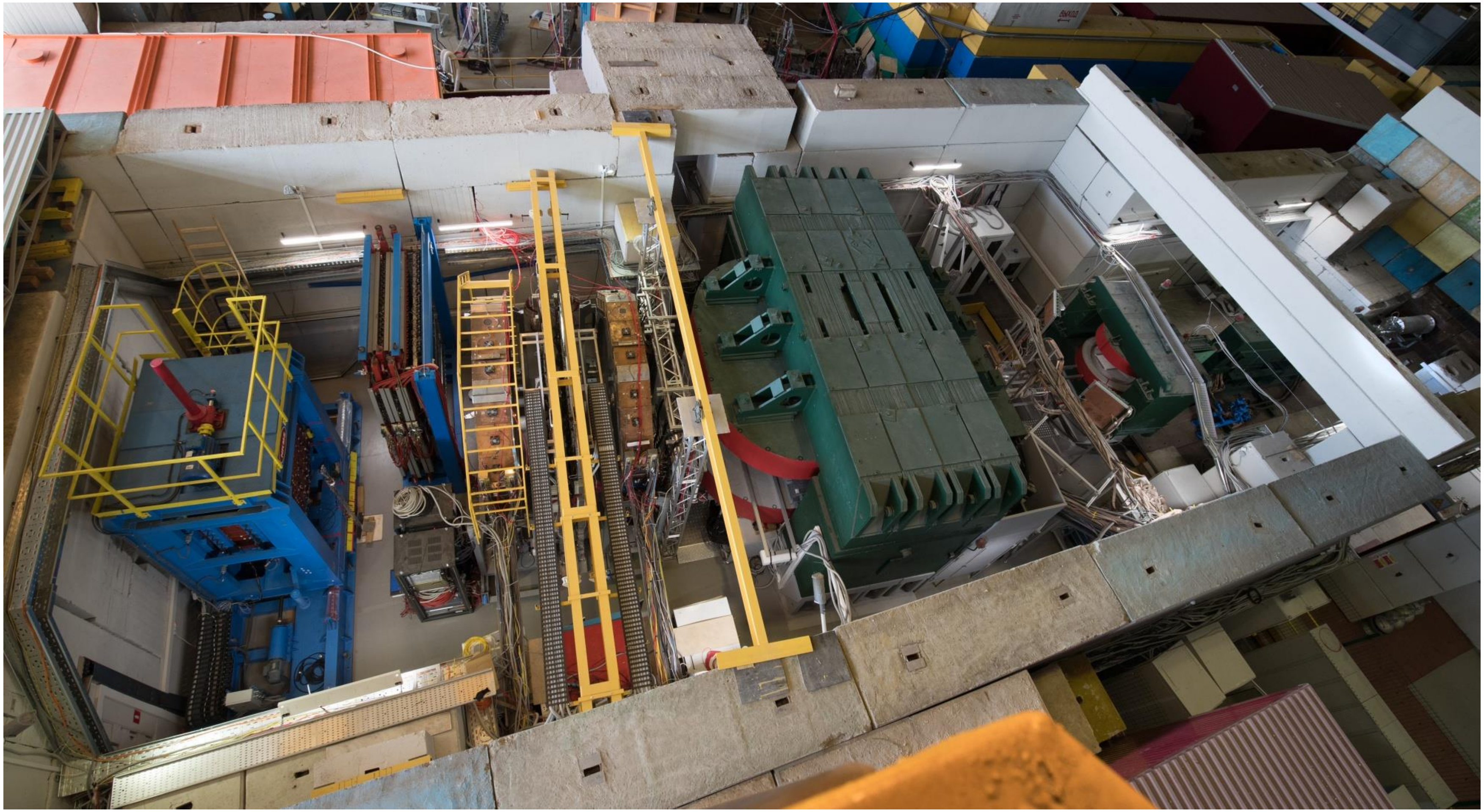
# Implementation of the BM@N project

## M.Kapishin



# Baryonic Matter at Nuclotron (BM@N) Collaboration:

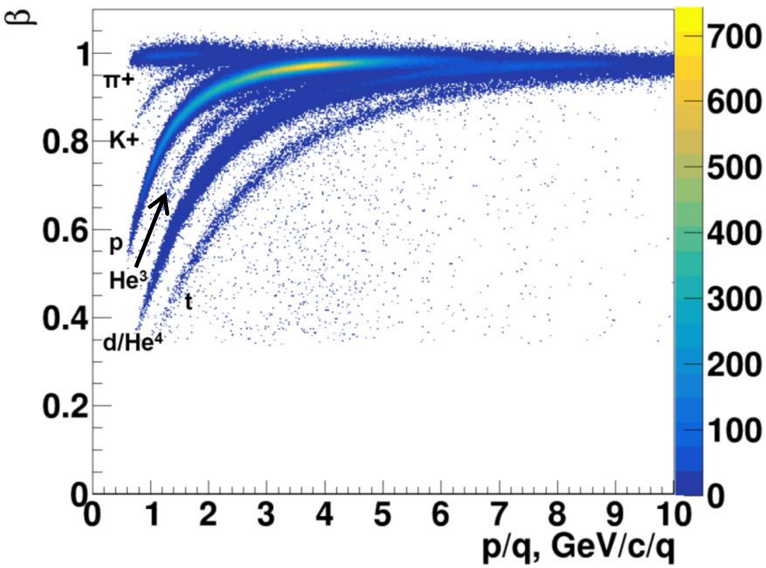
***10 Countries, 20 Institutions, 240 participants, 11 Institutions signed MoU + JINR***

- *University of Plovdiv, Bulgaria → MoU signed;*
- *St.Petersburg University → MoU signed;*
- *Shanghai Institute of Nuclear and Applied Physics, CFS, China;*
- *Nuclear Physics Institute CAS, Czech Republic→ MoU signed;*
- *CEA, Saclay, France;*
- *TU Darmstadt, Germany;*
- *GSI & FAIR, Germany;*
- *Tubingen University, Germany → MoU signed;*
- *Tel Aviv University, Israel;*
- *Joint Institute for Nuclear Research;*
- *Warsaw University of Technology, Poland→ MoU signed;*
- *University of Wroclaw, Poland → MoU signed;*
- *Institute of Nuclear Research RAS, Moscow, Russia → MoU signed;*
- *NRC Kurchatov Institute, Moscow;*
- *Institute of Theoretical & Experimental Physics, NRC KI, Moscow → MoU signed;*
- *Moscow Engineer and Physics Institute, Russia → MoU signed;*
- *Skobeltsin Institute of Nuclear Physics, MSU, Russia → MoU signed;*
- *Moscow Institute of Physics and Technics, Moscow, Russia → MoU signed;*
- *Massachusetts Institute of Technology, Cambridge, USA.*
- *Lebedev Physics Institite of RAS, Moscow → accepted into Collaboration*

**BM@N talks at conferences in 2021:**

**• P.Senger, International conference on Critical Point and Onset of De-confinement (CPOD 2021)**
**•D.Dementiev,19th International Conference on St rangeness in Quark Matter (SQM 2021)**
**• P.Senger + A.Maksymchuk + Al.Zinchenko 10th International Conference on New Frontiers in Physics (ICNFP 2021)**
**•P.Batyuk,20th Lomonosov Conference on Eleme ntary Particle Physics**

# Ongoing analyses of Carbon / Ar runs




**Ar beam , 3.2 AGeV , Ar + Al,Cu,Sn → X**

Yields of $\pi^{\pm}$, $K^{+}$, p, t, $He^{3}$, d/$He^{4}$ in *argon - nucleus* interactions (combination of ToF-400 and ToF-700)

**Advanced analyses:**

V.Plotnikov: π+, K+ in ToF-400 data

L.Kovachev, Yu.Petukhov: π+, K+ as well as p, t, $He^{3}$, d/$He^{4}$ in ToF-700 data

**Parallel analyses:**

K.Alishina (PhD student) and A.Huhaeva (student): p,t, $He^{3}$, d/$He^{4}$ in ToF-400 and ToF-700

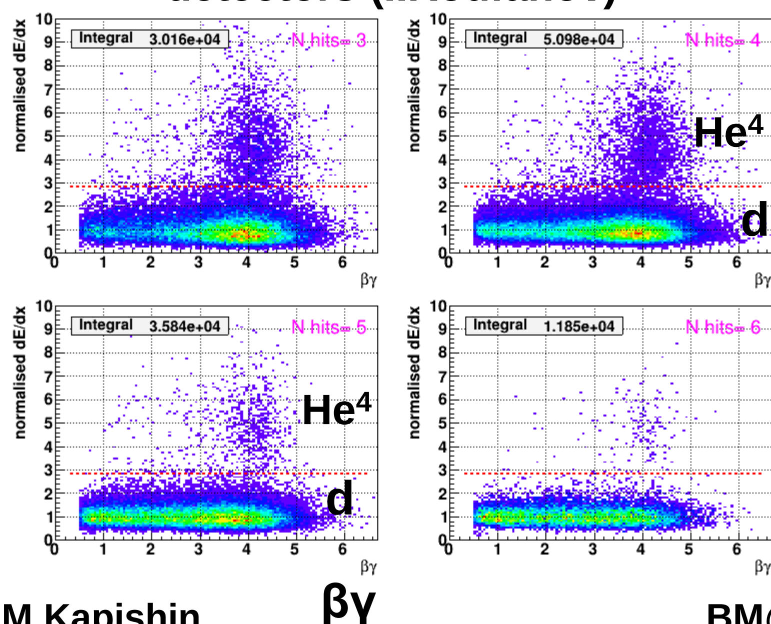
K.Mashitsin (student), S.Merts: π± in ToF-400 and ToF-700 data (independent tracking)

Yu.Stepanenko: Yields of Λ hyperons in *carbon - nucleus* interactions at 4.0, 4.5 AGeV,

