Computational model of microstrip detectors for the hybrid tracker in the BM@N experiment

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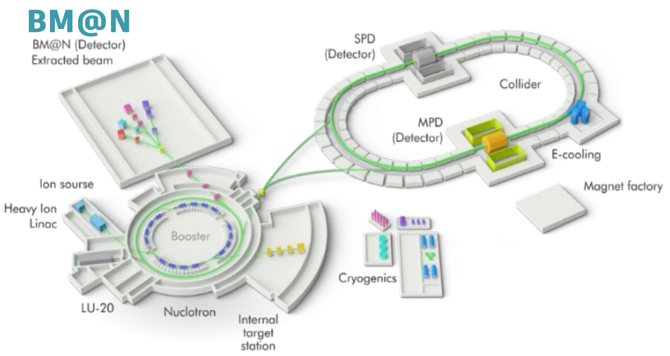
BM@N Experiment

BM@N (Baryonic Matter at Nuclotron) is the first stage experiment of mega-science project NICA

This is a fixed target experiment aimed to study dense baryonic matter on heavy-ion collisions at the NICA accelerator complex located at JINR in Dubna



At this moment **eight experimental RUNs** were performed since 2015:

BM@N EXPERIMENTAL RUNS

- **2015** — **RUN 1-2-3-4 (2015)** Beam: deuteron; Target: C, Cu
- **2016** — **RUN 5 (2016)** Beam: deuteron; Target: CH2, C, Cu, Pb
- **2017** — **RUN 6 (2017)** Beam: deuteron, C; Target: CH2, C, Al, Cu, Pb
- **2018** — **RUN 7 (2018)** Beam: Ar, Kr; Target: C, Cu
- **2023** — **RUN 8 (2023-2024)** Beam: Ar, Xe; Target: CsI
- **2025** — **RUN 9 (2025)** Beam: Xe; Target: CsI

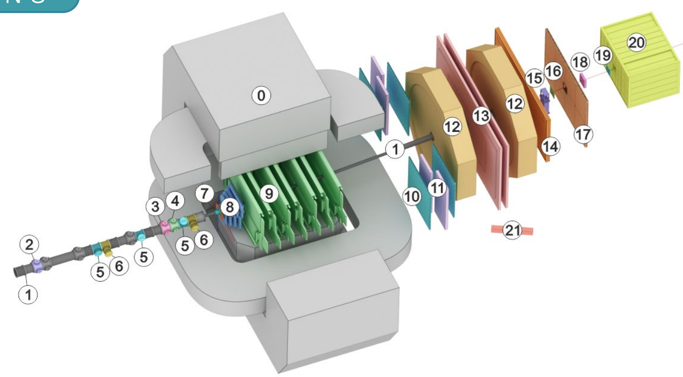
BM@N setup

TRACKING SYSTEM
- **SiBT** (Silicon Beam Tracker)
- **VSP** (Vertex Silicon Plane)
- **FSD** (Forward Silicon Detector)
- **GEM** (Gas Electron Multiplier)
- **CSC** (Cathode Strip Chamber)

PARTICLE INDENTIFICATION SYSTEM
- **TOF400** (Time Of Flight detector)
- **TOF700** (Time Of Flight detector)

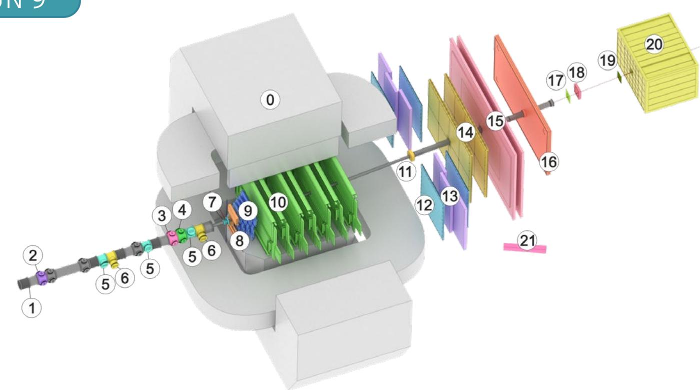
OTHER SYSTEMS
- **Trigger system**
- **FQH** (Forward Quartz Hodoscope)
- **ScWall** (Scintillator Wall)
- **FHCal** (Fwd. Hadron Calorimeter)
- **HGN** (High Granularity Neutron det.)

RUN 8



- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m^2 (10)
- TOF 400 (11)
- DCH (12)
- TOF 700 (13)
- ScWall (14)
- FD (15)
- Small GEM (16)
- CSC 2x1.5 m^2 (17)
- Beam Profilometer (18)
- FQH (19)
- FHCal (20)
- HGN (21)

