Coordinate reconstruction for microstrip tracking detectors in the BM@N experiment for the configuration of the first physics run

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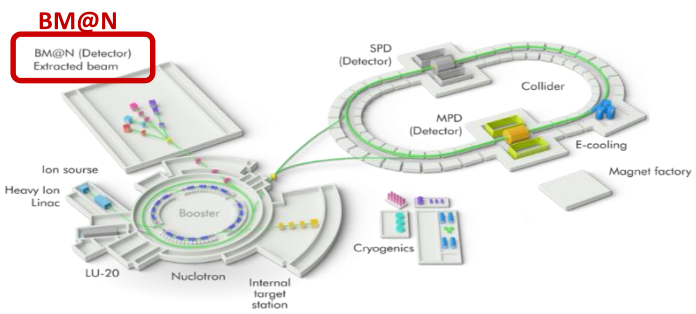
BM@N experiment

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

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



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

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

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

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

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

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

RUN 8 (2023)
beam: Ar, Xe; target: CsI

The detector setup of BM@N

Tracking system

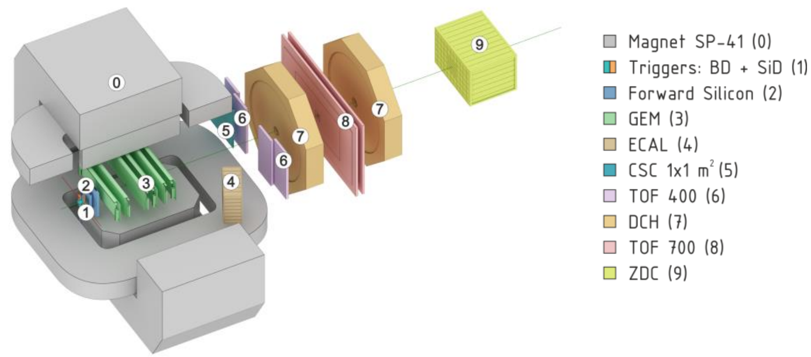
- **SiBT** (*Silicon Beam Tracker*)
- **FSD** (*Forward Silicon Detector*)
- **GEM** (*Gas Electron Multipliers*)
- **CSC** (*Cathode Strip Chambers*)
- **DCH** (*Drift Chambers*)

Particle identification system

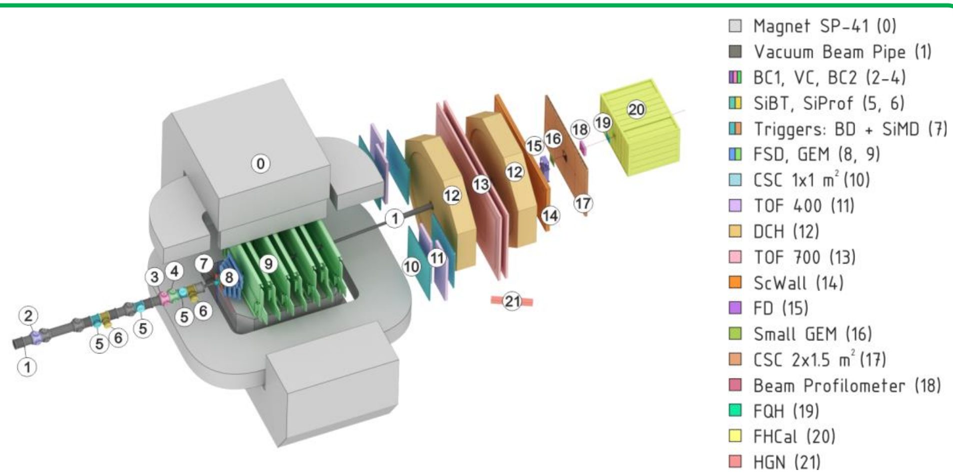
- **TOF400** (*1st Time-of-Flight detector*)
- **TOF700** (*2nd Time-of-Flight detector*)

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)*

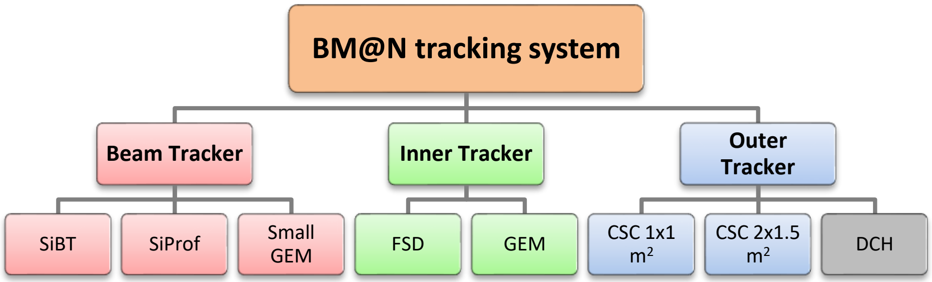


BM@N setup for the latest ***RUN-8*** *configuration (winter 2023)*

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 the beam. The inner tracker comprises detectors located inside the magnet, the outer – outside



BM@N tracking detectors for RUN-8:

Beam tracker:

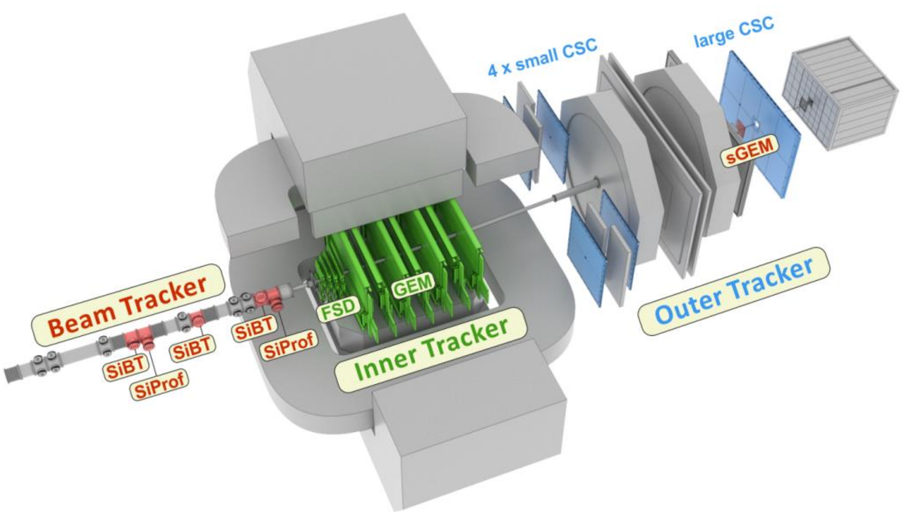
- **SiBT (Silicon Beam Tracker)** : 3 planes of 63x63 mm^2
- **SiProf (Silicon Profilometers)** : 2 planes of 63x63 mm^2
- **sGEM (small GEM *as beam profilometer*)** : 1 plane of 10x10 cm^2