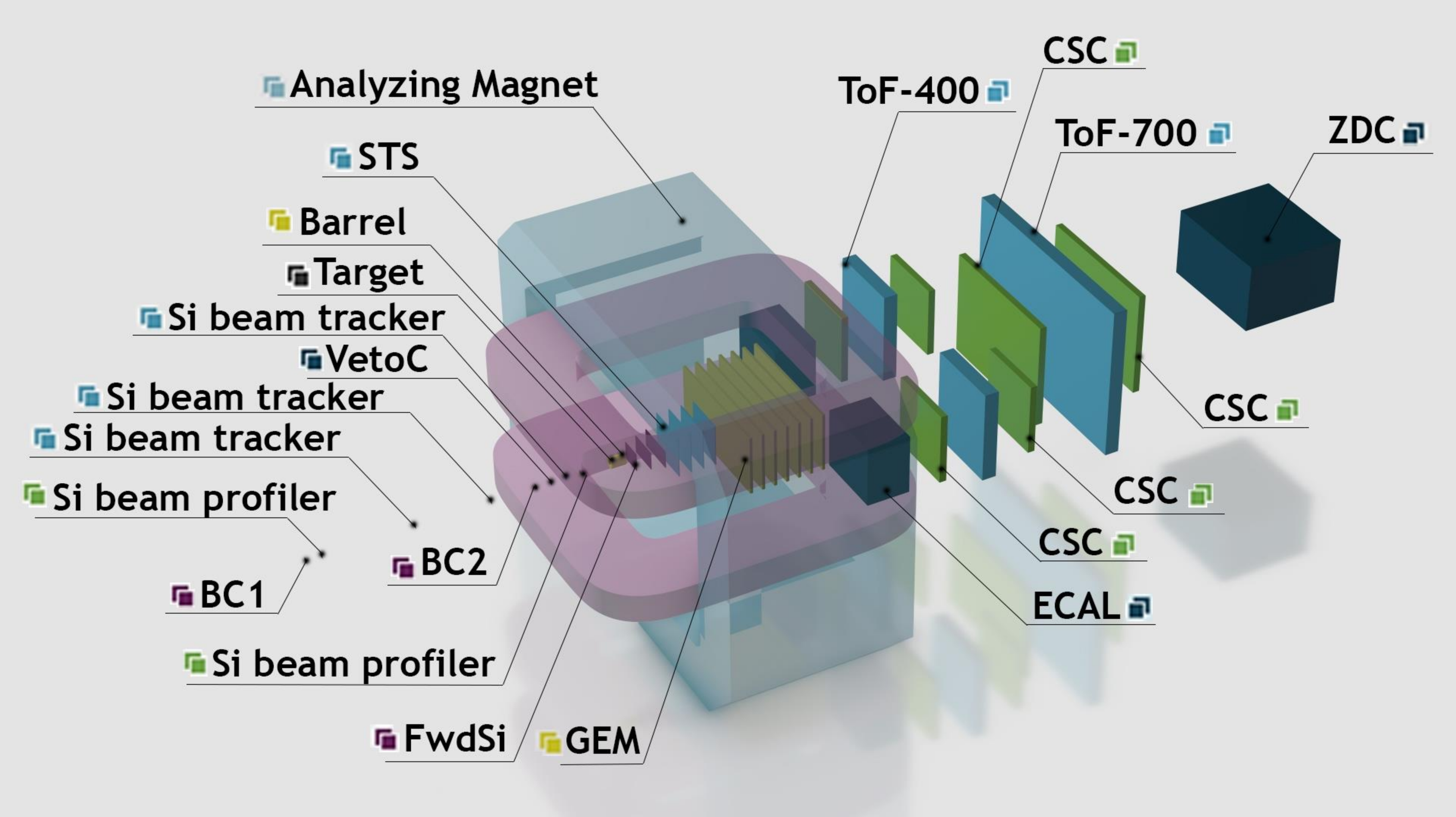
C+ C,Al,Cu → Λ + X

Yields of Λ hyperons in *argon - nucleus* interactions

$He^{4}$ / d separation by dE/dx in GEM detectors (I.Roufanov)



# Configuration of BM@N detector for heavy ion program (without beampipe)



**NICA main competitor → STAR experiment: BES Fixed Target program**
**Collected $2 \cdot 10^9$ interactions of Au+Au at $\sqrt{s}$ = 3 GeV in 2021**

# Plan for BM@N Experimental physics run for 800 hours (33 days) in spring 2022

## BM@N: Estimated hyperon yields in Xe + Cs collisions

4 A GeV Xe+Cs collisions, multiplicities from PHSD model,
Beam intensity $2.5 \cdot 10^5$/s, DAQ rate $2.5 \cdot 10^3$/s, accelerator duty factor 0.25

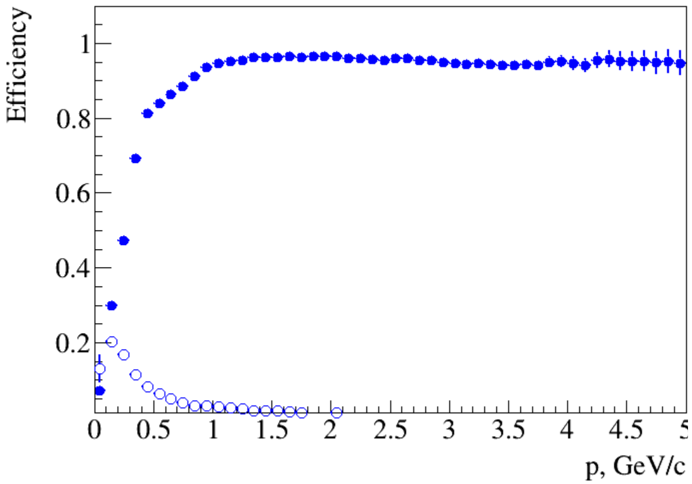
$1.8 \cdot 10^9$ interactions
$1.8 \cdot 10^{11}$ beam ions

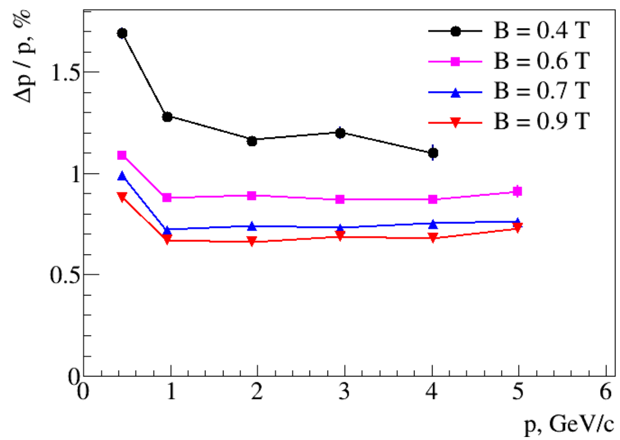
| Particle | $E_{thr}$NN GeV | M b<10 fm | ε % | Yield/s b<10fm | Yield / 800 hours b<10 fm |
|---|---|---|---|---|---|
| Λ | 1.6 | 1.5 | 3 | 220 | $0.8 \cdot 10^8$ |
| $\Xi^-$ | 3.7 | $2.3 \cdot 10^{-2}$ | 1 | 1.1 | $4 \cdot 10^5$ |
| $\Omega^-$ | 6.9 | $2.6 \cdot 10^{-5}$ | 1 | $1.3 \cdot 10^{-3}$ | 470 |
| Anti-Λ | 7.1 | $1.5 \cdot 10^{-5}$ | 3 | $2.2 \cdot 10^{-3}$ | 800 |

# 1st stage of hybrid central tracker: 3 Forward Si + GEM (spring 2022 configuration)

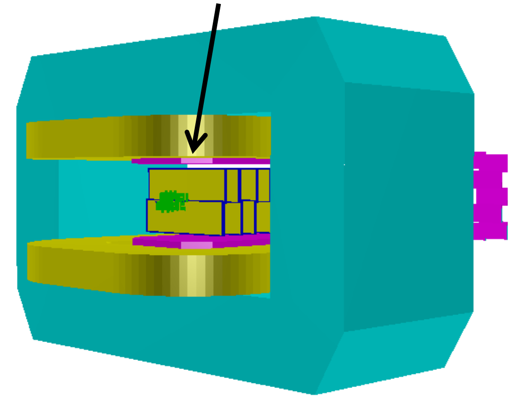
A.Zinchenko, V.Vasendina

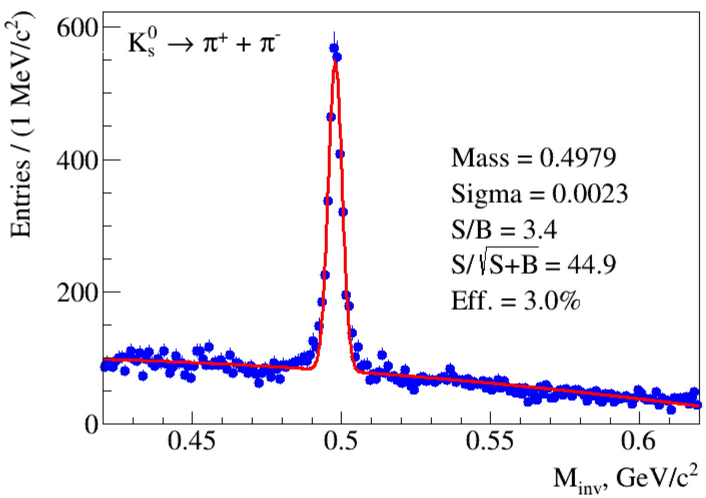
## DCM-SMM model: Xe + Sn , $T_0$= 3.9 AGeV