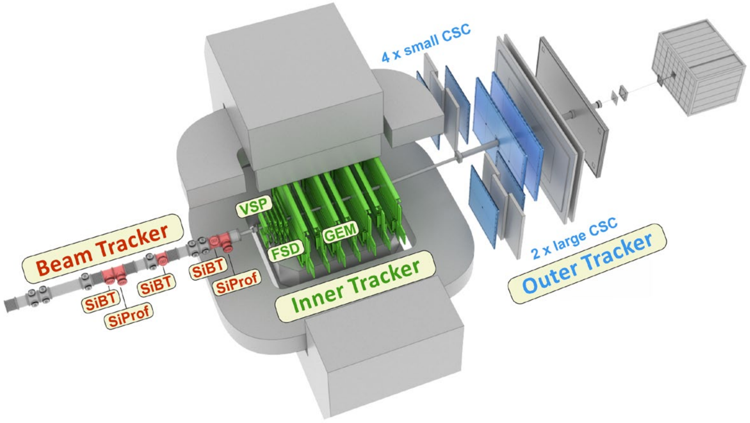
RUN 9



- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- BD (7)
- VSP(STS), FSD, GEM (8, 9, 10)
- FD (11)
- 4 x CSC 1x1 m^2 (12)
- TOF 400 (13)
- 2 x CSC 2x1.5 m^2 (14)
- TOF 700 (15)
- ScWall (16)
- Small GEM (17)
- Beam Profilometer (18)
- FQH (19)
- FHCal (20)
- HGN (21)

Hybrid Tracking System

The **hybrid tracking system** of the BM@N experiment consists of the different types of coordinate detectors to register trajectories of charged particles



Configuration of hybrid tracker for the RUN-9

Hybrid Tracking System

BEAM TRACKER — It includes detectors located inside the vacuum pipe in front of magnet SP-41

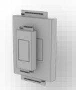
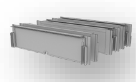
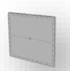
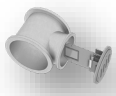
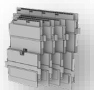
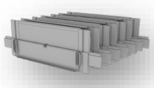
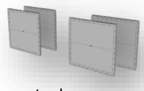
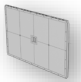
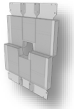
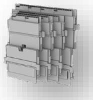
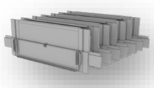
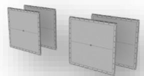
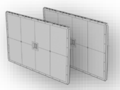
- **SiBT** (Silicon Beam Tracker) *(3 planes of 63x63 mm)*
- **SiProf** (Silicon Beam Profilometer) *(2 planes of 63x63 mm)*

INNER TRACKER — It comprises coordinate detectors located inside the magnet

- **VSP** (Vertex Silicon Plane based on STS) *(one plane of 6 modules)*
- **FSD** (Forward Silicon Detector) *(8 half planes)*
- **GEM** (Gas Electron Multipliers) *(14 half planes)*

OUTER TRACKER — It consists of detectors located behind the magnet

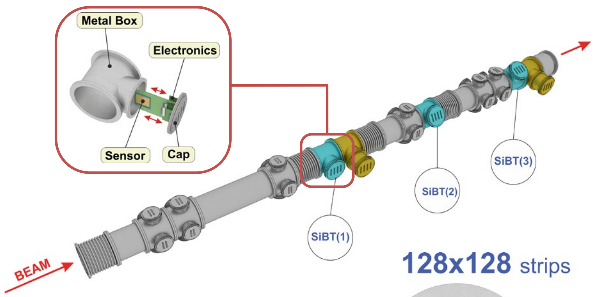
- **small CSC** (Cathode Strip Chambers) *(4 planes of 1x1 m)*
- **large CSC** (Cathode Srtrip Chambers) *(2 planes of 2x1.5 m)*

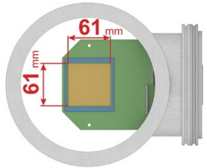
	SiBT Silicon Beam Tracker microstrip semiconductor detector	VSP Vertex Silicon Plane microstrip semiconductor detector	FSD Forward Silicon Detector microstrip semiconductor detector	GEM Gas Electron Multipliers microstrip gaseous detector	small CSC Cathode Strip Chambers microstrip gaseous detector	large CSC Cathode Strip Chambers microstrip gaseous detector
RUN 7 (2018)	—	—	 2 stations	 6 stations	 1 plane	—
RUN 8 (2023-2024)	 3 planes	—	 4 stations	 7 stations	 4 planes	 1 plane
RUN 9 (2025)	 3 planes	 1 plane	 4 stations	 7 stations	 4 planes	 2 planes

Microstrip Tracking Detectors

Silicon Beam Tracker (SiBT)

SiBT (Silicon Beam Tracker) is a microstrip detector designed to monitor and track the ion-beam. It consists of three silicon planes arranged along the beam axis in front of the target.

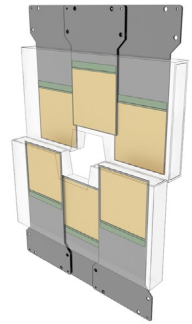


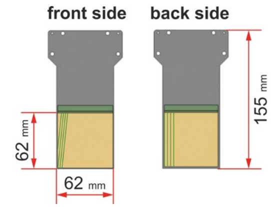


sensor area: **61x61 mm²**
sensor thickness: **175 μm**
strip pitch: **0.475 mm**
stereo angle between strips: **90°**

Vertex Silicon Plane (VSP)

VSP (Vertex Silicon Plane) is a high-precision microstrip coordinate detector of the inner tracker. it is represented by one station of six silicon modules.



