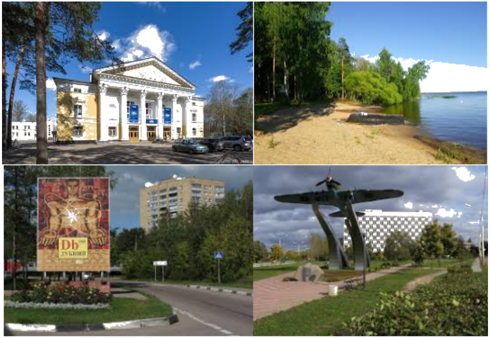
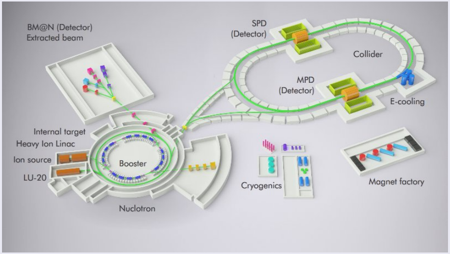


Nuclotron Based Ion Collider fAcility (NICA), introduction lecture

P. Batyuk, pavel.batyuk@jinr.ru

VBLHEP, Joint Institute for Nuclear Research

NICA Complex



- Set of accelerators providing particle beams for fixed target and collider experiments
- Experimental facilities
- Line for assembling and cryogenic testing of SC-magnets
- Workshops for construction of the detector elements
- NICA innovation center

Beams - p, d ... $^{197}Au^{79+}$
Collision energy:
$\sqrt{s_{NN}}$ = **4 - 11 GeV** E_{lab} = **1 - 6 AGeV**
Luminosity: $10^{27}\ cm^{-2}s^{-1}$ (Au), 10^{32} (p)

- 2 interaction points - **MPD** and **SPD**
- Fixed target experiment - **BM@N**

- **2018:** extracted beams of heavy ions (Ar, Kr) are available within the BM@N experiment
- **2020-2021**: a first configuration of the MPD setup available.
- **2023**: commissioning of the fully designed NICA-complex is foreseen.

Nuclotron (in operation since 1993)

Modernized in 2010 - 2015

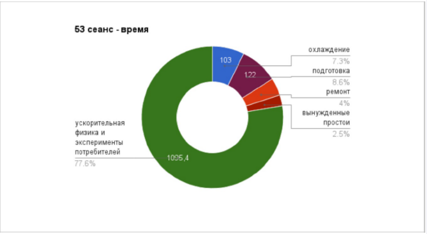
Parameters	Nuclotron
type	SC synchrotron
particles	↑p, ↑d, nuclei
injection energy [MeV/u]	5 (↑p, ↑d), 570-685 (Au)
max. kin. energy [GeV/u]	12.07 (↑p), 5.62 (↑d), 4.38 (Au)
magnetic rigidity [T · m]	25 - 43.25
circumference [m]	251.52
cycle for collider mode [s]	1.5-4.2 (active), 5.0 (total)
vacuum [Torr]	10^{-9}
intensity, Au [ions/pulse]	$1 \cdot 10^{9}$
spill of slow extraction [s]	up to 10

- The project approved in 1986
- Commissioning & first beam, March 1993
- Slow extraction in 2000

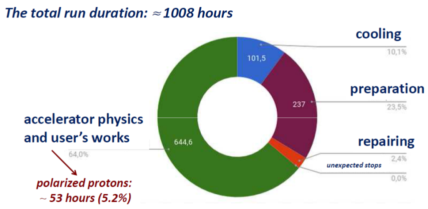
Ions from p to Xe
(C, Mg, Fe, Ar, Kr)
Polarized p & d beams

Nuclotron

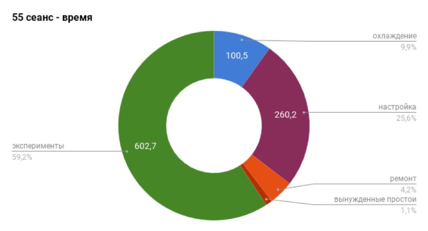
Run № 53, 1450 h, the longest one



Run № 54, 1150 h



Run55: Feb - Apr, 2018



- Run53 - Polarized, unpolarized deuterons, maximum energy of extracted beam 4.6 GeV/u
- Run54 - Carbon beam
- Run55 - Argon & Krypton beams

Booster

Commissioning started in 2018

Parameter	Booster
type	SC synchrotron
particles	ions $A/Z \leq 3$
injection energy [MeV/u]	**3.2**
maximum energy [MeV/u]	**600**
magnetic rigidity [$\mathrm{T} \cdot \mathrm{m}$]	**1.6 - 25.0**
circumference [m]	**210.96**
vacuum [Torr]	10^{-11}
intensity [Au ions/pulse]	$1.5 \cdot 10^{9}$
RF range [MHz]	**0.5 - 2.53**

Tunnel for Booster

- Fabrication of the magnetic system is completed.
- Start of assembly - September 2018.
- First (technological) run - end of 2019.
- Commissioning - end of 2020

First magnet was installed on 19 September 2018!

Main production areas:

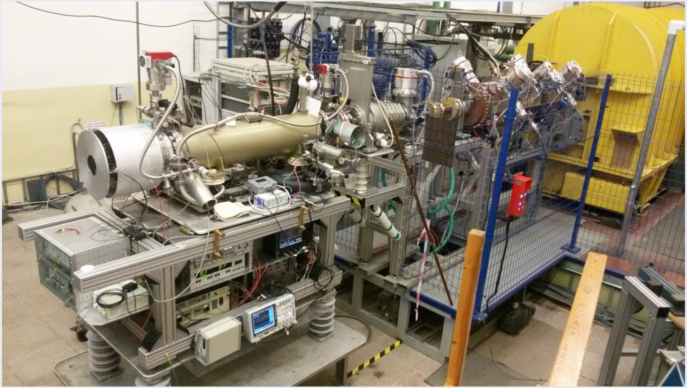
- Incoming inspection zone
- SC cable production hall
- SC coils production hall
- Area for assembling the magnets
- Area for the magnetic measurements under the room temperature
- Leakage test area
- Area for mounting the SC-magnets inside cryostats
- Cryogenic tests bench

All of the Booster magnets are produced & tested

450 magnets for NICA and FAIR projects

KRION 6T - heavy ion source

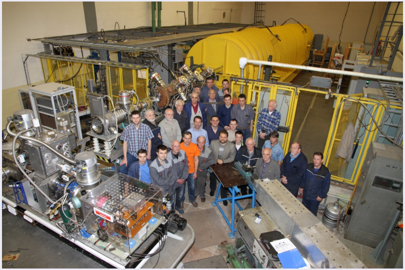
Used during Nuclotron RUN №55



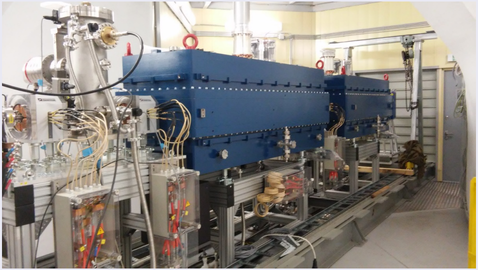
- **Cryogenic heavy ion source KRION - Electron String Ion Source (ESIS) - provides up to $2.5 \cdot 10^9$ Au^{31+} ion / cycle at repetition frequency up to 10 Hz**

