Experiments with relativistic heavy ions at the Nuclotron-NICA complex

Eugene A. Strokovsky
VBLHEP of JINR, Dubna, Russia

Abstract

Program of experiments at relativistic heavy ion beams at the *Nuclotron-NICA* complex will be outlined briefly.

Current status of the main spectrometers (the spectrometer *BM@N* at the extracted Nuclotron beams *and the MPD-detector at the NICA collider*, both are under construction) will be reported.


ДУБНА

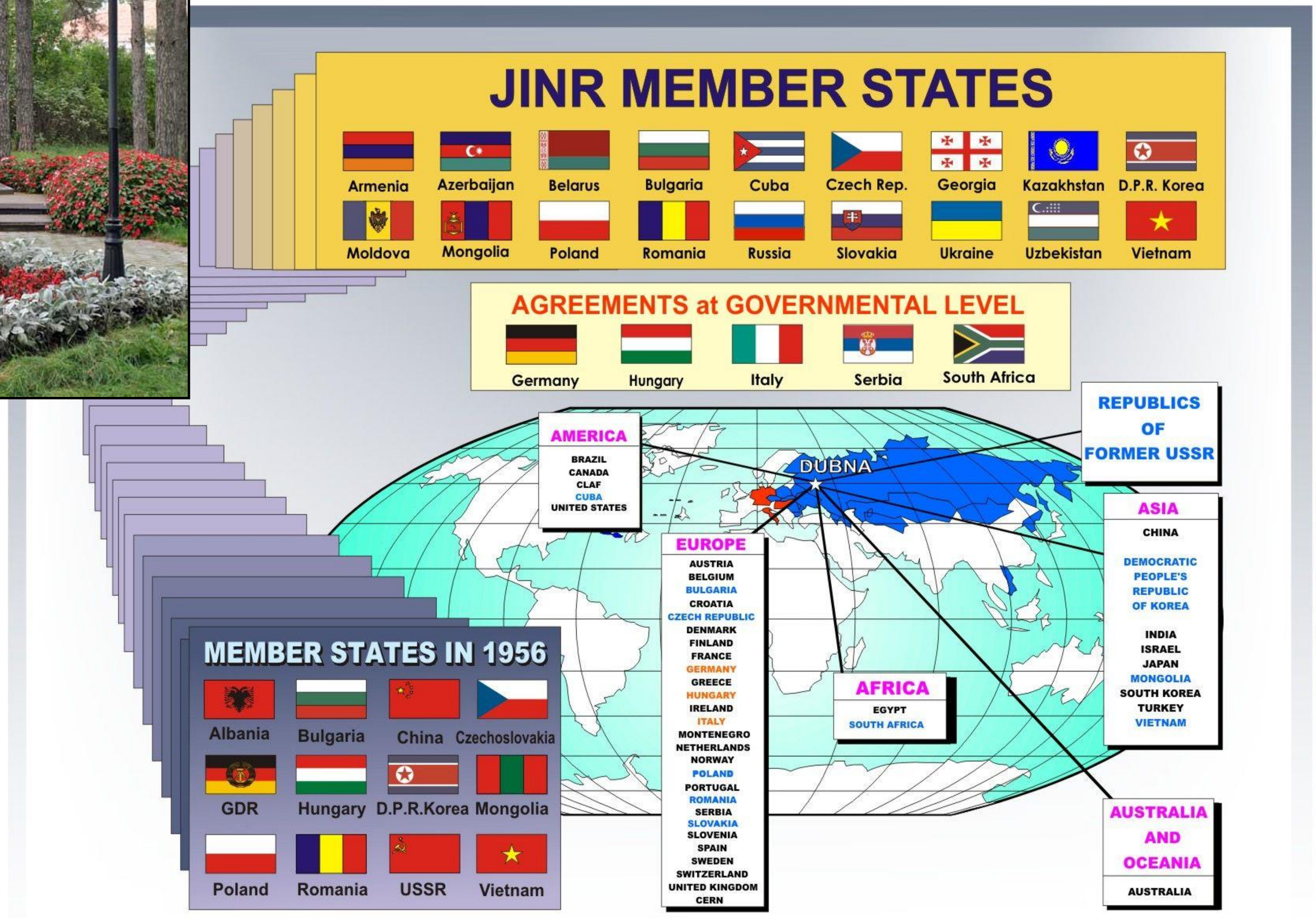
Introduction

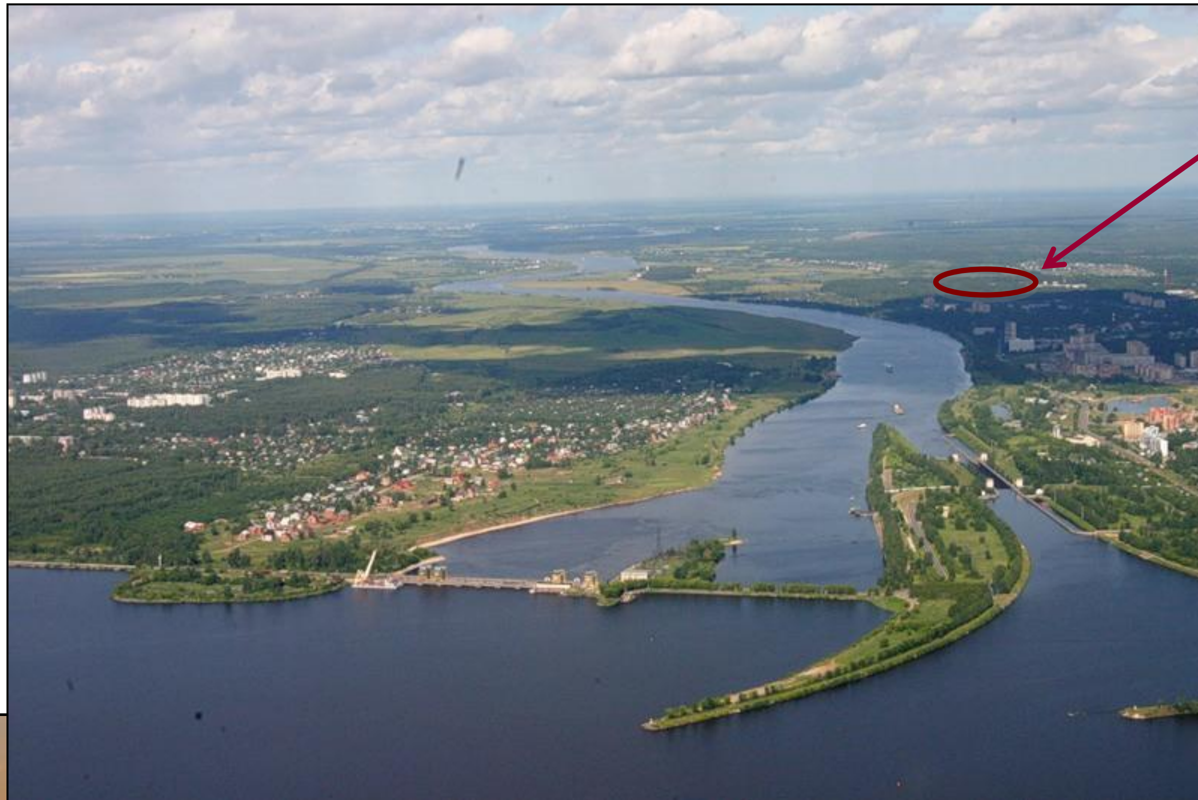
60 years to JINR in 2016

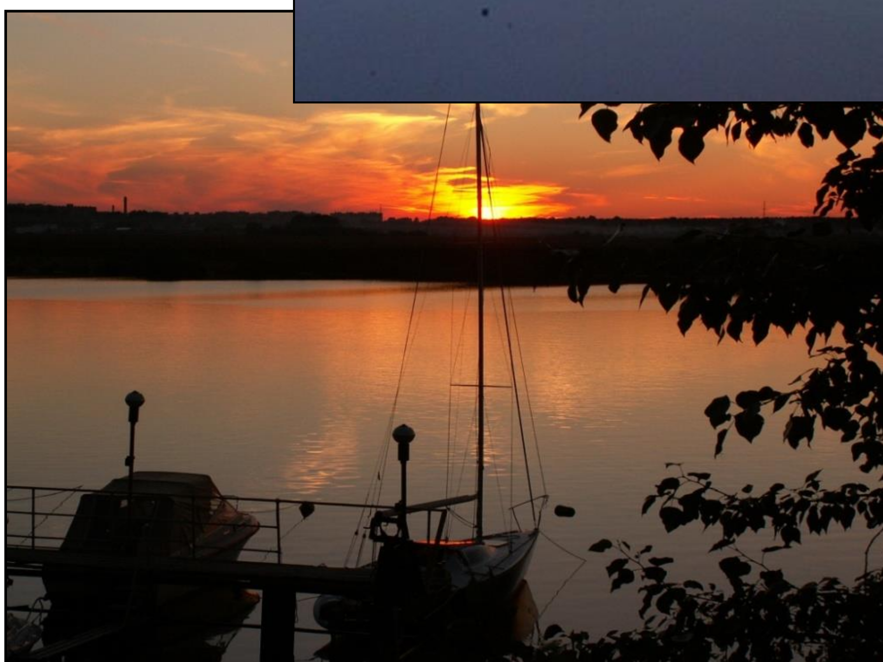
J
I
N
R

D
u
b
n
a

18 member-states



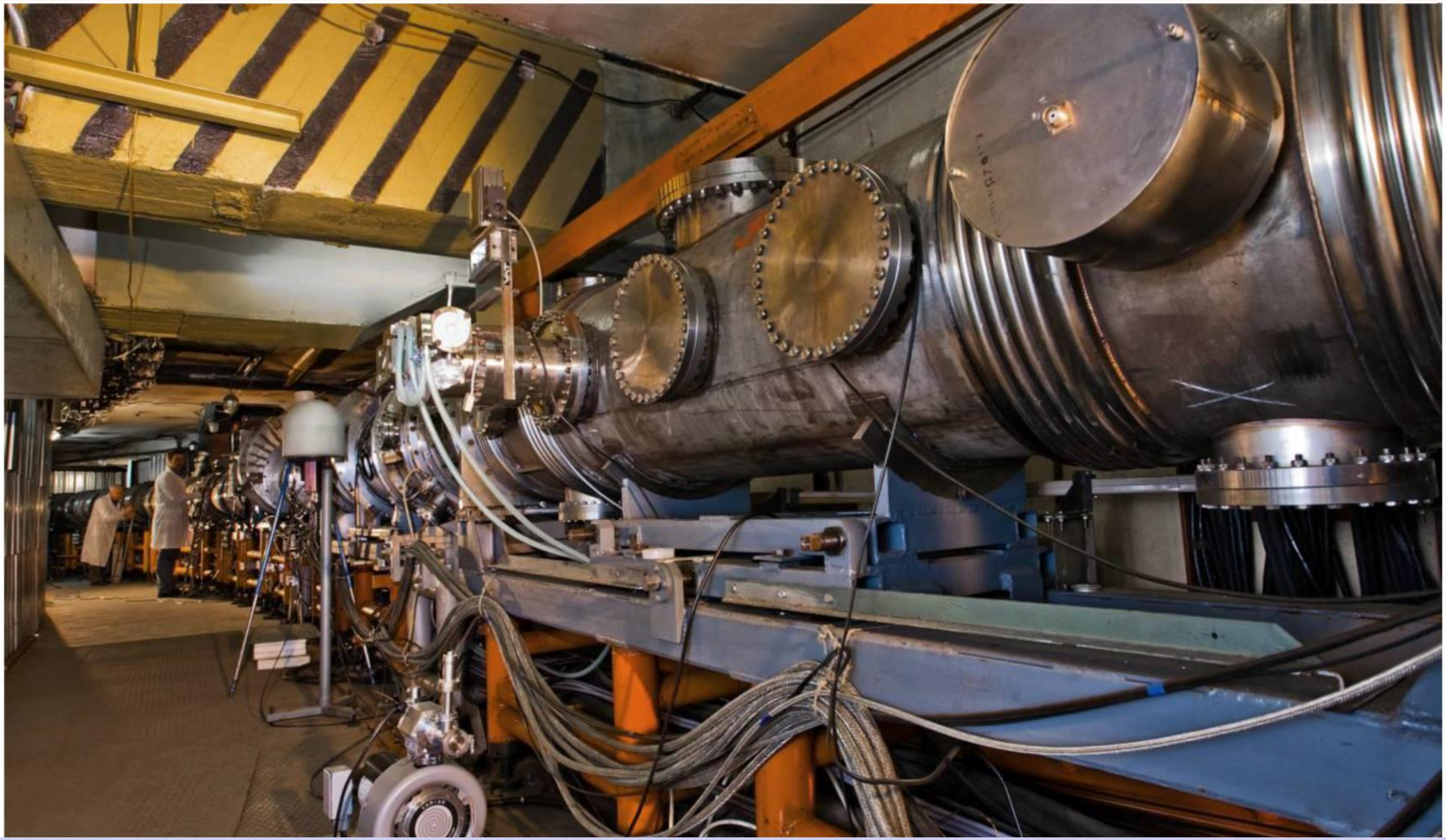

VBLHEP site



Veksler-Baldin
Laboratory of High Energy Physics of JINR
(VBLHEP)

E.A. Strokovsky, 34-th Reimei Workshop, 8.08.2016

Synchrotron **Nuclotron,** in operation since 1993
– based on superconducting magnets developed in Dubna



Nuclotron **provides accelerated proton and ion beams**
(up to Xe(A=124, Z=42); in the nearest years – up to Au(A=197, Z=79)
with energies up to 6 A·GeV (Z/A from 1/3 to 1/2)

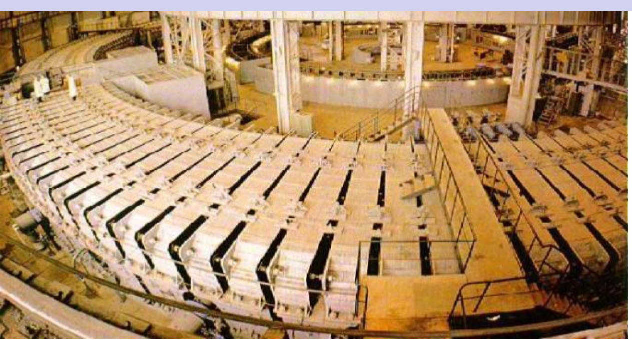
from the Synchrophasotron to the heavy ion collider

1957 Synchrophasotron

10 GeV synchrotron (*p*) – leader in the energy

Origin of the high energy physics

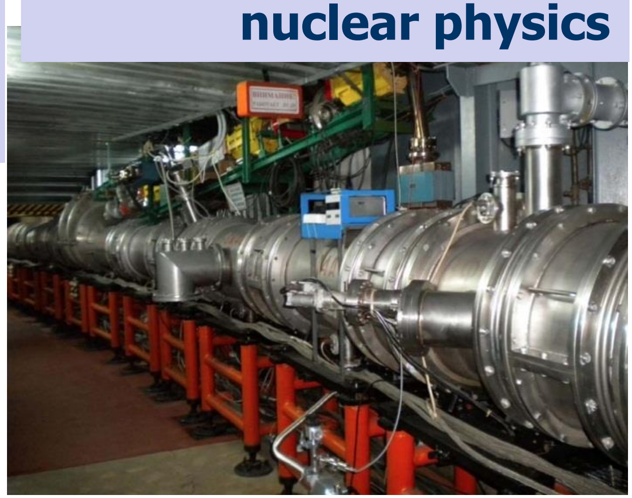
V.I.Veksler – the author of the *Phase Stability Principle* *(1944)*



1993 Nuclotron

The first superconductive heavy ion accelerator

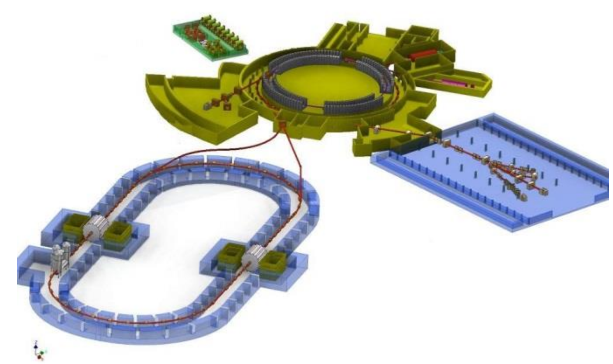
A.M. Baldin: pioneering studies in relativistic nuclear physics



2020 NICA

Superconductive collider for heavy ions

Study of nuclear and baryonic matter at extremal densities



See also

https://ufn.ru/en/articles/2016/4/

Physics – Uspekhi **59** (4) 383 – 402 (2016)

60th ANNIVERSARY OF THE JOINT INSTITUTE FOR NUCLEAR RESEARCH (JINR)

PACS numbers: **11.80.–m**, 13.85.Dz, 14.20.Dh

Relativistic nuclear physics at JINR: from the synchrophasotron to the NICA collider

N N Agapov, V D Kekelidze, A D Kovalenko, R Lednitsky, V A Matveev, I N Meshkov, V A Nikitin, Yu K Potrebennikov, A S Sorin, G V Trubnikov

DOI: 10.3367/UFNe.0186.201604c.0405

Relativistic Heavy Ion Physics at JINR
(in general)

The present strategic course of the JINR in relativistic heavy ions & particle physics is based on:

- **development of the home accelerator facility NICA**
  providing relativistic heavy ions & polarized beams
- **scientific programs at home & external accelerators including**
  study of various phases of strongly interacting matter,