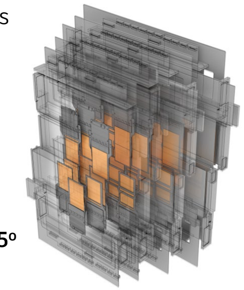


Si-module with one double-sided strip sensor mounted on a frame

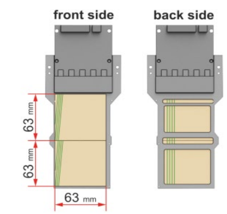
sensor area: **62x62 mm²**
sensor thickness: **300 μm**
strip pitch: **≈ 58 μm**
stereo angle between strips: **7.5°**

Forward Silicon Detector (FSD)

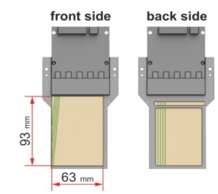
FSD (Forward Silicon Detector) is a high-precision coordinate detector of the inner tracker. It consists of 48 silicon modules which are conbined into 4 stations.



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



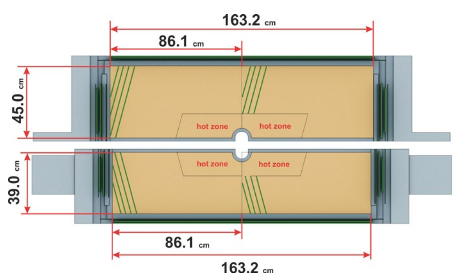
Si-module with two double-sided sensors of **63x63** mm² each



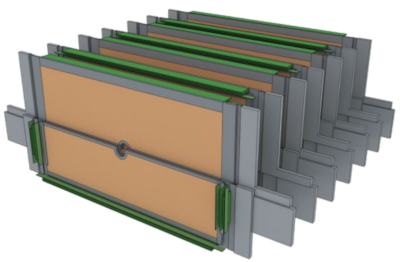
Si-module with one double-sided sensor of **63x93** mm²

Gas Electron Multipliers (GEM)

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



Each station is assembled by two chambers: upper and lower which are joined together to form a plane

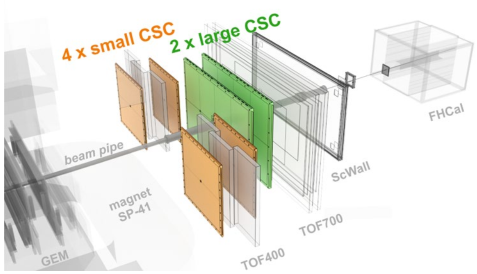


The configuration of this detector for RUN-9 comprises seven stations located inside the magnet along the beam axis.

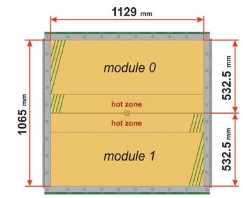
Gas volume thickness: **9 mm**
strip pitch: **800 μm**
stereo angle between strips: **15°**

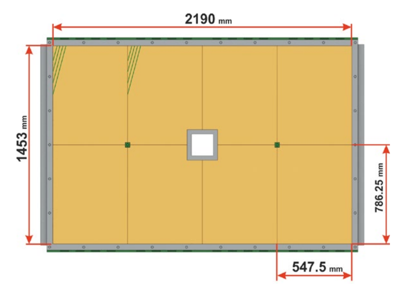
Cathode Strip Chambers (CSC)

CSC (Cathode Strip Chambers) is a gaseous detector with microstrip readout. It belongs to the outer tracker. Its configuration for the next run consists of four small and two large stations located behind the magnet.



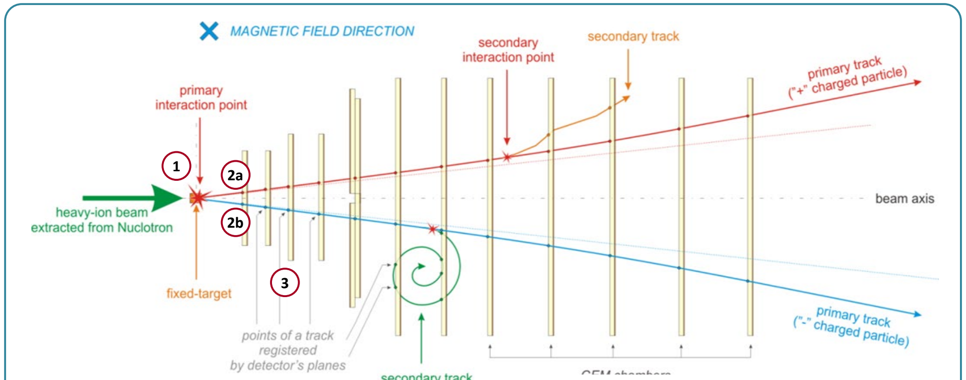
gas volume thickness (small CSC): **7.2 mm**
gas volume thickness (large CSC): **6.0 mm**
strip pitch: **≈ 2.5 mm**
stereo angle between strips: **15°**





