Detailed simulation of inner tracker for the first physics run in the BM@N experiment

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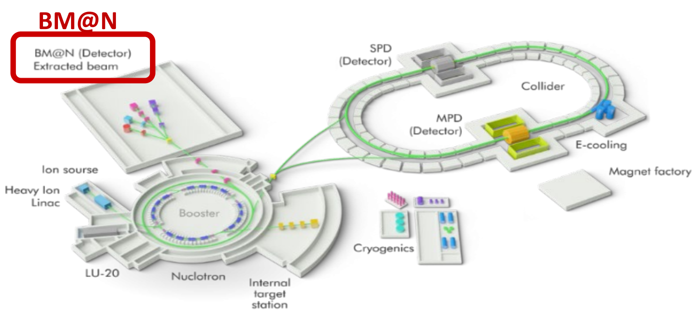
BM@N experiment

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, **eight 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 (2023)
beam: Ar, Xe; target: CsI

The detector setup of BM@N

Tracking system

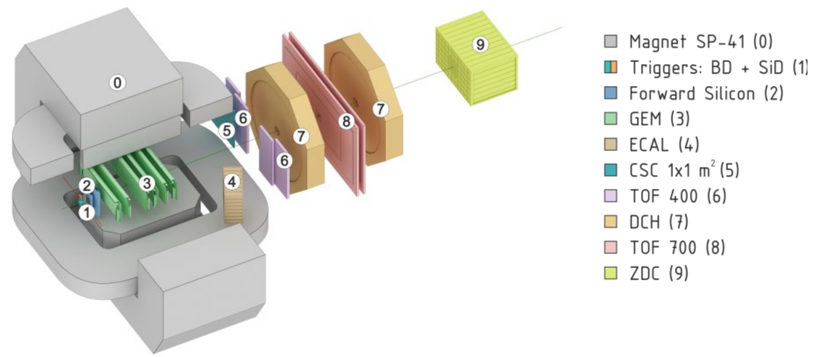
- **SiBT** (*Silicon Beam Tracker*)
- **FSD** (*Forward Silicon Detector*)
- **GEM** (*Gas Electron Multipliers*)
- **CSC** (*Cathode Strip Chambers*)
- **DCH** (*Drift Chambers*)

Particle identification system

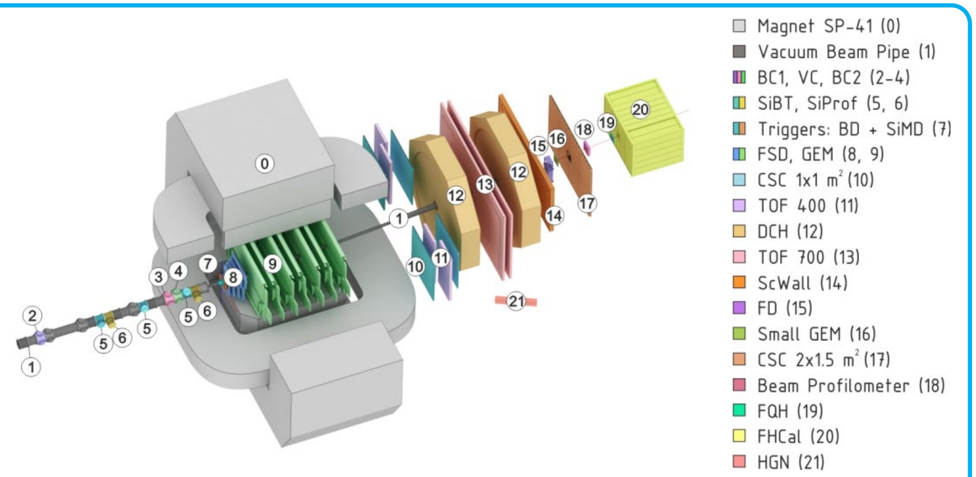
- **TOF400** (*1st Time-of-Flight detector*)
- **TOF700** (*2nd Time-of-Flight detector*)

Other detector systems

- **Triggers system**
- **FQH** (*Forward Quartz Hodoscope*)
- **ScWall** (*Scintillator Wall*)
- **FHCal** (*Fwd. Hadron Calorimeter*)
- **HGN** (*High Granularity Neutron*)



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

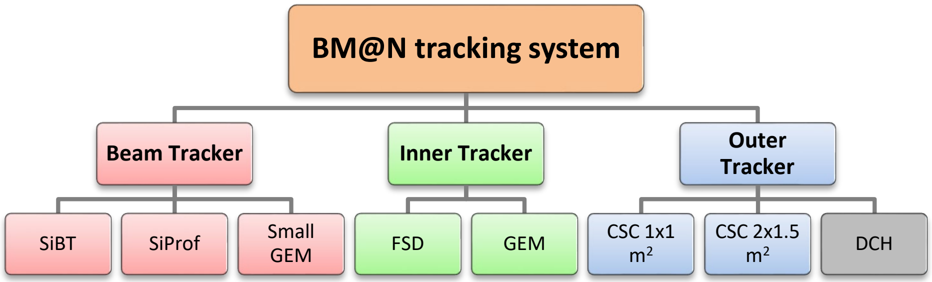


*BM@N setup for the latest **RUN-8** configuration (winter 2023)*

BM@N tracking system

BM@N tracking system consists of high-precision coordinate detectors for charged particle track registration.

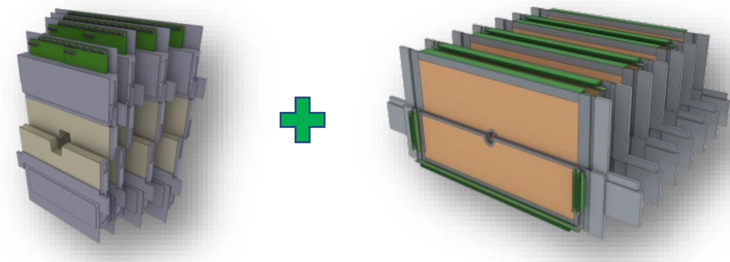
The tracking system is subdivided into three parts: **beam tracker**, **inner tracker** and **outer tracker**. The beam tracker includes detectors located inside the vacuum pipe to monitor and track the ion-beam. The inner tracker comprises detectors located inside the magnet, the outer – outside