  hot topics of particle physics and spin physics

Relativistic Heavy Ion Physics is a high priority task in many scientific centers (BNL, CERN, GSI) since last few decades

Theoretical motivation of relativistic heavy ion studies at JINR was developed in the works of:
A.Sissakian, A.Sorin, V.Toneev, G.Zinoviev etc.

… from particles $\rightarrow$ to hadronic/QCD matter …

A.M.Baldin

1970’

1986’

1996’

2008’

2015’

time

Relativistic Ion Facilities
from Synchrophasotron and AGS to NICA and FAIR

Over the last 30 years a lot of efforts have been made to provide the conditions for searching for new states of strongly interacting matter under extreme conditions.

Synchrophasotron: E_{lab} ~ 4.2 AGeV ($\sqrt{s_{NN}}$ = 3 GeV)
1971 - 1999, pioneer experiments in the field of relativistic nuclear physics.

AGS: E_{lab} ~ 11 AGeV ($\sqrt{s_{NN}}$ = 5 GeV)
1986 — 1992, study of compressed baryonic matter.

SPS: E_{lab} ~ 158 AGeV ($\sqrt{s_{NN}}$ = 18 GeV)
1986- up to now,
study of compressed baryonic matter.

RHIC: $\sqrt{s_{NN}}$ = 200 GeV (E_{lab} ~ 80000 AGeV)
1996 - up to now,

LHC: $\sqrt{s_{NN}}$ = 5520 AGeV (E_{lab} ~ $6.1 \cdot 10^7$ AGeV)
2008 - planned

SIS 300 (FAIR): E_{lab} ~ 34 AGeV
($\sqrt{s_{NN}}$ = 8.5 GeV),
full performance will be reached in 2015,
study of compressed baryonic matter.

NICA: $\sqrt{s_{NN}}$ = 9 GeV (E_{lab} ~ 40 AGeV).
full performance will be reached in 2013,
search for the mixed phase of strongly interacting matter.

The JINR plans: to start in the coming 3÷5 years experimental studies of hot and dense strongly interacting QCD matter as well as search for possible manifestation of signs of the mixed phase and critical endpoint in heavy ion collisions.

Instrumental basis :

NICA collider **(including modes with polarized beams) with the multipurpose detectors: *MPD*, SPD**
Nuclotron-M (including modes with extracted polarized beams and MPPT) with *BM@N*
External facilities at CERN (SPS, LHC), FAIR, RHIC

NICA Collaboration

<u>4-side Treatment</u> was signed in Dec. 2015 between Russia, China, JINR and Chinese Academy of Sciences about collaboration in NICA.

<u>JINR-Russia Treatment</u> about cooperation in NICA works: was signed in April 2016

Physics: program and suggestions see in
http://theor0.jinr.ru/twiki-cgi/view/NICA/WebHome

NICA White Paper – International Effort

NICA

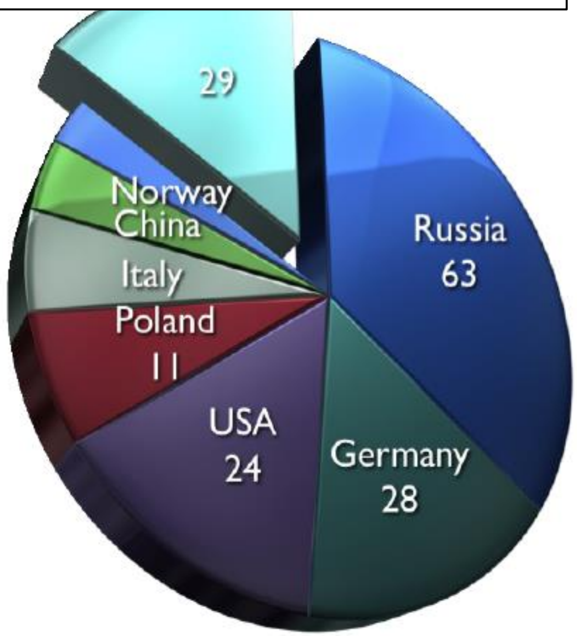
Draft v 8.03
January 24, 2013

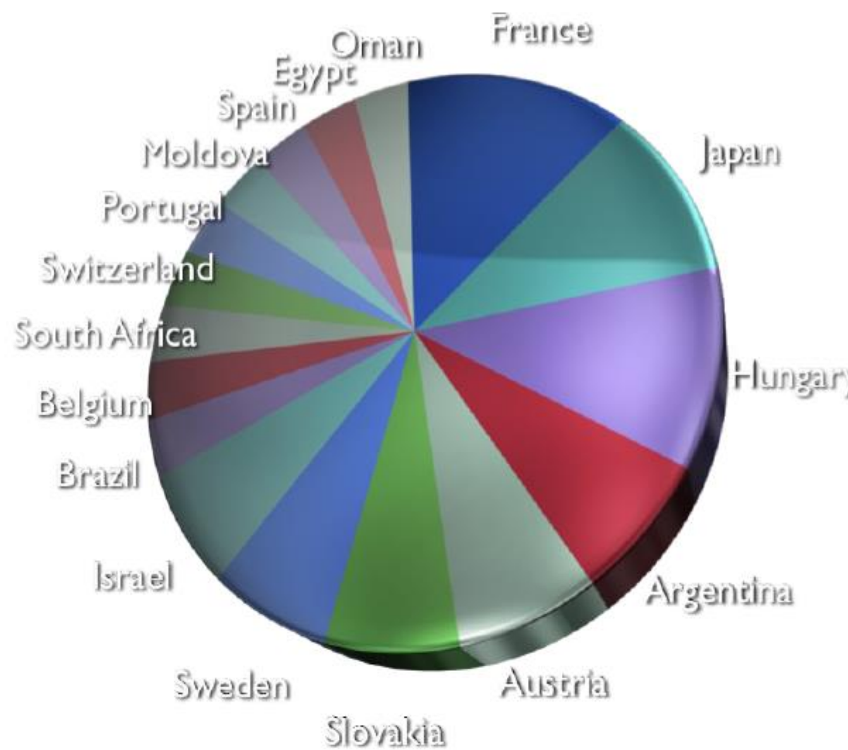
SEARCHING for a QCD MIXED PHASE at the
NUCLOTRON-BASED ION COLLIDER FACILITY
(NICA White Paper)

