Realistic simulation of central tracker detectors in the BM@N experiment

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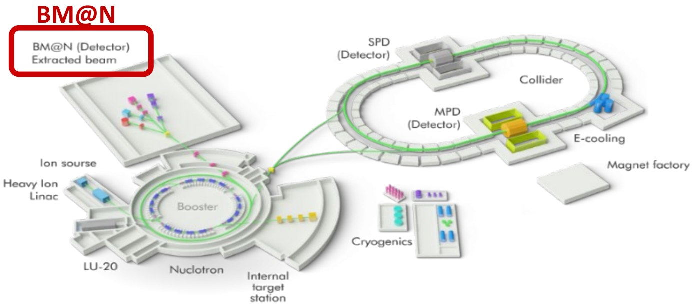
BM@N experiment

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: Xe; target: CsI

The detector setup of BM@N

Tracking system

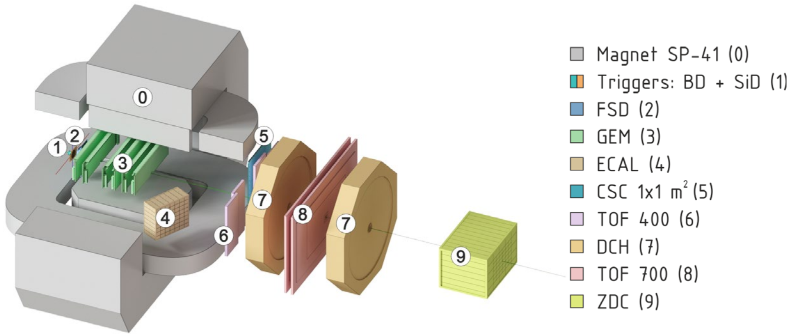
- **SiBT** (*Silicon Beam Tracker*)
- **FSD** (*Forward Silicon Detector*)
- **GEM** (*Gas Electron Multipliers*)
- **CSC** (*Cathode Strip Chambers*)
- **DCH** (*Drift Chambers*)

Particle identification system

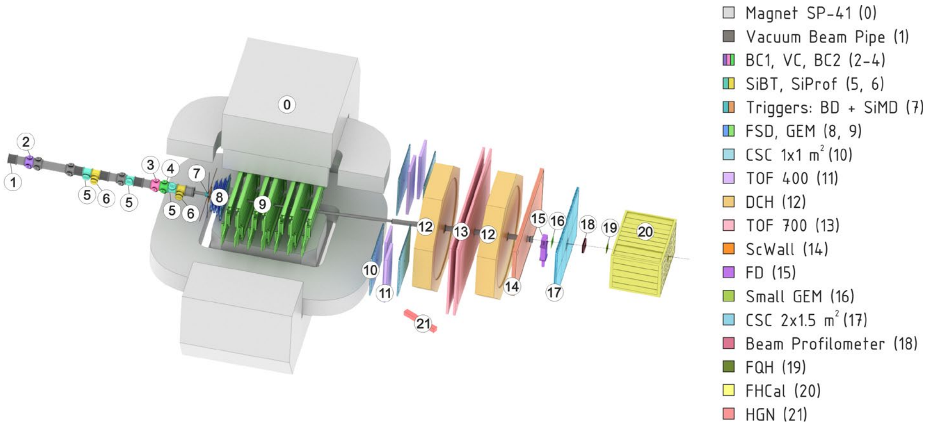
- **TOF400** (*1st Time-of-Flight detector*)
- **TOF700** (*2nd Time-of-Flight detector*)

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)*

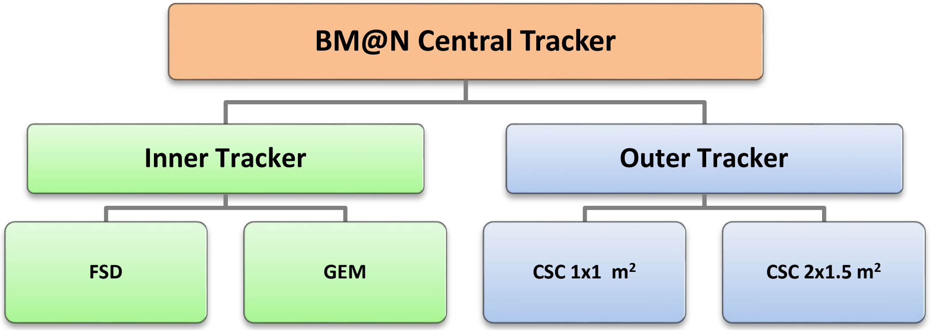


*BM@N setup for the latest **RUN-8** configuration (the beginning of 2023)*

BM@N central tracker

BM@N central tracker consists of high-precision microstrip coordinate detectors for charged particle track registration.