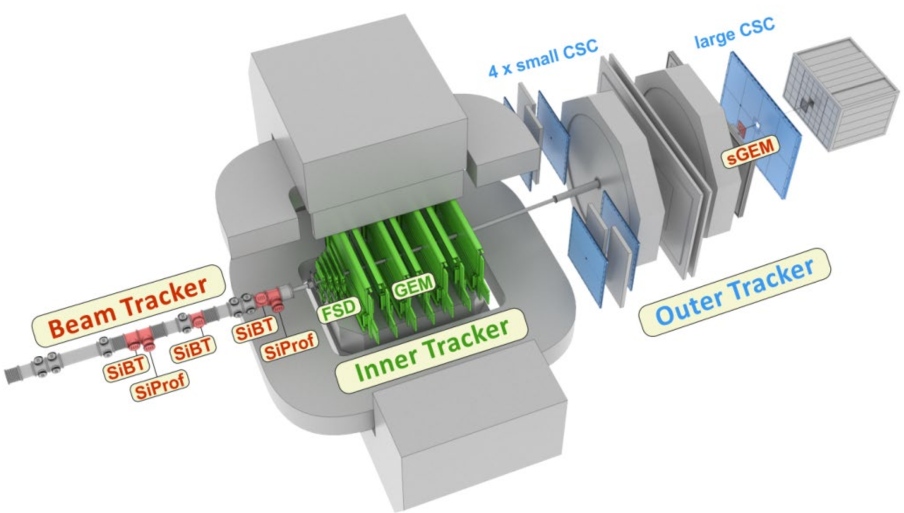


Inner tracker

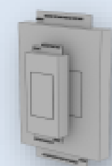
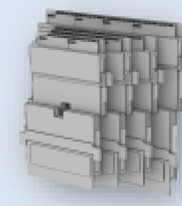
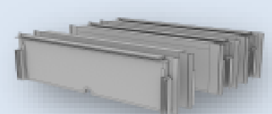
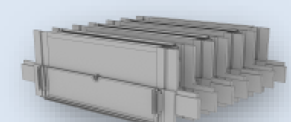
Inner tracker:

- **FSD (Forward Silicon Detector)** : 8 half-planes
- **GEM (Gas Electron Multipliers)** : 14 half-planes

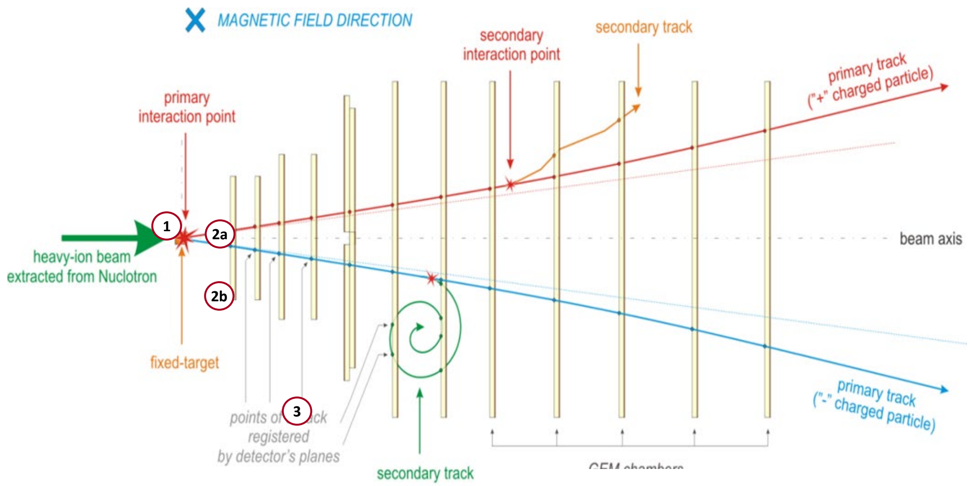




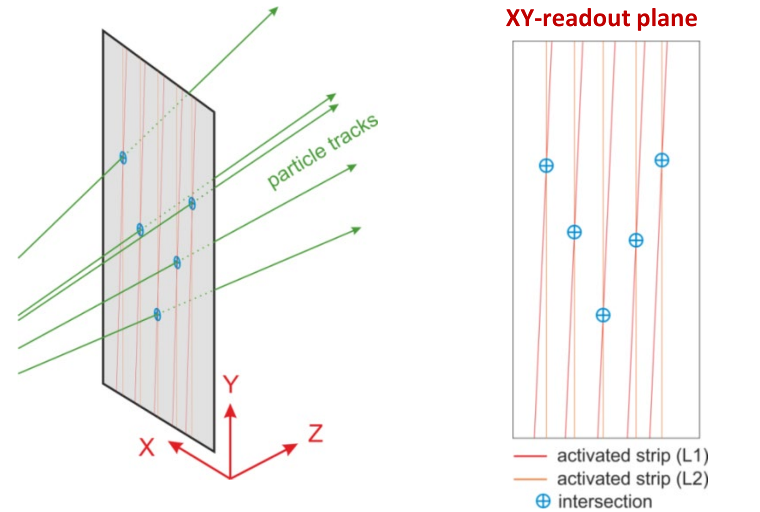
BM@N tracking system for RUN-8

Detector	RUN-7	RUN-8
FSD	 **2 stations** (14 Si-modules)	 **4 stations** (48 Si-modules)
GEM	 **6 stations** (6 half-planes)	 **7 stations** (14 half-planes)

Microstrip tracking detectors: particle registration



Scheme of particle track registration by planes of tracking detectors

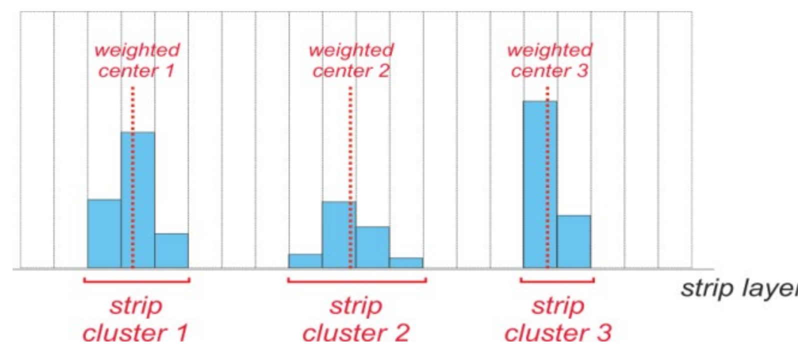


Tracking detectors in the BM@N setup (RUN-8) have two-coordinate microstrip readout. In order to reconstruct XY-coordinates the strips of one layer are rotated by certain angle with respect to another layer

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).

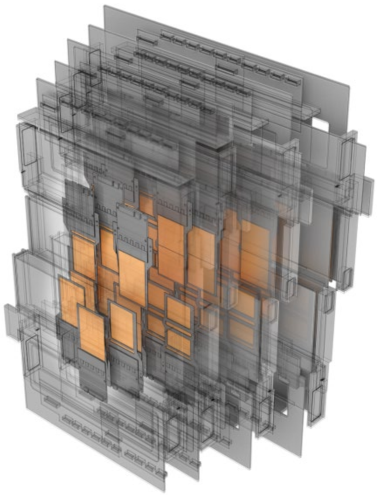
3. Passing through the detector planes, a particle leaves a "trace" (response) on each of them. The main goal is to reconstruct a spatial coordinates, called "hit", which the particle passed through. A set of these hits on different planes from one particle defines its trajectory.