Statistics of White Paper Contributions (as in 2015)

***111** contributions:*
***188** authors from **70** centers in **24** countries*

*Indicates wide international interest
to the physics at MPD & BM@N*





Main directions of studies with the relativistic heavy ions:

Probing of different regions of the phase diagram for hot ***and dense*** hadronic matter:

- **Phase transitions**
  - **Baryonic to hadronic and QCD (quark-gluon) matter**
  - **Critical endpoint (exists or not); mixed phase**
  - **Liquid-to-fog (at the condensing-hadronization stage 3)**
- **Exotic nuclei (hypernuclei ; stabilizing role of strangeness implemented into a nuclear matter)**

Other physics within the NICA: ***Spin and polarization phenomena***

- **nucleon structure, phenomenology of the nucleon-nucleon interactions**
- **few nucleon systems at short distances (probe of sub-nucleonic aspects; multinucleon forces etc.)**

***Flavour physics*, i.e.**

***Fundamental symmetries* and mechanisms of their violation**

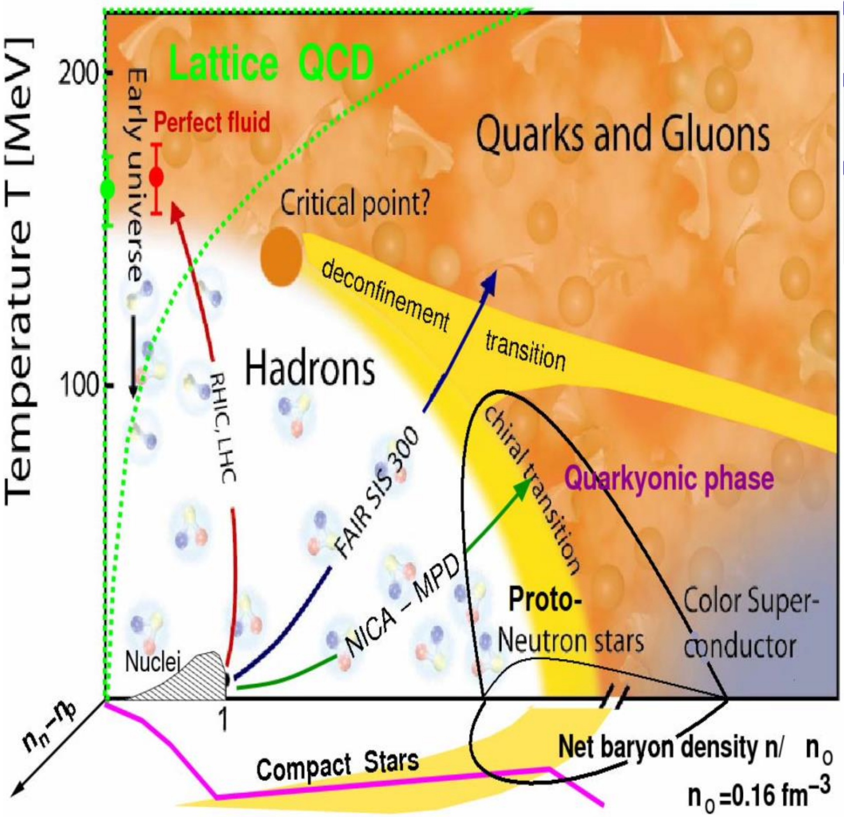
***Particle structure* (constituents, quark content) in empty space and in the strongly interacting medium, exotics)**

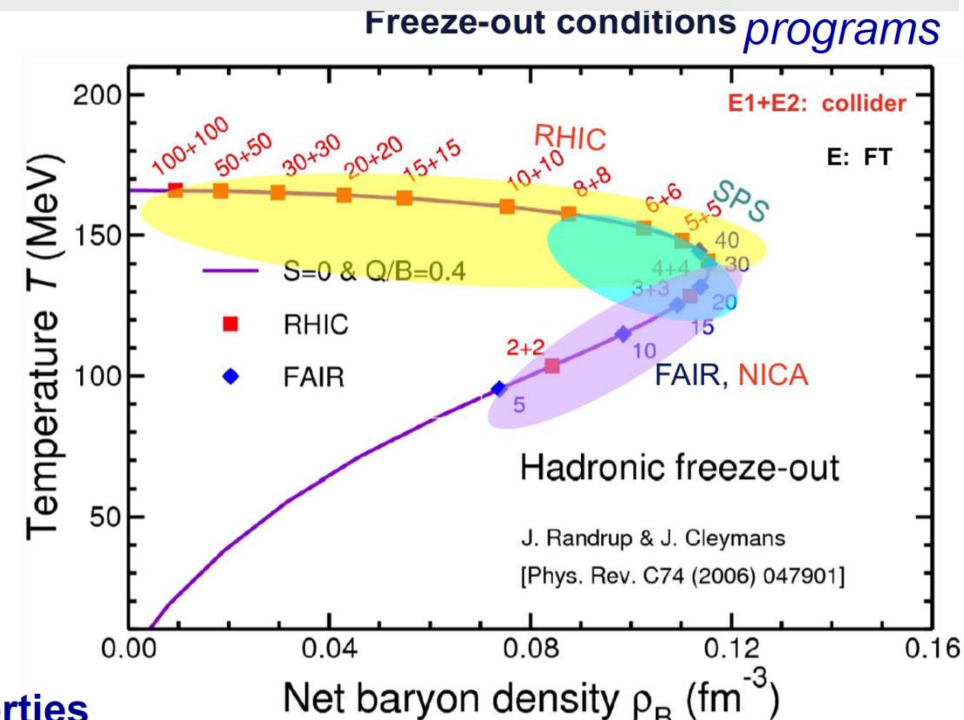
***Particle properties in medium* (cold and normal/sparse; hot and dense)**

Physics

QCD matter at NICA :

- *Highest net baryon density*
- *Energy range covers onset of deconfinement*
- *Complementary to the RHIC/BES, FAIR and CERN experimental programs*

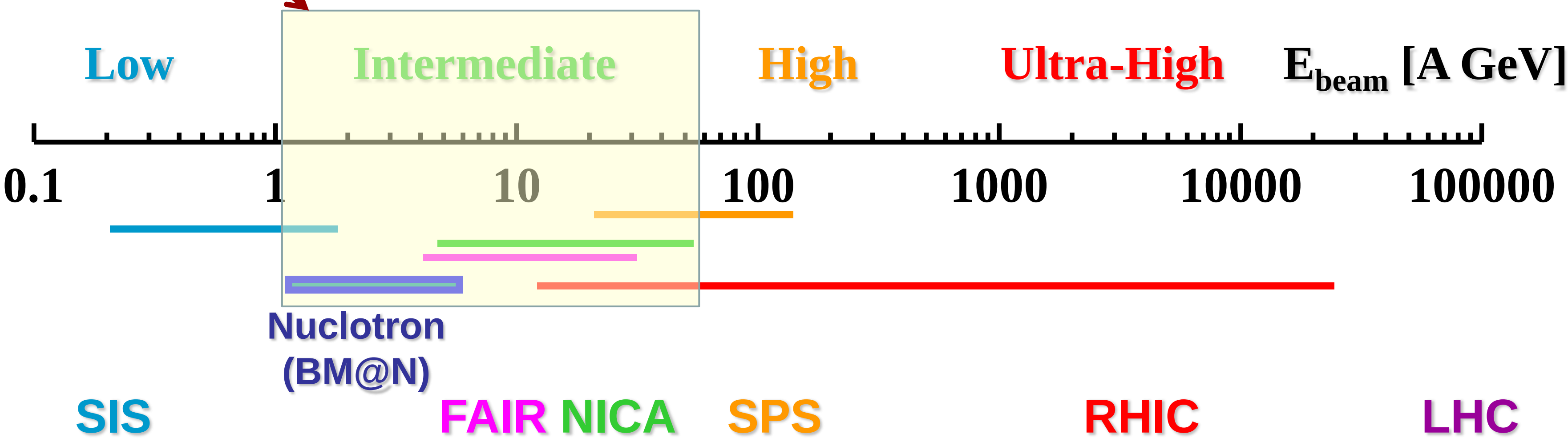




- **Bulk properties, EOS** - *particle yields & spectra, ratios, femtoscopy, flow*
- **In-Medium modification of hadron properties**
- **Deconfinement (chiral), phase transition at high ρ_B** - *enhanced strangeness production*
- **QCD Critical Point** - *event-by-event fluctuations & correlations*
- **Strangeness in nuclear matter** - *hypernuclei*

NOTE: a particle must live "long enough" inside the medium!