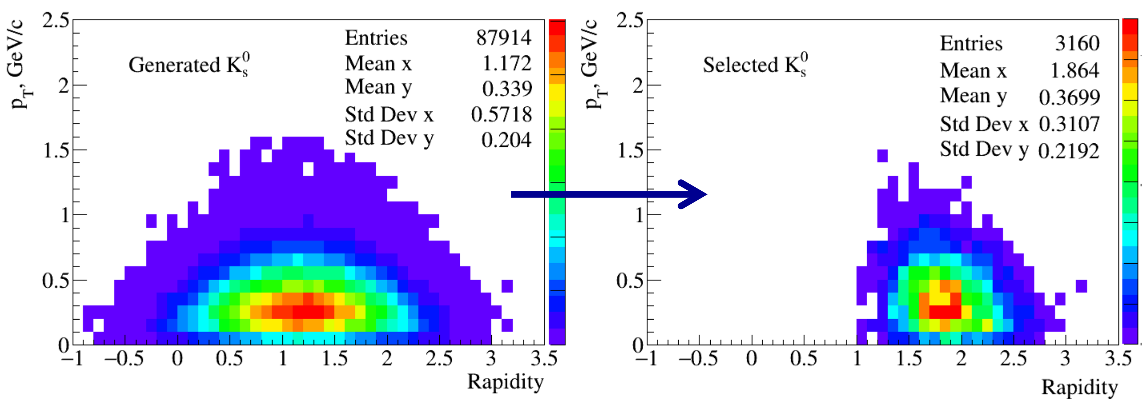




3 Forward Si + 7 GEM,
Si/GEM configuration 2022





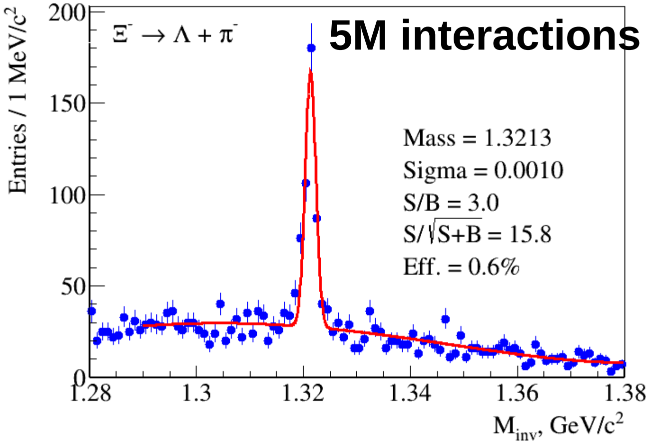

## Phase space of generated and reconstructed $K^0_S$

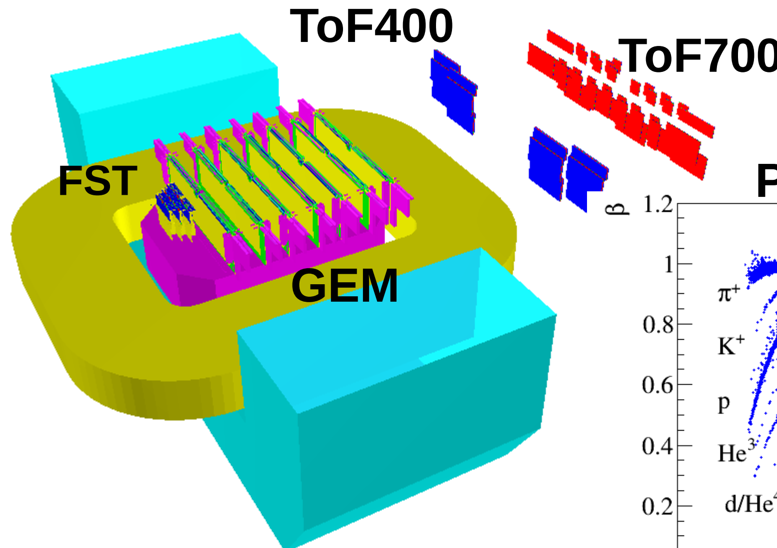



**Laboratory system**

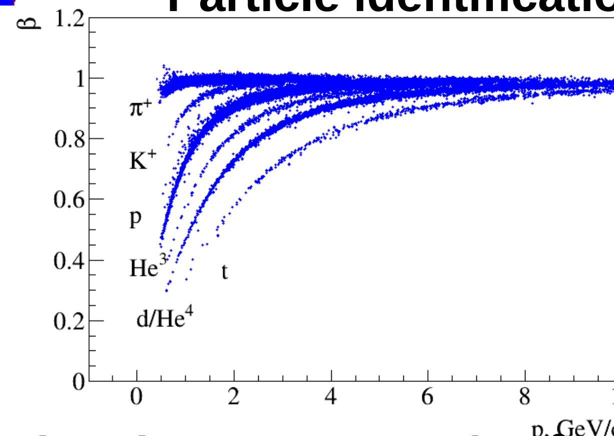
# Feasibility studies for first physics run: $\Xi^-$ and $_{\Lambda}H^3$ reconstruction in Xe +A interactions: 3 Forward Si + GEM tracker

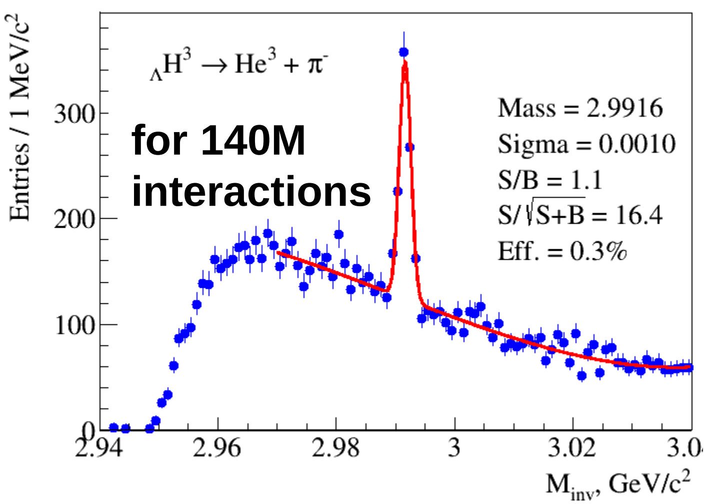
## DCM-SMM model: Xe + Sn , $T_0$= 3.9 AGeV