Inner tracker:

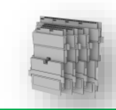
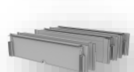
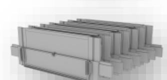
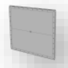
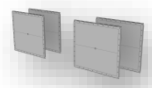
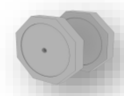
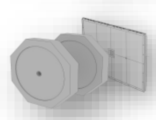
- **FSD (Forward Silicon Detector)** : 8 half-planes
- **GEM (Gas Electron Multipliers)** : 14 half-planes

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
- **DCH (Drift Chambers)** : 2 large multi-wire chambers



BM@N tracking system for RUN-8 consisting of microstrip detectors (highlighted with different colors)

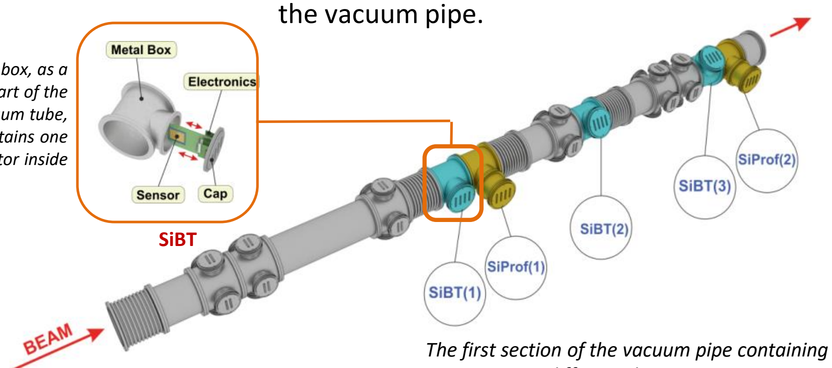
Detector	RUN-7	RUN-8	Features
FSD			**RUN-7**: 2 stations (14 Si-modules) **RUN-8**: 4 stations (48 Si-modules)
GEM			**RUN-7**: 6 stations (6 half-planes) **RUN-8**: 7 stations (14 half-planes)
CSC			**RUN-7**: 1 chamber (1x1 m^2) **RUN-8**: 4 chambers (1x1 m^2)
DCH + CSC			**RUN-7**: only 2 DCH **RUN-8**: 2 DCH + 1 large CSC (2x1.5 m^2)

SiBT and SiProf: microstrip tracking detectors before the target

SiBT (*Silicon Beam Tracker*) and **SiProf** (*Silicon Beam Profilometer*) are semiconductor microstrip two-coordiate detectors designed to monitor and track the ion beam.

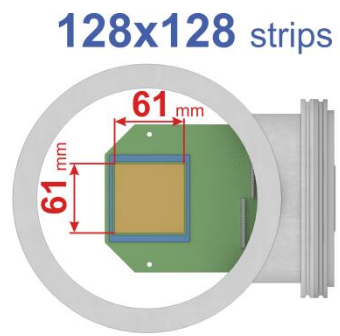
They are located before the target inside metal boxes integrated into the vacuum pipe.

Metal box, as a part of the vacuum tube, contains one detector inside



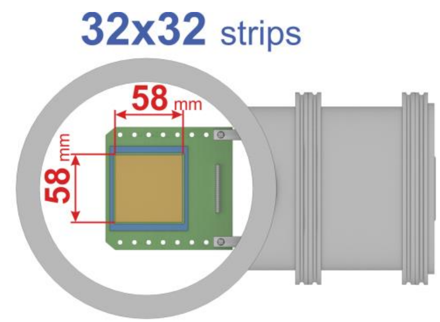
The first section of the vacuum pipe containing different detectors

Silicon Beam Tracker



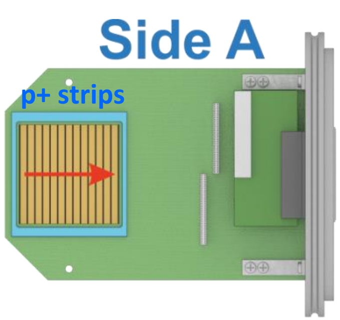
sensor: **61x61 mm²**
sensor thickness: **175 µm**
strip pitch: **0.475 mm**
stereo angle between strips: **90º**

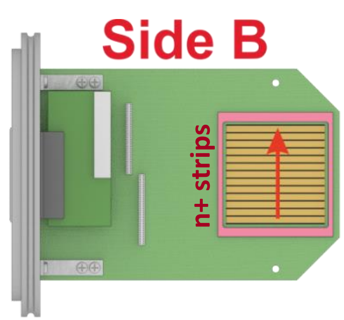
Silicon Beam Profilometer



sensor: **58x58 mm²**
sensor thickness: **175 µm**
strip pitch: **1.8 mm**
stereo angle between strips: **90º**

Strips in sensor zone

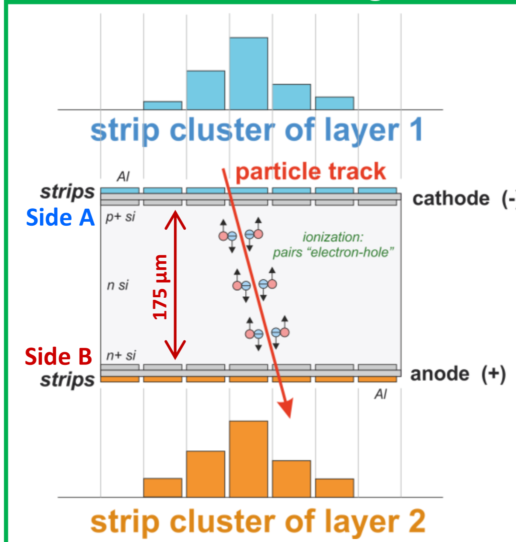




The sensor zone includes two sets of strips (p+ strips and n+ strips) - one on each side of the silicon.

In order to reconstruct XY coordinates in two-dimensional space one layer of strips is orthogonal to another.

Signal formation

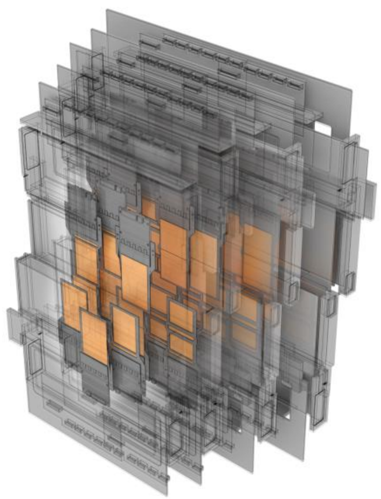


Signal formation in a silicon detector:

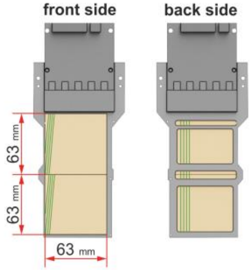
1. A particle, passing through the detector medium, produces electron-hole pairs.
2. Then mobile carriers (electrons and holes) drift to the electrodes, generating a current signal on the readout elements (strips) as 1D-clusters.