Microstrip Tracking Detectors: operation principle

Charged particle registration



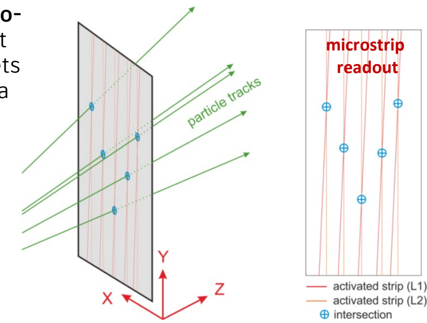
Scheme of particle registration by tracking detectors

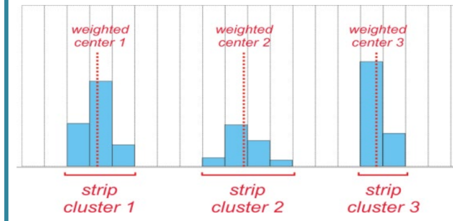
1. **Primary interaction** of heavy-ion beams with a fixed target ⇨
2. Charged particle production ⇨
3. Registration of the particles **as responses** on readout

Microstrip detector response

Our tracking detectors have **two-coordinate** microstrip readout which is represented by two sets of strips. They are rotated by a certain angle with respect to each other.

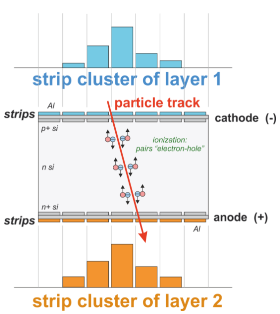
Passing particles cause detector response as lighted strips (clusters). The result of reconstruction is spatial coordinates ("hits") through which the particles passed.





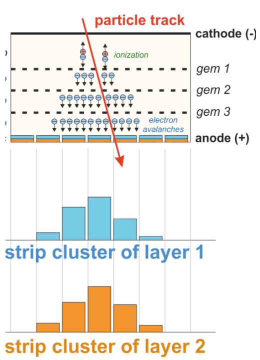
Each strip layer consists of a set of strips. The response from a particle is represented by lighted strips which are grouped into **a cluster**

Signal formation in silicon detectors



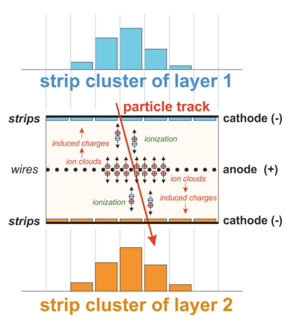
1. A particle, passing through the detector medium, produces electron-hole pairs.
2. Then mobile carriers (electrons and holes) drift to the electrodes, generating a current signal on the readout elements (strips) as 1D-clusters.

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.

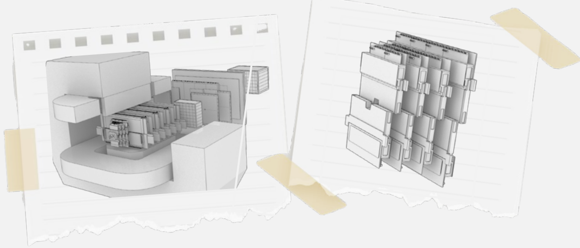
Signal formation in CSC



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.

Computational Model of Hybrid Tracking System

We use ROOT format **to describe the geometry** in our BMNROOT software based on ROOT data analysis framework. Geant4 transport engine is used as a basic tool to simulate the passage of charged particles through matter.



Detector Geometry

Hybrid Tracking System

microstrip detectors

SiBT	VSP	FSD	GEM	CSC

Simulation procedure allows us to obtain realistic responses on microstrip readout from charged particles. Our algorithms of realistic simulation take into account the features of signal formation in specific types of detectors. As a result we have sets of “digits” (clusters of lighted strips) which correspond to experimental data.

Simulation Of Detector Response

DESCRIPTION

COMPUTATIONAL MODEL

mathematical model of a detector implemented for computer execution

FUNCTIONALITY

Structure and Parameters

Coordinate Reconstruction

We developed a **specific format based on XML** language to define the hierarchical structure and parameters of a tracking detector.

```
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        <Module xShift="par1" yShift="par2" zShift="par3" ... >
            <Layer zone="0" type="par1" stripAngle="par2" pitch="par3" ... >
            </Layer>
            <Layer zone="0" type="par1" stripAngle="par2" pitch="par3" ... >
            </Layer>
            ...
        </Module>
        ...
    </Station>
    ...
</StationSet>
```
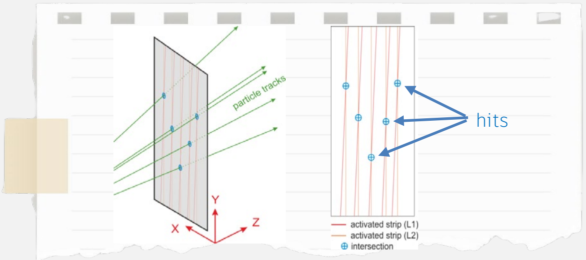

PROGRAM

parameters and algorithms implemented as a computer program

Using a special **reconstruction algorithm** we get a set of spatial coordinates called “hits”. Hit are points through which charged particles passed. In case of microstrip readout the reconstruction based on finding hits by crossing active strips.