Linacs

LU-20



HILAC



- **LU-20** - JINR, INR, ITEP, MEPhI (Commissioning - May 2016)
- **HILAC** - BEVATECH OHG (Commissioning - October 2018)

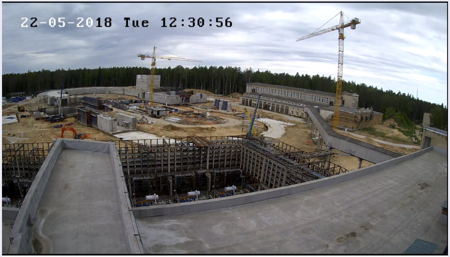
	LU-20	HILAC (NEW!)
Mass to charge ratio A/Z	1-3	1-6
Injection energy [keV / a.m.u.]	150 for A/Z 1-3	17
Extraction energy [MeV / a.m.u.]	5 (A/Z 1-3)	3.24 (A/Z = 6)

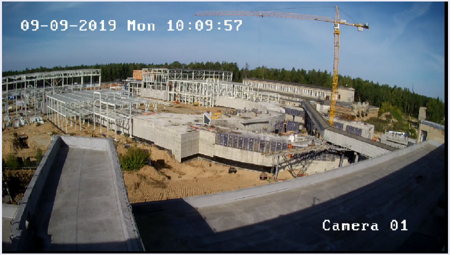
Collider as the main ingredient of the kitchen:)

Collider construction: Official start up of the construction is 25 March 2016

Collider

http://nucloweb.jinr.ru/nucloserv/205corp.htm



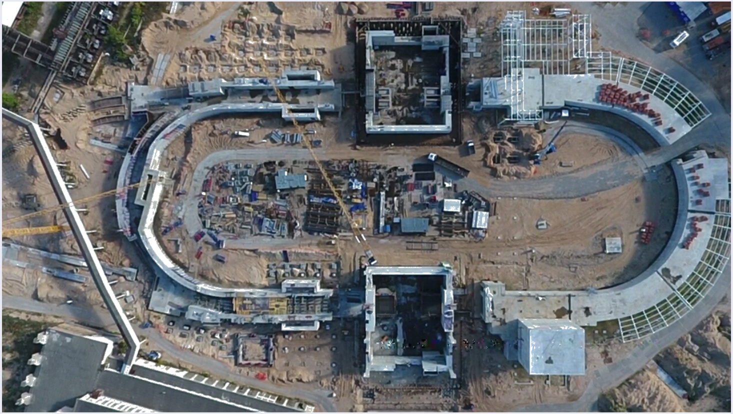


Technical params:

Ring circumference [m]	503.04
Number of bunches	22
$\Delta_{bunch\ length}$ [m]	0.6
Max. energy $\sqrt{s_{NN}}$ [GeV]	11
$\Delta p/p$ $[10^{-3}]$	1.6
Luminosity $[cm^{-2} \cdot s^{-1}]$	10^{27}

Collider

September 2018



Collider

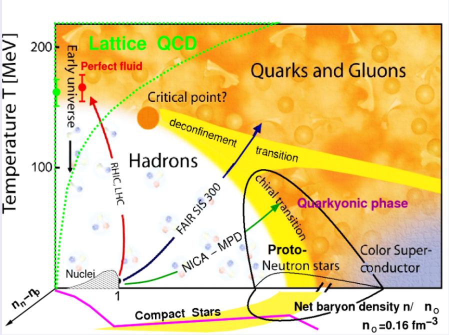
August 2019

Cryogenic facility

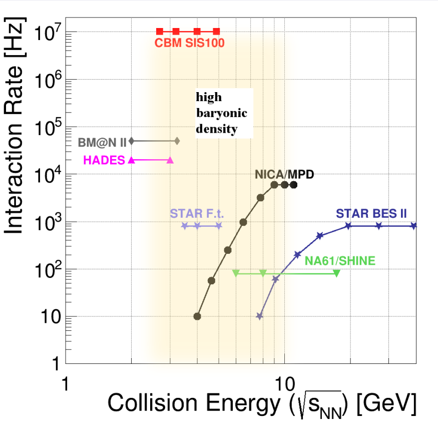
New helium liquefier (1000 L/H)

Finally the cooling power should be doubled from 4 kW to 8 kW @ 4.5K

QCD phase diagram



Landscape of experiments exploring QCD phase diagram



High energy:

- $N_{baryons} \approx N_{antibaryons}$
- **Lattice QCD predicts crossover transition between hadronic and partonic matter**
- **ALICE, ATLAS, CMS, STAR, PHENIX**

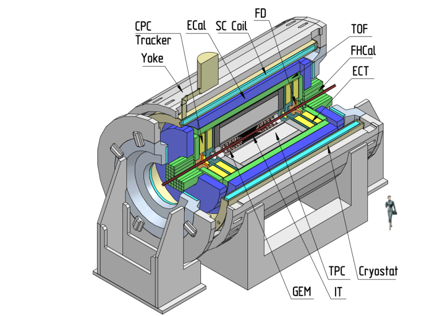
High net-baryon density:

- $N_{baryons} >> N_{antibaryons}$
- **Lattice QCD not applicable, models predict structures and exotic phases**
- **BES @ RHIC, NA61, CBM, NICA/MPD, BM@N**

Experiments in collider mode

MultiPurpose Detector (MPD) for $A + A$ collisions @ NICA

MPD Layout:



Benefits:

- Hermeticity, 2π-acceptance in azimuth
- 3D-tracking (TPC, ECT)
- Vertex high-resolution (IT)
- Powerful PID (TPC, TOF, ECAL)
  - π, K up to 1.5 GeV/c
  - K, p up to 3 GeV/c
  - γ, e from 0.1 GeV/c up to 3 GeV/c
- Precise event characterization (FHCAL)
- Fast timing and triggering (FFD)
- Low material budget
- High event rate (up to 7 kHz)

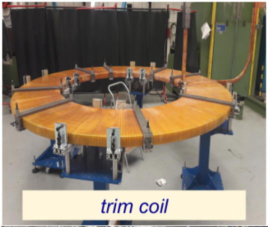
Participants:

- Tsinghua University, Beijing, China
- GSI, Darmstadt, Germany
- WUT, Warsaw, Poland
- MEPhI, Moscow, Russia
- INR, RAS, Russia
- PPC BSU, Minsk, Belarus
- Dubna, JINR, Russia

Realization progress:

- TDR - completed / close to completion
- Preparation for / start of mass production
- First stage - 2021 (ready for cosmics - end of 2020)
- Second stage and full commissioning (IT + end-cups) - 2023

Magnet fabrication: ASG (Genova) & Vitkovice HM


trim coil

End of 2018 – SC coils are ready
March 2019 – Solenoid is ready
July-October 2019 – Transportation to Dubna
Oct 2019 – Mar 2020 – Assembling of Magnet
Yoke and Solenoid at JINR, alignment
Apr-May 2020 – Magnetic field measurements


yoke control assembly at HM Vitkovice

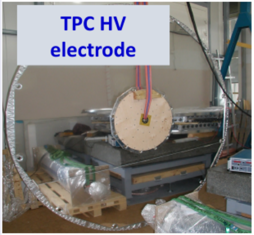

winding machine

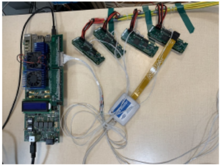

cryostat

Assembling MPD ...

