"

4. The obtained hits are used in the subsequent track finding procedures which find tracks and eliminate ghost hits.

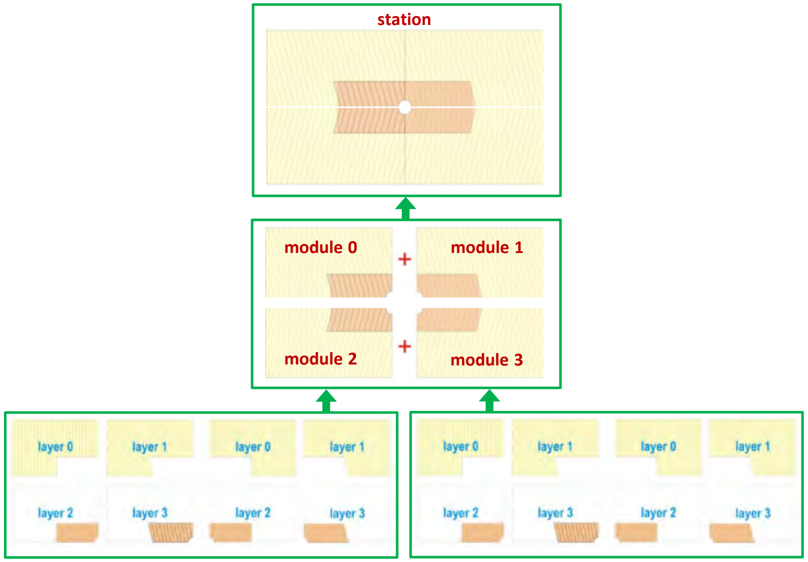
Tracking detectors: software structure

All the tracking detectors have the same hierarchical structure, where:

Strips are integrated into a layer,
Layers – into a module,
Modules – into a stations,
Stations – into a set of stations

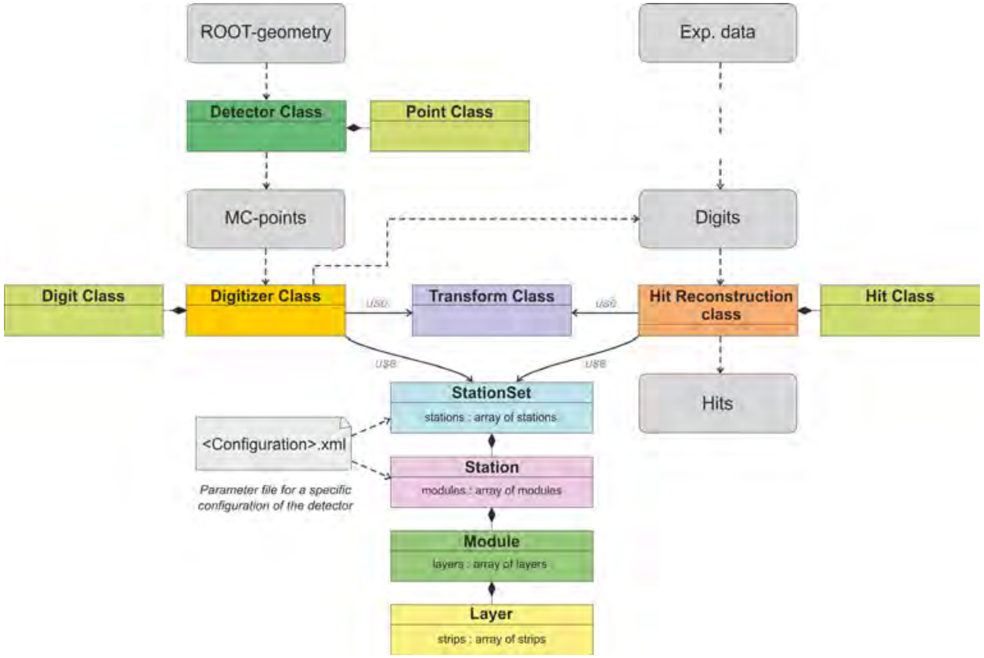


Program structure of a tracking detector



Example: structure of a GEM chamber

Program description of the tracking detectors for the next BM@N RUN-8, including Monte-Carlo and hit reconstruction procedures have been implemented in the BmnRoot framework and are ready to be used.