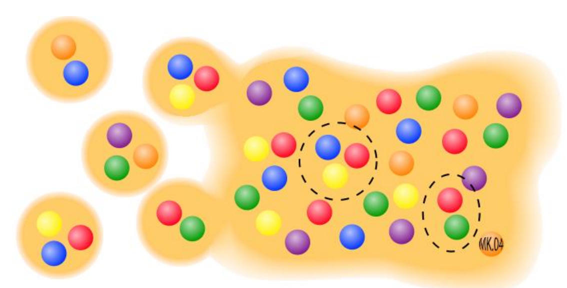
Heavy Ion Collision experiments



Baryonic matter
||
Meson and baryon spectroscopy
In-medium effects
EoS

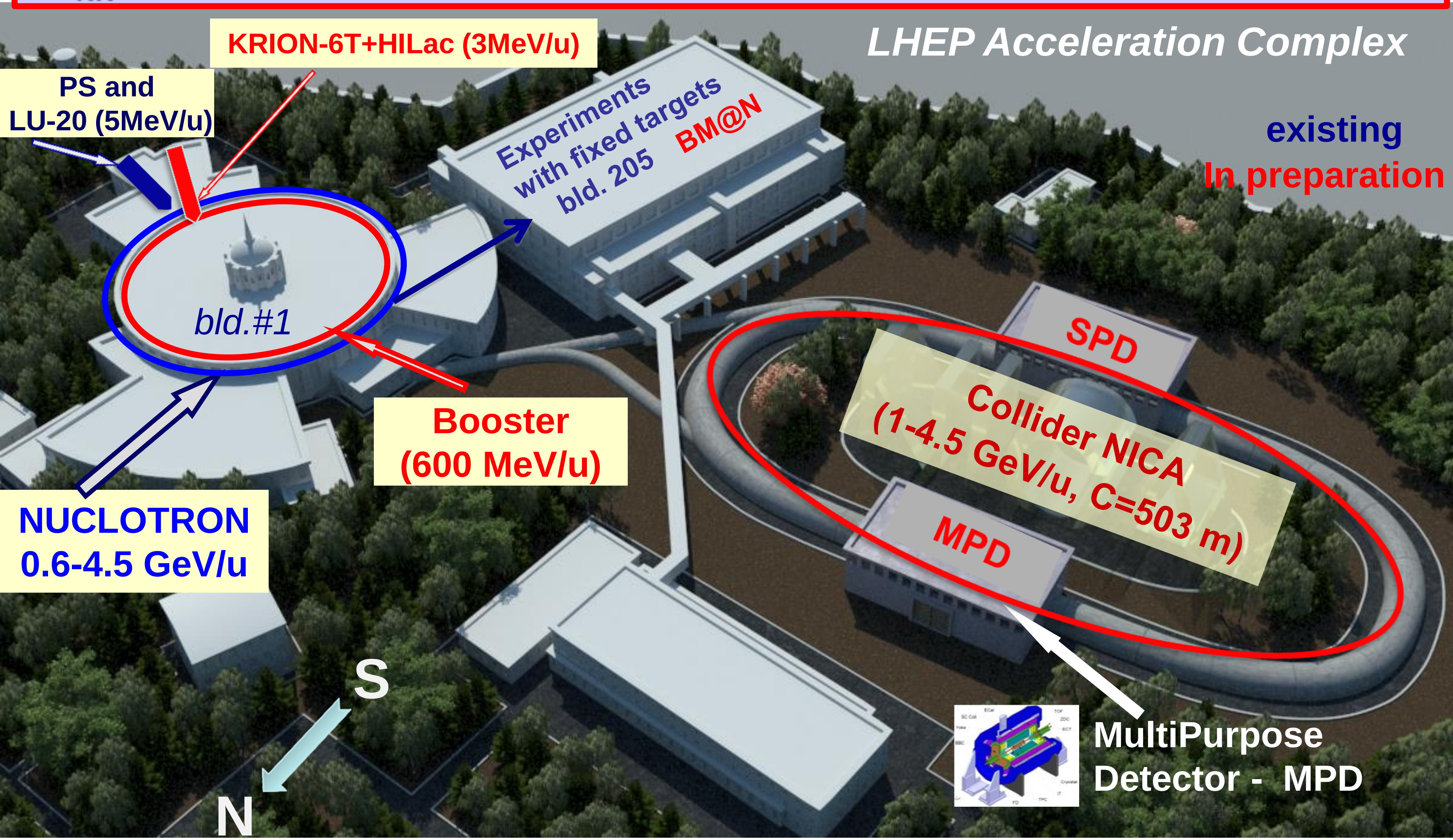
‚Mixed‘ phase:
hadrons (baryons, mesons) + quarks and gluons
||
In-medium effects
Chiral symmetry restoration
Phase transition to sQGP
Critical point in the QCD phase diagram

QGP: quarks and gluons
||
Properties of sQGP

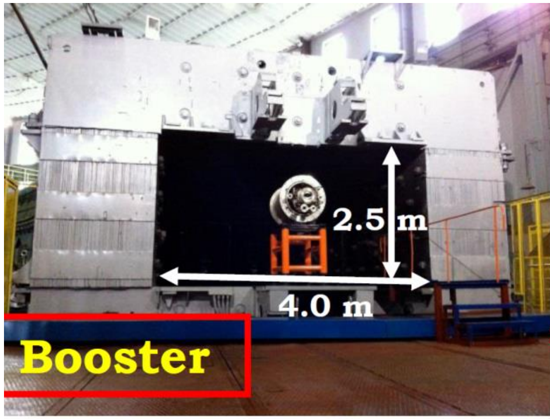


Complex NICA

Collider basic parameters:
$\sqrt{s_{NN}}$ = **4-11** GeV; ***beams***: *from* **p** to **Au**; **L~10^{27}** cm^{-2} c^{-1} (Au), ~**10^{32}** cm^{-2} c^{-1} (p)



NICA – Stage I



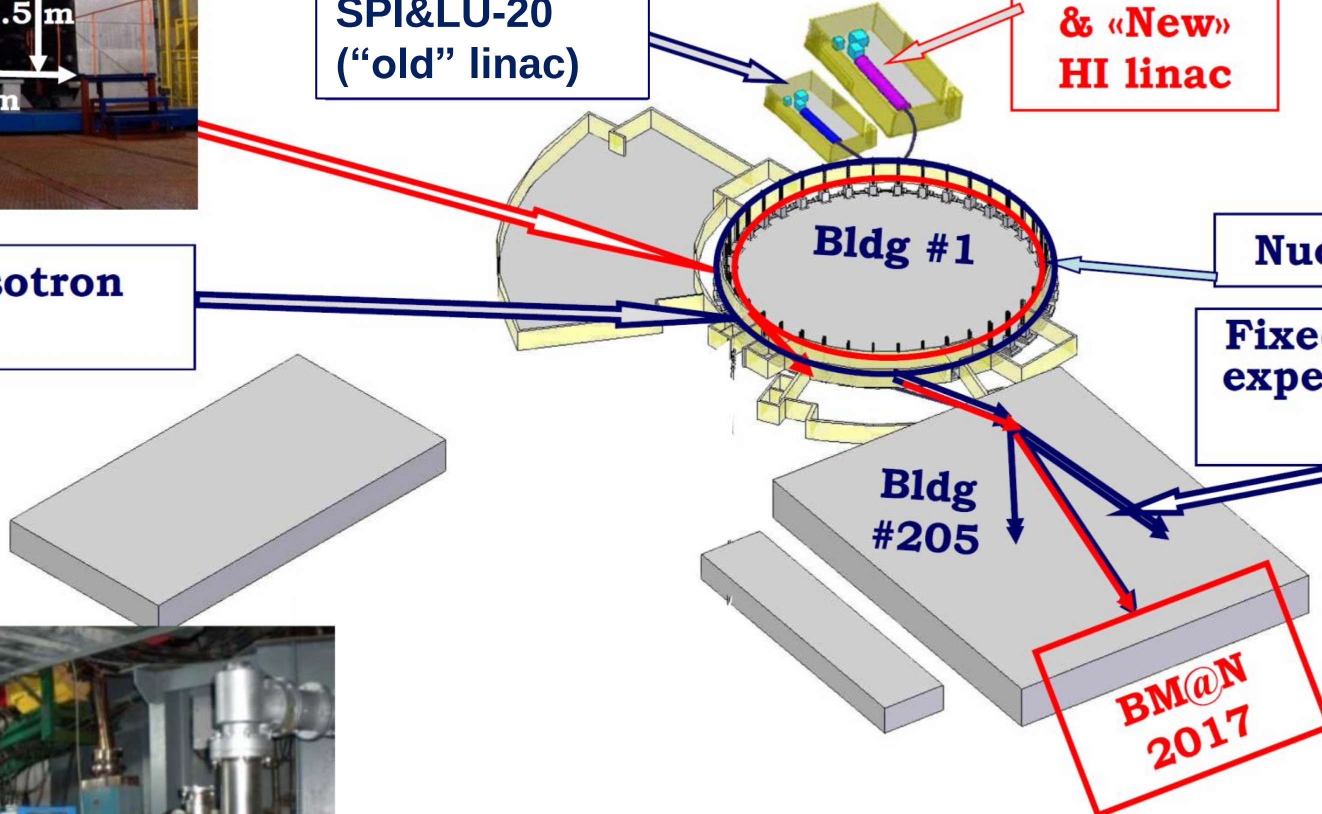
SPI&LU-20
(“old” linac)