MPD TPC status

Delivered to JINR





Gas system

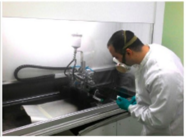
MPD TPC FEE: FEC64SAM based on SAMPA

item	Date
Testing FEC v1.0 finished	Feb. 2019
Receive SAMPA V4 chips at Dubna 4500 (all)	June 2019
32 preproduction vervion 2.1 FE Card assembled (1/2ROC)	Jul. 2019
Testing of half ROC equipped with FECards	Aug. - Oct 2019
Production FE Cards for 1 ROC and Tests	Dec. 2019-Apr. 2020
Production FE Cards for 3 ROCs (Total 4) May	May 2020
Production FE Cards for the first 10 ROCs (Total 14)	July 2020
Production FE Cards for the second 10 ROCs (Total 24)	August 2020

Assembling MPD ...

MPD TOF status

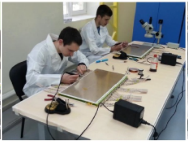
Ultrasonic wave glass cleaning



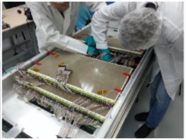
Painting of the HV conductive layer

MRPC assembling

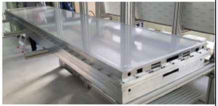
Optical quality control



Cables and connectors soldering



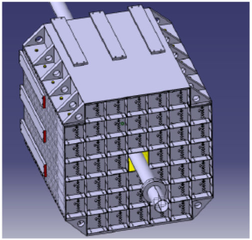
Detectors installation to the TOF box



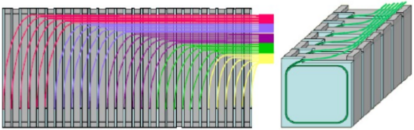
	Number of detectors	Number of readout strips	Sensitive area, m^2	Number of FEE cards	Number of FEE channels
MRPC	1	24	0.192	2	48
Module	10	240	1.848	20	480
Barrel	280	6720	51.8	560	13440 (1680 chips)

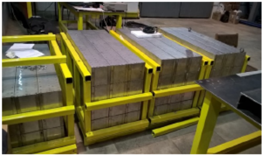
So far 10% of all mRPCs are assembled
At the end of March 2020 all mRPCs will be assembled

MPD FHCal status and readiness for beam tuning



- **Two-arms at ~3.2 m from the interaction point.**
- **Each arm consists of 45 individual modules.**
- **Module size 150x150x1100cm^3 (55 layers)**
- **Pb(16mm)+Scint.(4mm) sandwich**
- **7 longitudinal sections**
- **6 WLS-fiber/MAPD per section**
- **7 MAPDs/module**





1. We have 80 modules ready (need 88)
   Plan to have 100 modules in September 2019
   Produced modules are under test on Cosmic
2. FE Electronics is under production – will be ready at the end of 2019
3. Design of the Support platform for FHCal is under way

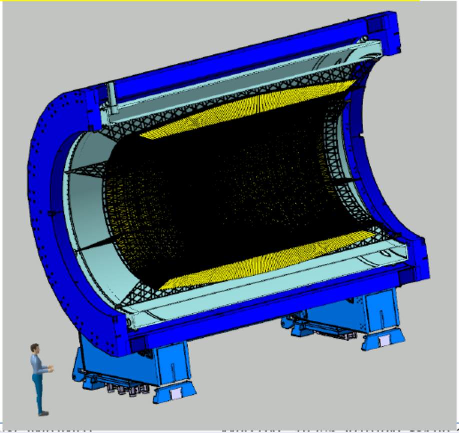
Assembling MPD ...

ECAL status

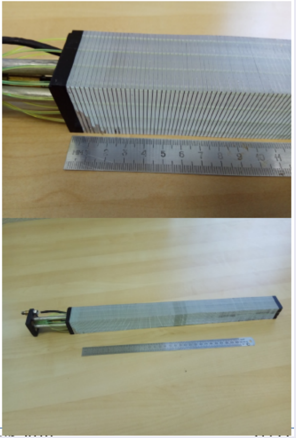
ECal – THU – Tsinghua University., Yi Wang , SDU –Shandong University, HU- Huzhou University Fuqing Wang

There is expectation that ECal modules assembling (75%) in China will be financed soon (middle of this year). Production of 25% modules in Russia is going on according to the Plan

Barrel ECAL ~ 43000 ECAL modules

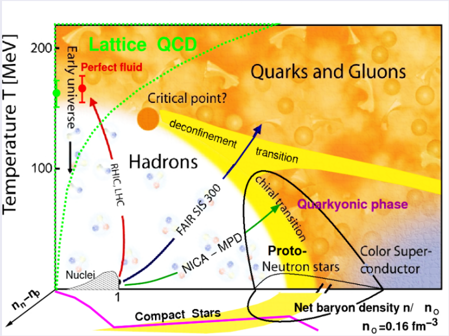


Prototype of one module



MPD physics cases

QCD phase diagram



Deconfinement (chiral) phase transition at high baryonic density

enhanced strangeness production
Chiral Magnetic (vortical) effect,
Λ-polarization

Bulk properties, EOS

particle yields & spectra, ratios,
femtoscopy, flow
measure: γ, π, K, p, Λ, Ω,
(anti)-particles, light nuclei

In-Medium modification of hadron properties

onset of low-mass dilepton
enhancement
measure: ρ, ω, ϕ, e^+e^-

QCD Critical Point

event-by-event fluctuations and
correlations

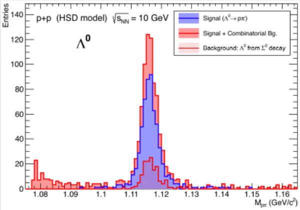
Strangeness in nuclear matter

hypernuclei

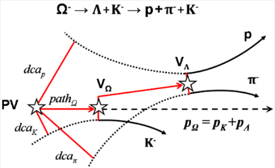
Multi-strangeness @ MPD

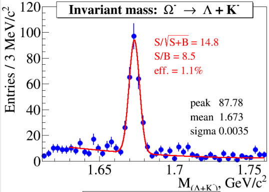
Hyperon yields for 1 week of running (Stage 1)

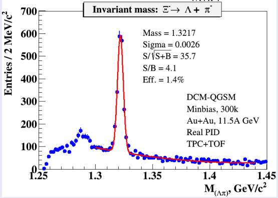
Particle	Yield
Λ^0	$3 \cdot 10^7$
$\overline{\Lambda}^0$	$3.5 \cdot 10^5$
Ξ^-	$1.5 \cdot 10^5$
$\overline{\Xi}^+$	$8.0 \cdot 10^3$
Ω^-	$7 \cdot 10^3$
$\overline{\Omega}^+$	$1.5 \cdot 10^3$