Detector Geometry (ROOT)

What ROOT geometry is

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

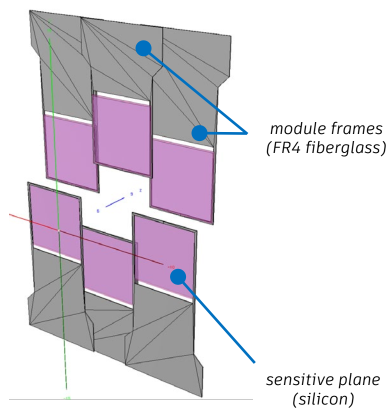
Some detectors have two geometry versions:

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

ROOT geometry is created with a macro code in C++ language

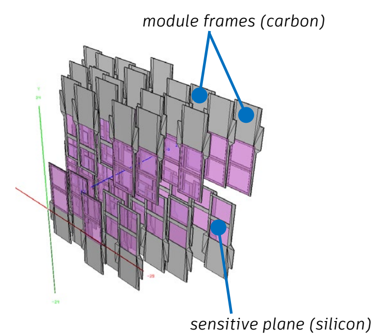
Vertex Silicon Plane (VSP)

The geometry of the VSP detector describes the configuration for next run which consists of 6 silicon modules placed on fiberglass frames

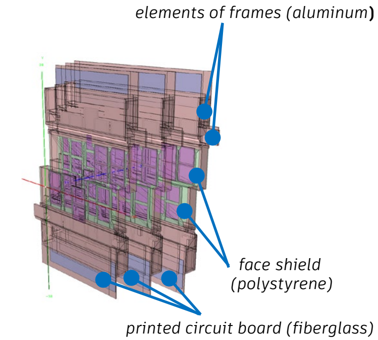


Forward Silicon Detector (FSD)

The configuration of the FSD detector has 48 silicon modules. Its geometry was developed in two versions (basic and detailed) according to the drawings and schemes prepared by the detector group.



Basic geometry

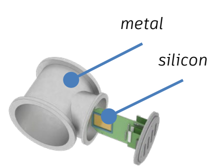


Detailed geometry

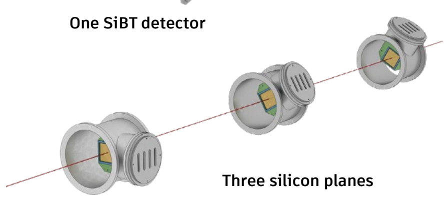
Adding passive elements to the geometry allows us to take into account materials which affect the passage of particles. It improves the accuracy of Monte-Carlo simulation.

Silicon Beam Tracker (SiBT)

ROOT geometry for SiBT detector consists of three silicon planes placed into three metal boxes which are the parts of the vacuum pipe.



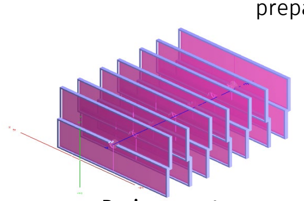
One SiBT detector



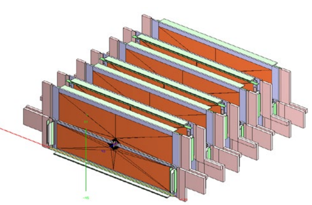
Three silicon planes

Gas Electron Multipliers (GEM)

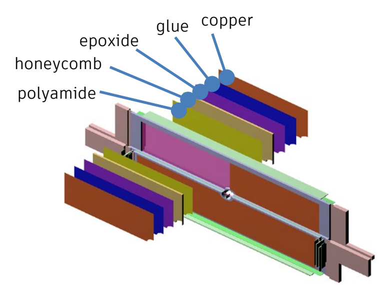
The configuration of the GEM detector has 14 half-planes which have a complex structure. Two geometry models – basic and detailed – were prepared for this detector.



Basic geometry



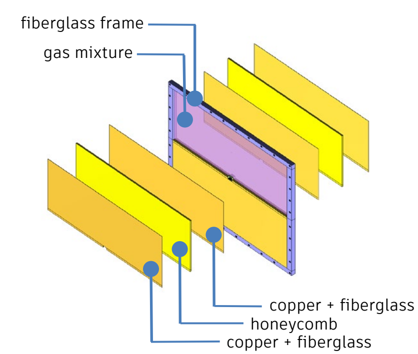
Detailed geometry



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

Cathode Strip Chambers (CSC)

The configuration of the CSC detector includes 4 small and 2 large chambers. Its geometry was also created in two variants: basic and detailed. The geometry of chamber has also a multi-layer structure.