The central tracker is subdivided into two parts: inner tracker and outer tracker. The inner tracker comprises detectors located inside the magnet, the outer – outside



BM@N Central Tracker

Inner Tracker

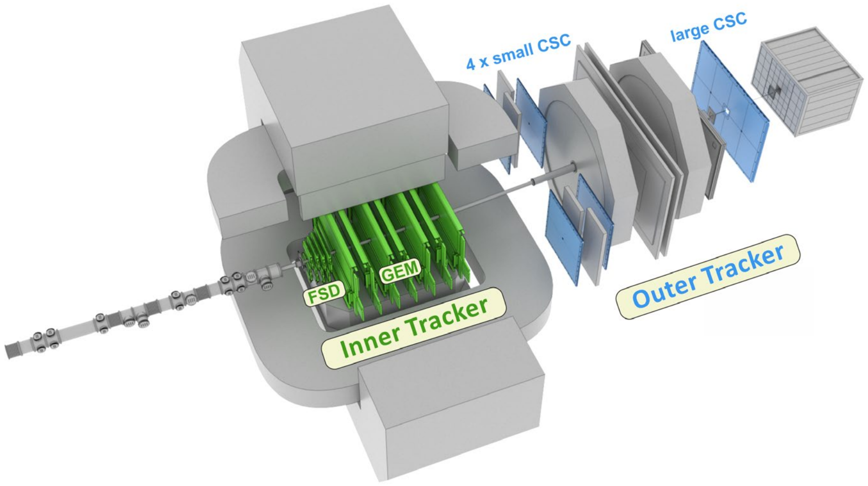
Outer Tracker

FSD

GEM

CSC 1x1 m^2

CSC 2x1.5 m^2



Microstrip detectors of the central tracker for RUN-8

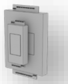
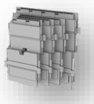
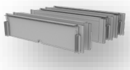
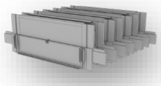
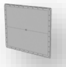
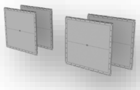
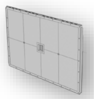
BM@N central tracker

Inner tracker:

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

Outer tracker:

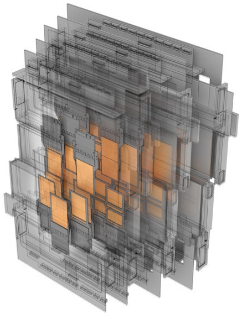
- ☐ **small CSC (Cathode Strip Chamber)** : 4 planes of 1x1 m^2
- ☐ **large CSC (Cathode Strip Chamber)** : 1 plane of 2x1.5 m^2

Detector	RUN-7	RUN-8	Features
FSD			**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)
small CSC			**RUN-7**: 1 chamber (1x1 m^2) **RUN-8**: 4 chambers (1x1 m^2)
large CSC	NONE		**RUN-7**: none **RUN-8**: 2 DCH + 1 large CSC (2x1.5 m^2)

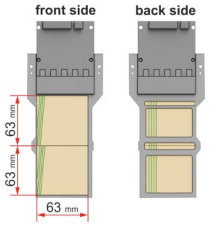
Central tracker detectors

FSD (Forward Silicon Detector)

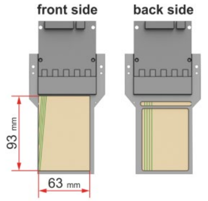
FSD is a high-precision coordinate detector of the inner tracking system in the BM@N setup. It consists of a set of microstrip silicon modules which are assembled into 4 stations.



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



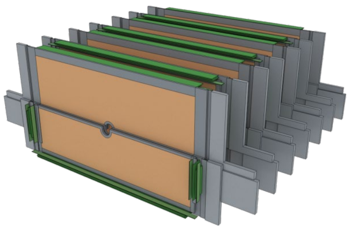
*Si-module with two double-sided strip sensors of **63x63** mm^2 each*



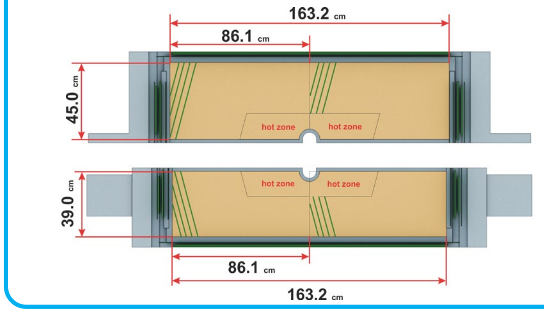
*Si-module with one double-sided strip sensor of **63x93** mm^2*

GEM (Gas Electron Multiplier)

GEM is a microstrip coordinate detector of the inner tracker. It consists of gaseous chambers with electron multiplier system inside.