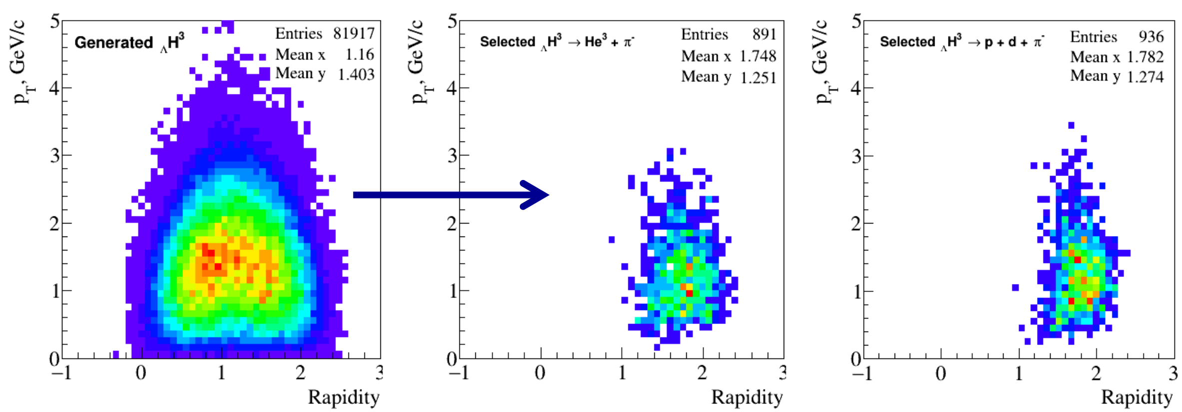




## Particle identification

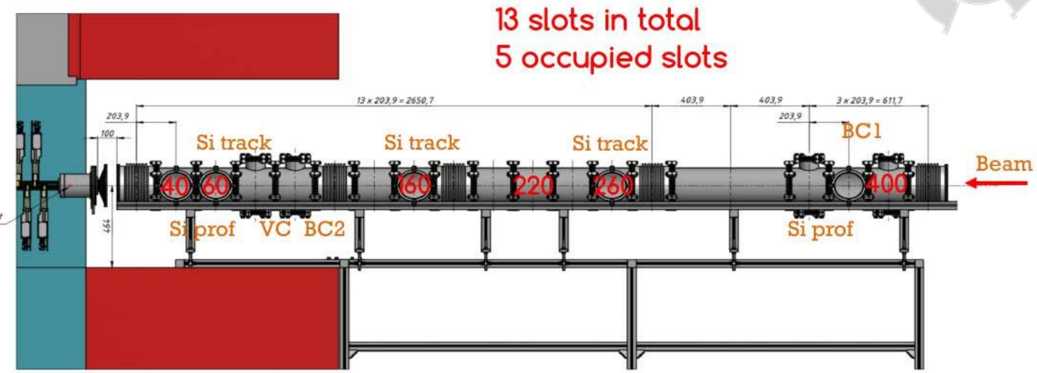



## Phase space of generated and reconstructed $_{\Lambda}H^3$

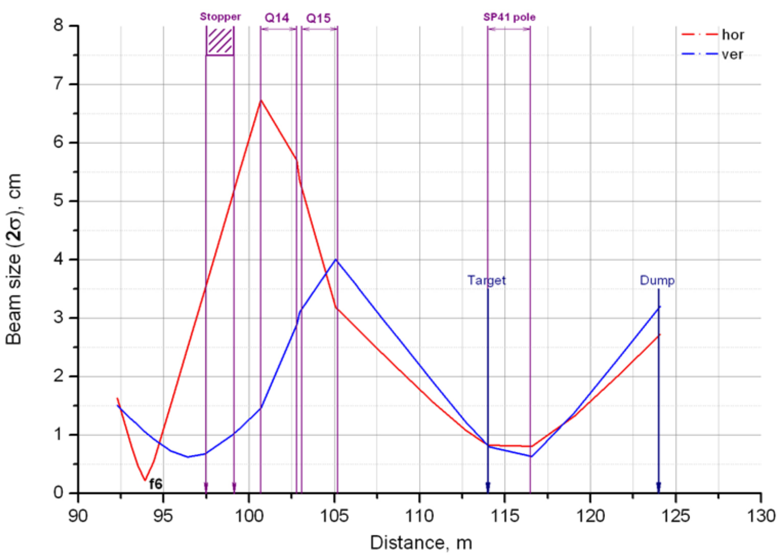


# Beam tracking with 3 Si detectors

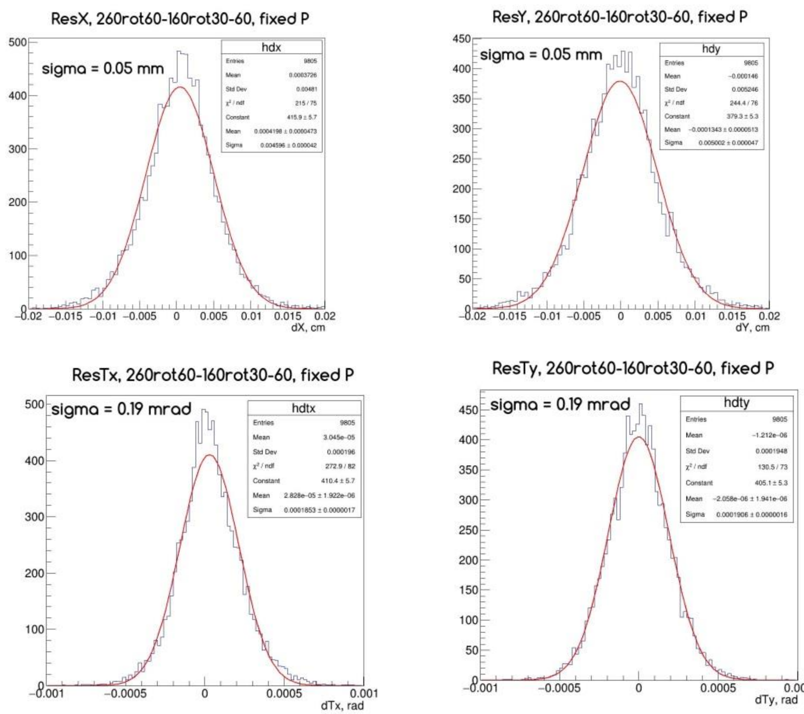



**Magnetic Optics in BM@N area: angular beam spread of ~2 mrad**

Beam envelopes at the BM@N area




**Vertex and beam angular resolution from simulation of 3 Si detectors (S.Merts)**

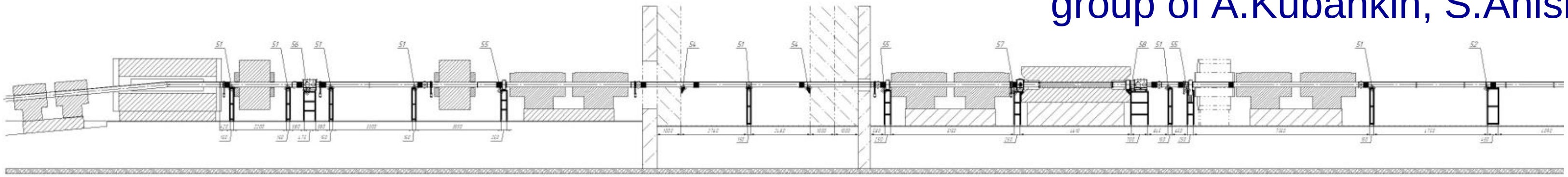


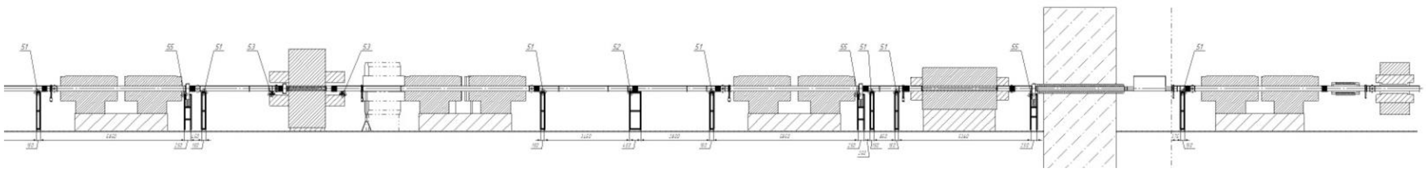

**Measured beam spot at target**

| | $C^{12}$ 2017 | Ar 2018 | Kr 2018 |
|---|---|---|---|
| $\sigma_X$ = | 6 mm | 5 mm | 5.3 mm |
| $\sigma_Y$ = | 4.9 mm | 5 mm | 3.2 mm |

# Vacuum ion beam pipe from Nuclotron to BM@N

group of A.Kubankin, S.Anisimov



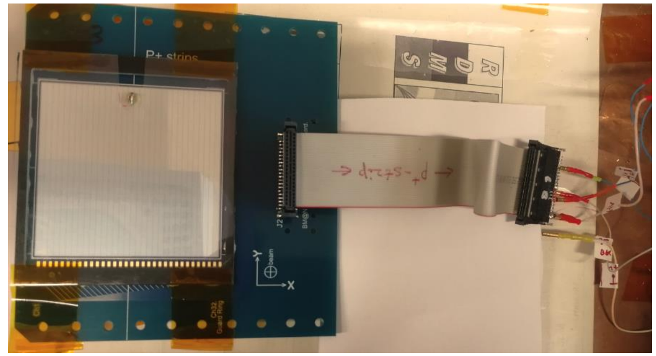



# BM@N main detector activities towards heavy ion run

## Central tracking system

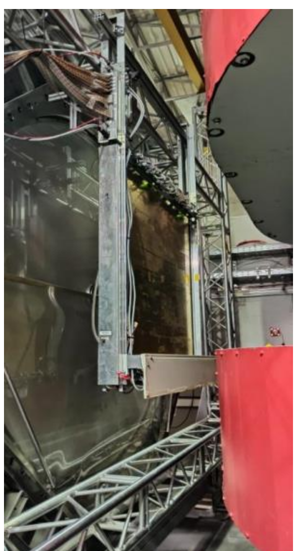
**GEM detectors on positioning mechanics in magnet**

**Silicon detector of beam profile meter**



**Carbon fiber vacuum beam pipe, $1.3 \cdot 10^{-3}$ Torr**

**Outer tracker: Cathode Strip Chambers → 4 CSC of 106x106 cm2**



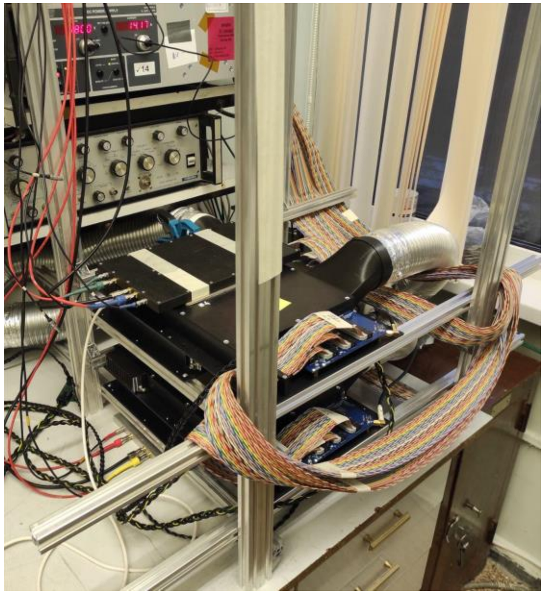
**Production of big CSC of 220x145 cm2**

**Silicon beam tracking detector in SRC setup**

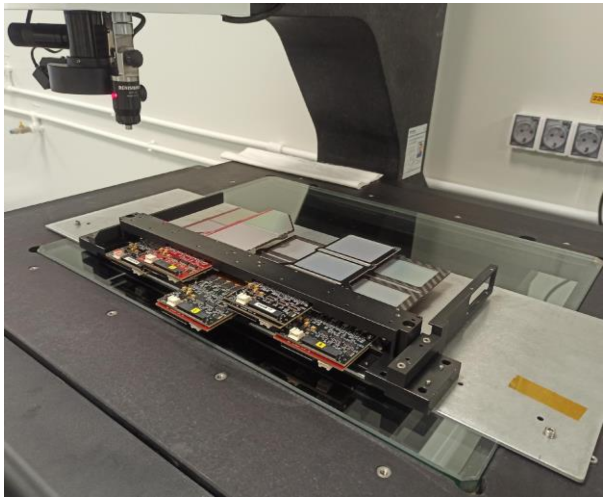
**Forward hodoscope in front of FHCAL**

# Forward Silicon Tracker towards heavy ion run

**Setup for FST tests with Cosmic rays**



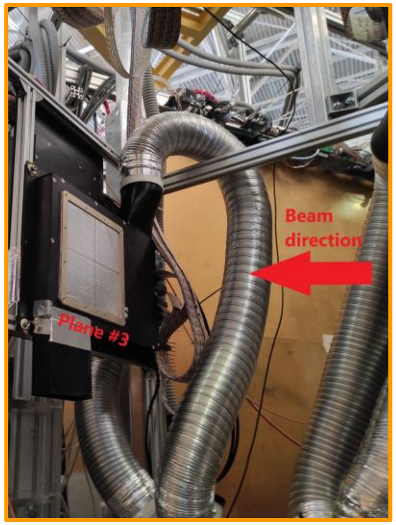
**Setup for FST inner alignment**



**N.Zamiatin group**

**FST support mechanics**

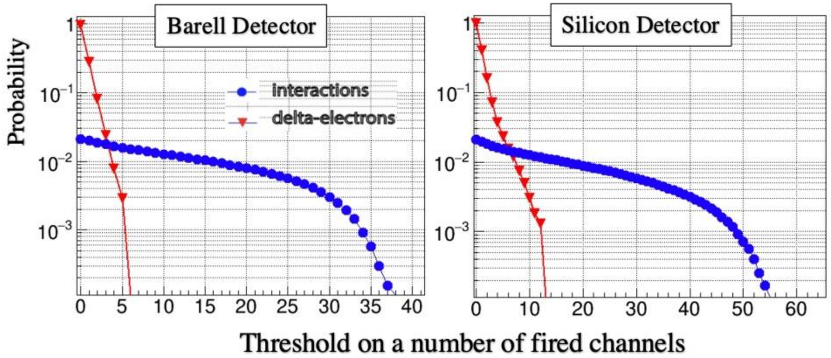
**FST modules in SRC setup**



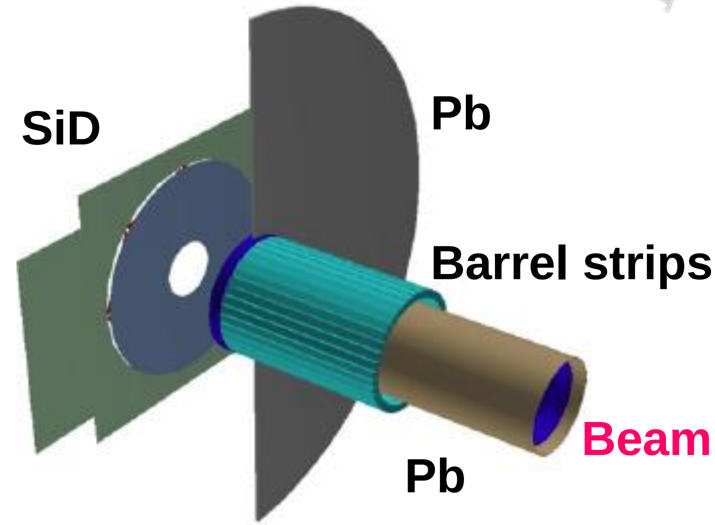

►some delay due to multi-step process of assembly and tests

►32 (29) out of 42 module for 3 FST stations are assembled (tested), remaining modules to assemble and test in February 2022