Forward Silicon Detector

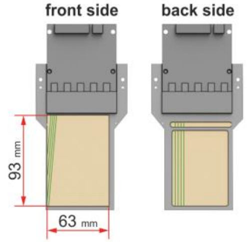
Forward Silicon Detector (FSD) is a high-precision coordinate detector of the inner tracking system in the BM@N setup. It consists of a set of microstrip silicon modules which are assembled into 4 stations.



Silicon module types



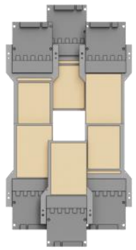
*Si-module with two double-sided strip sensors of **63x63** mm^2 each*



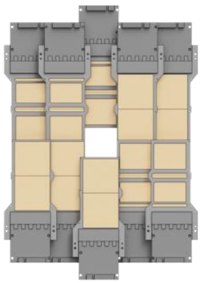
*Si-module with one double-sided strip sensor of **63x93** mm^2*

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

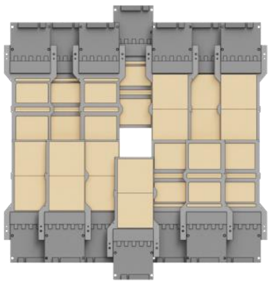
Silicon stations



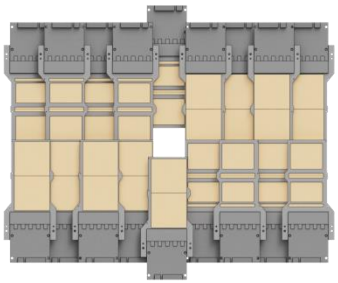
Station 1:
6 modules of 63x93 mm^2



Station 2:
10 modules of 63x126 mm^2

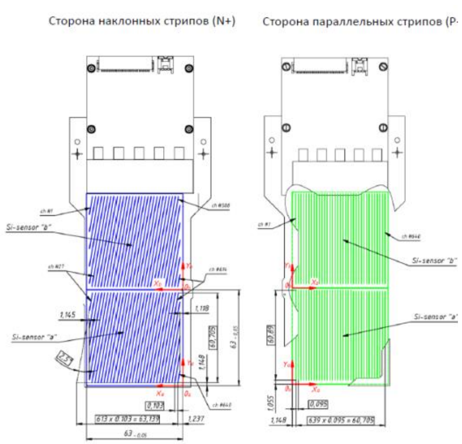


Station 3:
14 modules of 63x126 mm^2

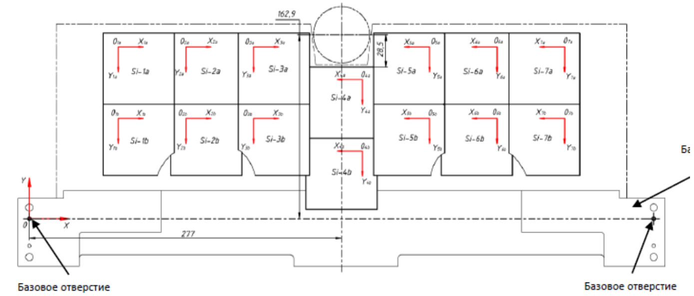


Station 4:
18 modules of 63x126 mm^2

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	

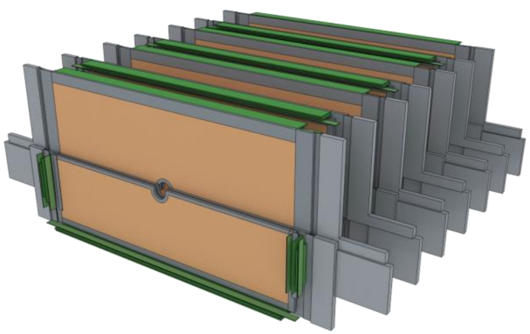
*-положение точки начала координат Si-сенсора в координатной плоскости 0XY (привязана к наружным базовым отверстиям).

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

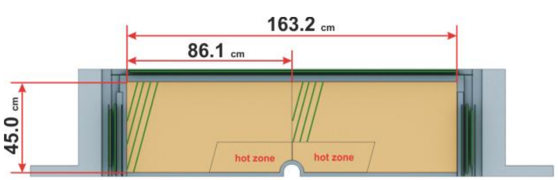
GEM detector

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

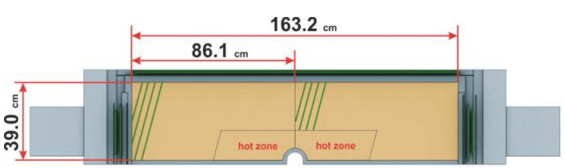
The configuration of this detectors for RUN-8 comprises **seven stations** located inside the magnet along the beam axis.



GEM chamber types

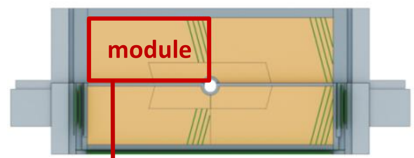


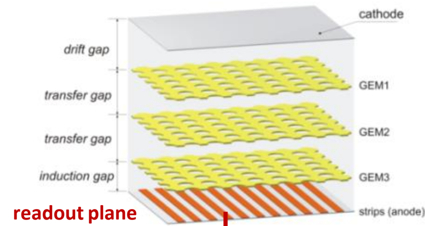
Upper half-plane



Lower half-plane

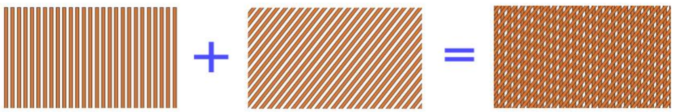
Strip readout





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

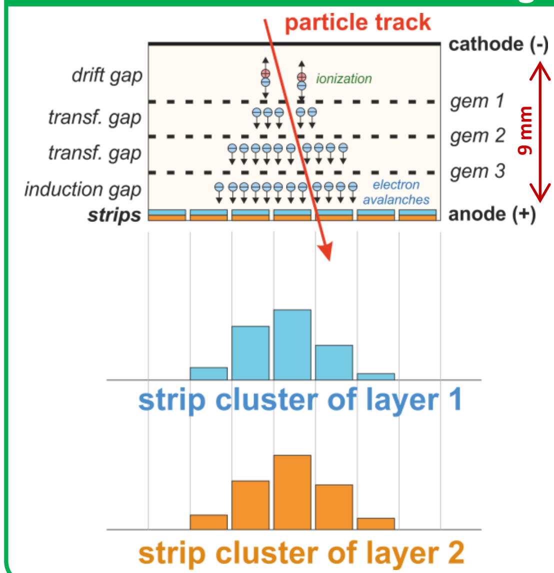
Readout plane of each module in a GEM station is formed by two sets of anode strips (layers): straight and inclined



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°**

Signal formation



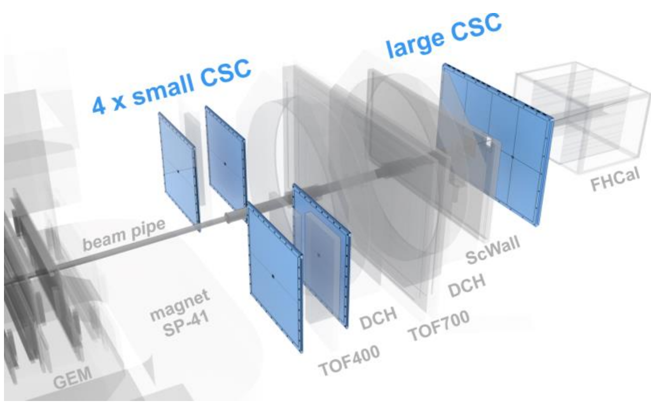
Signal formation in a GEM chamber:

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.