Decay topology

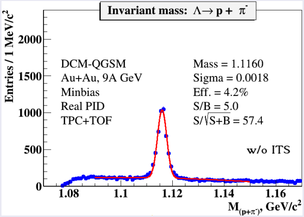


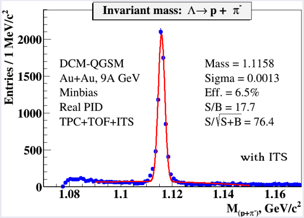




Data & Analysis

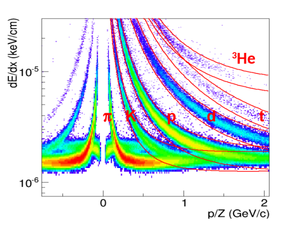
- $5 \cdot 10^5$ events, AuAu @ $\sqrt{s_{NN}} = 9$ GeV
- Λ-candidates are in inv. mass window $\pm 3\sigma$
- Topological cuts are optimized to improve significance

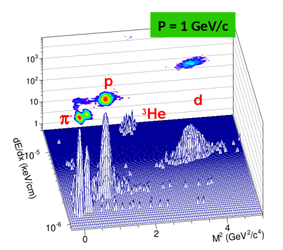




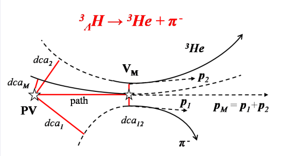
Hypernuclei @ MPD

Particle Identification





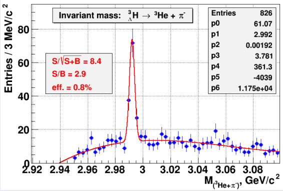
Decay topology



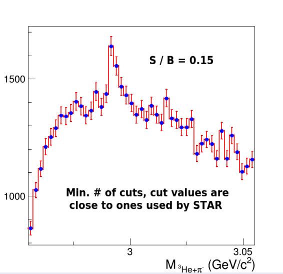
Data & Analysis

- Particles are selected within $\pm 3\sigma$-cuts in dE/dx or $dE/dx - M^2$
- V_0 finding is done with quality cuts for max. significance

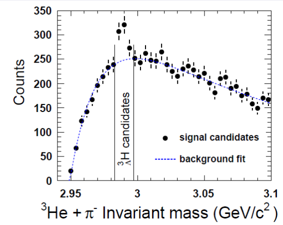
"Strong" cuts



"Soft" cuts

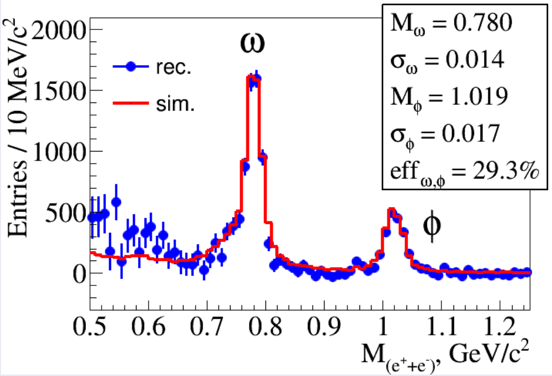


STAR preliminary

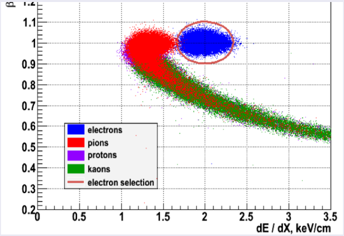


Dileptons @ MPD

Invariant mass of dileptons (background subtracted): red - MC, blue - reco

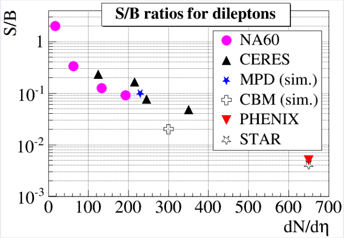


PID



MPD

$0.2 < M_{(e^+e^-)} < 1.1 GeV/c^2$

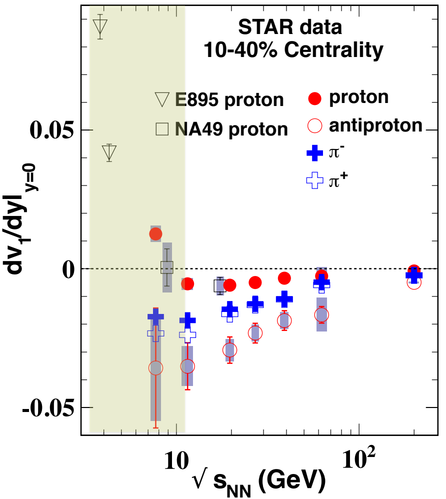


Yield, decay modes ... for dileptons

Particle	Yield 4π	Yield $y = 0$	Decay mode	BR	Eff. [%]	Yield [per 1 week]
ρ	**31**	**17**	e^+e^-	$4.7 \cdot 10^{-5}$	**35**	$7.3 \cdot 10^4$
ω	**20**	**11**	e^+e^-	$7.1 \cdot 10^{-5}$	**35**	$7.2 \cdot 10^4$
ϕ	**2.6**	**1.2**	e^+e^-	$3 \cdot 10^{-4}$	**35**	$1.7 \cdot 10^4$

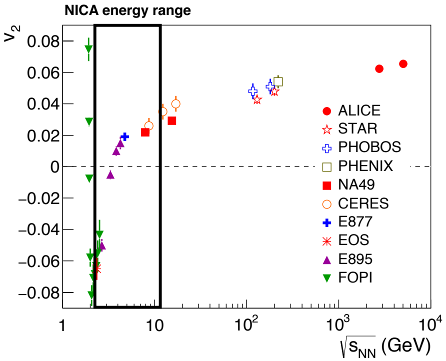
Flow @ MPD

Direct flow



Slope of v_1 changes sign in the NICA energy range

Elliptic flow

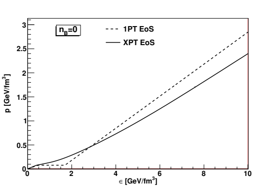


v_2 becomes very close to zero in the NICA energy range

- Large uncertainties in existing experimental data in the NICA energy range
- Non-monotonic $|dv_1/dy|_{y=0}$ behavior could be a signature of phase transition
- More differential (centrality classes) measurements required

Femtoscopy @ MPD with vHLLE+UrQMD

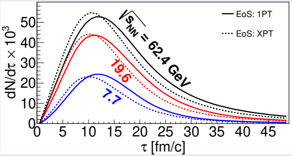
Thermodynamic pressure as a function of energy density



Parameters τ_0, $R_\perp$, R_η and η/s adjusted using basic observables in the RHIC BES region.

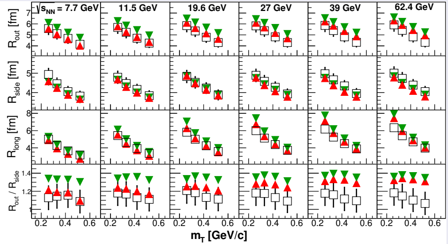
$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

Pion emission times at the last interaction



Phys. Rev. C 96, 024911 (2017)

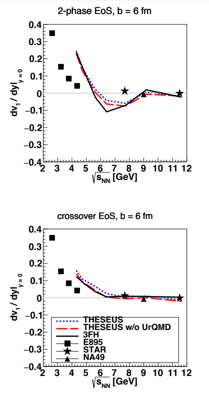
Comparison of extracted radii with the STAR data



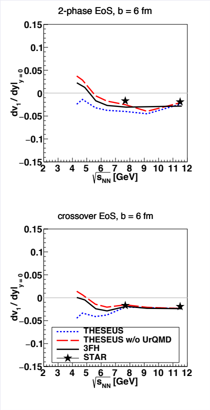
- EoS with a crossover in the fluid phase results in a quite reasonable reproduction of 3D pion femtoscopic radii measured by the STAR collaboration (empty squares).
- EoS with a first-order phase transition leads to fact that the "out" and "long" Gaussian femtoscopic radii are systematically larger if comparing with the crossover EoS; the "side" radii coincide for both types of EoS.