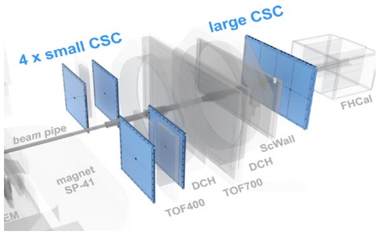
Each station is combined from two chambers: upper and lower, which are joined together to form a plane

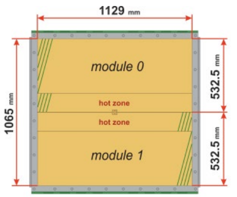


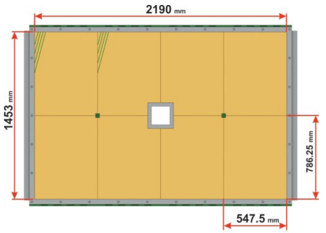
CSC (Cathode Strip Chamber)

CSC is a gaseous detector with microstrip readout. It belongs to the outer tracking system.

The configuration of this detector for RUN-8 consists of four small and one big stations located behind the magnet.

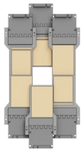






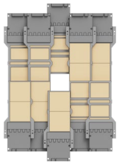
Configuration of FSD stations

Station 1



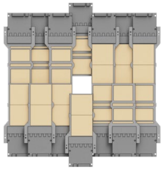
6 modules of 63x93 mm^2

Station 2



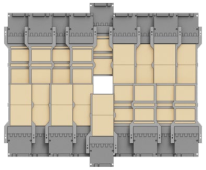
10 modules of 63x126 mm^2

Station 3



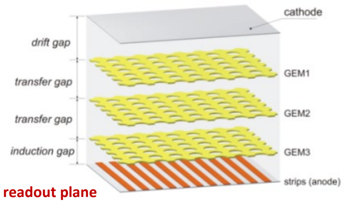
14 modules of 63x126 mm^2

Station 4



14 modules of 63x126 mm^2

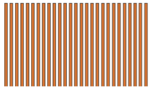
Triple GEM chambers



The GEM chamber has three cascaded GEM foils, separated by gas gaps, and a two-dimensional projective readout on anode strips

Readout plane is formed by two sets of anode strips (layers): straight and inclined

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

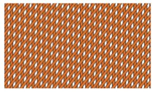


Layer of inclined strips

+

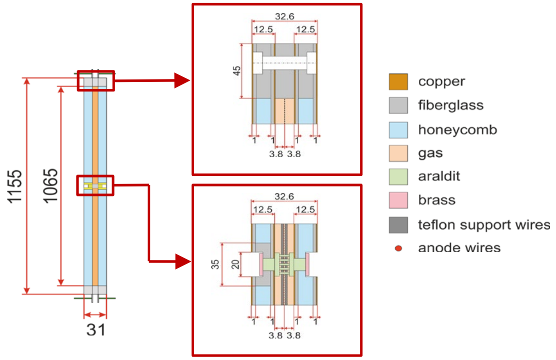
Layer of straight strips

=



2D strip readout plane

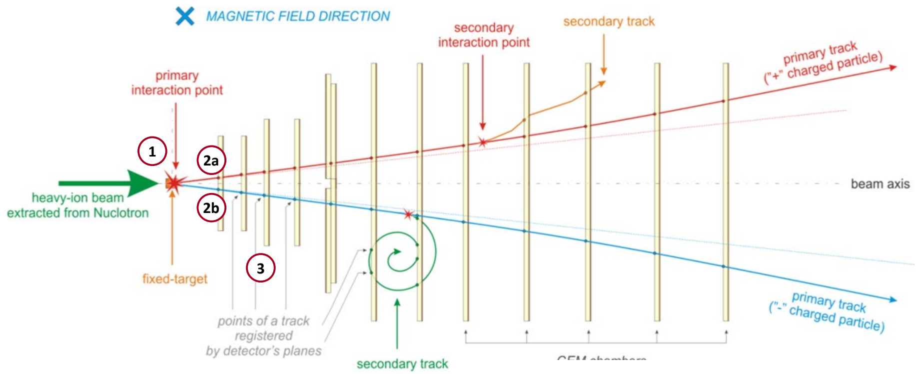
CSC chamber structure



gas volume thickness: **7.2 mm (small CSC) and 6 mm (large CSC)**
strip pitch: ≈ **2.5 mm**
stereo angle between strips: **15°**