KRION-6T
& «New»
HI linac

Synchrophasotron
yoke

Nuclotron

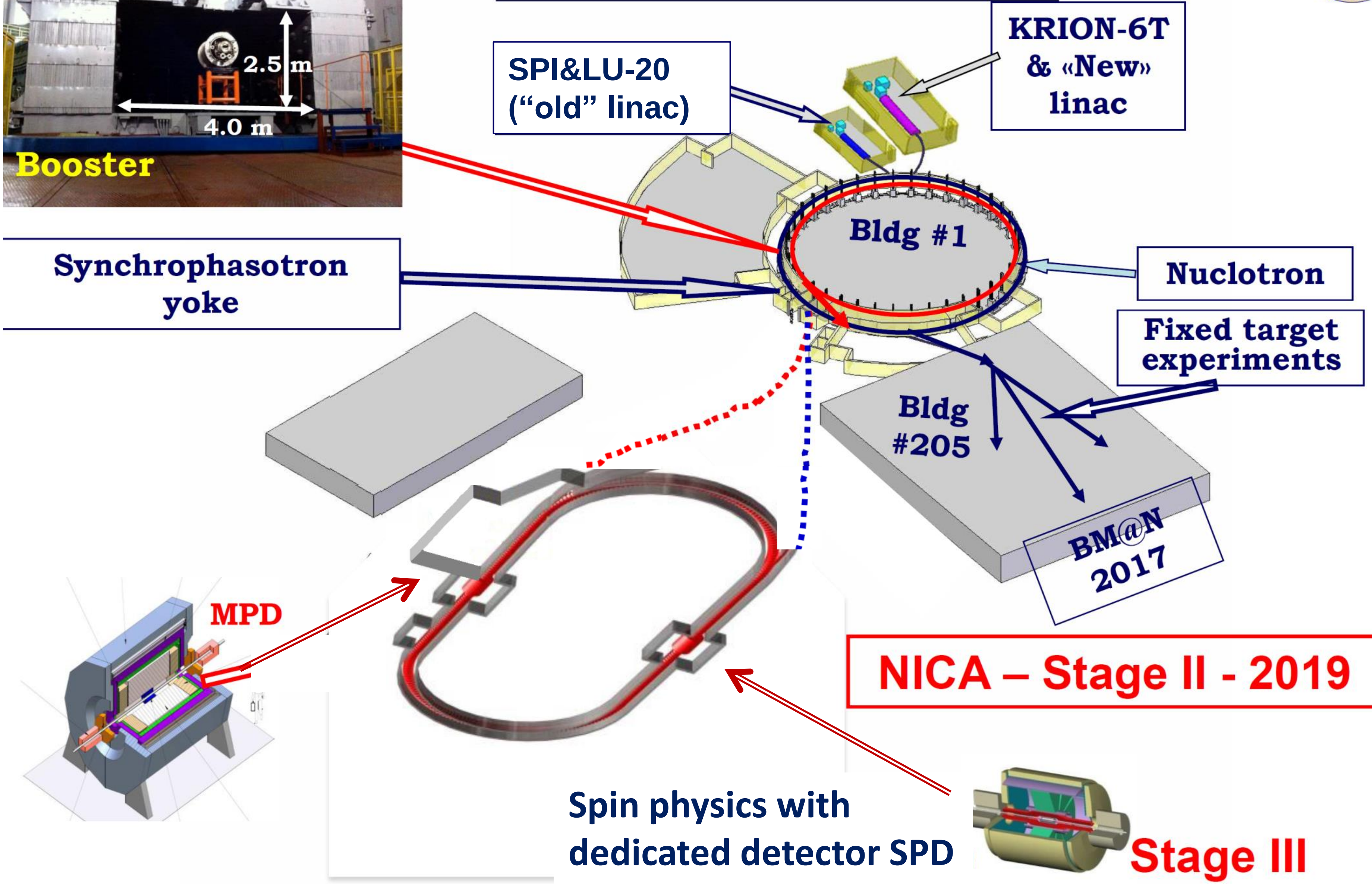
Fixed target
experiments
2014



Nuclotron facility today

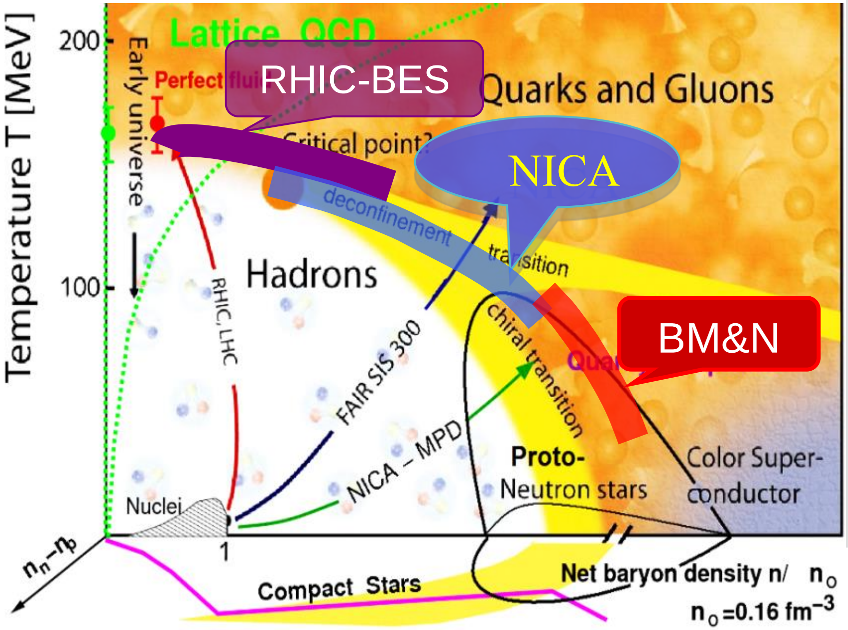
NICA – Stage I – 2017

NICA – Stages II & III

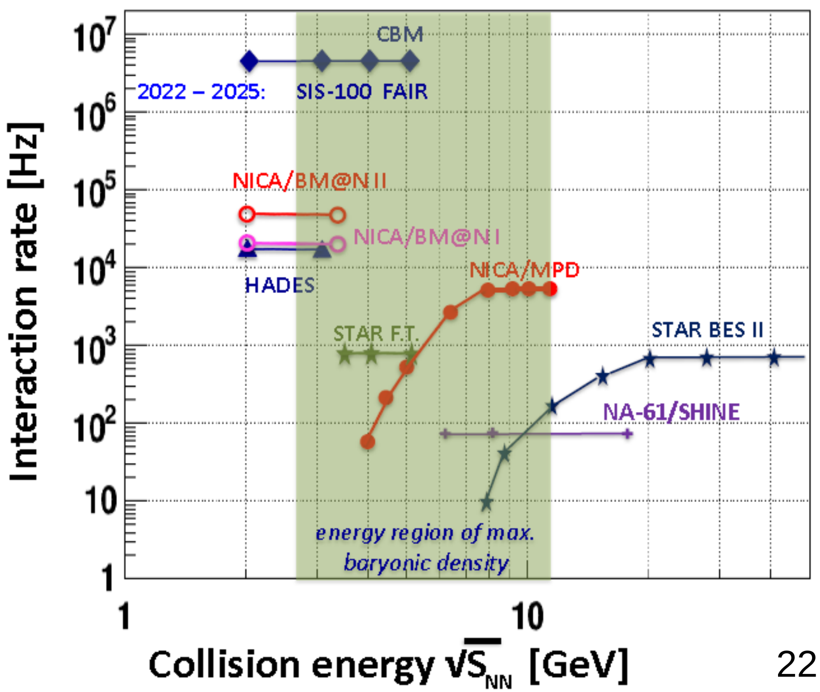


MPD (physics and status)

NICA-MPD heavy-ion program



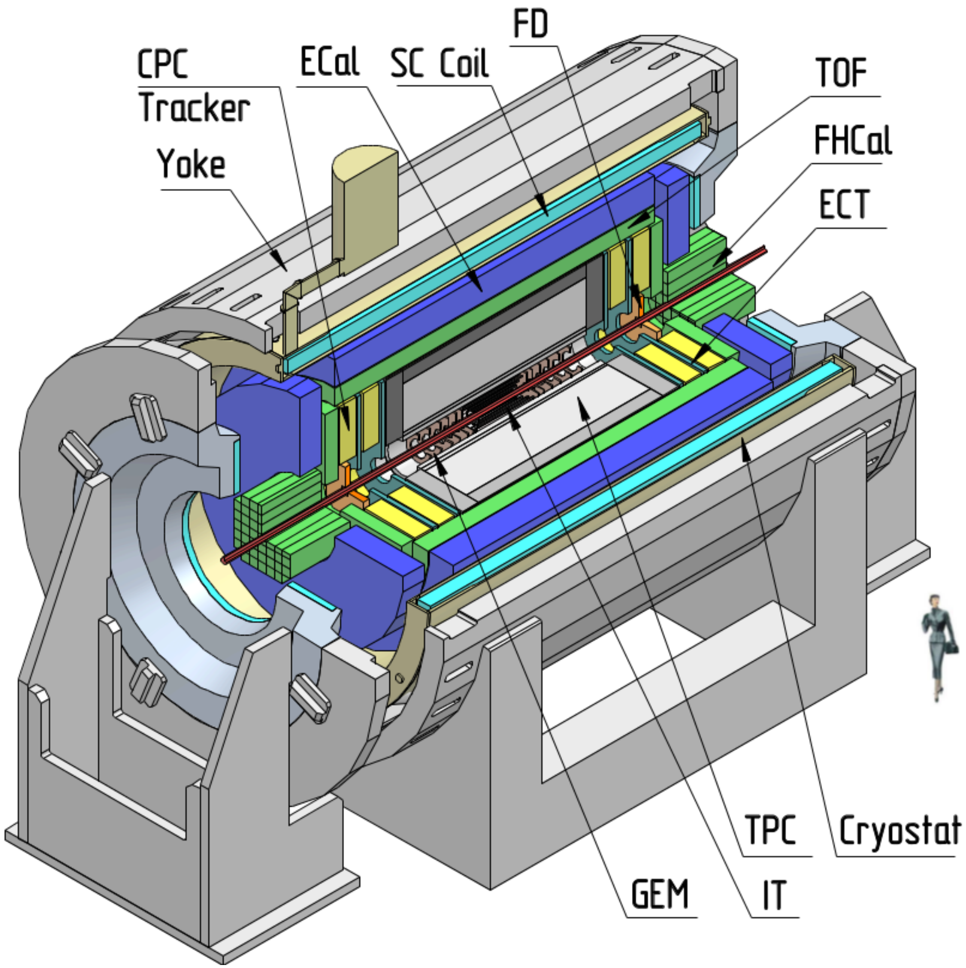
- *Bulk properties, EOS*
  - particle yields & spectra, ratios, femtoscopy, flow
- *In-Medium modification of hadron properties*
  - onset of low-mass dilepton enhancement
- *Deconfinement (chiral) phase transition at high ρ_B*
  - enhanced strangeness production
  - Chiral Magnetic (Votical) effect, Λ polarization
- *QCD Critical Point*
  - event-by-event fluctuations & correlations
- *Y-N interactions in dense nuclear matter*
  - hypernuclei



QCD matter at NICA :

- **Highest net baryon density $\sqrt{s}$ = 4-11A GeV**
- **Energy range brackets onset of deconfinement**

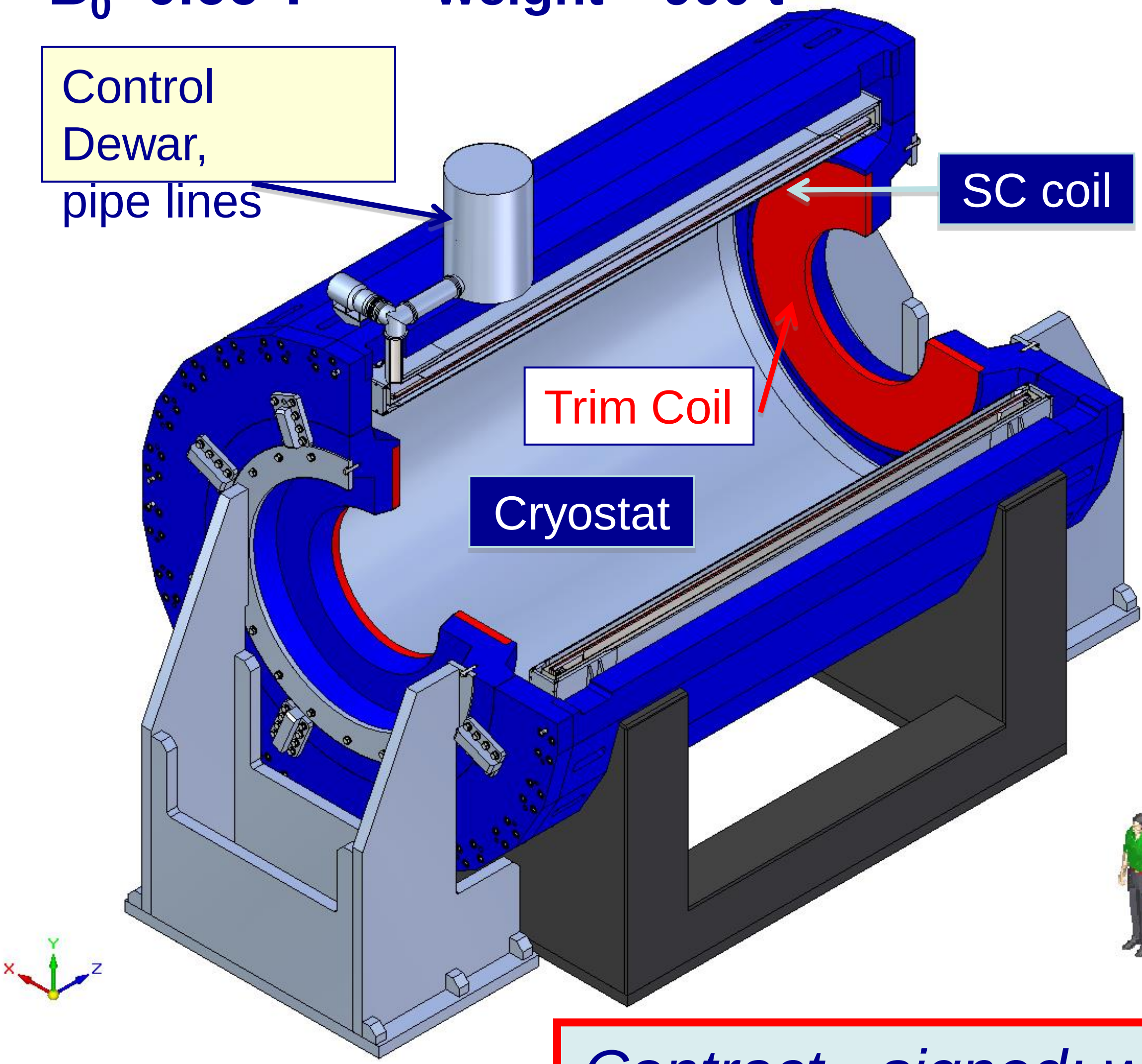
MultiPurpose Detecor for A+A collisions @ NICA