Observables @ MPD with THESEUS

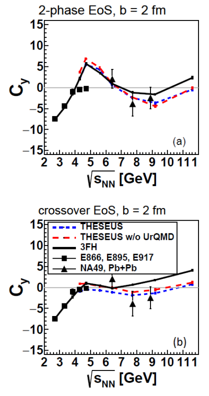
$|dv_1/dy|_{y=0}$ protons



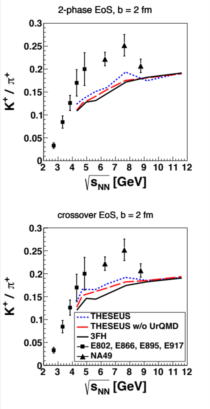
$|dv_1/dy|_{y=0}$ pions



Curvature of net-proton rapidity distribution



The "horn" effect?



- Hadronic cascade has a small effect on dv_1/dy for protons
- Hadronic cascade changes flow to antiflow for pions at low energies. The effect becomes weaker with the collision energy rise.

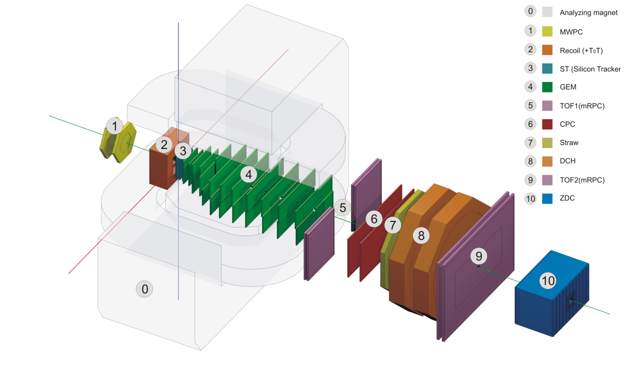
- The "wiggle" as a feature for the EoS with a 1-st order phase transition is robust against hadronic FSI.

- Turning the hadronic cascade on does not influence the kaon to pion ratio.

Experiments in fixed-target mode

BM@N experiment

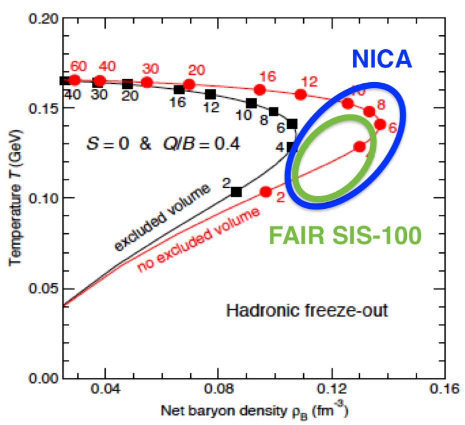
Full setup, layout

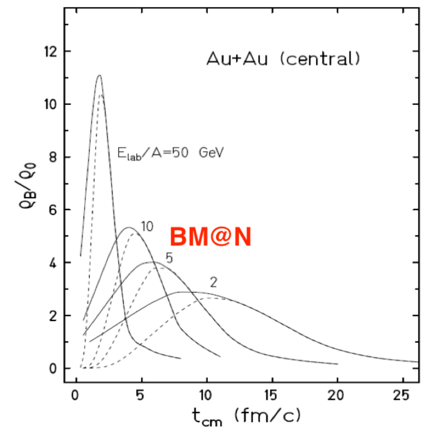


- Central tracker (Silicon tracker + GEM) inside analyzing magnet to reconstruct AA-interactions
- Outer tracker (CPC, DCH) behind magnet to link tracks from central tracker to ToF detectors
- TOF1 & TOF2 system based on mRPC and T0 detectors to identify hadrons and light nuclei
- Detectors to form T0 and beam monitors
- ZDC calorimeter to measure centrality of AA-collisions
- Electromagnetic calorimeter for γ, e^+, e^-

BM@N advantages:

- large aperture analyzing magnet
- sub-detector systems are resistant to high multiplicities of charged particles
- PID: "near to magnet" (TOF1), "far from magnet" (TOF2)





Nuclotron is well suited to study high density (dominantly baryonic) matter since at that energies baryon-dominated system exists comparatively long lifetime

Physics possibilities at the Nuclotron

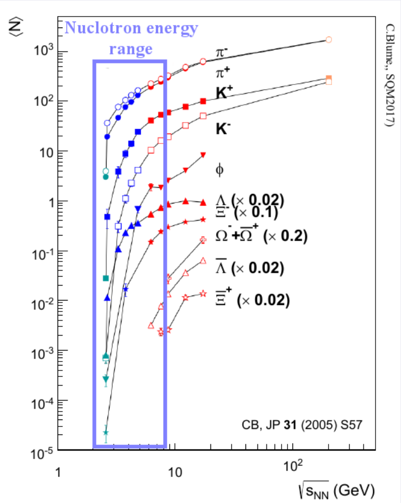
$A + A$ collisions:

- strangeness at threshold
- Need more precise data for strange mesons, hyperons and hypernuclei, multi-variable distributions, unexplored energy range

$p + p$, $p + n$, $p + A$ collisions:

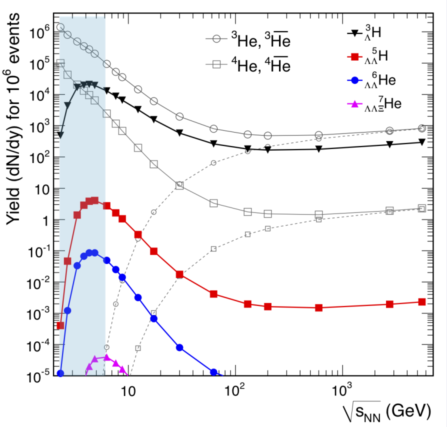
- Hadron production in elementary reactions and “cold” nuclear matter as a “reference” to determine exactly nuclear effects