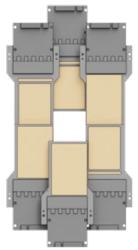
Each readout layer consists of a set of strips. The response from a passing particle is represented by one or several fired strips (on each layer) that form a cluster (group of fired strips from one particle).

Forward Silicon Detector

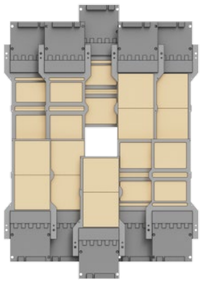
Forward Silicon Detector (FSD) is a high-precision coordinate detector of the inner tracking system in the BM@N setup. It consists of a set of microstrip silicon modules which are assembled into 4 stations.



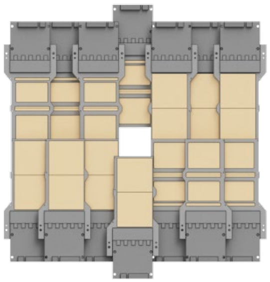
Silicon stations



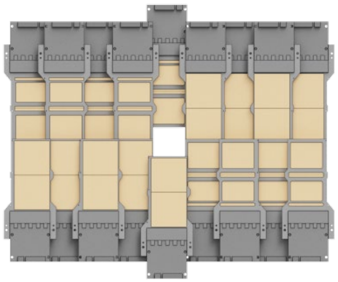
***Station 1*:**
6 modules of 63x93 mm^2



***Station 2*:**
10 modules of 63x126 mm^2

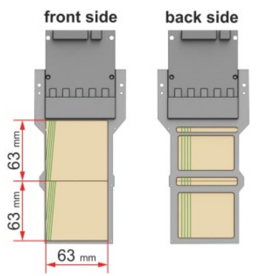


***Station 3*:**
14 modules of 63x126 mm^2

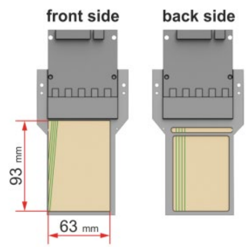


***Station 4*:**
14 modules of 63x126 mm^2

Silicon module types



Si-module
with two double-sided strip
*sensors of **63x63** mm^2 each*

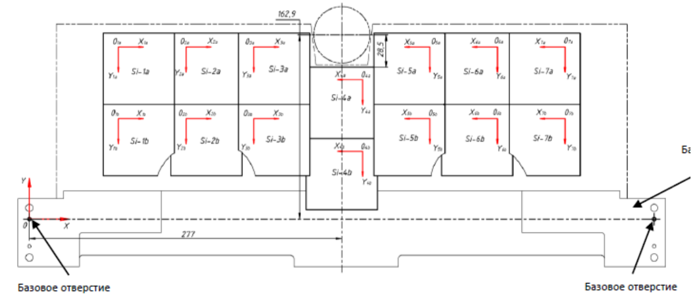


Si-module
with one double-sided strip
*sensor of **63x93** mm^2*

sensor thickness: **300 µm**
strip pitch: ≈ **100 µm**
stereo angle between strips: **2.5°**

Strip configuration in modules

The configuration of strips in each module is represented by the corresponding schemes



Положение Si-сенсоров в полуплоскости # 7/1 (17.03.22)

Позиция сенсора	X±0.02* (мм)	Y±0.02* (мм)	Разворот в плоскости 0XY (град.)**	Z±0.2*** (мм)	Серийный номер модуля
Si-1a	65.59	164.17	0.05 пр. час.	27.7	#14
Si-1b	65.48	101.15	0.05 пр. час.	27.6	
Si-2a	125.53	164.26	0.06 пр. час.	15.8	#36
Si-2b	125.57	101.28	0.05 пр. час.	15.6	
Si-3a	185.55	164.18	0.07 пр. час.	27.6	#9
Si-3b	185.57	101.18	0.06 пр. час.	27.5	
Si-4a	308.56	134.28	0.03 по час.	13.9	#33
Si-4b	308.47	71.31	0.03 пр. час.	13.9	

Позиция сенсора	X±0.02* (мм)	Y±0.02* (мм)	Разворот в плоскости 0XY (град.)**	Z±0.2*** (мм)	Серийный номер модуля
Si-5a	368.61	164.27	0.02 по час.	25.4	#30
Si-5b	368.53	101.27	0	25.9	
Si-6a	428.63	164.26	0.02 по час.	14.2	#15
Si-6b	428.55	101.27	0.01 по час.	14.0	
Si-7a	488.77	164.20	0.08 по час.	25.6	#29
Si-7b	488.63	101.21	0.08 по час.	26.0	

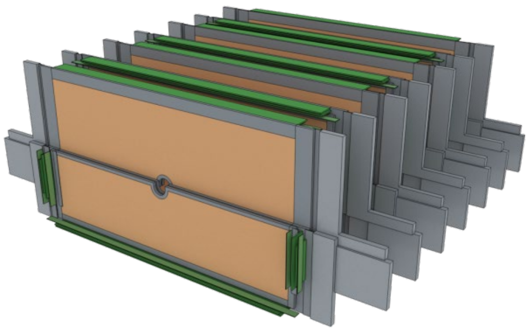
*-положение точки начала координат Si-сенсора в координатной плоскости 0XY (привязана к наружным базовым отверстиям).

Silicon sensors have specific positions in each module of a station. They were measured with a high precision microscope to be taken into account in the model of the detector

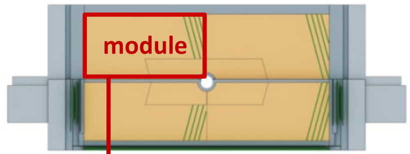
GEM detector

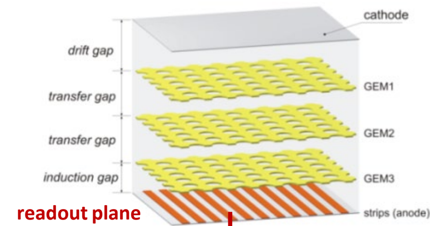
GEM (Gas Electron Multipliers) is a microstrip coordinate detectorof the central tracker in the BM@N setup. It consists of gaseous chambers with electron multiplier system inside.