# BM@N Trigger detectors



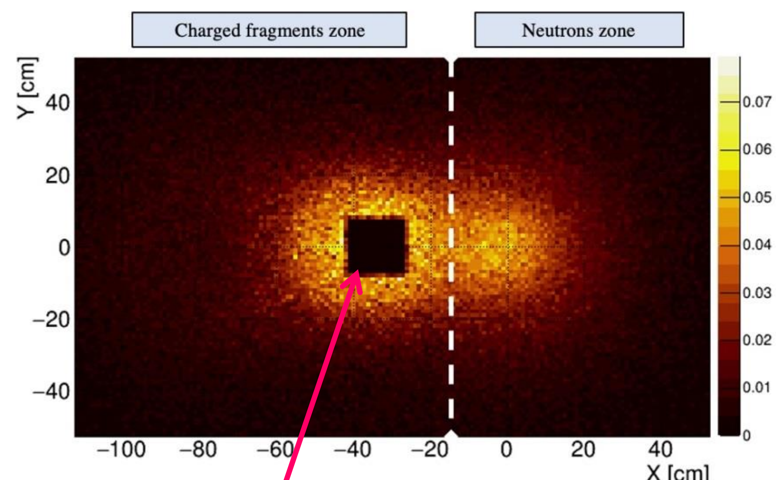

## Trigger detectors in target area: multiplicity SiD and Barrel BD




## Variants of trigger logics

| Trigger type | Trigger logic |
|---|---|
| Beam Trigger (BT) | BT = BC1 * $VC_{veto}$ * BC2 |
| Min. Bias Trigger (MBT) | MBT = BT * $FD_{veto}$ * FHCal |
| Centrality Trigger 1 (CCT1) | CCT1 = MBT * BD(low) * SiD(low) |
| Centrality Trigger 2 (CCT2) | CCT2 = MBT * BD(high) * SiD(high) |
| No Interaction Trigger (NIT) | NIT = BT * $FD_{Au\text{-}ion}$ * $FHCal_{veto}$ |

## FHCAL rates



# Status of BM@N detector upgrade

**Forward Si tracking detectors:**
►Proven technology and FEE readout electronics → used in C, Ar, Kr runs
►32 (29) out of 42 modules are assembled (tested), remaining to assemble and test in February 2022

**Beam Si tracking detectors and beam profile meters:**
►Tracking detectors ready to be tested standalone in SRC run
►Profile meters ready, electronics in February

**GEM tracking detectors:**
►All detectors produced at CERN, → tested in C, Ar, Kr runs and recently with cosmic rays

**Trigger and T0 detectors:**
► Produced, detector performance to be tested in first heavy ion run

**Large aperture STS tracker:**
►Complicated module, readout cables and ladder assembly, delay in production and commissioning phase → 2 stations out of 4 to be ready by end of 2023

**CSC chambers for Outer tracker:**
►4 chambers are ready and tested
►1st big CSC chamber expected in spring 2022, second → end 2022

**Time of Flight identification system:**
►Detectors and readout electronics are in operation since 2018

**Carbon fibre beam pipe inside BM@N:**
►Vacuum beam pipe and target station are ready, under tests till spring 2022

**Beam pipe in front of target:**
► Beam pipe elements and detector boxes are delivered to BM@N

**New FHCAL hadron calorimeter:**
►FHCAL, Forward Quartz Hodoscope and Fragment Wall installed into BM@N setup

# Requirements for physics runs with heavy ion beam

**SRC physics run with C12 beam (4 weeks, end of January - February)**

**Limitations / requirements for BM@N physics run with Xe beam in spring 2022 (800 hours of physics data taking to collect $2\cdot10^9$ Xe + CsI interactions)**

- **Need Booster – Nuclotron accelerator system**
- **Need 2 months for transition from SRC set-up to heavy ion setup + 0.5 month for magnetic field map measurement**
- **Full vacuum transport channel from Nuclotron to BM@N**
- **Xe beam of maximal possible energy (up to 3.9 AGeV)**
- **Need few days for technical run before physics run to prove beam quality and detector response, in case of problems → postpose physics run**
- **Due to the SRC run extension to February 2022:**
  **→ shift BM@N physics run to May - June 2022**

**Requirements for future BM@N physics run with Bi beam (800 hours of physics data taking to collect $2\cdot10^9$ Bi + Bi interactions)**

- **Full vacuum transport channel from Nuclotron to BM@N**
- **Bi beam energy of maximal possible energy (up to 3.8 AGeV)**

**►To perform main BM@N physics program need 10 times more statistics → $2\cdot10^{10}$ Bi+Bi interactions with beam energies from 1.5 AGeV up to 3.8 AGeV**

# BM@N DAC questions / answers:

DAC: The team presented a plan with 4 different tracking configurations arguing that the only reliable way to prove the performance of the STS is by running two intermediate stages with the forward Si detectors (Fwd-Si +Pilot STS + GEM and Fwd-Si + STS + GEM). DAC advocates, however, a plan with two tracking configurations only, going from stage 1 (FwdSi + GEM) directly to the final stage (4 STS + GEM), and making technical runs as detectors become available. DAC argues that running with four configurations will delay the progress toward reaching the final setup of BM@N and will complicate the data analysis requiring large amount of additional work in terms of calibrations and Monte Carlo simulations.

**Answer: Taking into account slow process of the STS development and big time intervals between the BM@N physics runs, we foresee one intermediate configuration of the BM@N central tracker: 3 Fwd-Si +2 Pilot STS + GEM. It will help to understand STS readout, timing correlation between STS and BM@N tracking detectors and increase capacity of the central tracker to reconstruct Au+Au interactions**

DAC is repeating its recommendation for adequate vacuum in the transport line for heavy ions from the Nuclotron to the experimental site. To ensure the best conditions of heavy ion experiments (with low halo and little fragmentation) the beam lines need to have 10-5 to 10-6 Torr. Furthermore, for Au beams, the DAC recommended to have a windowless transport line from Nuclotron to the target area, with needed safety features for protecting the accelerator in case of sudden leak in the experimental area.

**Answer: The measured vacuum in the transport line between the Nuclotron and BM@N is few $10^{-6}$ Torr. Still, few meters of the beam line from the exit window of the Nuclotron are not with vacuum yet and should be realized in a new contract. A windowless transport line from the Nuclotron to the target area requires a comparable vacuum in the Nuclotron ring and the beam transport line and could be realized in a long term perspective.**

DAC requests the BM@N statement that the silicon beam detector life time is equivalent to 2 months of continuous running assuming $10^6$ Au ions per second to be investigated more precisely as a function of spot size and intensity of Au ions at low and high beam energies (different dE/dx and different emittance of the beam). Furthermore, the DAC does not remember having seen studies of beam induced atomic processes (e.g., X-rays and delta electrons impacting on silicon detectors) which will affect all detectors inside the beam line.

**Answer: The effect of the silicon sensitive volume degradation due to interactions with Au ions normalized to 1 MeV neutrons is 450 times higher and dominate over effects of X-rays and delta-electrons. The silicon beam detector response will be monitored during first heavy runs to propagate the detector life time estimations for longer operation.**

DAC recommends to extend the trigger studies to include p+p and p+A collisions. Deuteron beams could be used instead or in addition to p beams and light targets of Beryllium could be used instead of a liquid hydrogen target as done in the SRC experiment.