Particle registration and signal formation

Charged particle registration



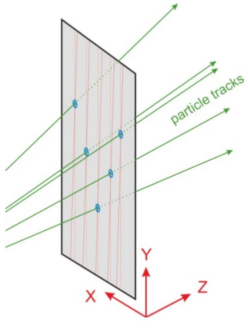
Scheme of particle registration by planes of tracking detectors

① **Primary interaction** of a heavy-ion beam with a fixed target ⇨ ② Charged particle production ⇨ ③ Registration of the particles by readout planes **as responses** in detectors

Microstrip detector response

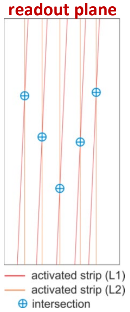
Tracking detectors in the BM@N setup (RUN-8) have **two-coordinate** microstrip readout

In order to reconstruct XY-coordinates the strips of one layer are rotated by a certain angle with respect to another layer

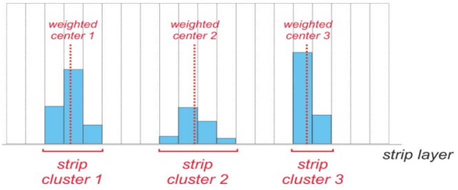


Passing through the detector, a particle leaves a "trace" (response).

readout plane

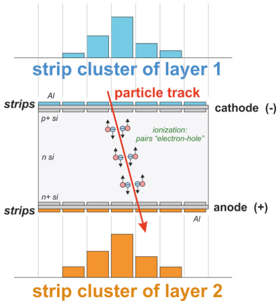


The result of reconstruction is spatial coordinates ("hits") which a particle passed through. A set of the hits from one particle defines its trajectory.



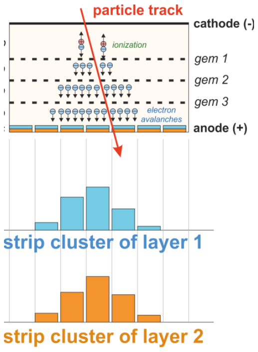
Each layer consists of a set of strips. The response from a particle is represented by a few fired strips which are grouped into **a cluster**

Signal formation in FSD



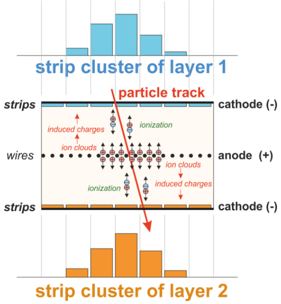
1. A particle, passing through the detector medium, produces electron-hole pairs.
2. Then mobile carriers (electrons and holes) drift to the electrodes, generating a current signal on the readout elements (strips) as 1D-clusters.

Signal formation in GEM



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.

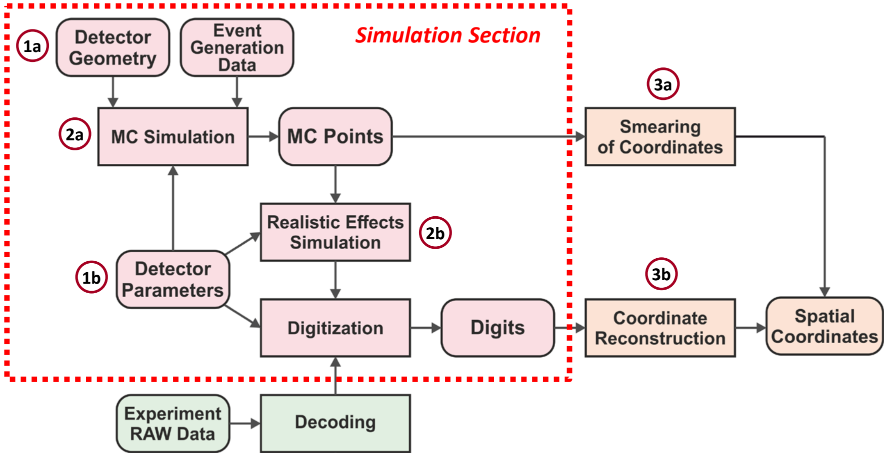
Signal formation in CSC



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.