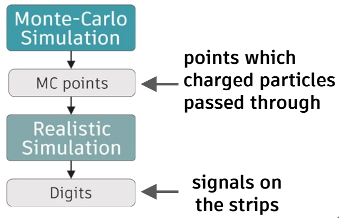


Simulation of Detector Response

Simulation procedure

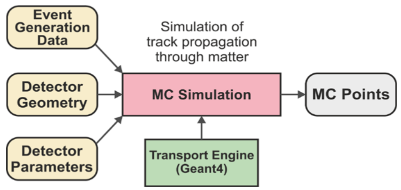
Full simulation consists of **two stages**:

1. Monte-Carlo simulation
2. Realistic simulation

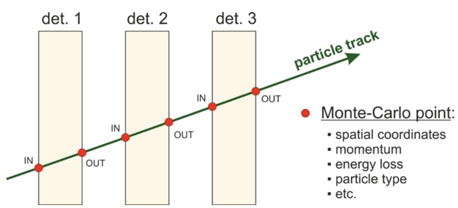


Stage 1: Monte-Carlo simulation

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

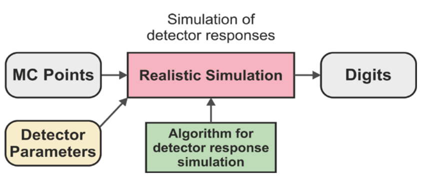


Result: A set of MC points which charged particles left in detectors

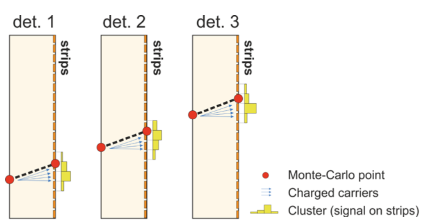


Stage 2: Realistic simulation

Realistic simulation is used to create signals on the strips (digits) taking into account the features of signal formation in a certain type of detectors.

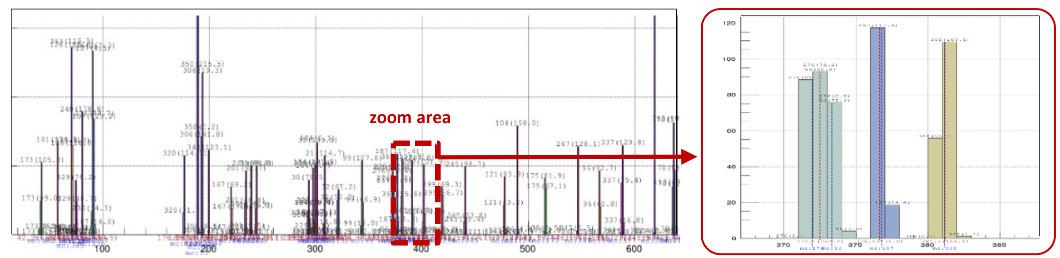


Result: A set of digits (lighted strips) as real responses of detectors



Signal on the strips (clusters)

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



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

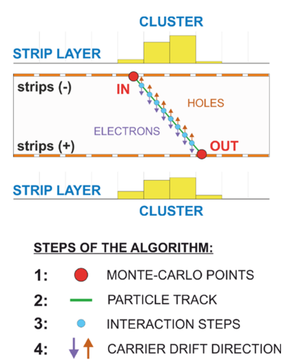
Realistic simulation in different types of detectors

The simulation algorithm for realistic responses depends on a detector type

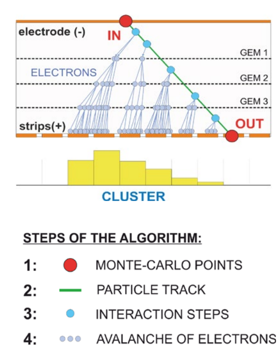
Basic steps:

1. Information from MC-data **(INPUT)**
2. Defining particle track through the detector volume
3. Generation of interaction steps along the particle trajectory where energy loss is distributed among interactions.
4. Signal formation on the strips **(OUTPUT)**

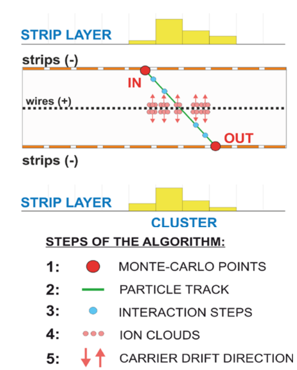
Signal formation in silicon-based detectors



Signal formation in GEM detector



Signal formation in CSC detector

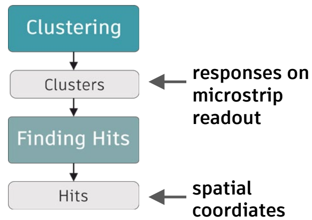


Coordinate Reconstruction

Coordinate reconstruction

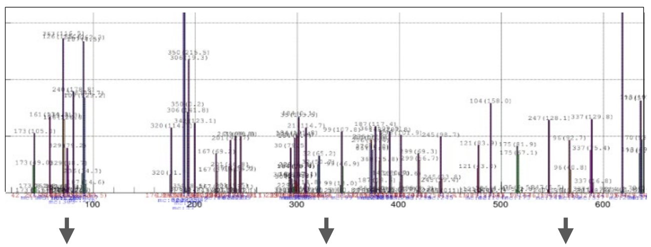
Spatial coordinate reconstruction from microstrip readout consists of **two procedures**:

1. Clustering procedure
2. Finding hits procedure

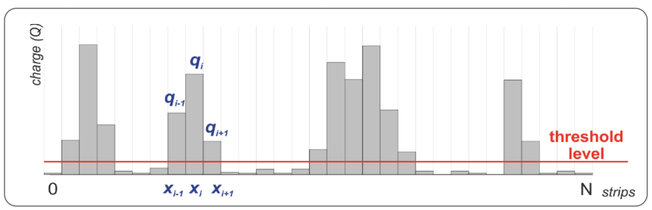


Clustering

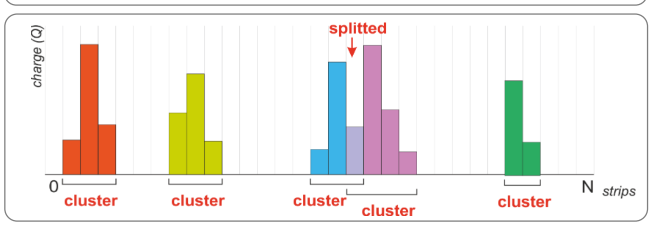
The purpose is to **find clusters** and calculate their parameters in a strip layer



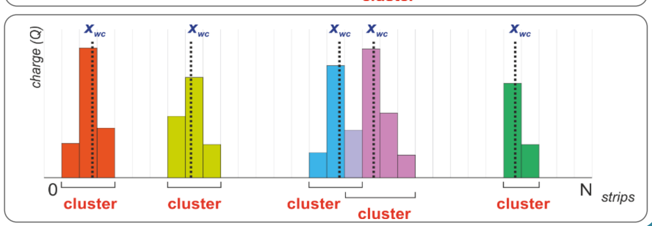
1 Defining threshold level and cutting noisy strips



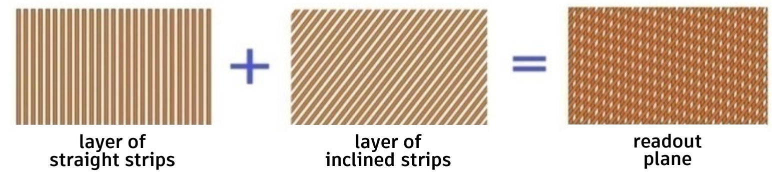
2 Finding and splitting welded clusters with “Peak and Valley” algorithm



3 Calculation of weighted centers with “Center of Gravity” algorithm



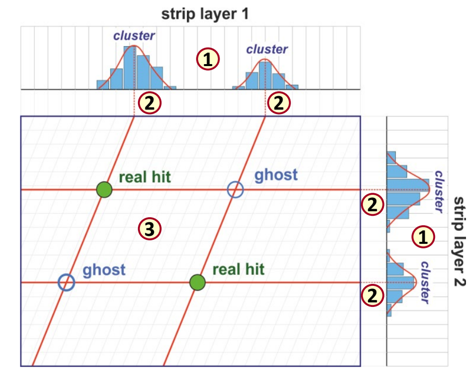
Finding hits



1 Finding strip clusters

2 Calculation of weighted position of a cluster to collapse it into one weighted strip

3 Crossing weighted strips of one layer with another to get intersections where one part of them are hits from real particles and another – “ghosts”.

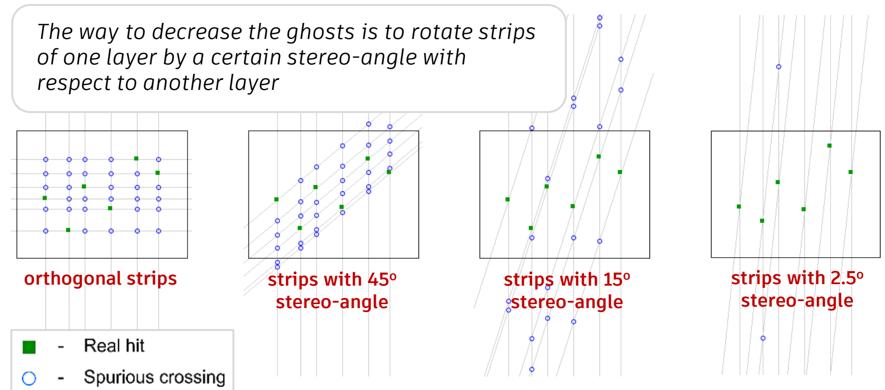


“**Hit**” is a reconstructed spatial point with coordinates (x, y, z) which a charged particle passed through

Shortcoming of microstrip readout

The principal disadvantage of microstrip readout is the appearance of spurious intersections called “ghosts”

The way to decrease the ghosts is to rotate strips of one layer by a certain stereo-angle with respect to another layer