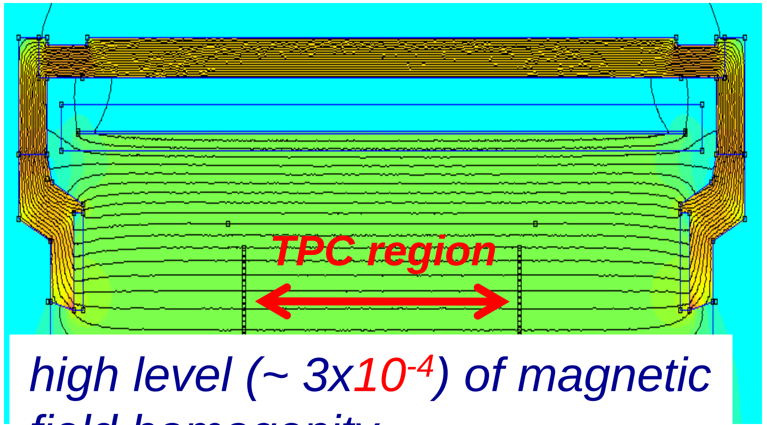


- Hermeticity, 2π acceptance in azimuth
- 3-D tracking (TPC, ECT)
- High resolution vertexing (IT)
- Powerful PID (TPC, TOF, ECAL)
  - π/K up to 1.5 GeV/c,
  - K/p up to 3 GeV/c,
  - γ, e : 0.1<p<3 GeV/c
- Precise event characterization (FHCAL)
- Fast timing and triggering (FFD)
- Low material budget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

MPD superconducting solenoid

B_0=0.66 T **weight ~ 900 t**





high level (~ 3×10^{-4}) of magnetic field homogenity

ASG superconductors (Genova, Italy)**:**

- *Cold Mass + Cryostat*
- *Vacuum System*
- *Trim Coils*
- *Control System*
- *PS*
- ***General responsibility***

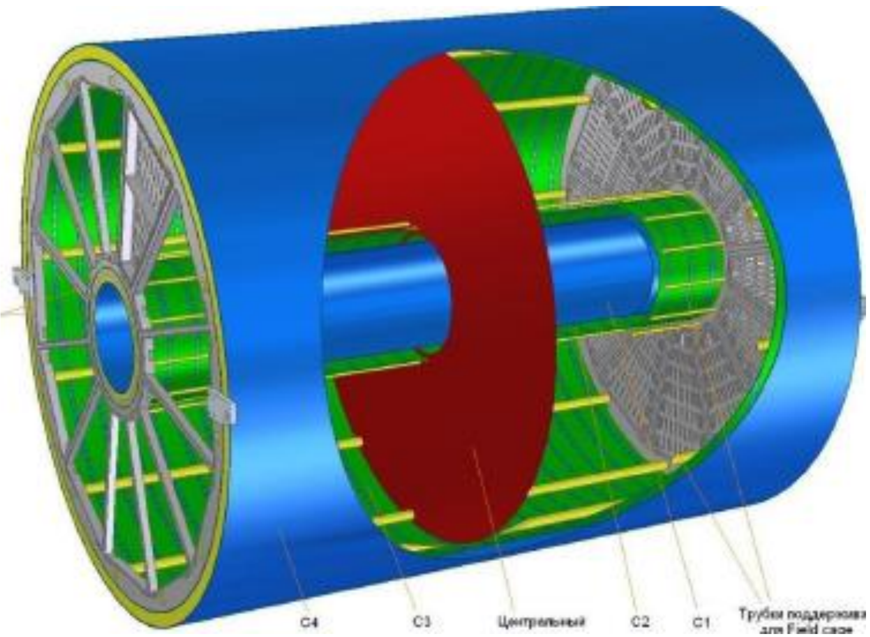
Contract - signed; works – in progress

MPD magnet : mechanical elements

Forged pieces of the MPD magnet support rings
Vitcovice, Czech Republic
June 2016

Forged pieces of the MPD magnet poles
Vitcovice, Czech Republic
June 2016

MPD Time Projection Chamber



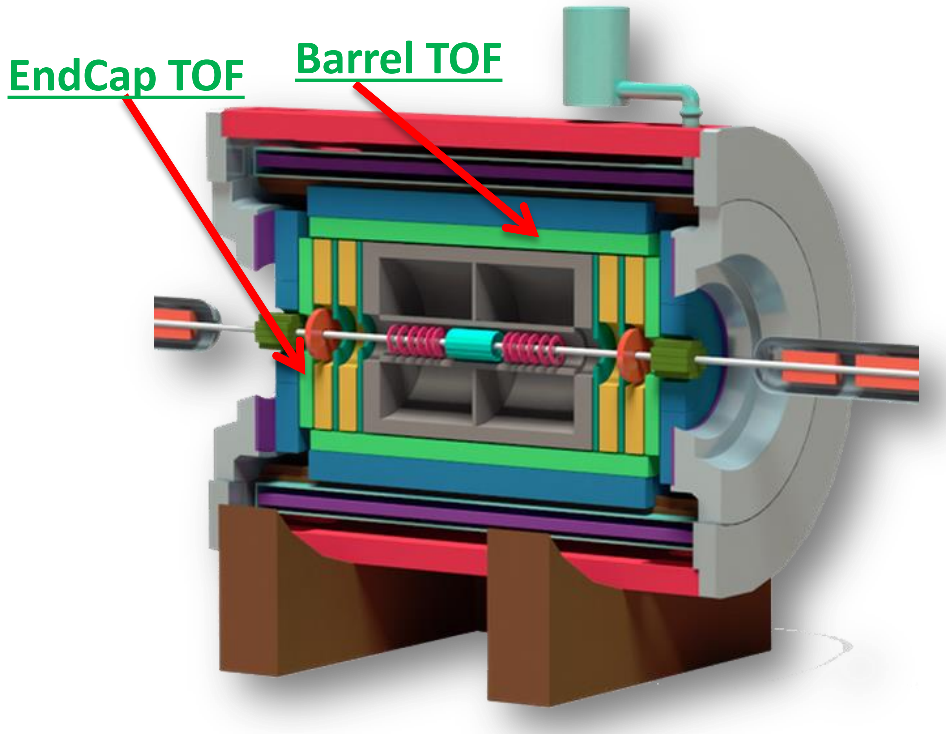
Item	Dimension
Length of the TPC	340cm
Outer radius of vessel	140cm
Inner radius of vessel	27 cm
Outer radius of the drift volume	133cm
Inner radius of the drift volume	34cm
Length of the drift volume	170cm (of each half)
Drift gas	90% Ar+10% Methane, Atmospheric pres. + 2 mbar
Gas amplification factor	~ 10^4
Drift velocity	5.45 cm/μs;
Drift time	< 30μs;
Pad size	$5x12mm^2$ and $5x18mm^2$
Number of pads	95232

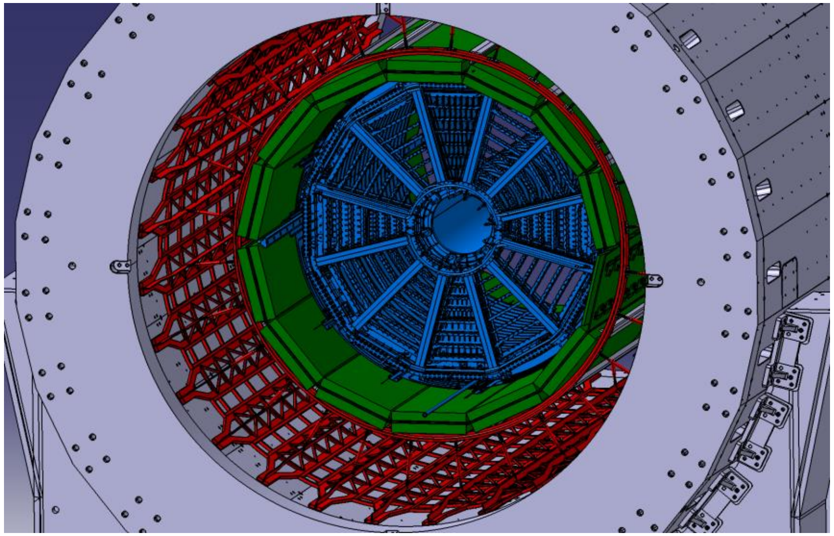
Works are going in accordance with the schedule

MPD Time Projection Chamber (progress at June'16)

TDR status:	**Reviewed by MPD DAC in 2015, the recommen- dations implemented, revision 2.0 ready, next evaluation 22.06.2016**
Room & assembling tooling:	**In progress**
RoC & Padplanes:	**Production and testing ongoing**
FEE:	**(PASA-ALTRO) – under production;** **new (thin) SAMPA chips under tests**
Service systems (gas, cooling):	**In progress**
TPC Integration:	**In progress**

MPD TOF : progress in 2016





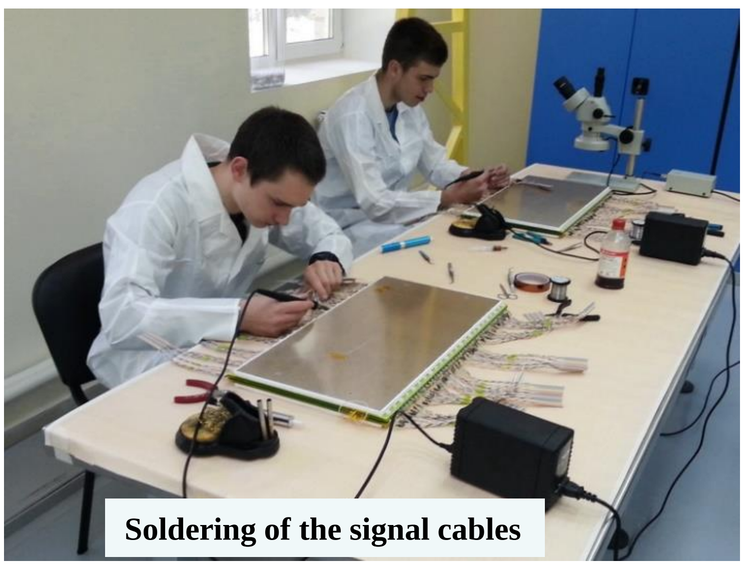
- **TDR status**: recent evaluation in December 2015, all recommendation implemented
  - Additional MC simulation done
  - Issue of integration and installation clarified

- **Preparation for mass-production** : material ordering (mylar, conductive paint, screws, monofilament line, wires and connectors purchased), equipment installation, personnel training

TOF : preparation for mass-production
(June’16 status)