Simulation of tracking detectors

Data processing in BMNROOT


Simulation Section
1a Detector Geometry
Event Generation Data
2a MC Simulation
MC Points
Realistic Effects Simulation 2b
1b Detector Parameters
Digitization
Digits
3a Smearing of Coordinates
3b Coordinate Reconstruction
Spatial Coordinates
Experiment RAW Data
Decoding

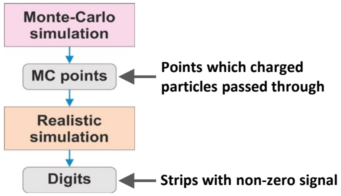
Stages of data processing for microstrip tracking detectors in BMNROOT

1. **Complete description of a detector**:
   a) Detector geometry (ROOT files)
   b) Detector parameters (XML files)
2. **Simulation**:
   a) Monte-Carlo simulation
   b) Realistic simulation
3. **Procedures of getting “hits”**:
   a) Smearing coordinates of Monte-Carlo points
   b) Coordinate reconstruction from “digits”

Stages of simulation

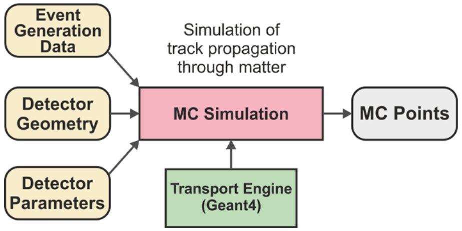
Full simulation consists of **two stages**:

1. Monte-Carlo simulation
2. Realistic simulation


Monte-Carlo simulation
MC points
Points which charged particles passed through
Realistic simulation
Digits
Strips with non-zero signal

Stage 1: Monte-Carlo simulation

Monte-Carlo simulation is used for imitation of charged particle passing through matter. In order to do this **Geant4** transport engine is used as a standard tool for track propagation in the **BMNROOT** framework.

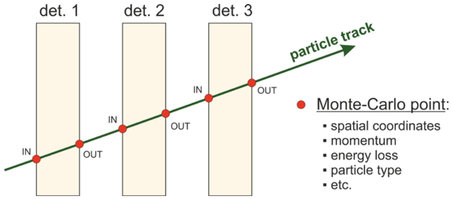

Event Generation Data
Detector Geometry
Detector Parameters
Simulation of track propagation through matter
MC Simulation
MC Points
Transport Engine (Geant4)

Must be prepared preliminary:

- ❑ Detector geometry (ROOT format)
- ❑ Detector parameters (XML format)
- ❑ Data from an event generator

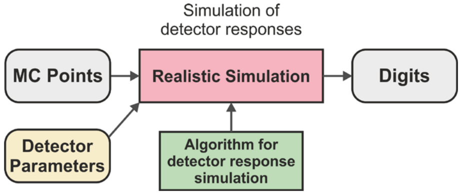
Result: description of particle tracks

A set of MC points on the detector planes, which charged particles passed through



Stage 2: Realistic simulation

Realistic simulation is used to create signals on the strips (digits) taking into account the features of physics processes in detectors. In order to do this we developed **special algorithms for response simulation** depending on the type of a detector.

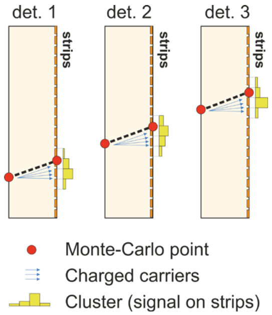

Simulation of detector responses
MC Points
Realistic Simulation
Digits
Detector Parameters
Algorithm for detector response simulation

Must be prepared as input data:

- ❑ Information from MC data (coordinates, particle type, momentum, energy loss, etc.)
- ❑ Detector parameters (XML format)

Result: detector responses

A set of digits (fired strips) as the real responses of detectors to passing particles



Central tracker detectors: ROOT geometry

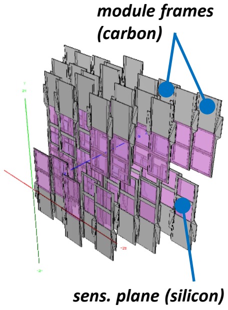
What ROOT geometry is

***.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.

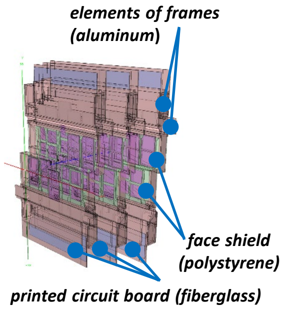
Detector geometry describes physical dimensions of detector elements, their hierarchical structure and media that are need for Geant4 transport engine to propagate the charge particles through matter.