CSC detector

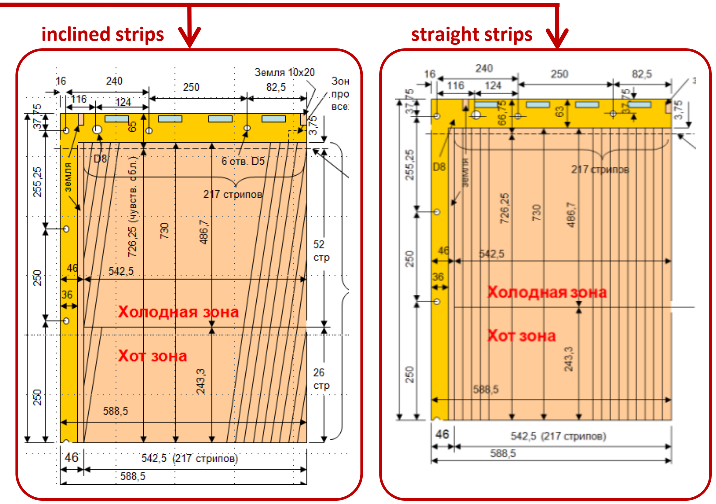
CSC (Cathode Strip Chamber) is a gaseous detector with microstrip readout. It belongs to the **outer tracking system** in the BM@N setup.

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



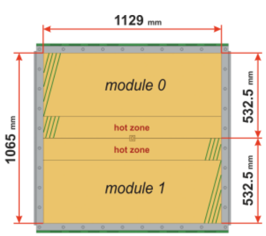
Strip configuration

The configuration of the strips for each CSC module is described in detail by corresponding schemes

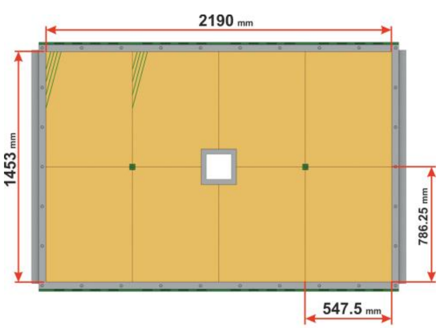


Example: scheme of the strip configuration for the first module of the large CSC

CSC chamber types



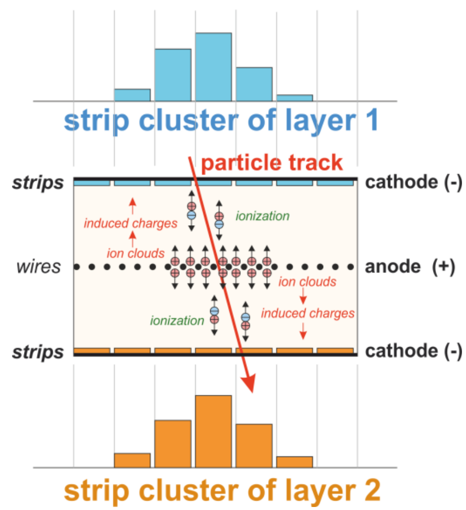
Small CSC



Large CSC

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

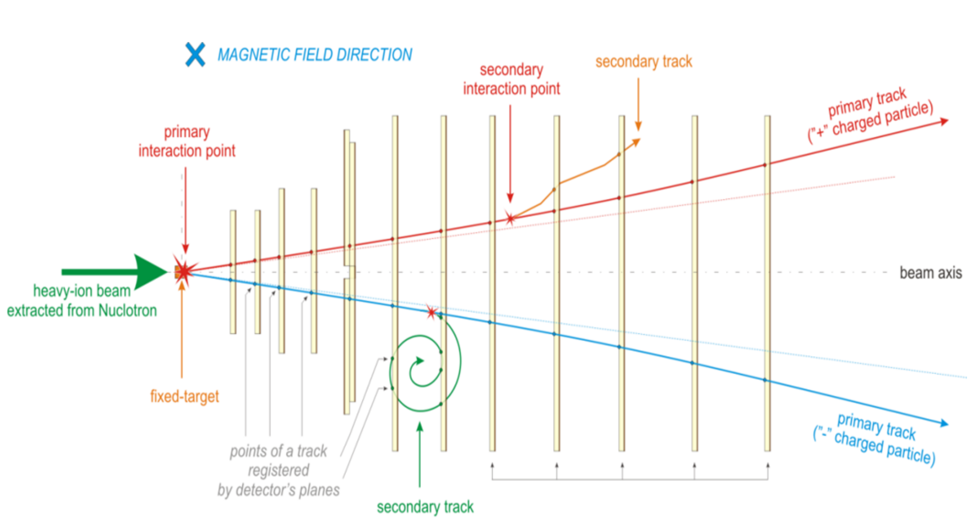
Signal formation



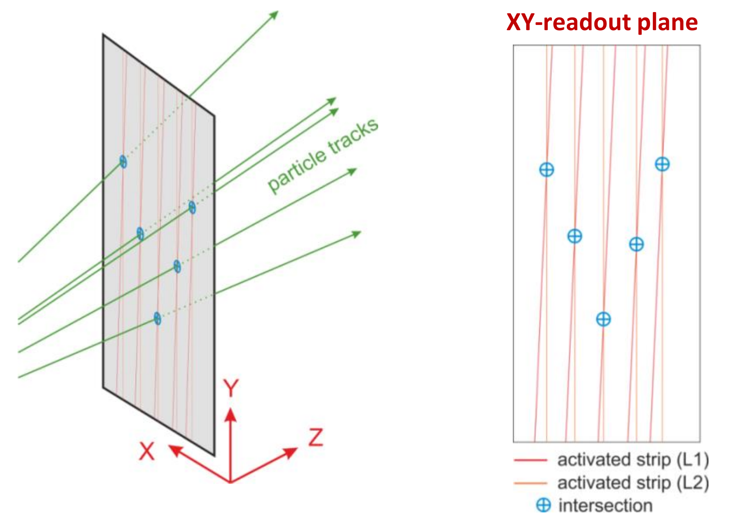
Signal formation in a Cathode Strip chamber:

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.