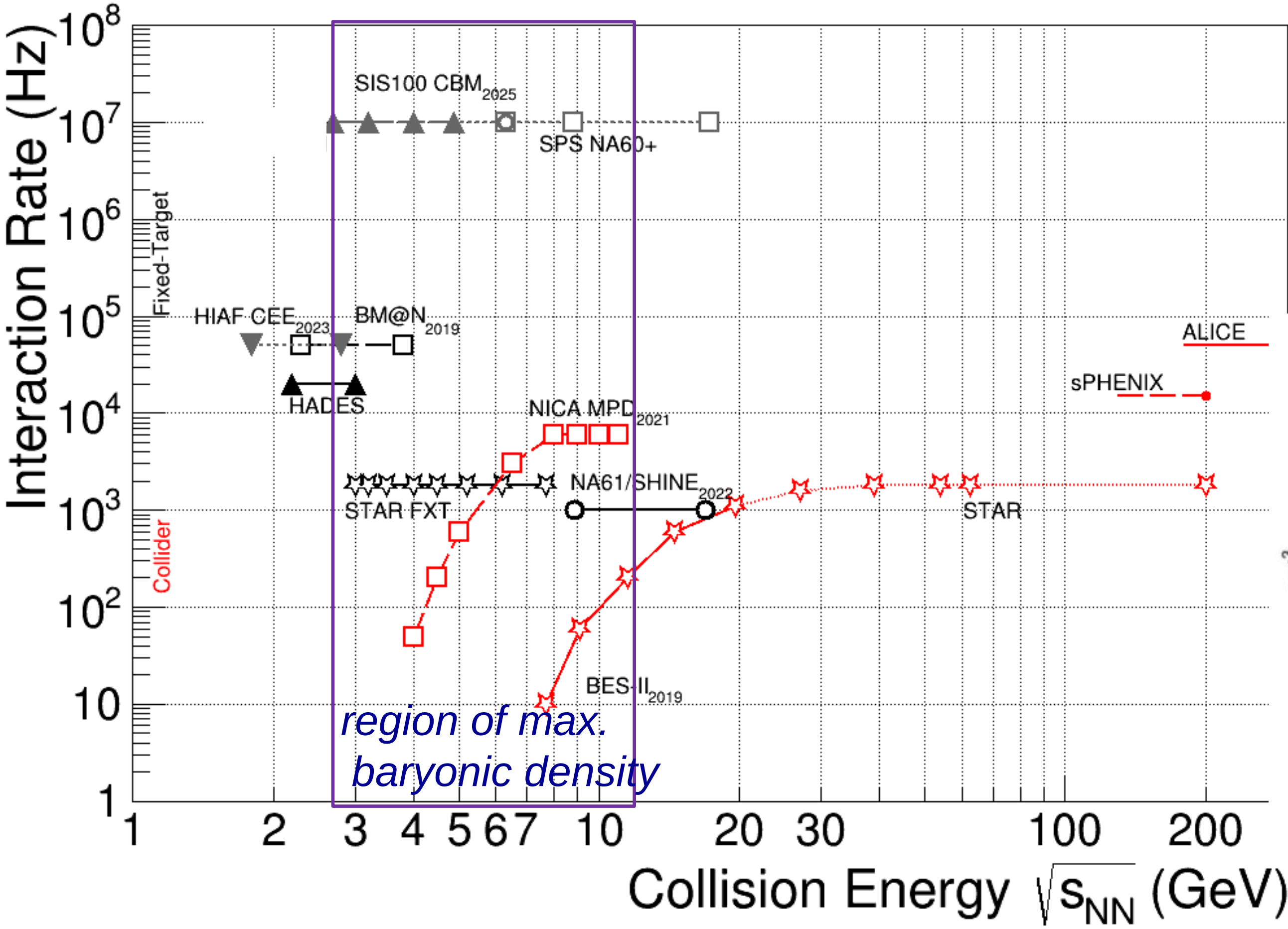
**Answer: The BM@N trigger system comprises the multi-strip Barrel Detector around the target, the segmented silicon Multiplicity Detector behind the target and the Fragment Detector in front of the FHCAL calorimeter. Each detector response will be cross monitored. The efficiency of the Fragment Detector to trigger interactions of proton and light nucleus beams with targets is expected to be higher than that of the trigger detectors around the target.**

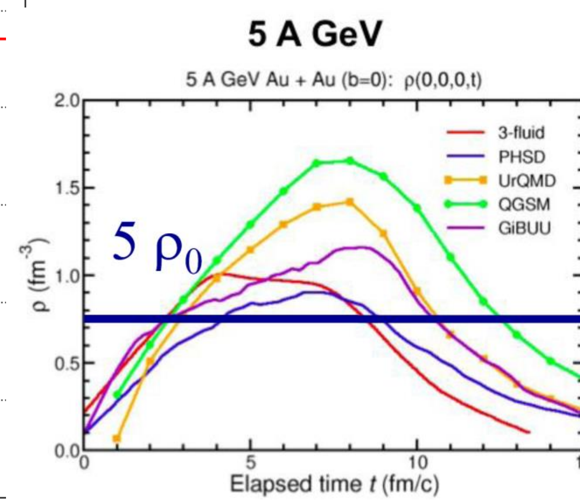
DAC: BM@N foresees Pb shielding of 3-4 mm around the target against delta rays. Are the calculations made with the magnetic field included?

**Answer: Yes, in simulation we assumed the magnetic field of 0.9T for operation with the 3.8A GeV Au beam.**

# Thank you
# for attention!

# Heavy Ion Collision Experiments




**BM@N: $\sqrt{s_{NN}}$= 2.3 - 3.3 GeV**
**MPD: $\sqrt{s_{NN}}$= 4 - 11 GeV**

**BM@N competitors:**

HADES BES (SIS): Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV, Ag+Ag at $\sqrt{s_{NN}}$ = 2.42 GeV, 2.55 GeV.

STAR BES (RHIC): Au+Au at $\sqrt{s_{NN}}$ = 3-200 GeV

Future CBM experiment: Au+Au at $\sqrt{s_{NN}}$~ 2.7 – 4.9 GeV

# Plan for BM@N experimental physics run with Au (Bi) beam for 800 hours (33 days) in spring 2023

## BM@N: Estimated hyperon yields in Au+Au collisions

4 A GeV min. bias Au+Au collisions, multiplicities from statistical model,
Beam intensity $2.5 \cdot 10^5$/s , DAQ rate $2.5 \cdot 10^3$/s, accelerator duty factor 0.25

Experimental run for 800 hours (33 days)

$1.8 \cdot 10^9$ interactions
$1.8 \cdot 10^{11}$ beam ions

| Particle | $E_{thr}$NN GeV | M central | M m.bias | ε % | Yield/s m. Bias | Yield / 800 hours m. Bias |
|---|---|---|---|---|---|---|
| $\Xi^-$ | 3.7 | $1 \cdot 10^{-1}$ | $2.5 \cdot 10^{-2}$ | 1 | 2.5 | $4.5 \cdot 10^5$ |
| $\Omega^-$ | 6.9 | $2 \cdot 10^{-3}$ | $5 \cdot 10^{-4}$ | 1 | $5 \cdot 10^{-2}$ | $0.9 \cdot 10^4$ |
| Anti-$\Lambda$ | 7.1 | $2 \cdot 10^{-4}$ | $5 \cdot 10^{-5}$ | 3 | $1.5 \cdot 10^{-2}$ | 2700 |
| $\Xi^+$ | 9.0 | $6 \cdot 10^{-5}$ | $1.5 \cdot 10^{-5}$ | 1 | $1.5 \cdot 10^{-3}$ | 270 |
| $\Omega^+$ | 12.7 | $1 \cdot 10^{-5}$ | $2.5 \cdot 10^{-6}$ | 1 | $2.5 \cdot 10^{-4}$ | 45 |
| | | | | | ${}_{\Lambda}^{3}H$ | $0.9 \cdot 10^5$ |

# Comparison HADES, STAR FxT, BM@N

| | year | A+A | $E_{kin}$ A GeV | # Events | Rare Observables | | |
|---|---|---|---|---|---|---|---|
| | | | | | $e^+e^-$ | $\Xi^-$, $\Omega^-$ | hypernuclei |
| HADES | 2012 | Au+Au | 1.23 | $7 \cdot 10^9$ | ✓ | --- | --- |
| HADES | 2019 | Ag+Ag | 1.58 | $1.4 \cdot 10^{10}$ | ✓ | --- | 800 ${}^3_\Lambda H$ |
| STAR FxT | 2018 | Au+Au | 2.9 | $3 \cdot 10^8$ | --- | $10^4$ $\Xi^-$ | $10^4$ ${}^3_\Lambda H$,<br>$6 \cdot 10^3$ ${}^4_\Lambda H$, |
| STAR FxT | 2021<br>planned | Au+Au | 2.9 | $2 \cdot 10^9$ | --- | $7 \cdot 10^4$ $\Xi^-$,<br>$\Omega^-$ ? | $7 \cdot 10^4$ ${}^3_\Lambda H$,<br>$4 \cdot 10^4$ ${}^4_\Lambda H$,<br>${}^5_\Lambda He$, ${}^7_\Lambda Li$, ${}^7_\Lambda He$, ? |
| BM@N | simulated | Au+Au | 3.8 | $2 \cdot 10^{10}$ | --- | $5 \cdot 10^6$ $\Xi^-$<br>Expected:<br>$10^5$ $\Omega^-$<br>$3 \cdot 10^4$ anti-$\Lambda$<br>$5 \cdot 10^2$ $\Omega^+$ | $10^6$ ${}^3_\Lambda H$,<br>${}^4_\Lambda H$, ${}^5_\Lambda He$,<br>${}^7_\Lambda Li$, ${}^7_\Lambda He$,<br>Expected:<br>$10^2$ ${}^5_{\Lambda\Lambda} H$ |

Reaction rates: HADES ≈ 20 kHz, BM@N ≈ 20 kHz, STAR FxT ≈ 2 kHz
Energy Au beams: HADES: 0.2 - 1.25 A GeV, BM@N: 1.5 – 3.8 A GeV, STAR FxT: > 2.9 A GeV
Conclusion:
HADES and BM@N are complementary , no cascade hyperons ($\Xi^-$,$\Omega^-$ ) at HADES
Statistics at BM@N ≈70 times higher ($\Xi^-$) than at STAR FxT

# Beam parameters and setup at different stages of the BM@N experiment

| Year | 2016 | 2017 spring | 2018 spring | 2022 spring | 2023 | After 2023 |
|---|---|---|---|---|---|---|
| Beam | d(↑) | C | Ar,Kr, C(SRC) | Xe | Au (Bi) | Au (Bi) |
| Max.intensity, Hz | 0.5M | 0.5M | 0.5M | 0.5M | 0.5M | 2M |
| Trigger rate, Hz | 5k | 5k | 10k | 10k | 10k | up to 50k |
| Central tracker status | 6 GEM half planes | 6 GEM half planes | 6 GEM half planes + 3 forward Si planes | 7 GEM full planes + 3 forward Si planes | 7 GEM full planes + 4 forward Si + 2 large STS planes | 7 GEM full planes + 4 large STS planes |
| Experimental status | technical run | technical run | technical run+physics | stage 1 physics | stage1 physics | High rate stage 2 physics |