ROOT geometry of FSD

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



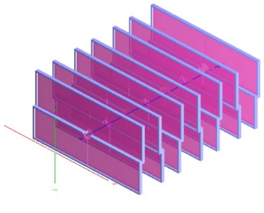
Detailed ROOT geometry of the FSD detector

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.

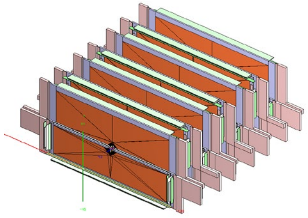
ROOT geometry of GEM

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.



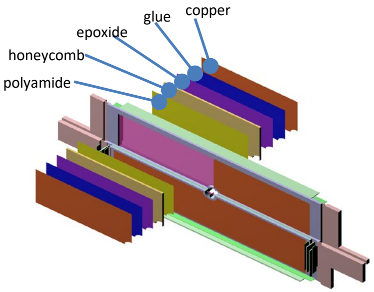
Basic ROOT geometry of the GEM detector



Detailed ROOT geometry of the GEM detector

Sensitive area of a CSC chamber:

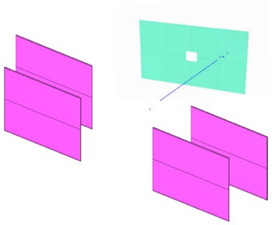
Each active zone of GEM chamber has a **multi-layer structure**. A layer has the following properties: thickness, material type and other characteristics which are taken into account in the Monte-Carlo simulation process.



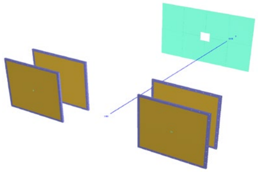
ROOT geometry of CSC

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 for small CSC filled with an active gas mixture (without any frames) and one – for large CSC
- **Detailed ROOT geometry** includes, in addition to gas volumes, passive elements, such as frames, material layers and other constructive components



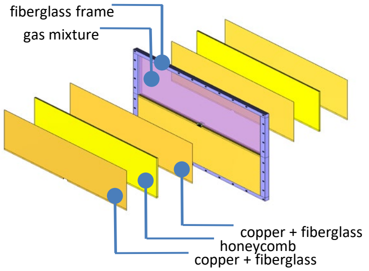
Basic ROOT geometry of the CSC detector



Detailed ROOT geometry of the CSC detector

Sensitive area of a CSC chamber:

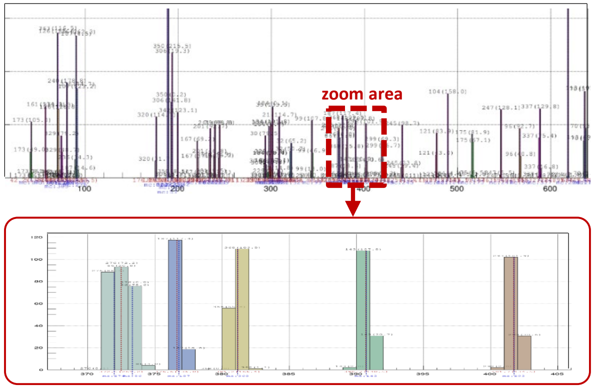
Active zone of CSC chamber has a multi-layer structure



Realistic simulation of detector response

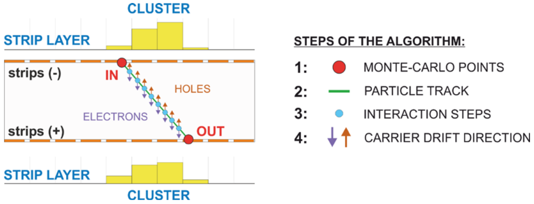
FSD detector

The goal of realistic simulation is to produce signals on the strips (digits) which are consistent with experimental data



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)

Steps of the realistic simulation algorithm:



STEPS OF THE ALGORITHM:

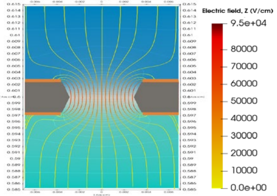
1: ● MONTE-CARLO POINTS
2: — PARTICLE TRACK
3: ● INTERACTION STEPS
4: ↓↑ CARRIER DRIFT DIRECTION

1. INPUT: Extracting the necessary information from Monte-Carlo data (coordinates of entry and exit points of the particle, ionization energy loss)
2. Defining particle track through the volume of the detector
3. Generation of interaction steps along the particle trajectory. Energy loss is distributed between interactions points with the formation of virtual charge carriers.
4. Projection of virtual charge carriers onto the readout plane in the longitudinal and transverse drift directions. OUTPUT: signals on the strips in the form of a cluster structure.