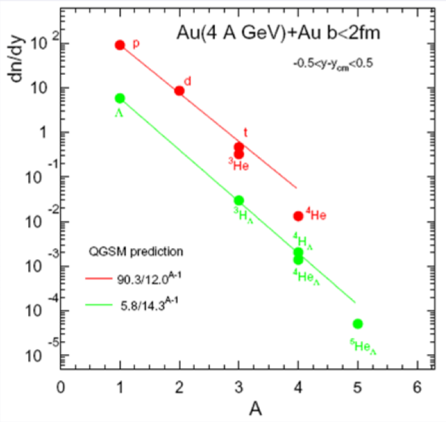
AGS NA49 BRAHMS



Heavy ions $A + A$: Hypernuclei production

A. Andronic et al., Phys. Lett. B697 (2011) 203





BM@N energy range is suited for the search of (double) hypernuclei

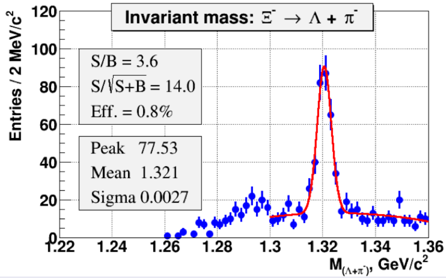
- In heavy-ion collisions: production of hypernuclei through coalescence of Λ with light fragments enhanced at high baryon densities
- Maximal yield predicted for $\sqrt{s_{NN}} =$ 4 - 5 AGeV (stat. model)

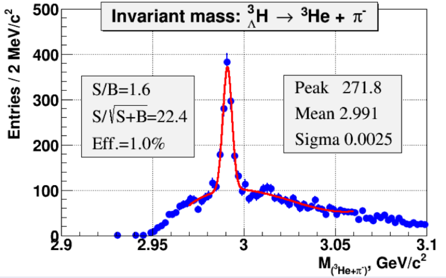
BM@N feasibility study

Simulation: UrQMD & DCM-QGSM, Au+Au, T = 4.5 AGeV

900k central events,
7.5M Ξ^- in 1 month
20 kHz trigger

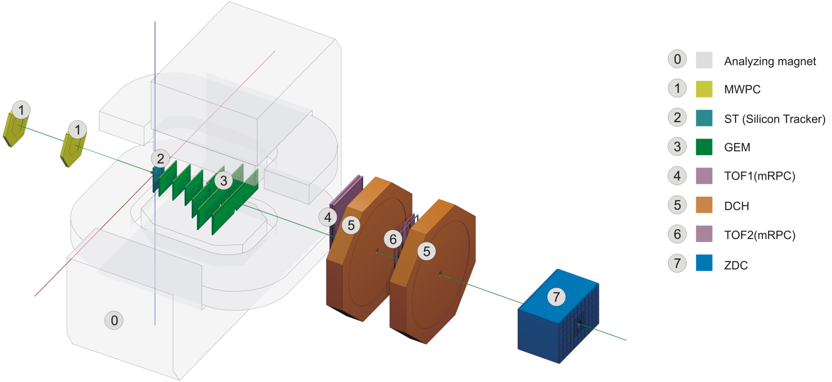
2.6M central events,
8.5M ${}^3_\Lambda H$ in 1 month
20 kHz trigger





The feasibility study indicates reliable reconstruction of cascades and hypernuclei of order of 10 millions per month

BM@N, carbon run



Input beams:

Deuteron beam (d),
$T = 4.0, 4.6$ **AGeV**
Carbon beam (C),
$T = 3.5, 4.0, 4.5$ **AGeV**

Aims:

- **Focus on tests and commissioning of central tracker inside analyzing magnet $\rightarrow$ GEM detectors and forward Si detector for tracking**
- **Test / calibrate ToF, trigger detectors, calorimeters**

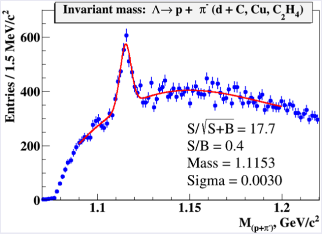
Program:

- **Trace beam through detectors, align detectors, measure beam momentum in mag. field of 0.3 - 0.85 T**
- **Measure inelastic reactions d (C) + target $\rightarrow$ X with deuteron and carbon beam energies of 3.5 - 4.6 GeV/n on targets CH_2, C, Al, Cu, Pb**

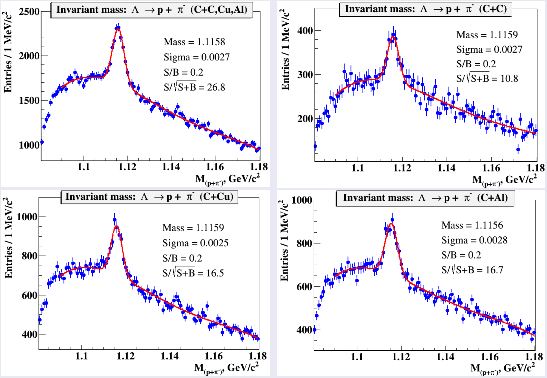
Λ^0 in deutron and carbon runs

d (C) + target $\rightarrow$ X
Λ^0-signal width $\sim$ 2.5-3 MeV

Deuteron run



Carbon run, T = 4 AGeV



PEPAN Lett., v.15, p.136, 2018(2): First results from BM@N technical run with deuteron beam

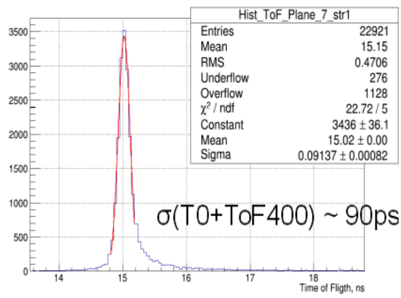
To improve vertex and momentum resolution and reduce background under Λ^0:

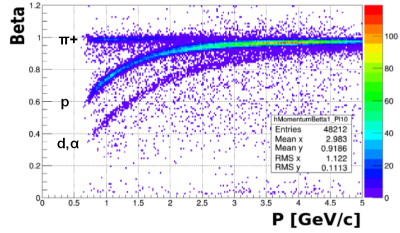
- Need few planes of forward Silicon detectors $\rightarrow$ 3 planes used in last run
- Need more GEM planes to improve track momentum reconstruction

TOF1 and TOF2 performance in carbon run

$T = 3.5$ GeV/n, C + Al $\rightarrow$ X

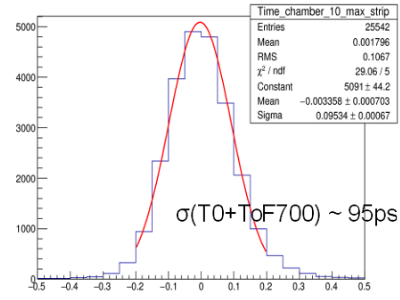
Includes inf. from GEM tracking

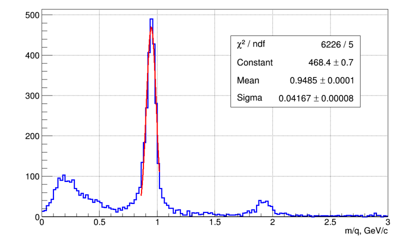




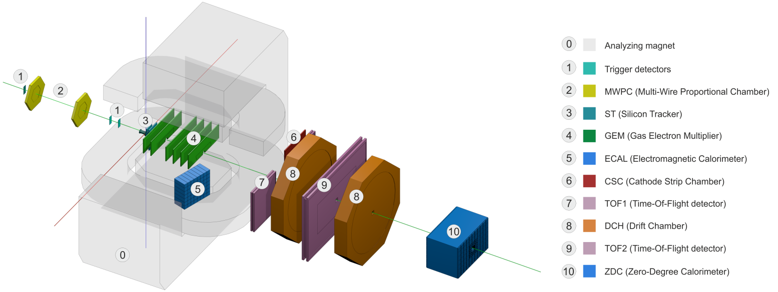
$T = 4.5$ GeV/n, C + Cu $\rightarrow$ X

Includes inf. from GEM and DCH trackings





BM@N, Argon & Krypton runs



Input beams:

Ar beam, $T = 3.2$ **AGeV**
Kr beam,
$T = 2.4, 3.0$ **AGeV**

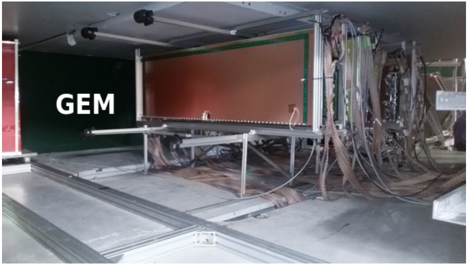
Aims:

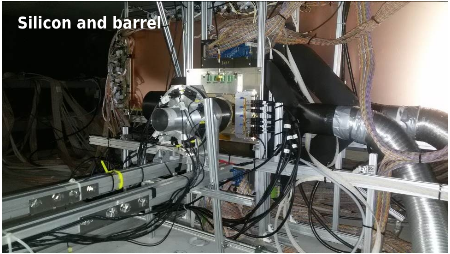
- Central tracker inside analyzing magnet $\rightarrow$ 6 GEM detectors $163 \cdot 45 cm^2$ and forward Si strip detectors for tracking
- Test ToF system, trigger detectors, hadron and EM calorimeters, outer tracker supplemented by CSC

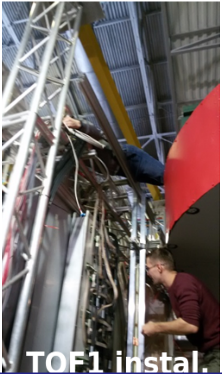
Program:

- Measure inelastic reactions Ar (Kr) + target $\rightarrow$ X on targets Al, Cu, Sn, Pb
- Hyperon production measured in central tracker (Si + GEM)
- Charged particles and nuclear fragments identified with ToF
- Gamma and multi-gamma states identified in ECAL

BM@N setup in the last run (before magnet)



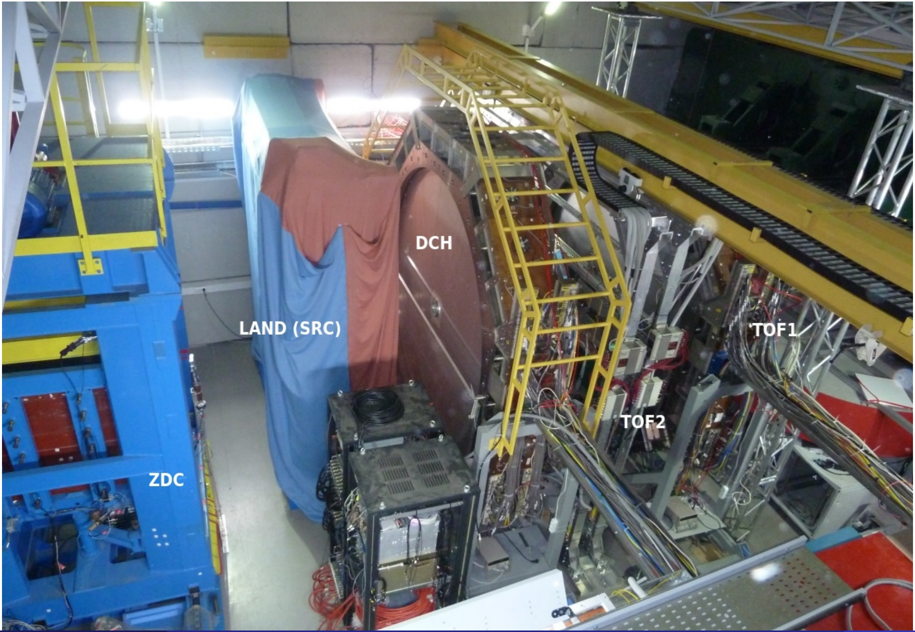




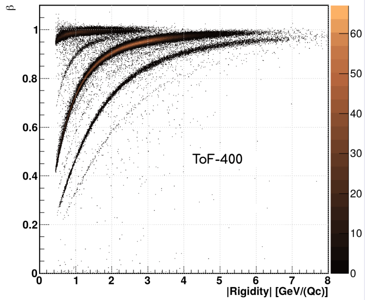
New detector components:

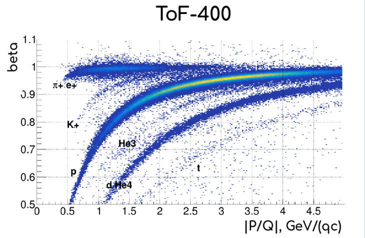
- Six big GEMs
- Trigger detectors
- Three Si detectors
- CSC chamber
- Full set of TOF detectors

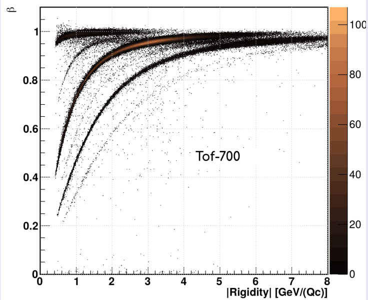
BM@N setup in the last run (behind magnet)

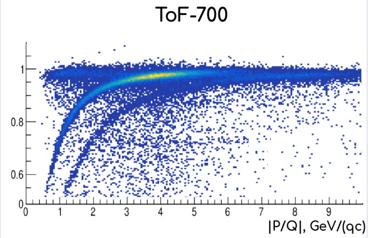


Particle Identification





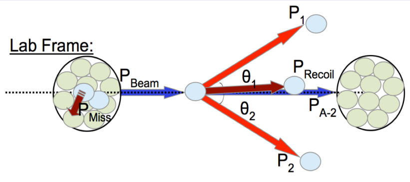




Short Range Correlation (SRC) programme as an extension to the BM@N experiment

How to study SRC?

Inverse kinematics



$^{12}_{6}C + p \rightarrow 2p + ^{10}_{5}B + n$ (np SRC)

$^{12}_{6}C + p \rightarrow 2p + ^{10}_{4}Be + p$ (pp SRC)

Participants

- JINR: BM@N
- Israel: Tel Aviv University
- Germany: TUD and GSI
- USA: MIT
- France: CEA

Super exclusive measurement!