Microstrip tracking detectors: particle registration

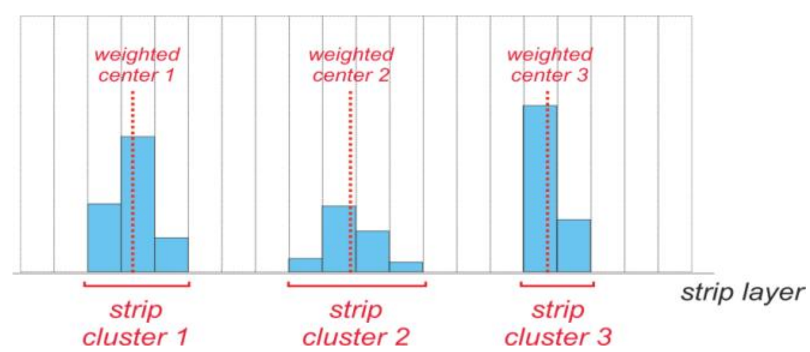


Scheme of particle track registration by planes of tracking detectors



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.



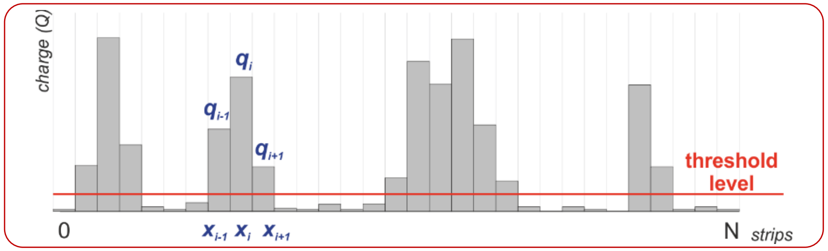
Each readout layer consists of a set of strips. The **response** from a passing particle is represented by one or several fired strips (on each layer) that form a cluster (group of fired strips from one particle).

COORDINATE RECONSTRUCTION:

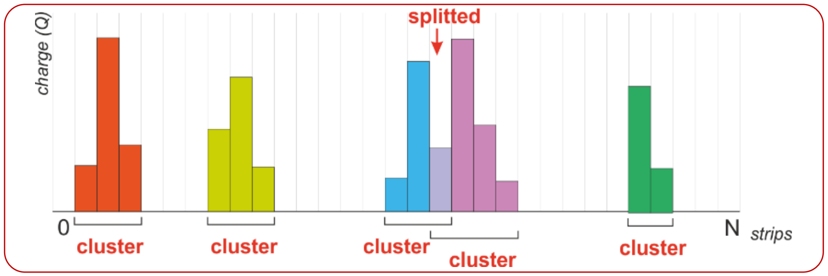
CLUSTERING → HIT FINDING

Clustering steps

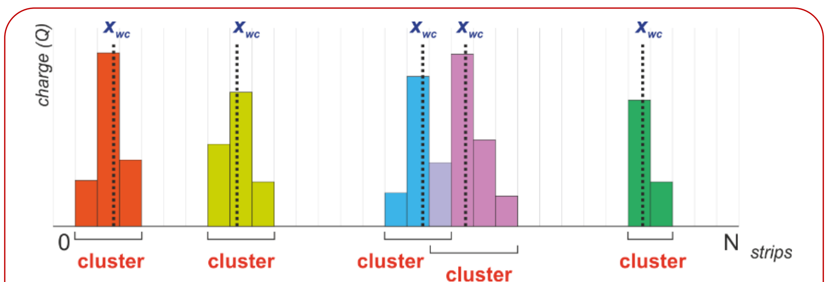
1 Defining threshold level and cutting noise strips



2 Finding and splitting welded clusters by the “Peak and Valley” algorithm



3 Calculation of weighted centers of clusters by the “Center of Gravity” algorithm and estimating their deviations



$$x_{wc} = \frac{\sum_{i=1}^{n} x_i q_i}{\sum_{i=1}^{n} q_i}$$

center of gravity

$$x_{err} = \sqrt{\frac{\sum_i^n (x_i - x_{wc})^2 q_i}{\sum_i^n q_i}}$$

root mean square deviation

$$|x_{err}| = \frac{\sum_i^n |x_i - x_{wc}| q_i}{\sum_i^n q_i}$$

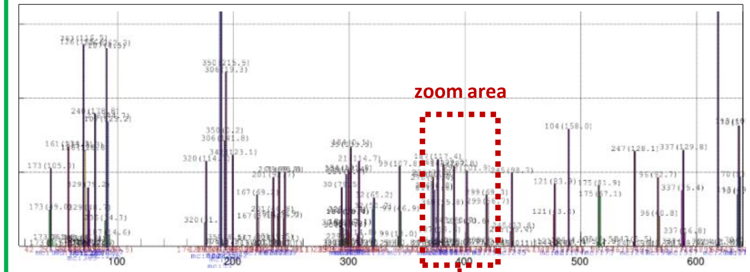
mean absolute deviation

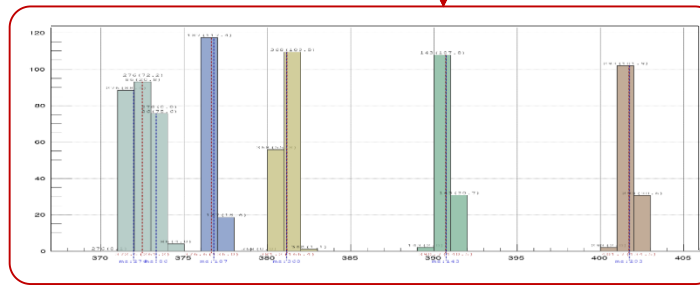
$$x_{err} = \frac{1}{\sqrt{12}}$$

1-strip clusters

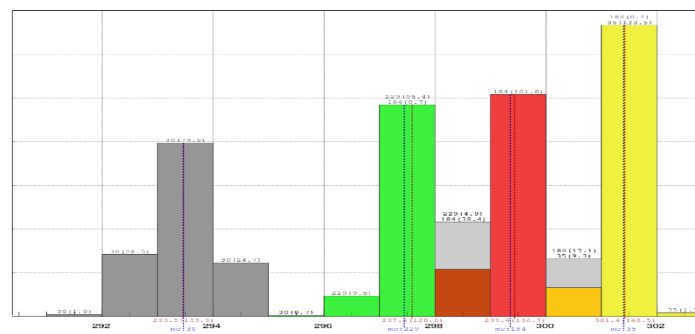
Real clusters

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)





Example: the result of the clustering algorithm



Found clusters are marked with different colors. Their calculated weighted centers are shown by vertical lines

COORDINATE RECONSTRUCTION:

CLUSTERING → HIT FINDING

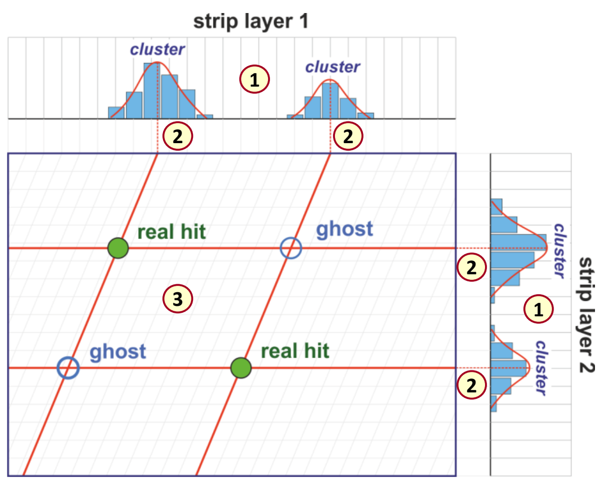
Hit finding steps

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

2. We calculate weighted position of each cluster to collapse its 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".

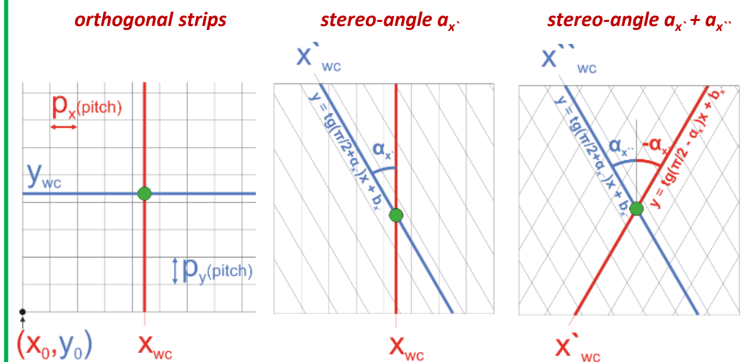
4. The obtained hits are used in the subsequent procedures such as track finding.



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

Reconstruction of spatial coordinates

Reconstruction of the **XY coordinates** on the readout plane is performed by finding the intersections of the weighted centers of the clusters for both strip layers:



Orthogonal strips:

$$x = x_0 + x_{wc} \cdot p_x$$

$$y = y_0 + y_{wc} \cdot p_y$$

Stereo-angle $a_{x'}$:

$$x = x_0 + x_{wc} \cdot p_x$$

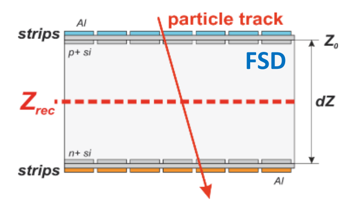
$$y = tg\left(\frac{\pi}{2} + \alpha_{x'}\right) \cdot x + b_{x'}$$

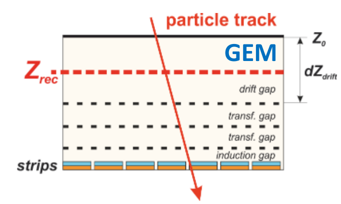
Stereo-angle $a_{x'} + a_{x''}$:

$$x = \frac{b_{x''} - b_{x'}}{tg\left(\frac{\pi}{2} - \alpha_{x'}\right) - tg\left(\frac{\pi}{2} + \alpha_{x''}\right)}$$

$$y = tg\left(\frac{\pi}{2} - \alpha_{x'}\right) \cdot x + b_{x'}$$

Z coordinate reconstruction along the particle flight trajectory depends on the type of detectors:

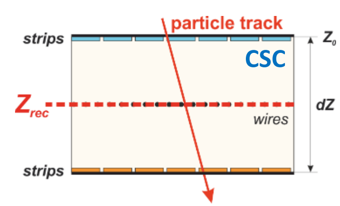




FSD: $Z_{rec} = z_0 + \frac{dz}{2}$

GEM: $Z_{rec} = z_0 + \frac{dz_{drift}}{2}$

CSC: $Z_{rec} = z_0 + \frac{dz}{2}$

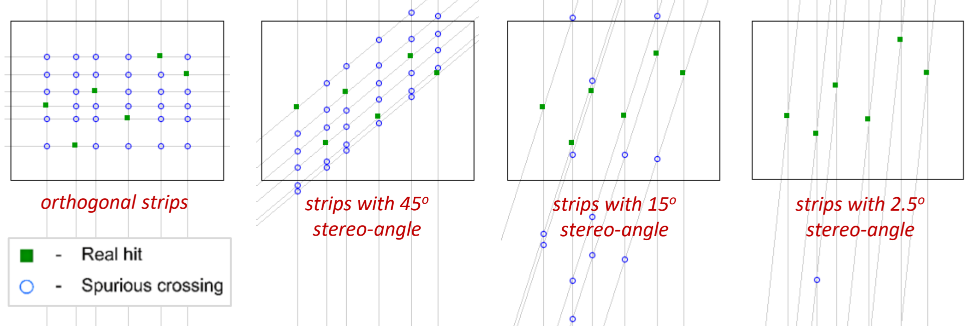


Coordinate reconstruction: hit finding (2)

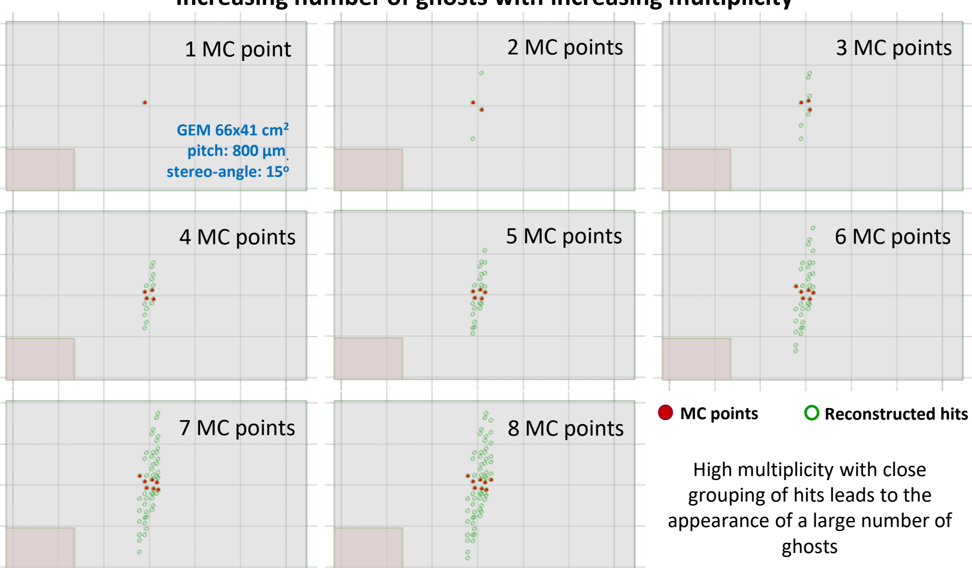
Shortcoming of microstrip readout

The principal disadvantage of using strips is the appearance of spurious intersections ("ghosts" or "fakes")