GEM detector

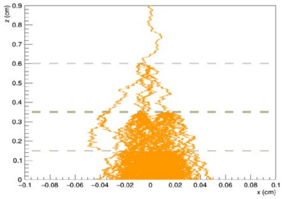
Because the triple GEM detector has complex structure and complicated signal formation, **auxiliary tools** were used for detailed simulation of physics processes in gas chambers.

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



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

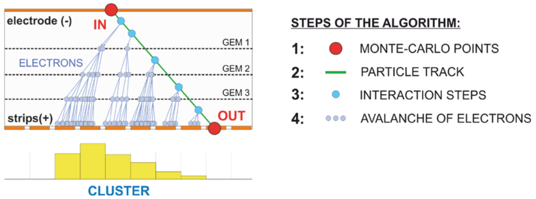
We used **Garfield++** for detailed simulation of physics processes in our GEM chambers:



Example of electron avalanche production in our triple GEM

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

Steps of the realistic simulation algorithm:



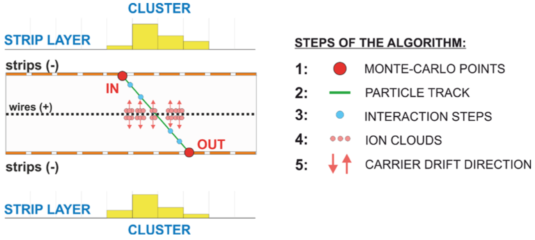
STEPS OF THE ALGORITHM:

1: ● MONTE-CARLO POINTS
2: — PARTICLE TRACK
3: ● INTERACTION STEPS
4: ●●● AVALANCHE OF ELECTRONS

1. INPUT: Extracting the necessary information from Monte-Carlo data (coordinates of entry and exit points of the particle, ionization energy loss, particle momentum)
2. Defining particle track through the volume of the detector
3. Generation of interaction steps along the particle trajectory in accordance with distribution of mean free path in a certain gas mixture.
4. Generation of virtual charge carriers in each GEM gap. Projection of virtual charge carriers onto the readout plane in the longitudinal and transverse drift directions according with obtained Garfield's distributions. OUTPUT: clusters on the strips.

CSC detector

Steps of the realistic simulation algorithm:



STEPS OF THE ALGORITHM:

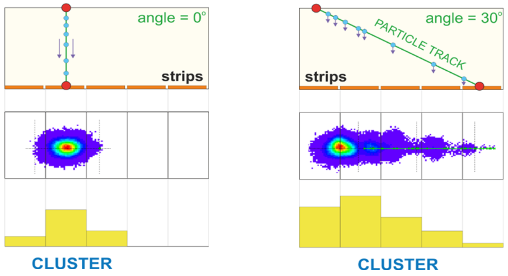
1: ● MONTE-CARLO POINTS
2: — PARTICLE TRACK
3: ● INTERACTION STEPS
4: ●●● ION CLOUDS
5: ↓↑ CARRIER DRIFT DIRECTION

1. INPUT: Extracting the necessary information from Monte-Carlo data (coordinates of entry and exit points of the particle, ionization energy loss)
2. Defining particle track through the volume of the detector
3. Generation of interaction steps along the particle trajectory in accordance with distribution of mean free path in a certain gas mixture.
4. Generation of virtual charge carriers (ions) on wires at each interaction step.
5. Projection of virtual charge carriers onto the readout planes (top and bottom strips) in the longitudinal and transverse drift directions. OUTPUT: clusters on the strips.

Advantages of realistic simulation

Realistic simulation takes into account:

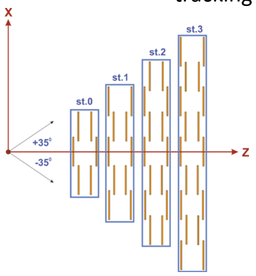
- Charged particle inclination angle to a detector plane
- Features of signal formation



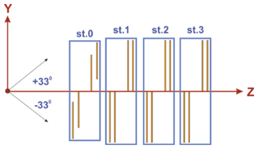
Data simulation

FSD detector

Using the developed algorithms, simulated data were prepared for the latest configuration (RUN-8) of the tracking detectors.