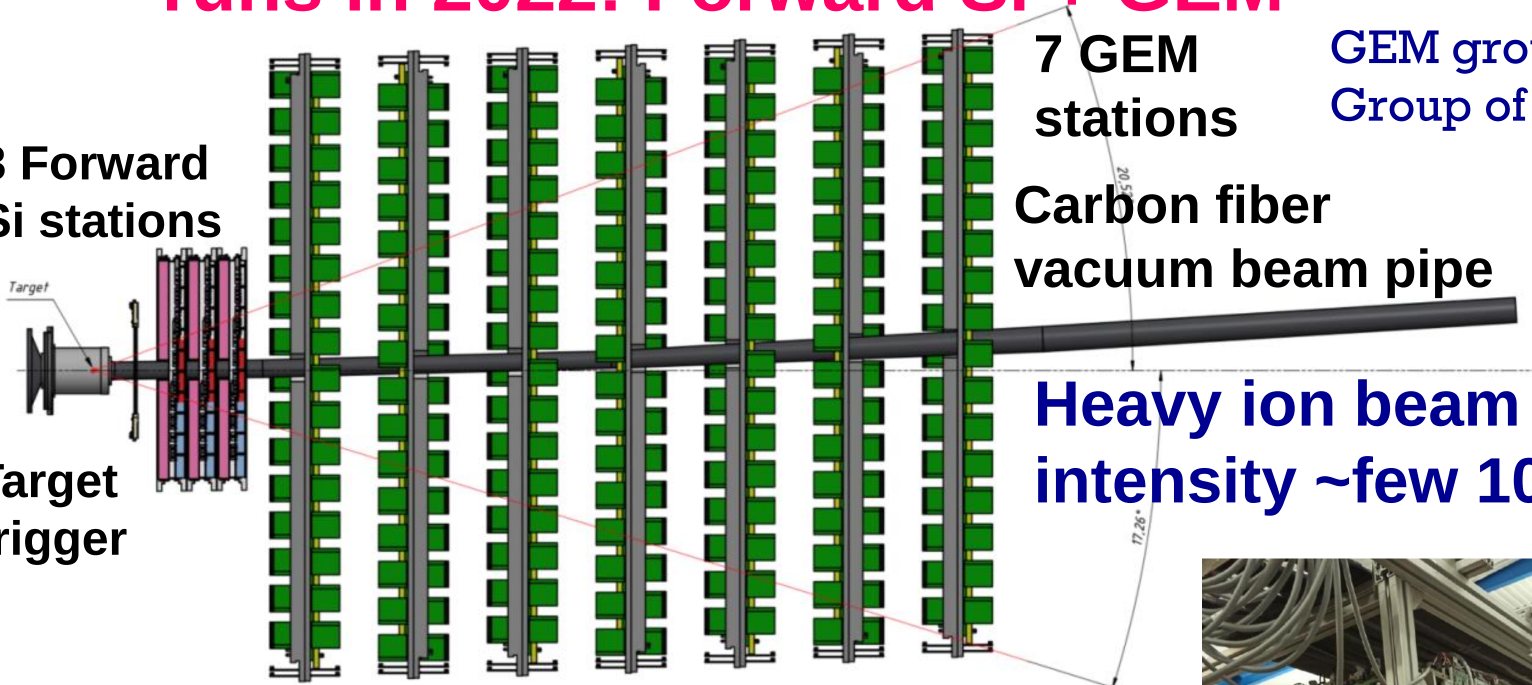
# Initial Hybrid Central Tracker for heavy ion runs in 2022: Forward Si + GEM

7 GEM stations

GEM group
Group of N.Zamiatin

3 Forward Si stations

Carbon fiber vacuum beam pipe

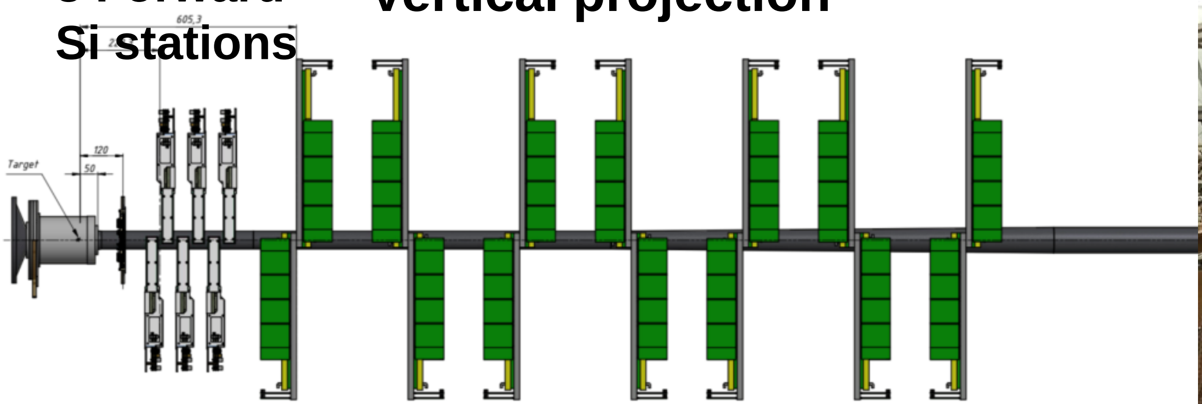


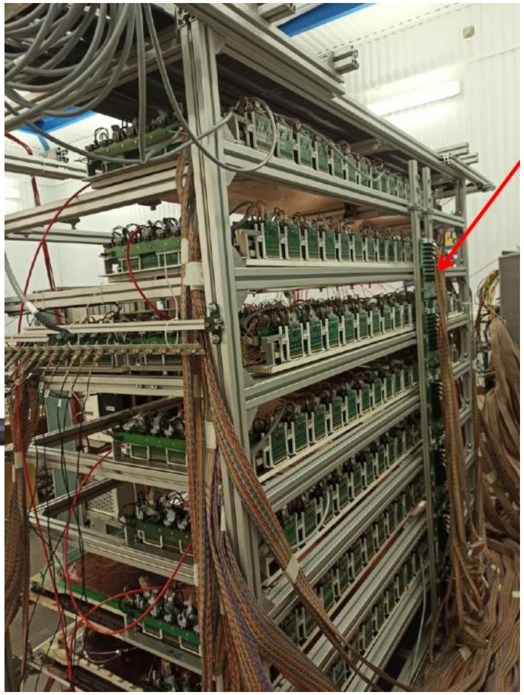

Heavy ion beam intensity ~few $10^5$ Hz

Target trigger

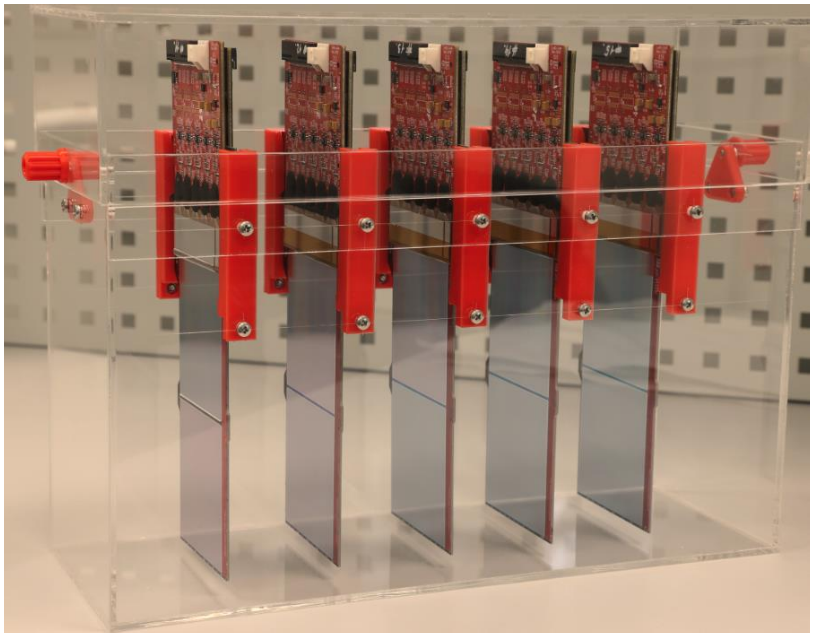
3 Forward Si stations

Vertical projection



# Forward Silicon Tracker status summary



- Forward Silicon Tracker FEE and Si modules test bench was designed and assembled;
- All 84 FEE PCB were fully assembled (100%);
- 72 from 84 FEE PCB were tested (86%);
- All tested PCB have $<ENC_{PCB}>$ less than 1500 ē RMS;
- 67 from 72 tested PCB have bad channels ratio ≤ 3%;
- 32 from 42 FST Si modules fully assembled (76%);
- 29 from 42 FST Si modules were tested (69%);
- 27 from 29 tested modules have $<ENC_{side}>$ less than 2500 ē RMS;
- Most Si modules have mean $SNR_{side}$ > 10 (mip signal amplitude distribution is separated from the noise);
- 25 from 29 tested Si modules have bad channels ratio ≤ 3%

# Beam tracker radiation hardness FAQ

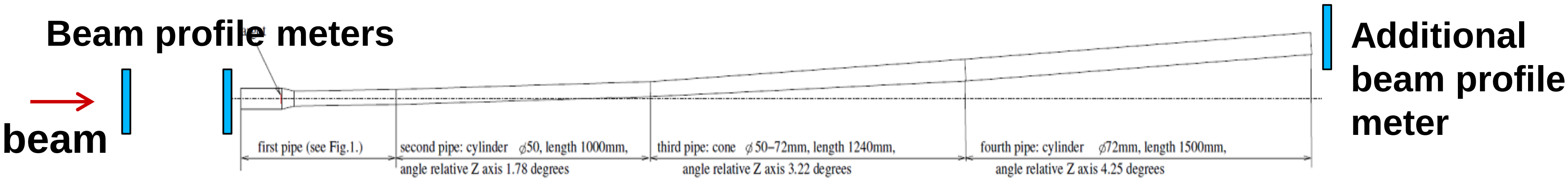
**Radiation damage caused by δ-electrons and X-rays (damage caused by secondary electrons produced by photons):**

**Bulk damage can be neglected:**
**electrons energy should be > 200 keV to produce Si atom displacement;**
**NIELs for the electrons energy range from 200 keV to 10 GeV are $2.5 \cdot 10^{-6}$ to $1.34 \cdot 10^{-4}$ $MeV \cdot cm^2 \cdot g^{-1}$ (15 times lower than 1 MeV neutron);**