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



Microstrip readout





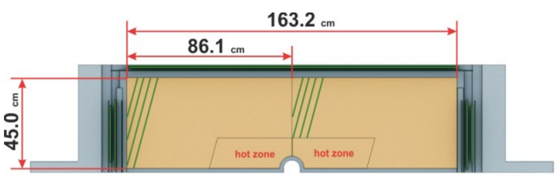
The detector chamber used in BM@N has three cascaded GEM foils, separated by gas gaps, and a two-dimensional projective readout on anode strips

Readout plane of each module in a GEM station is formed by two sets of anode strips (layers): straight and inclined

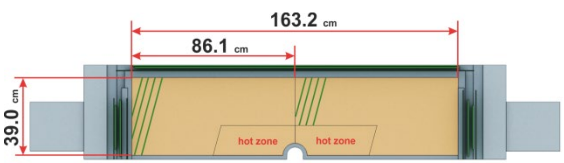
Layer of straight strips — *Layer of inclined strips* — *2D strip readout plane*

Gas volume thickness: **9 mm**
strip pitch: **800 µm**
stereo angle between strips: **15°**

GEM chamber types

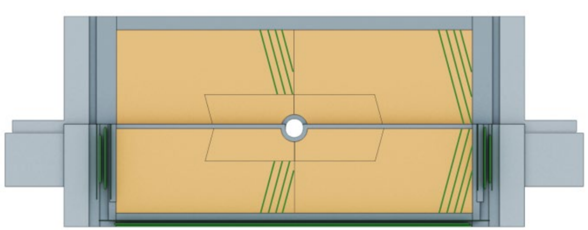


Upper half-plane

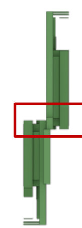


Lower half-plane

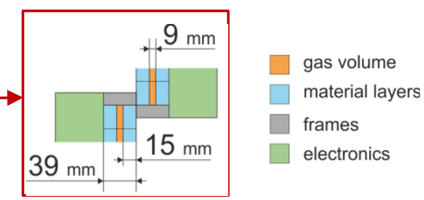
GEM station assembly



1st GEM station (front view)



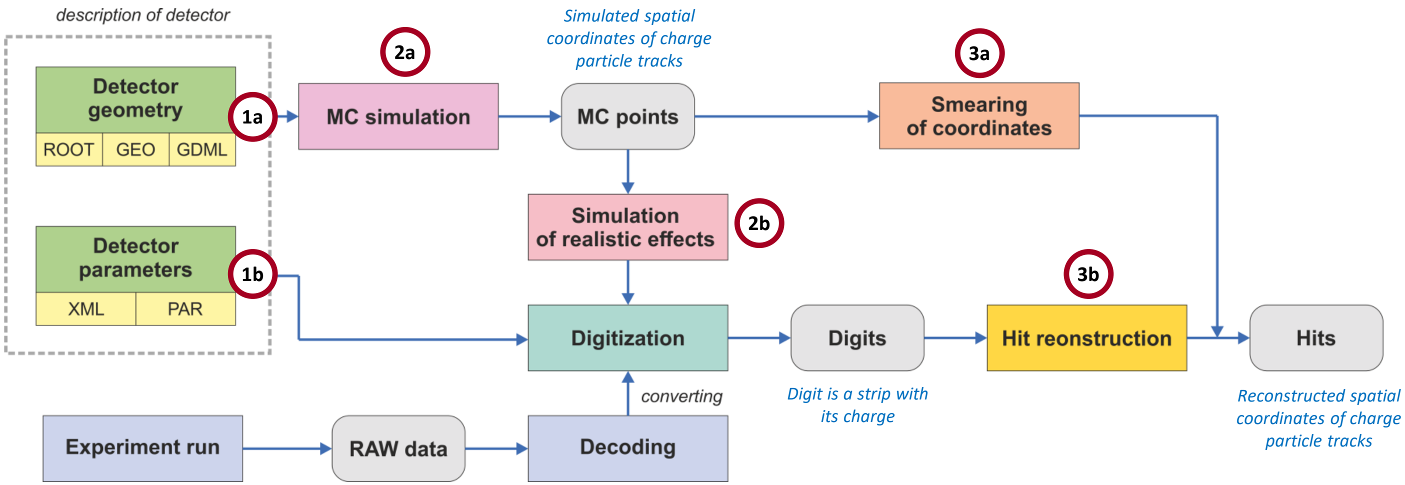
1st GEM station (side view)



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

Simulation stages for tracking detectors

Data processing in BMNROOT



The **BMNROOT** framework is the official software developed for simulation, reconstruction and data analysis in the BM@N experiment

Stages of data processing for microstrip tracking detectors in BMNROOT

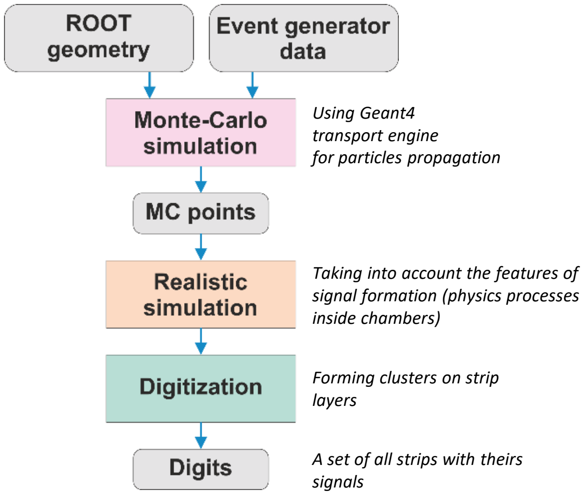
Stages of data processing

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

Simulation steps

Simulation for tracking detectors consists of the steps:

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)



ROOT geometry for tracking detectors

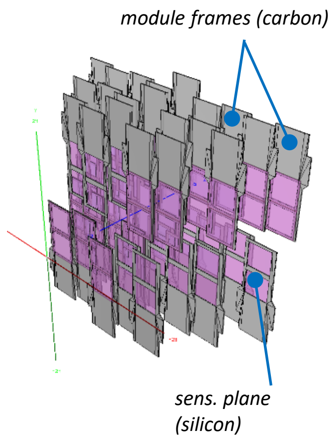
What ROOT geometry is

***.ROOT** – is a specific format developed for the ROOT data analysis framework which stores arrays of data and describes their structure, including the description of detector geometry.

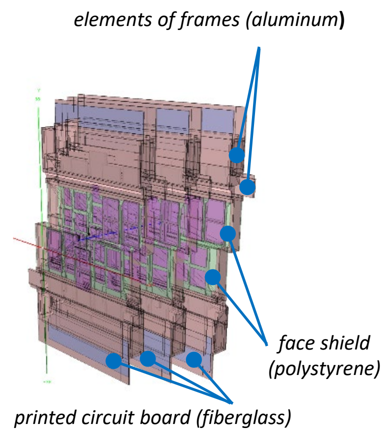
Detector geometry describes physical dimensions of detector elements, their hierarchical structure and media that are need for Geant4 transport engine to propagate the charge particles through matter.