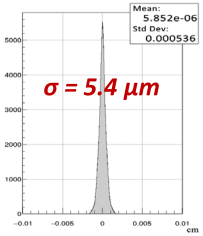


Acceptance angle X of FSD detector

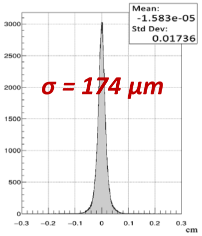


Acceptance angle Y of FSD detector

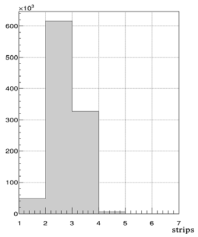
The distributions below have been obtained for the MC-tracks which can be detected in according with the acceptance angles of the **first station**



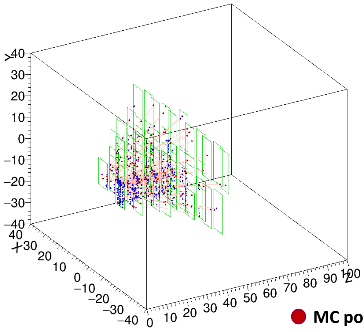
X residuals between simulated and real coordinates



Y residuals between simulated and real coordinates



Distribution of cluster size

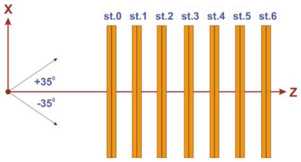


Examples of data simulation and coordinate reconstruction for FSD detector for RUN-8 configuration

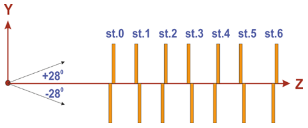
● **MC points** ● **Reconstructed hits**

GEM detector

Configuration of GEM for RUN-8:

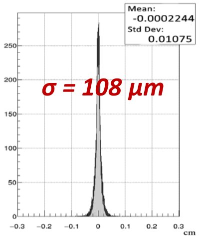


Acceptance angle X of GEM detector

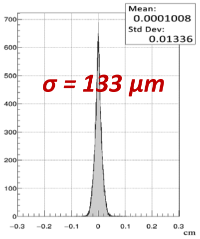


Acceptance angle Y of GEM detector

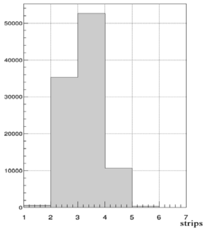
Distributions based on first station of GEM for RUN-8:



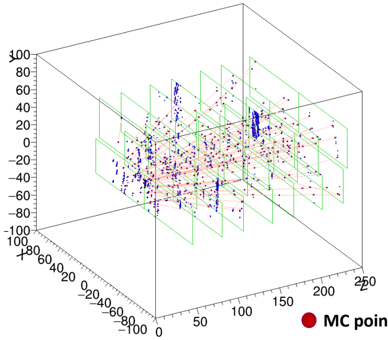
X residuals between simulated and real coordinates



Y residuals between simulated and real coordinates



Distribution of cluster size

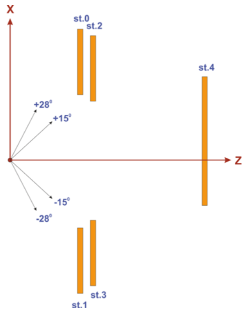


for GEM detector

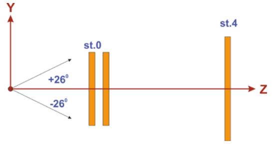
● **MC points** ● **Reconstructed hits**

CSC detector

Configuration of CSC for RUN-8:

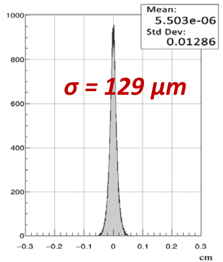


Acceptance angle X of CSC detector

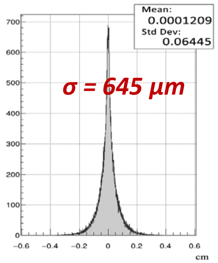


Acceptance angle Y of CSC detector

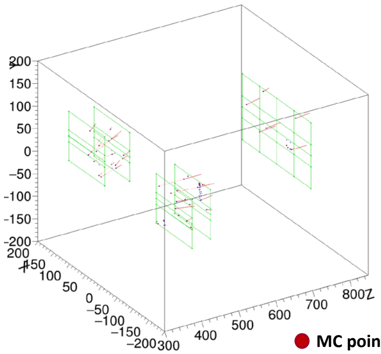
Distributions based on first station of CSC for RUN-8:



X residuals between simulated and real coordinates



Y residuals between simulated and real coordinates



for CSC detector

● **MC points** ● **Reconstructed hits**

Summary

What has been done:

- ☐ Realistic simulation was developed and implemented into BMNROOT for central tracker detectors:
  - FSD (Forward Silicon Detector)
  - GEM (Gas Electron Multiplier)
  - CSC (Cathode Strip Chamber)

Thank you for your attention…