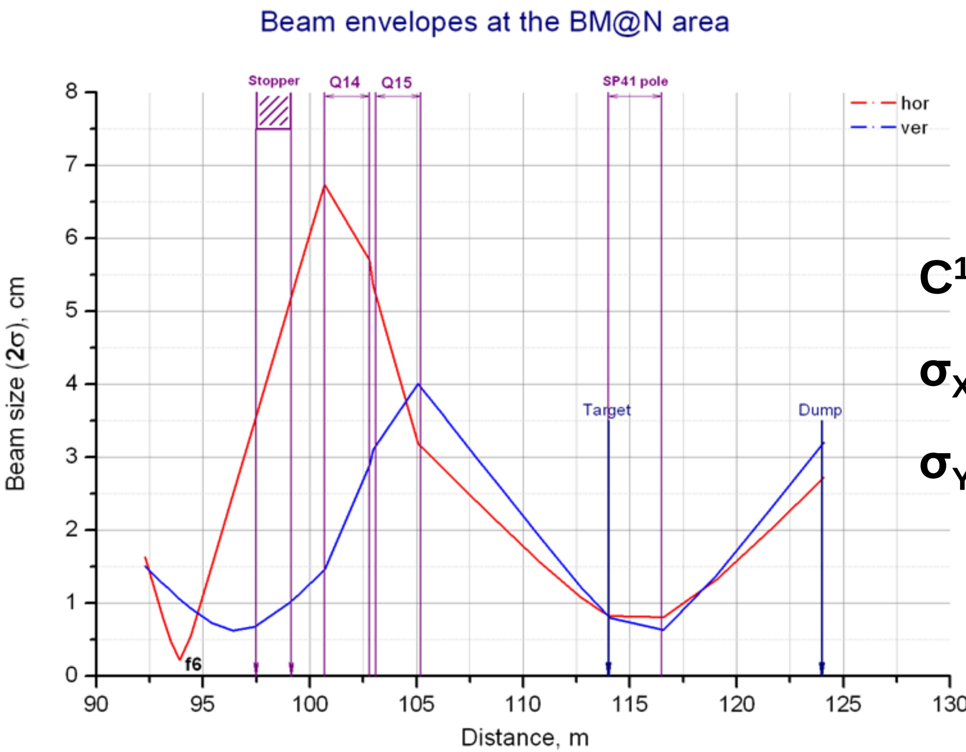
**Surface damage:**
**$SiO_2$ layer is placed between strips and near a guard ring region. δ-electrons and X-rays irradiation will cause an increase of the total oxide charge $+N_{ox}$ in $SiO_2$ layer, which leads to an increase of the surface current $I_{sur}$. To compensate this effect the inner guard ring ($GR_1$) is biased to the same potential as of the detector strips.**

**Radiation damage caused by ions:**
**The main macro effects of bulk damage by ions are the dark current and full depleted voltage increasing (expected values are shown on previous slides without self-annealing effects) these lead to:**
**Detector ENC increasing. Due to the high particle signals it can be neglected;**
**Power dissipation increasing. To compensate this effect the 175 µm detector thickness was chosen and the detector is placed on PCB thermal pads to effectively heat sink.**

# Beam tracing through BMN beam pipe and profile monitoring



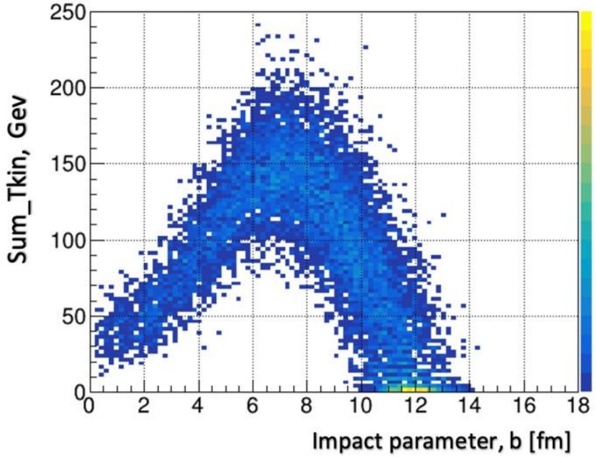

**First task of the next run → trace beam and monitor its profile in the end of the setup (try to find optimal trajectory to reduce background)**



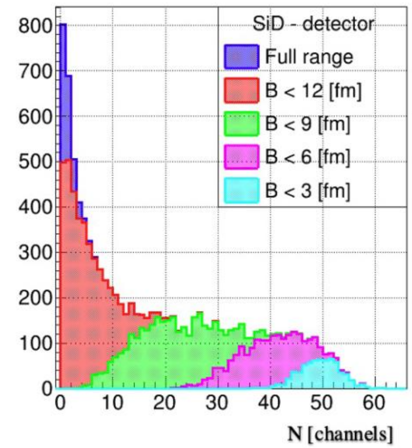

| $C^{12}$ 2017 | Ar 2018 | Kr 2018 |
|---|---|---|
| $\sigma_X$ = 6 mm | 5 mm | 5.3 mm |
| $\sigma_Y$ = 4.9 mm | 5 mm | 3.2 mm |

# Centrality selection with trigger detectors

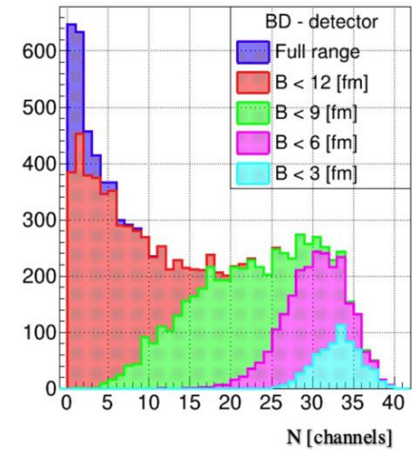
## Energy in FHCAL



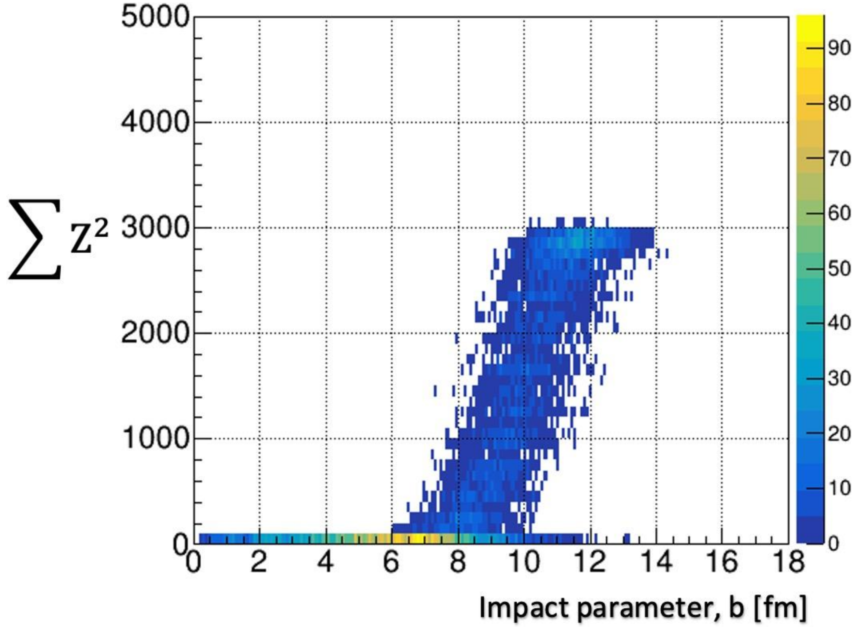

## SiD multiplicity



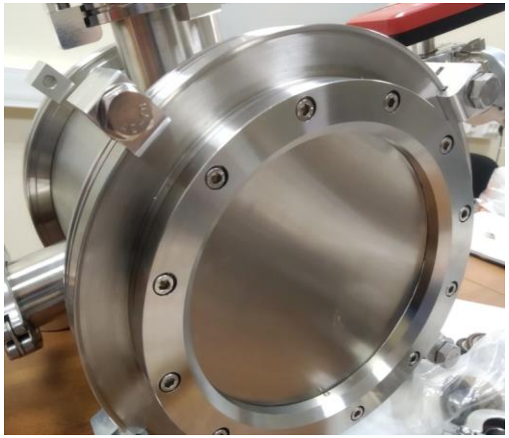

## Barrel multiplicity



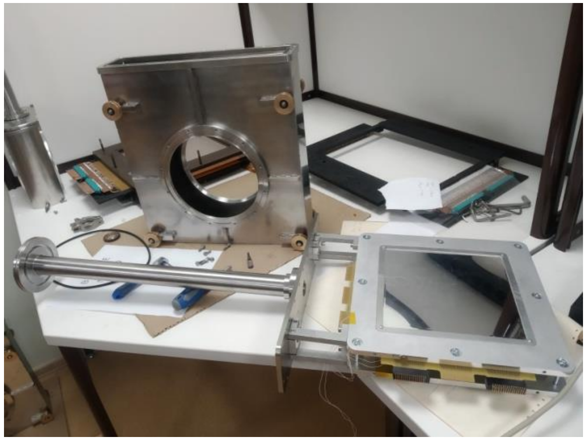

## Fragment detector $Z^2$



# Vacuum boxes and profile meters for the ion beam pipe



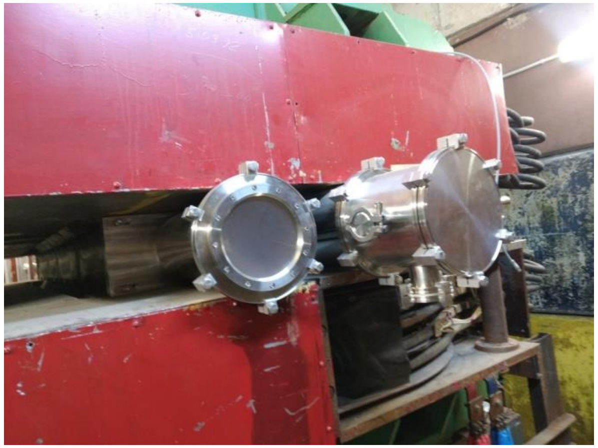
Group of
A.Kubankin



**Titanium windows, thickness of 100 μm, apertures of 100, 150 and 180 mm**

**Ion beam profile meters. Effective area of 80x80 $mm^2$, 128x128 $mm^2$ and 192x192 $mm^2$.**

**Vacuum box for Ion beam profile meter. Detector movement range is 30 cm**



**Vacuum box for the internal space of deflecting magnets**