In order to decrease the ghost quantity is to rotate strips of one layer by a certain stereo-angle with respect to another layer

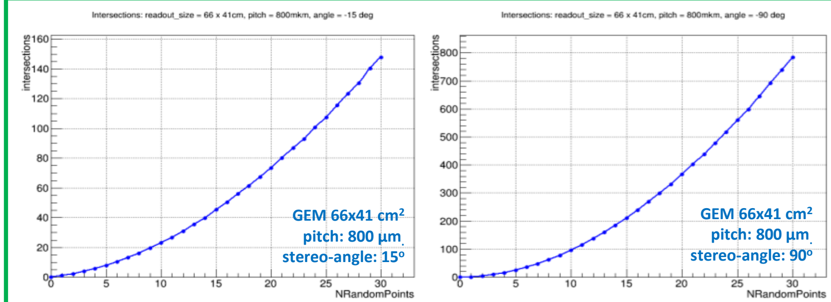


Increasing number of ghosts with increasing multiplicity



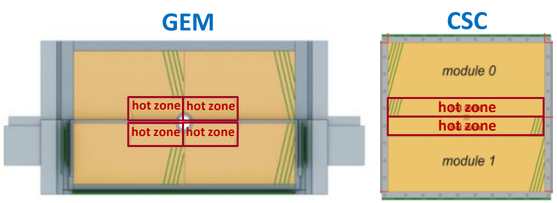
High multiplicity with close grouping of hits leads to the appearance of a large number of ghosts

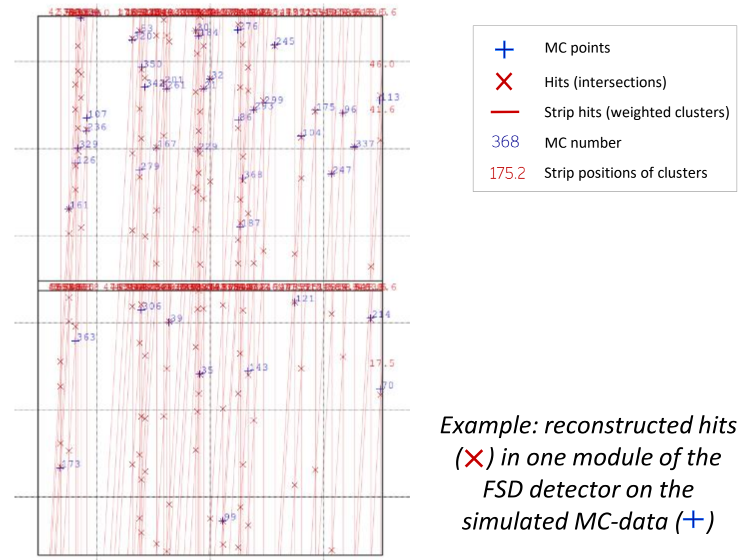
Dependence of ghosts on the number of points



Dependencies of the number of hits on the number of MC point for strips with 15° stereo-angle and orthogonal strips

The use of "**hot zones**" with the independent set of strips in the areas with high multiplicity reduces the number of spurious hits





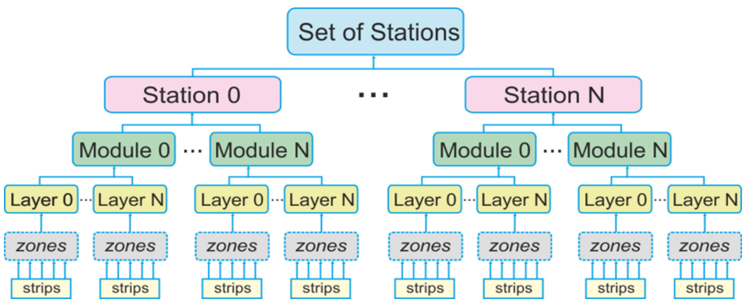
Example: reconstructed hits (×) in one module of the FSD detector on the simulated MC-data (+)

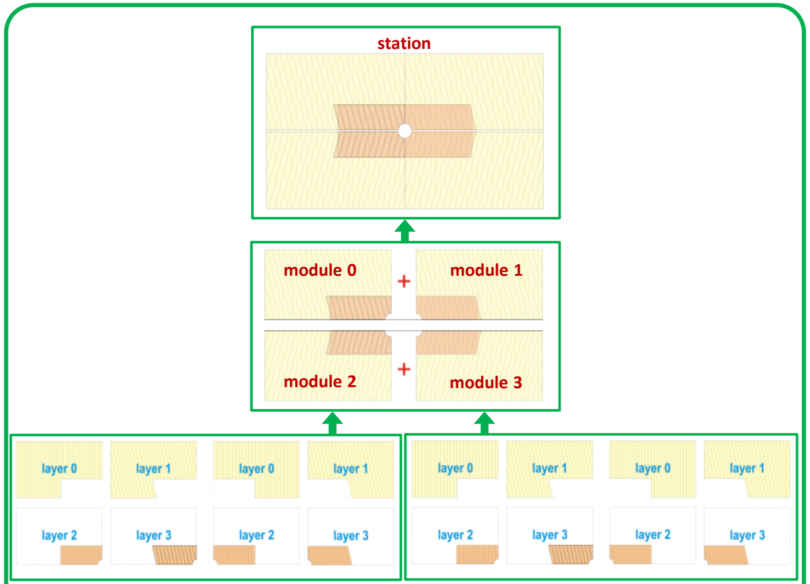
Microstrip tracking detectors: software implementation

Structure of tracking detectors

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

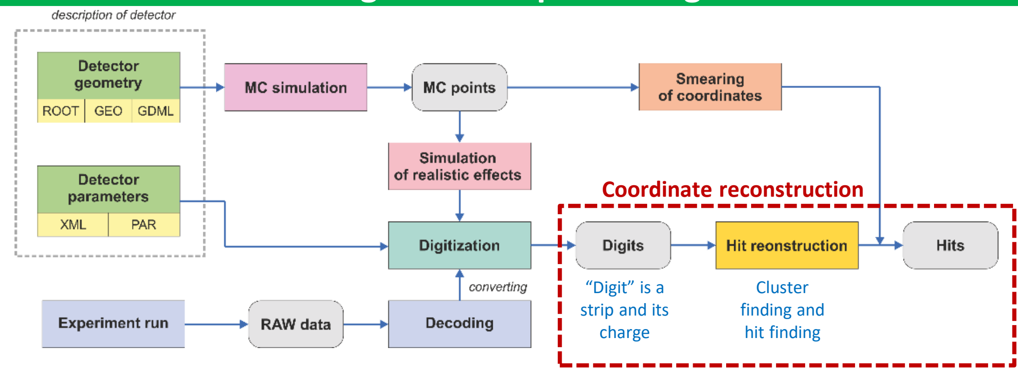
Strips are integrated into a layer,
Layers – into a module,
Modules – into a stations,
Stations – into a set of stations