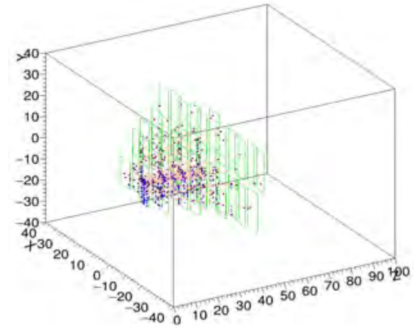
Structure of software for the tracking detectors (class diagram)

Conclusion: what has been done

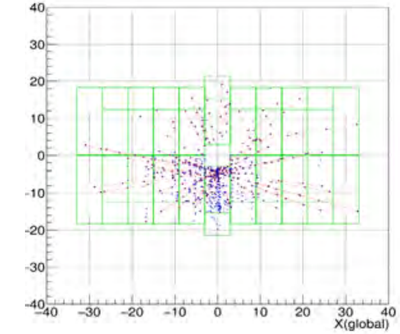
There are what we have done for the tracking detectors (RUN-8 configuration) at this moment:

- ✓ Full geometry description (basic and detailed versions for each detector)
- ✓ Algorithm for realistic Monte-Carlo simulations
- ✓ Algorithm for the reconstruction of spatial coordinates from micro-strip readout planes (hit reconstruction)

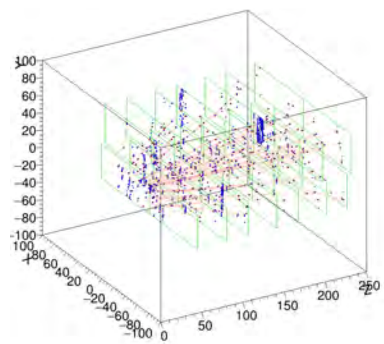
Example of a single event as a results of Monte-Carlo simulation and hit reconstruction for the three tracking detectors



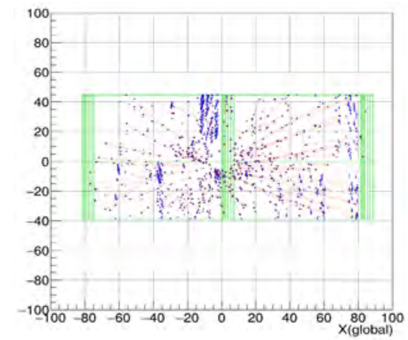
Forward Silicon *detector (3D view)*



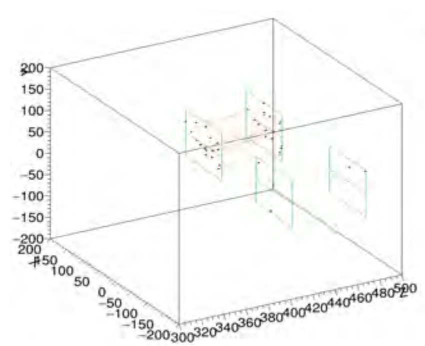
Forward Silicon *detector (XY view)*



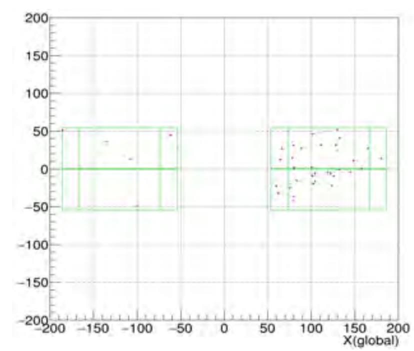
GEM *detector (3D view)*



GEM *detector (XY view)*



CSC *detector (3D view)*



CSC *detector (XY view)*

In the pictures:
Red marks are MC- points;
Blue marks are reconstructed hits;
Green rectangles are borders of sens. areas

Thank you for your attention…