ROOT geometry of FSD detector

There are two versions of the ROOT geometry for MC-simulation: basic and detailed. The **basic geometry** consists of only sensor elements. The **detailed geometry** completely describes the detector including passive elements such as electronics, housing and supporting components.



Basic ROOT geometry of the FSD detector



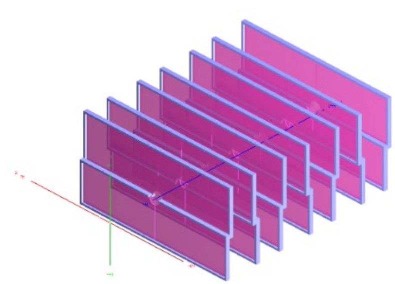
Detailed ROOT geometry of the FSD detector

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.

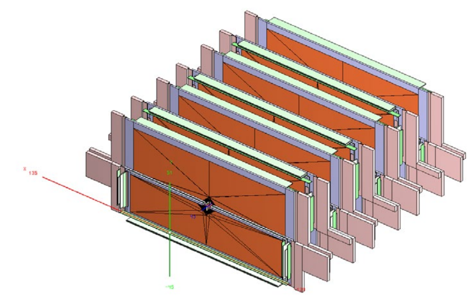
ROOT geometry of GEM detector

The GEM detector has also two versions of geometry:

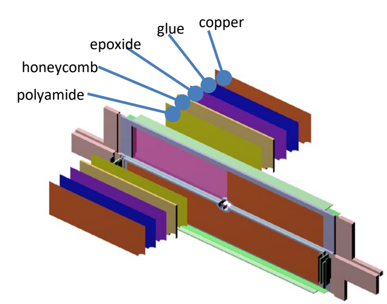
- **Basic ROOT geometry** comprises 14 sensitive volumes with simplified frames around each one.
- **Detailed ROOT geometry** completely describes the detector including passive elements such as electronics, housing and supporting components.



Basic ROOT geometry of the GEM detector



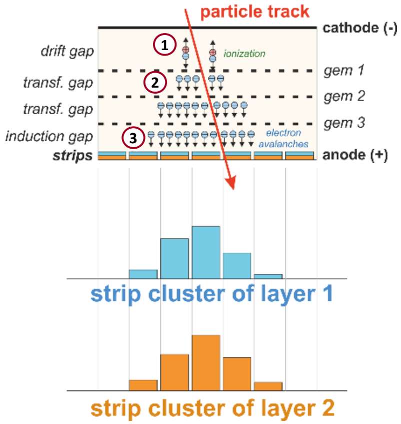
Detailed ROOT geometry of the GEM detector



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.

Detailed simulation of GEM detector

Operation principle



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.

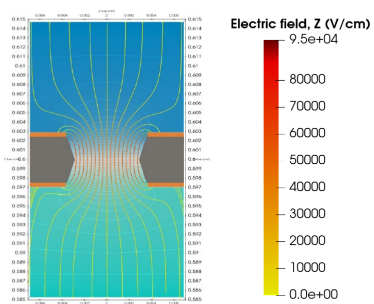
2. Primary electrons, passing through amplifying GEM cascades, gain their kinetic energy and enable secondary ionization. As a result of it is a lot of secondary electrons (electron avalanches). Amplification is about $10^4 - 10^5$.

3. Being collected on the anode, electrons form **clusters on each strip layer**.

Auxiliary tools for detailed simulation

Because the triple GEM detector has complex structure and complicated signal formation, **auxiliary tools** were used for detailed simulation of physics processes in gas chambers.

To take into account electromagnetic field in simulation we used **GMSH** and **ELMER** tools for calculation of required fields:

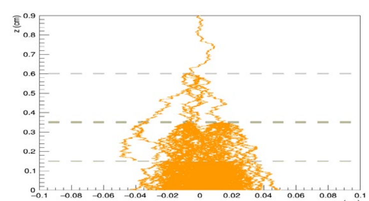


Example of calculated field for one GEM cell: equipotential and electric field lines (GEM hole, GEM1 = 0.6 cm)

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

Physics processes steps:

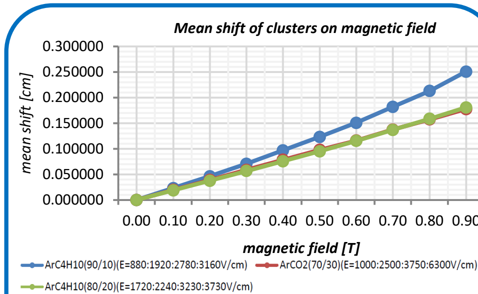
1. Gas ionization by a charged particle.
2. Electron drift to an anode readout (under electric and magnetic fields)
3. Electron avalanches production (as result of multiplication in GEM holes)
4. Electron shift (under the Lorentz force influence in mag. field)



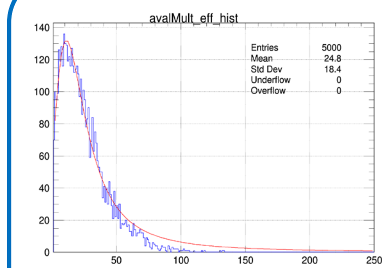
Electron avalanche production in our triple GEM

Detailed simulation procedure in BMNROOT

Based on obtained distributions and dependencies (from auxiliary tools) required for realistic simulation, the algorithm was developed to simulate the digits (signals on strips)



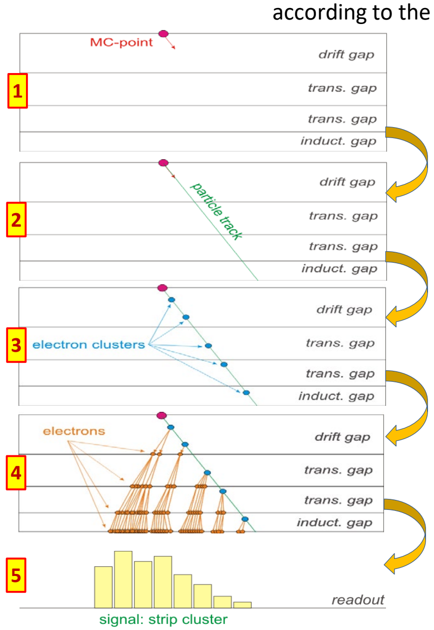
Example of dependency of mean cluster shift on magnetic field for various gas mixtures in a GEM chamber (from Garfield++)



Example of distribution of produced electrons that form a signal

Detailed simulation steps:

The characteristics obtained from Garfield++ allow us to build a data acquisition model according to the following scheme:



1. Based on the information extracted from the MC-point obtained by using the Geant4 simulation, we have parameters such as: coordinates of the particle entry into the GEM chamber; momentum of the particle, its type and direction

2. We determine the track of the particle in the volume of chamber (a line from the entry point of the particle to its exit)

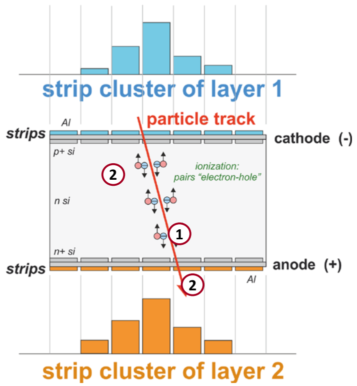
3. Based on the ionization characteristics obtained in Garfield++, we determine positions of primary interaction clusters

4. Based on the distributions of the mean shift and diffusion of electrons, we genrate the distribution of electron avalanches on the readout plane (on the strips)

5. Result: **clusters on the strips**

Detailed simulation of FSD detector

Operation principle



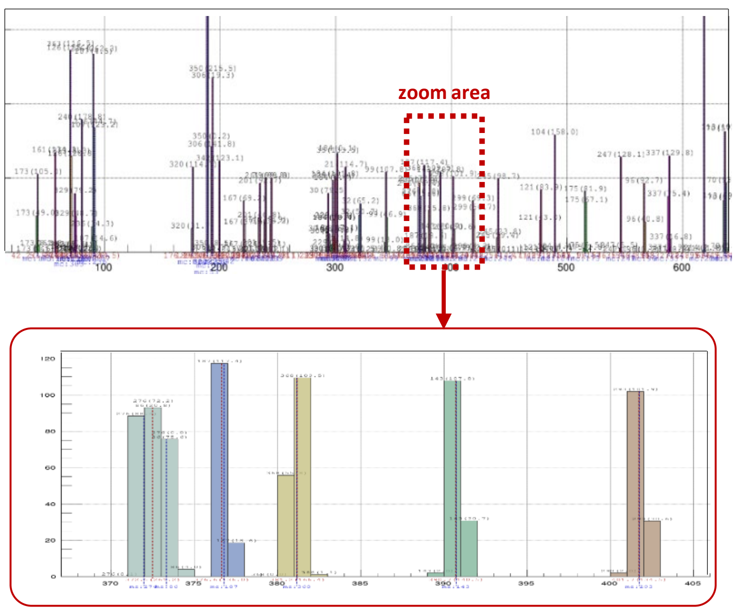
Signal formation in a silicon module:

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

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

Clusters on the silicon strip readout

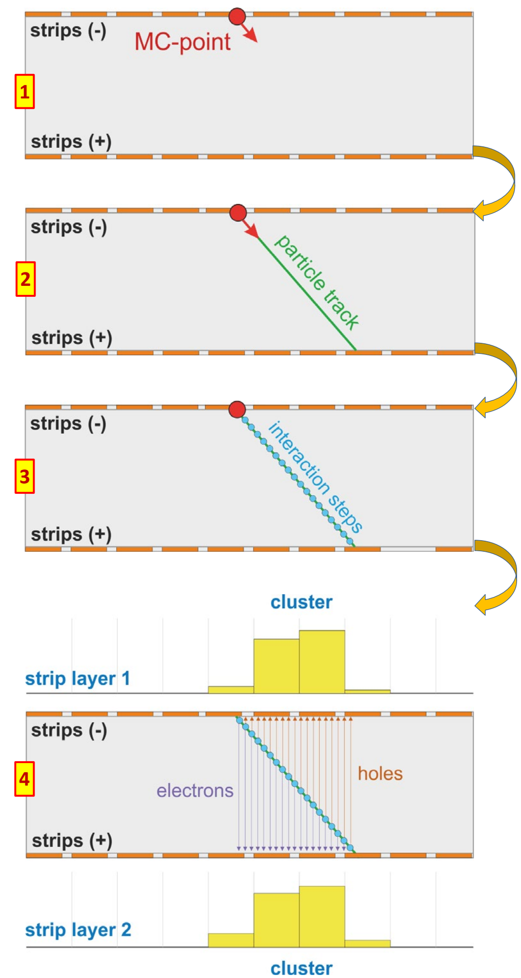
Example: A set of clusters of the strip layer in one module of the FSD detector on experimental data (RUN-8: Xe beam with CsI target)



Detailed simulation procedure in BMNROOT

The signal formation on strips in a silicon detector doesn't has amplification effects (in comparison with a triple GEM chamber). The main signal is formed due to charged carriers (electron and holes) produced as a result of primary impact ionization.

Steps of the detailed simulation algorithm:



1. Based on the information extracted from the MC-point obtained by using the Geant4 simulation, we have parameters such as: coordinates of the particle entry into the Silicon module; momentum of the particle, energy loss, its type and direction

2. We determine the track of the particle in the volume of module (a line from the entry point of the particle to its exit)

3. We set a certain step (1-10 μm) and divide the distance along the track into small segments

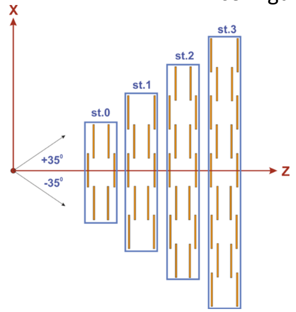
4. Based on the information from a MC-point about energy loss, we generate signal on the strips at each step

5. Result: **clusters on the strips**

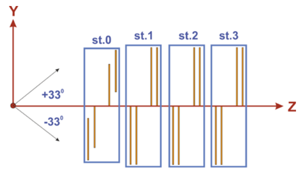
Data simulation for RUN-8

FSD detector

Using the developed algorithms, simulated data were prepared for the latest configuration of the track detectors.