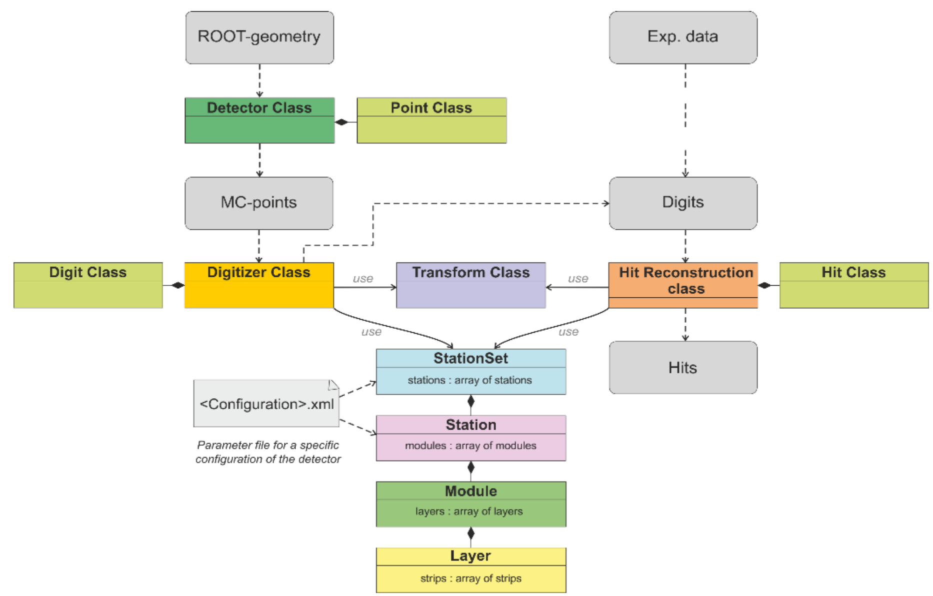
Visual example of the structure of one GEM chamber

Stages of data processing



Basic stages of data processing for microstrip tracking detectors in BmnRoot

Software implementation

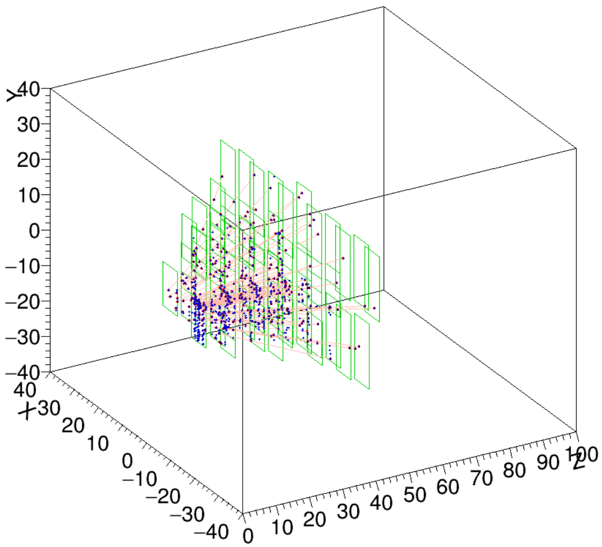


Software structure for the microstrip tracking detectors (as a class diagram)

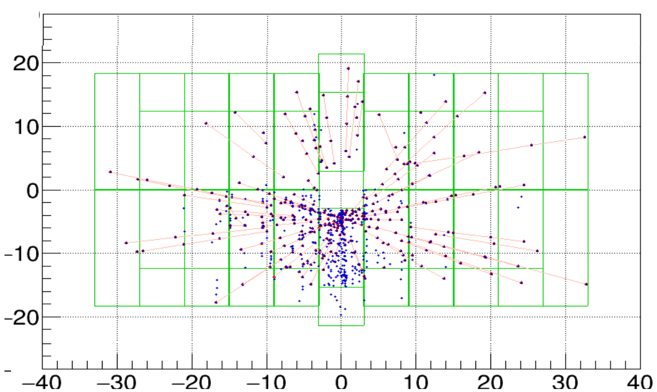
Coordinate reconstruction: the result of the algorithms

Hit reconstruction in Forward Silicon Detector

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



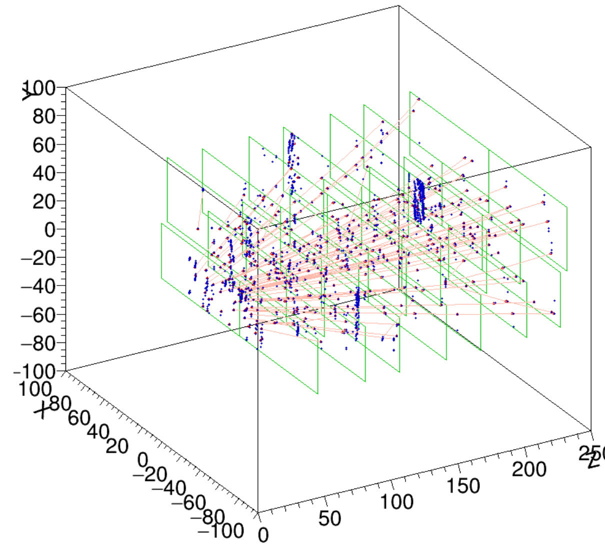
Forward Silicon *detector (3D view)*



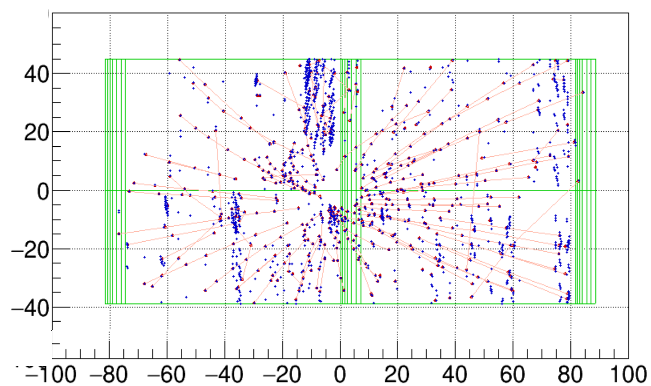
Forward Silicon *detector (XY view)*

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

Hit reconstruction in GEM Detector



GEM *detector (3D view)*



GEM *detector (XY view)*

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

Summary

What has been done:

- Software for coordinate reconstruction for microstrip tracking detectors (RUN-8 configuration):
  - Silicon Beam Tracker and Beam Profilometers
  - Forward Silicon and GEM detectors
  - Small and large CSC detectors

Thank you for your attention…