Four particles detected:

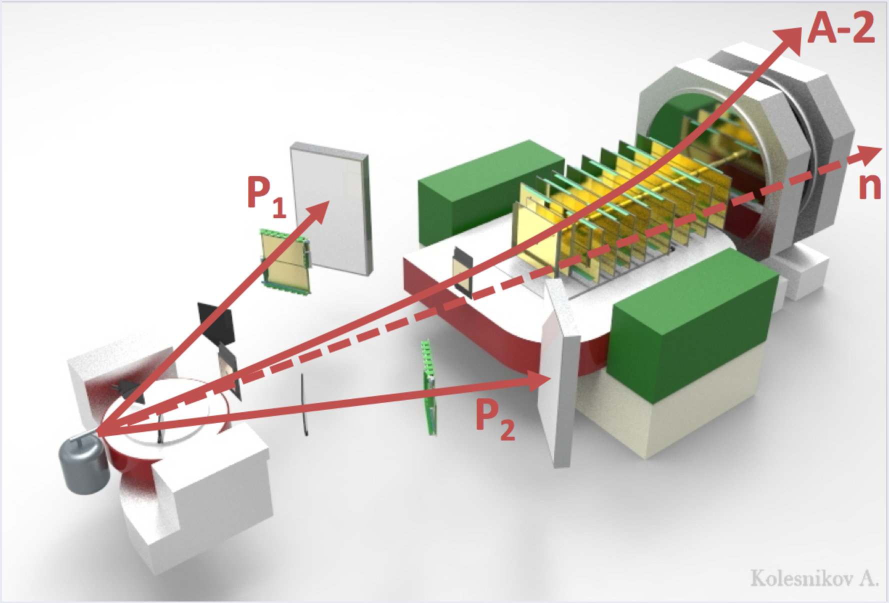
- scattered probe
- knocked-out nucleon
- recoil
- (A-2)-fragment system

Objectives

- identifying 2N-SRC events with inverse kinematics
- studying isospin decomposition of 2N-SRC
- studying (A-2) spectator nuclear system

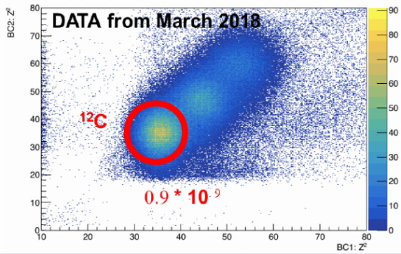
First BM@N SRC program run in March 2018: $\sim$ 30 MEvents collected

Experimental setup

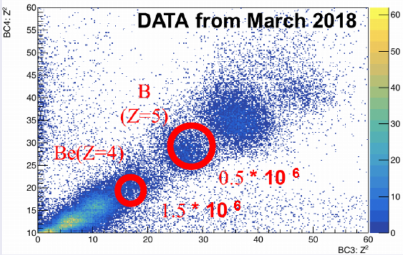


Counter analysis (A - 2) identification

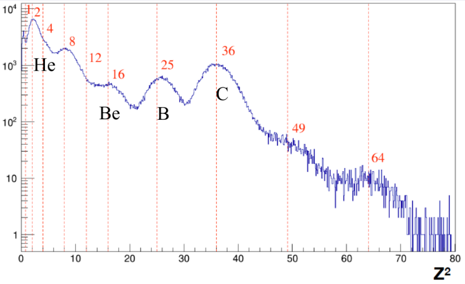
Before target:

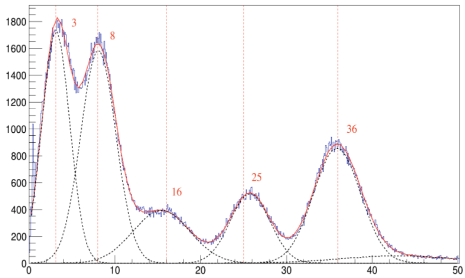


After target:



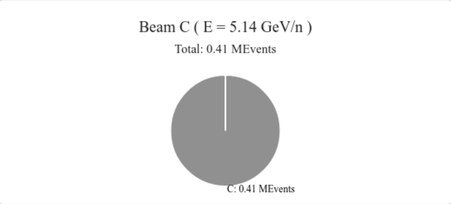
Nuclear fragment identification

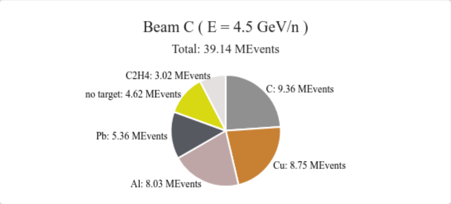


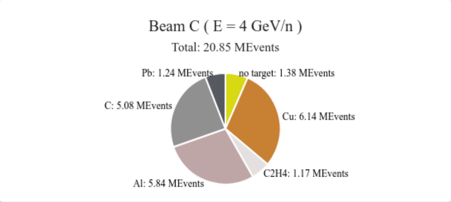


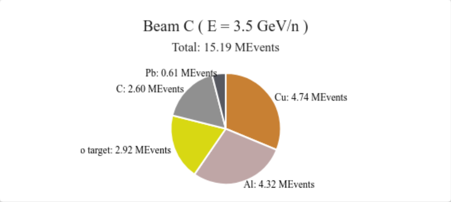
BM@N, data collected

Carbon run



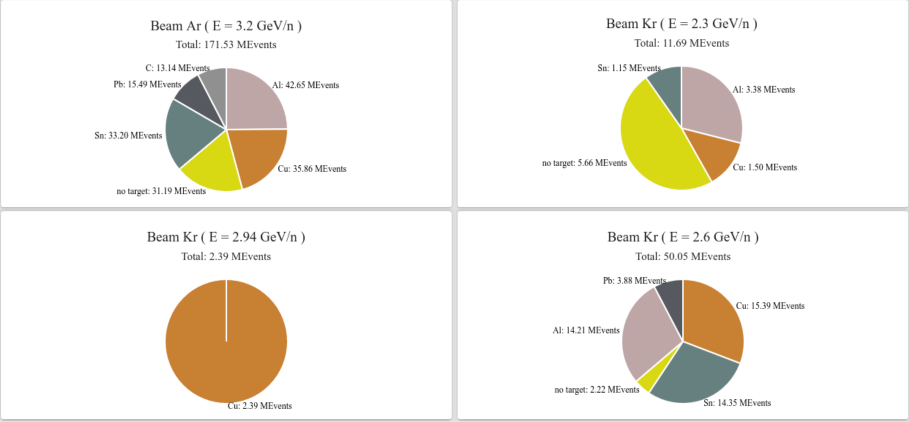






BM@N, data collected

Argon and Krypton run



- The 1st collaboration meeting (April, 11-13 2018)
- The 2nd collaboration meeting (October, 29-30 2018)

The 3rd collaboration meeting (April, 16-17 2019)

At present:

BM@N:
10 Countries,
17 Institutions,
216 Participants

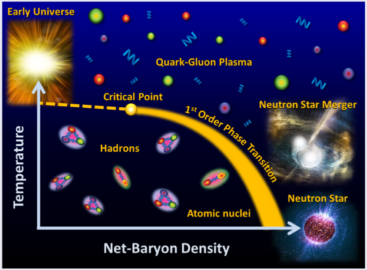
MPD:
10 Countries,
26 Institutions,
436 Participants

- N. B.: The 4th collaboration meetings are coming
  October, 14-15 (BM@N), October, 24-25 (MPD)

Summarising ...

NICA energy region:

- Maximum in K^+/π^+-ratio
- Maximum in Λ/π-ratio
- Maximum yield of hypernuclei
- Maximum in the net-baryon density
- Transition from a Baryon dominated system to a Meson dominated one
- Maximum of Λ-polarization
- 1st order ph. transition & mixed phase creation
- Critical end-point???



- The construction of accelerator complex and both detectors BM@N & MPD are going close to the schedule
- NICA got a recognition as a part of European research infrastructure
- You are kindly invited to join the BM@N or/and MPD Collaborations