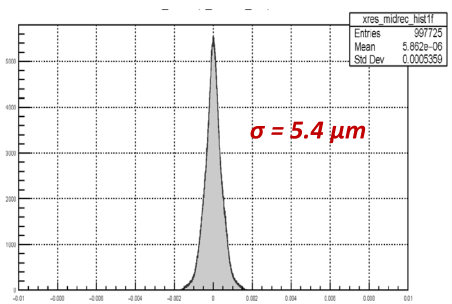


Acceptance angle X of FSD detector

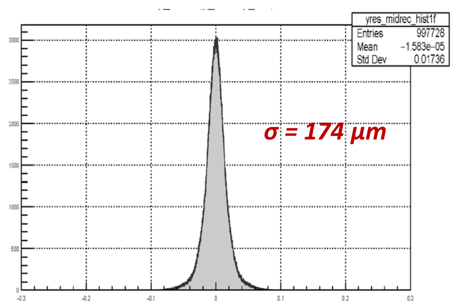


Acceptance angle Y of FSD detector

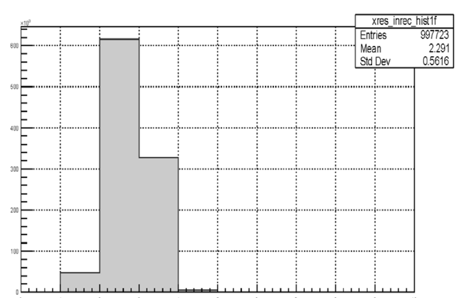
The distributions below have been obtained for the MC-tracks which can be detected in according with the acceptance angles of the first station



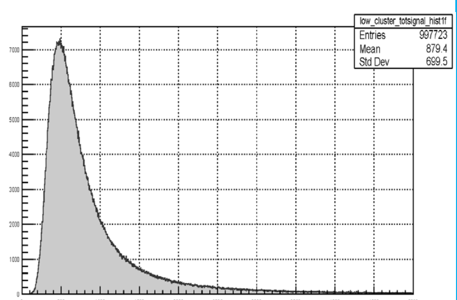
X residuals between simulated and real coordinates



Y residuals between simulated and real coordinates

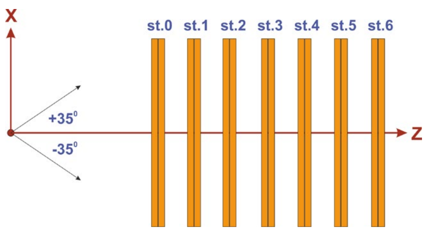


Distribution of cluster size

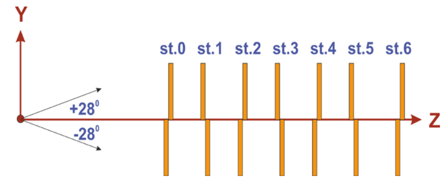


Signal distribution of clusters

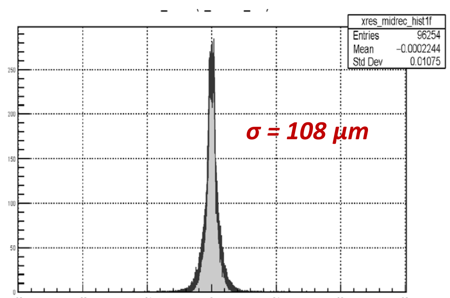
GEM detector



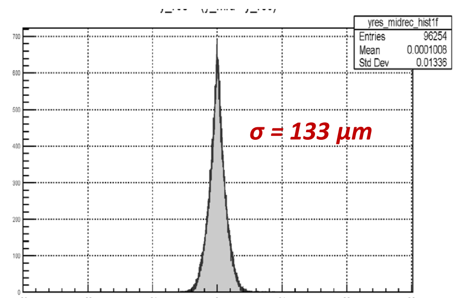
Acceptance angle X of GEM detector



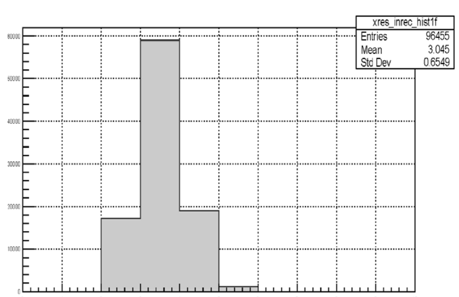
Acceptance angle Y of GEM detector



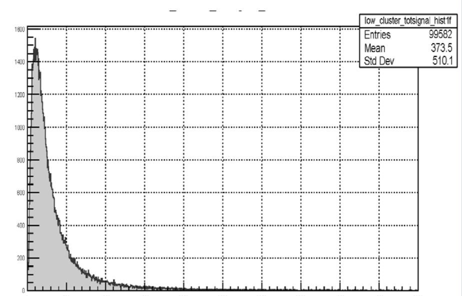
X residuals between simulated and real coordinates



Y residuals between simulated and real coordinates



Distribution of cluster size

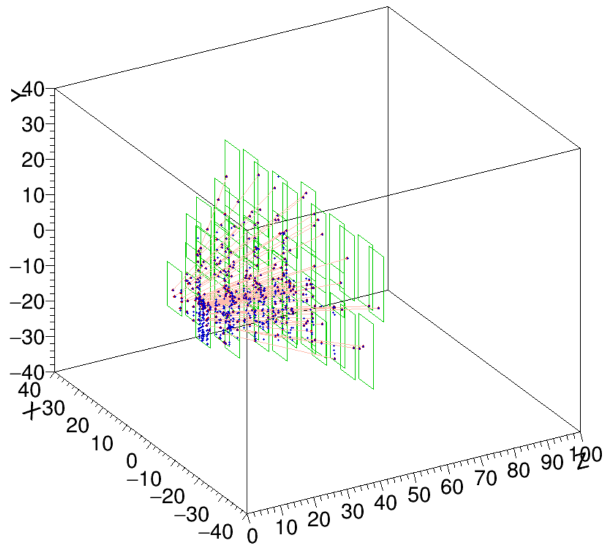


Signal distribution of clusters

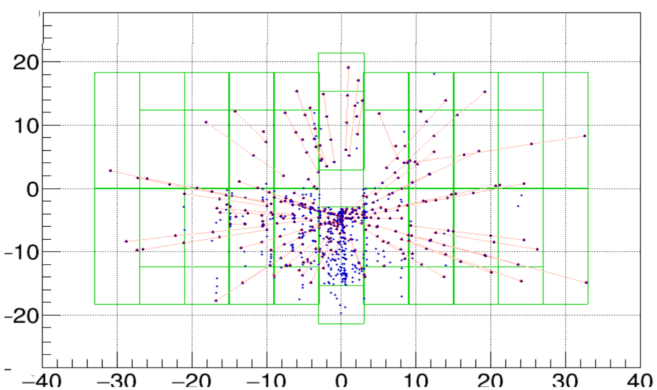
Data simulation and reconstruction for RUN-8

FSD detector

Examples of data simulation and coordinate reconstruction for the FSD and GEM detectors in the BM@N experiment for RUN-8 configuration