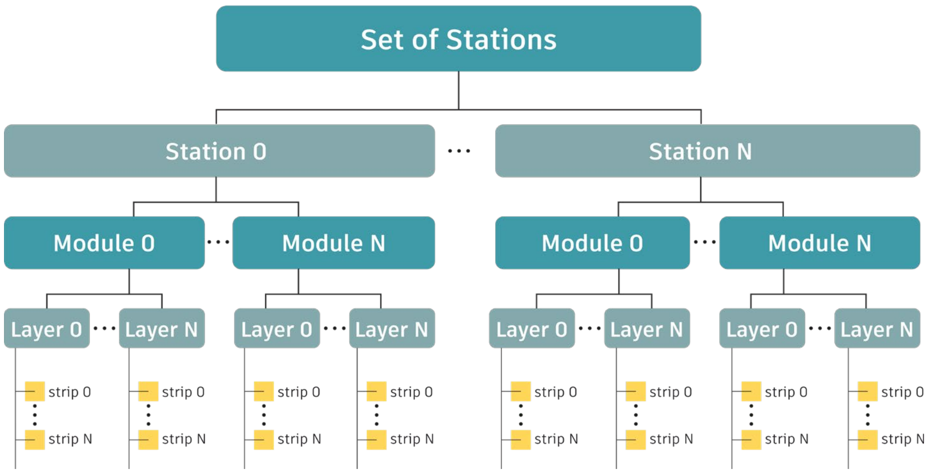


Software Implementation

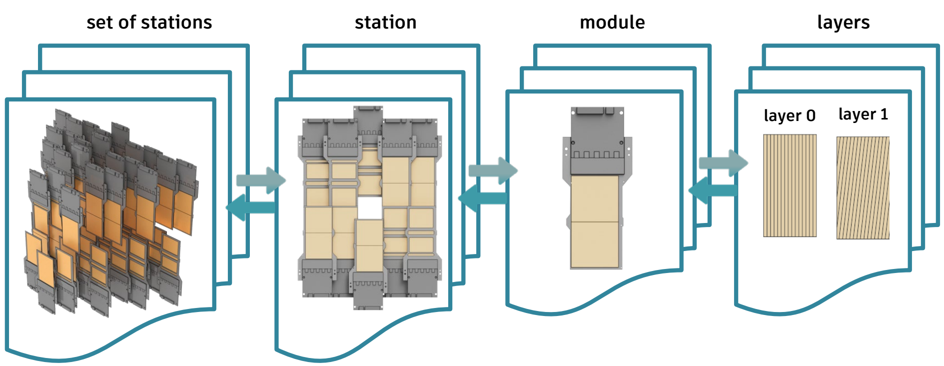
Structure of detector

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

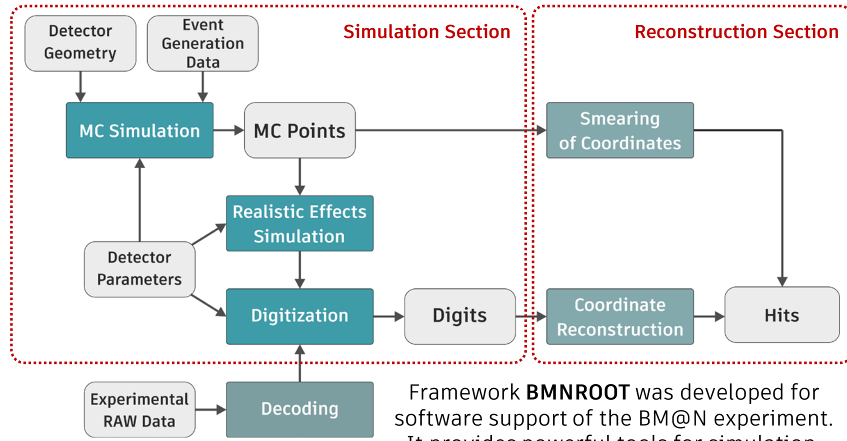


Composition of detector elements



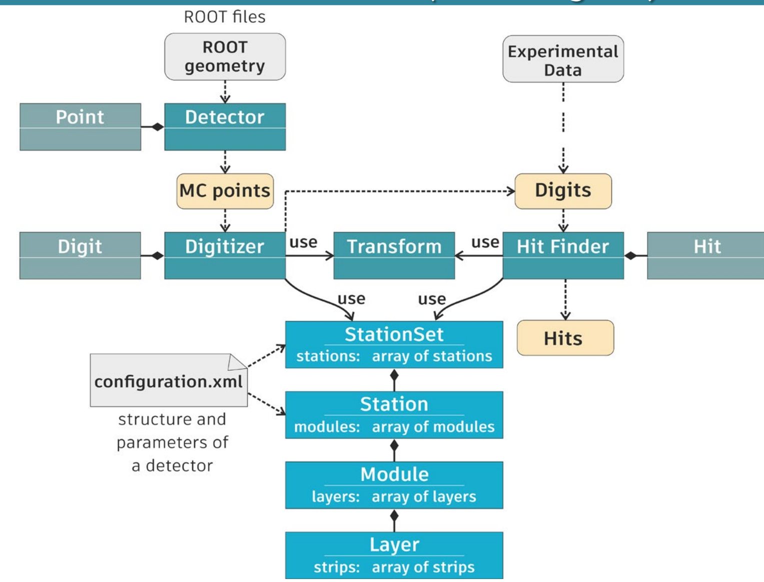
Data processing in BMNROOT

Stages of data processing for tracking detectors in BMNROOT



Framework **BMNROOT** was developed for software support of the BM@N experiment. It provides powerful tools for simulation, reconstruction and data analysis.

Software structure (class diagram)



What has been done:

- Software for realistic simulation and coordinate reconstruction for microstrip tracking detectors of the next BM@N run:
  - Silicon Beam Tracker (SiBT)
  - Vertex Silicon Plane (VSP) *bases on STS modules*
  - Forward Silicon detector (FSD)
  - GEM detector
  - Small and large CSC detectors

Thank you for your attention …