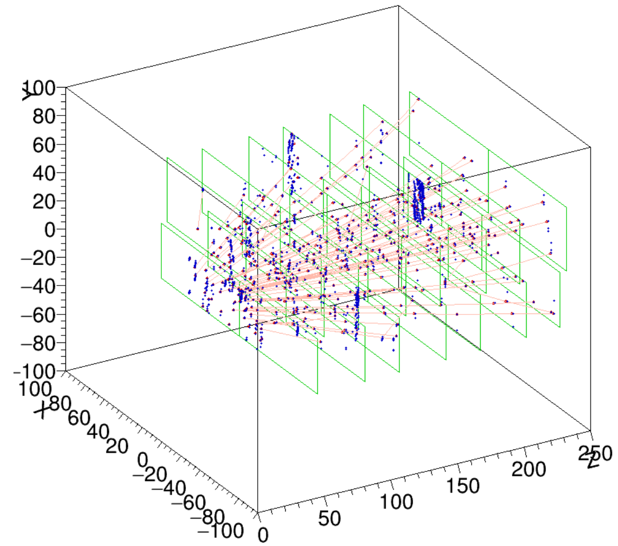
Forward Silicon *detector (3D view)*



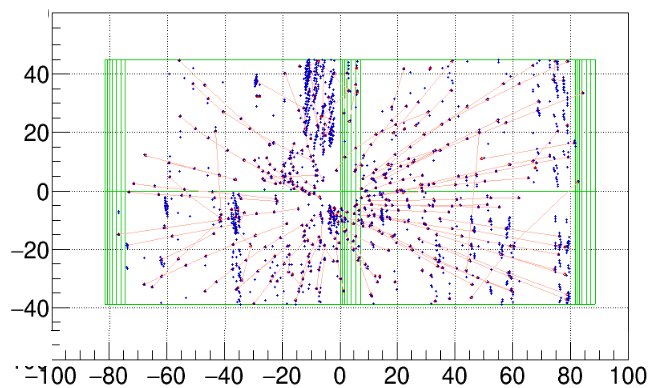
Forward Silicon *detector (XY view)*

● MC points ● Reconstructed hits

GEM detector



GEM *detector (3D view)*



GEM *detector (XY view)*

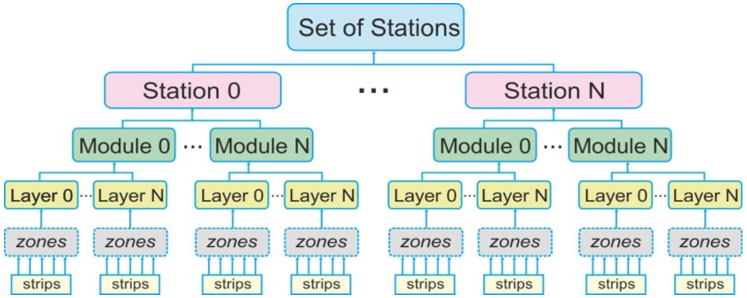
● MC points ● Reconstructed hits

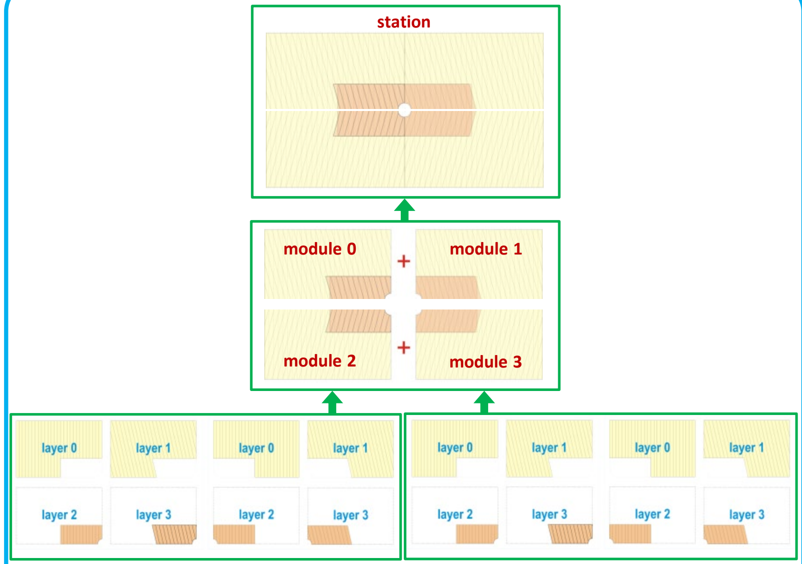
Microstrip tracking detectors: software implementation

Structure of inner tracking detectors

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

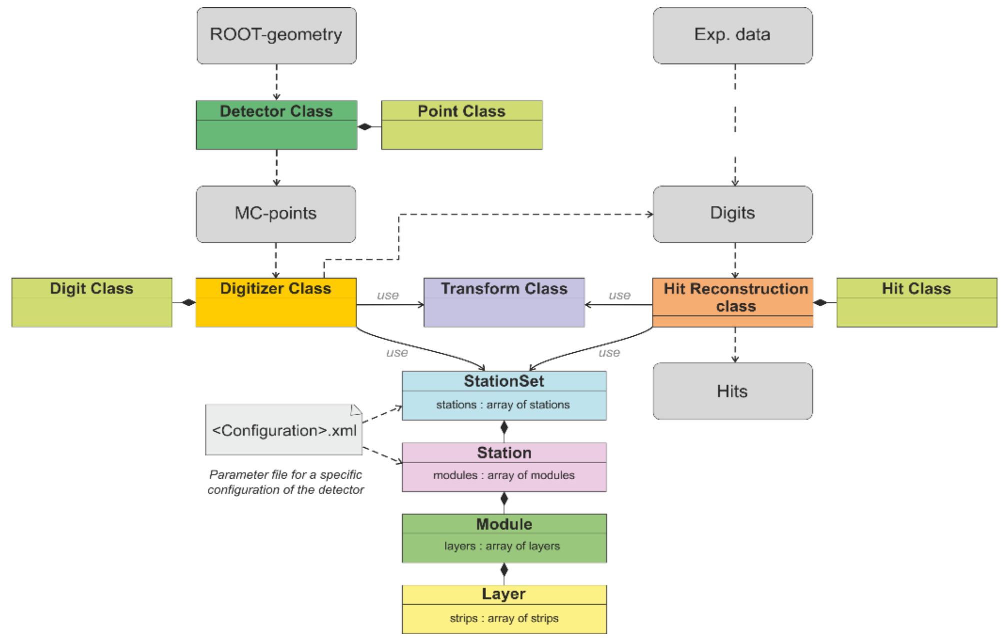
Strips are integrated into a layer,
Layers – into a module,
Modules – into a stations,
Stations – into a set of stations





Visual example of the structure of one GEM chamber

Software implementation



Software structure for the microstrip detectors of inner tracking system (as a class diagram)

Summary

What has been reviewed:

- Software for detailed simulation of inner tracking detectors (BM@N RUN-8 configuration):
  - Forward Silicon Detector
  - GEM detector

Thank you for your attention…