Glass quality control

Painting of the conductive layer



Soldering of the signal cables

MRPC assembling

Conclusions

- Significant progress is achieved in the MPD project realization
- The MPD TDR preparation is going further: the DAC helps in its evaluation
- Construction of the MPD Magnet has started
- Preparation for the mass-production of the MPD elements (TPC, TOF, ECAL) is ongoing
- The "Integration plan" for the MPD barrel is nearing completion, endcaps and the IT integration is the next step

SPD (spin physics at NICA)

SPD (Spin Physics Detector) at NICA

Collider provides both:
transversally & longitudinally
polarized ***p*** & ***d***
with energy up to $\sqrt{S}$ *=* ***27 GeV***

The issues to be studied:

- ► *MMT-DY processes*
- ► *J/Ψ production processes*
- ► *Spin effects in inclusive high-*p_T *reactions*
- ► *Spin effects in one and two hadron production processes*
- ► *Polarization effects in heavy ion collisions*

The Collaboration is being formed

The Project is under preparation

Baryonic Matter at the Nuclotron
(the *BM@N* project)

(The flagship "fixed target" experiment)

The Nuclotron parameters for the BM@N:
- Energy range: Elab = 1-6 GeV /nucl
- Beams: from ***p*** to ***Au***
- Intensity: 10^9 (Au), 10^{12} (p)

The Baryonic Matter at Nuclotron (BM@N) project

- approved in 2012

The final goal:

Search for the mixed phase and phase transitions of a strongly interacting matter in processes:

AA, pA and pp interactions

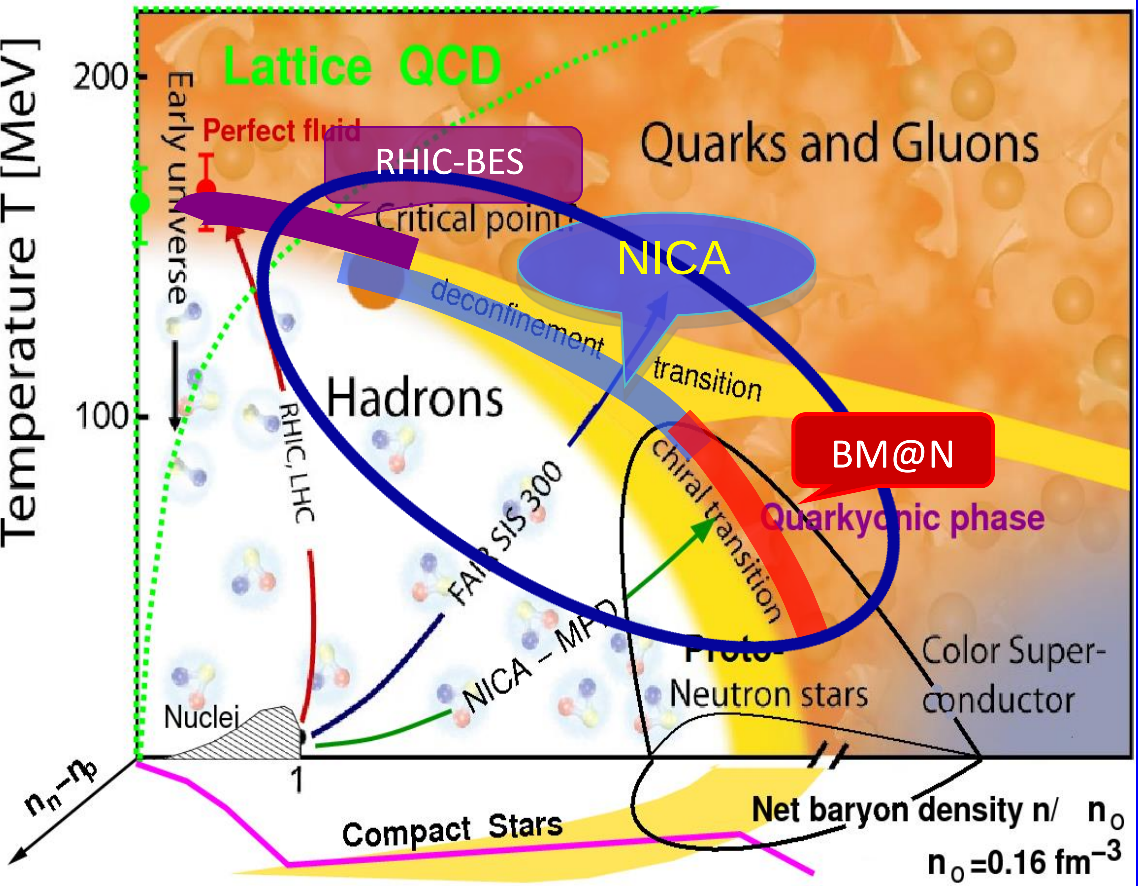
using variety of nuclei A (from p to Au)

scanning over energy range: E_{beam} = 1 – 6 GeV / nucleon

Strategy: beam energy & nuclei scans

19 scientific centers: INR, SINP MSU, IHEP + 2 Universities (Russia);
GSI, Frankfurt U., Gissen U. (Germany): + CBM-MPD IT-Consortium + **….**
expressed an interest

QCD phase diagram - Prospects for NICA/BM@N



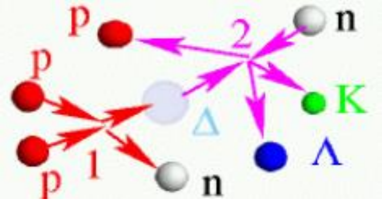
- **NICA/BM@N is complementary to RHIC/BES, FAIR, CERN experimental programs**

Search for the mixed phase of partons and hadrons:

- Signatures of deconfinement phase transition at high net baryon densities ρ_b

→ enhanced strangeness production (baryons and mesons)

- Study of the Equation of State (EoS) at high ρ_b and temperatures
→ strange particle yields & ratios at thresholds, collective flows
- In-medium modification of hadron properties as a sign of chiral symmetry restoration at high ρ_b
→ onset of a low-mass di-lepton enhancement
- Y-N interactions in the dense nuclear matter and hyper-nuclei production



Study of „in-medium“ K^+ and K^- properties in heavy-ion collisions at thresholds

- **baryon-baryon collisions:**

$$B+B \rightarrow B+Y+K$$

$$B+B \rightarrow B+B+K+\overline{K}$$

$$B+Y \rightarrow B+B+\overline{K}$$

$K = (K, K^0)$

$\overline{K} = (K^-, \overline{K}^0)$

$B = (N, \Delta, ...)$

$Y = (\Lambda, \Sigma)$

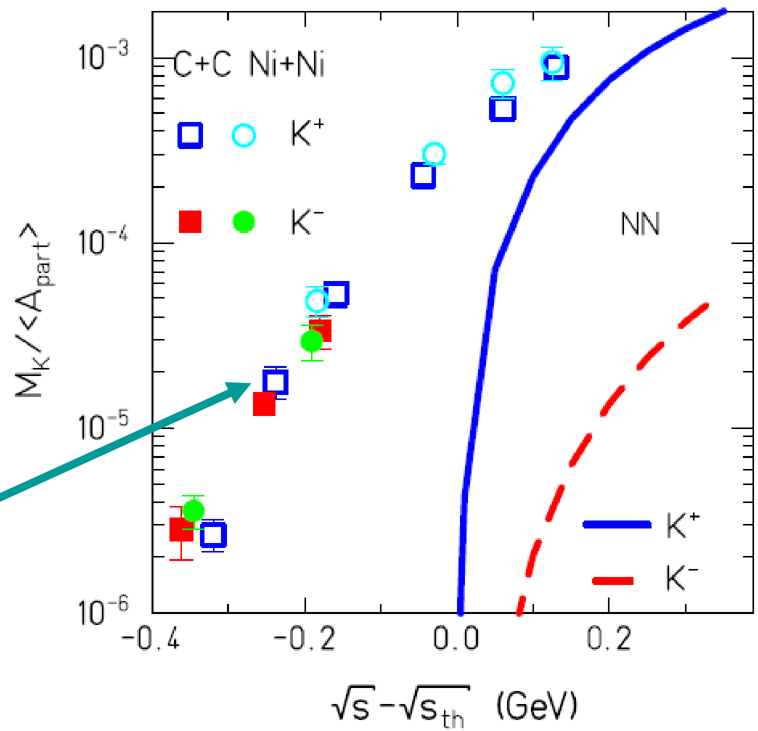
- **meson-baryon collisions:**

$$\pi+B \rightarrow Y+K$$

$$\pi+B \rightarrow B+K+\overline{K}$$

$$\pi+Y \rightarrow B+\overline{K}$$

dominant channel for low energy K^- production!



- **meson-meson collisions:** $\pi+\pi \rightarrow K+\overline{K}$

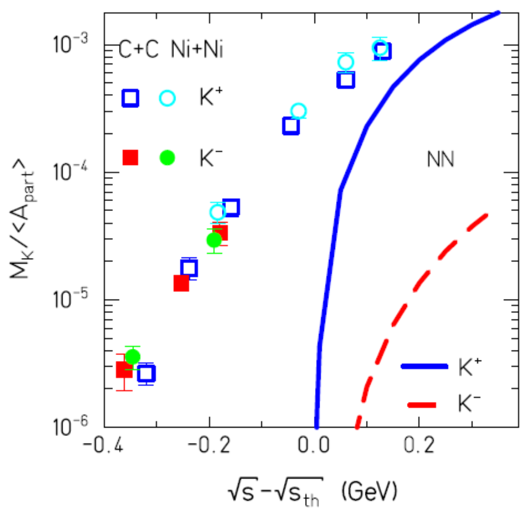
Opportunities at the Nuclotron

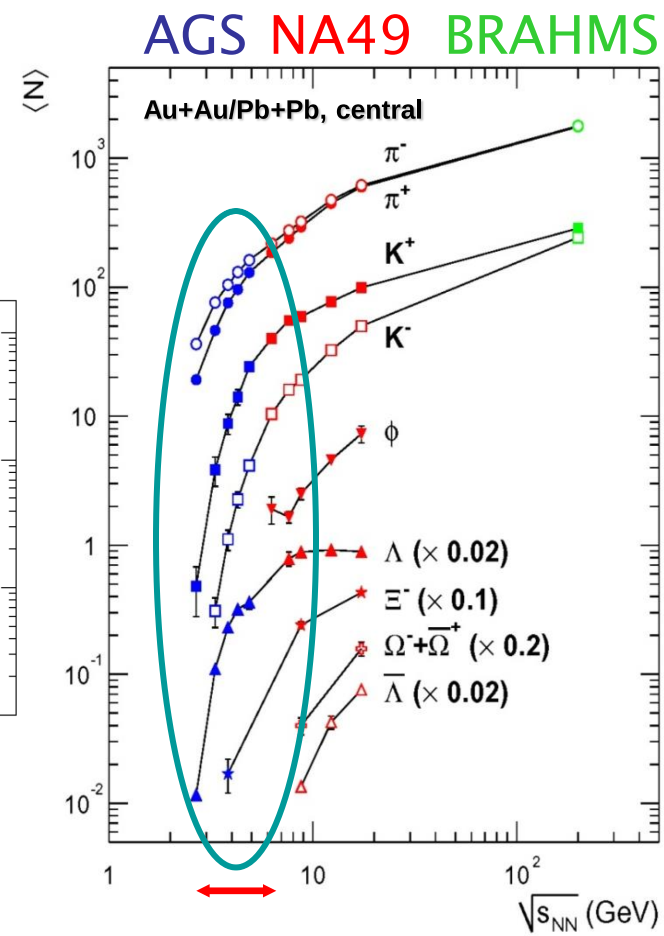
I. In A+A collisions at Nuclotron energies:

❑ **Opening thresholds for strange and multi-strange hyperon production**

➔ **strangeness at thresholds**

➔ **More precise data for strange mesons and hyperons, multi-variable distributions, in the unexplored energy range are needed.**



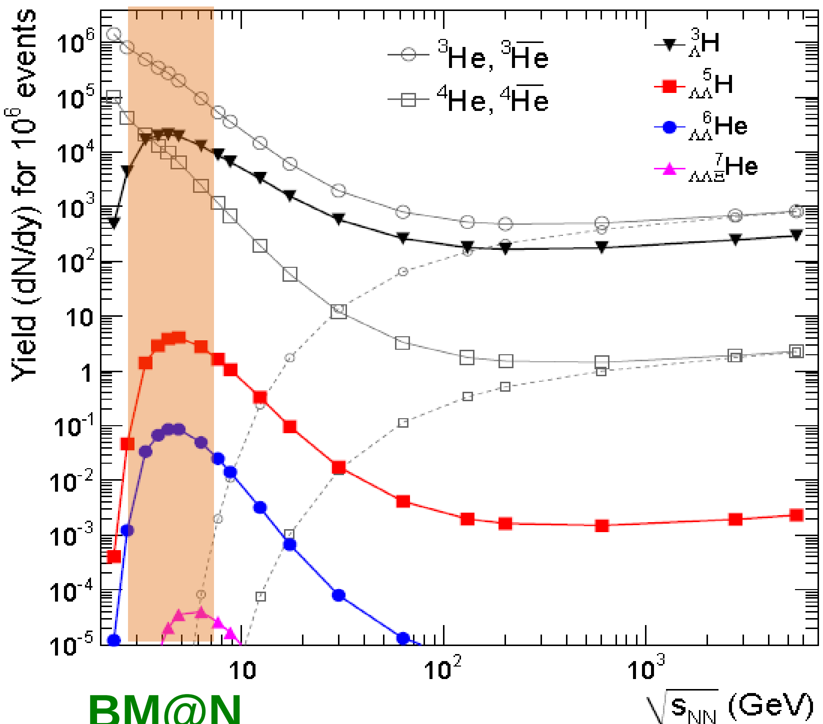


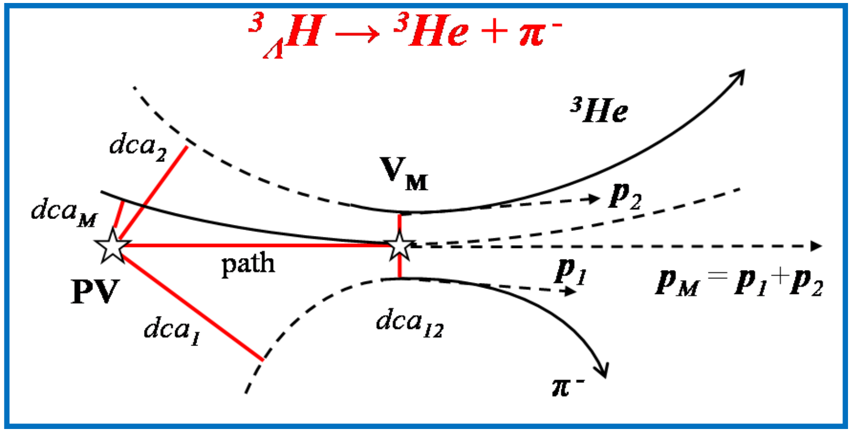
Nuclotron energies

II. In *p+p, p+n, p+A* collisions:

➔ **hadron production in elementary reactions and "cold" nuclear matter as a "reference" to pin down specific nuclear effects .**

Heavy-ions A+A: Hypernuclei production





- **In heavy-ion reactions:** production of hypernuclei through coalescence of Λ with light fragments is to be enhanced at high baryon densities
- **Maximal yield** predicted for √s=4-5A GeV (stat. model) (interplay of Λ and light nuclei excitation function)

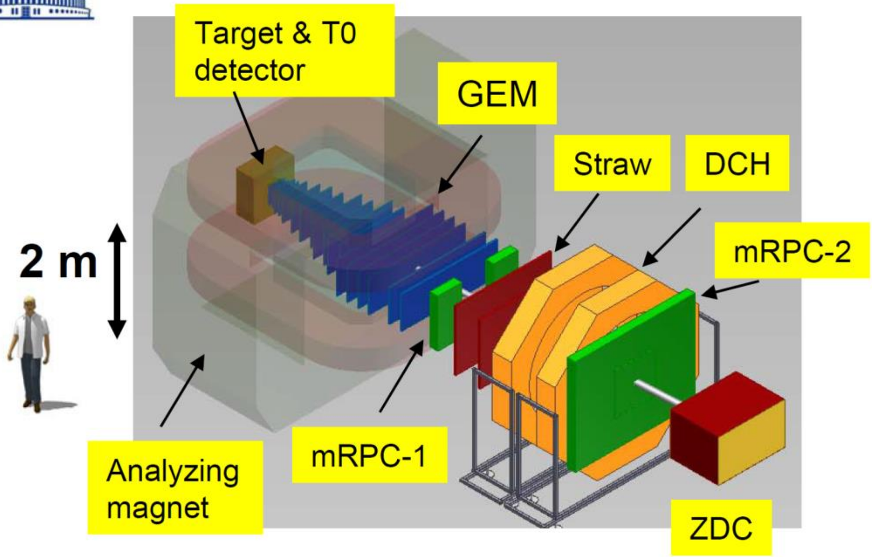
➔**BM@N energy range** is **ideally suited** for the search of (double) hypernuclei

- Statistical model, Au+Au collisions @ 4A·GeV
- Beam intensity 10^7, 1% interaction length target

Particle	$E_{\text{thr}\,NN}$, GeV	Multiplicity central	Multiplicity min.bias	ϵ, %	Yield/s min.bias	Yield/week min.bias
Ξ^-	3.7	$1\cdot10^{-1}$	$2.5\cdot10^{-2}$	3	75	$4.5\cdot10^{7}$
Ω^-	6.9	$2\cdot10^{-3}$	$5.0\cdot10^{-4}$	3	1.5	$9.0\cdot10^{5}$
$\bar{\Lambda}$	7.1	$2\cdot10^{-4}$	$5.0\cdot10^{-5}$	15	0.75	$4.5\cdot10^{5}$
Ξ^+	9.0	$6\cdot10^{-5}$	$1.5\cdot10^{-5}$	3	$4.5\cdot10^{-2}$	$2.7\cdot10^{4}$
Ω^+	12.7	$1\cdot10^{-5}$	$2.5\cdot10^{-6}$	3	$7.5\cdot10^{-3}$	$4.5\cdot10^{3}$

Hyper-nuclei	Multiplicity central	ϵ, %	Yield/s central	Yield/week central
${}^{3}_{\Lambda}\mathrm{H}$	$2\cdot10^{-2}$	8	160	$1.0\cdot10^{8}$
${}^{5}_{\Lambda\Lambda}\mathrm{H}$	$1\cdot10^{-6}$	1	$1\cdot10^{-3}$	$6\cdot10^{2}$
${}^{6}_{\Lambda\Lambda}\mathrm{He}$	$3\cdot10^{-8}$	1	$3\cdot10^{-5}$	18

BM@N setup



BM@N advantage: large aperture magnet (~1 m gap between poles)

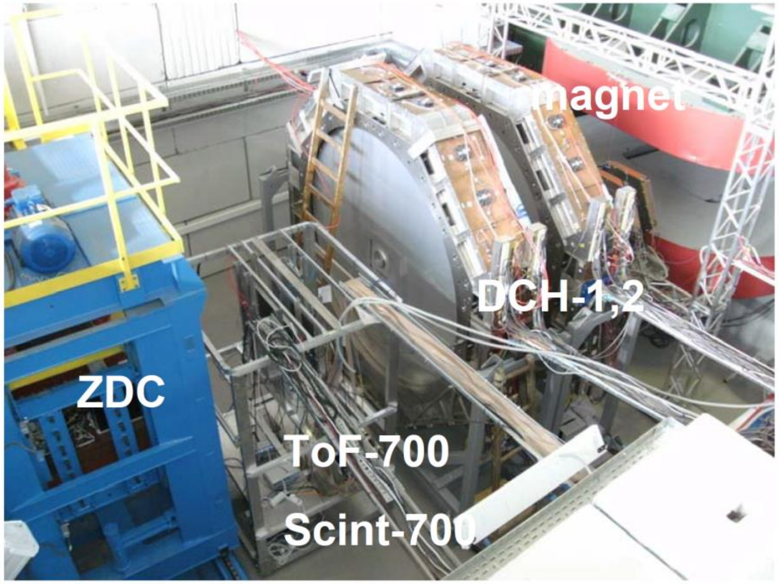
→ fill aperture with coordinate detectors which sustain high multiplicities of particles

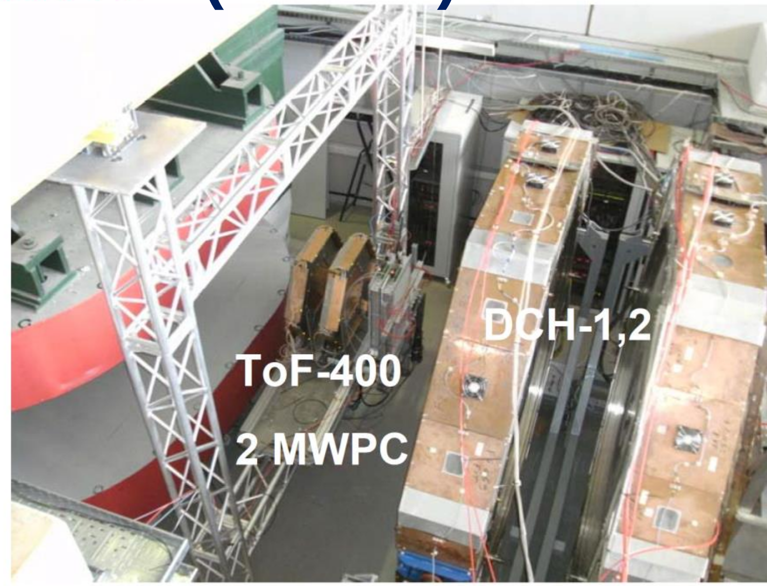
→ divide detectors for particle identification to “near to magnet” and “far from magnet” to measure particles with low as well as high momentum (p > 1-2 GeV/c)

→ fill distance between magnet and “far” detectors with coordinate detectors

- Central tracker (GEM) inside analyzing magnet to reconstruct AA interactions
- Outer tracker (DCH, Straw) behind magnet to link central tracks to ToF detectors
- ToF system based on mRPC and T0 detectors to identify hadrons and light nucleus
- ZDC calorimeter to measure centrality of AA collisions and form trigger
- Detectors to form T0, L1 centrality trigger and beam monitors
- Electromagnetic calorimeter for γ,e+e-

BM&N setup in the first technical run in February-March 2015 **(Run 51)**



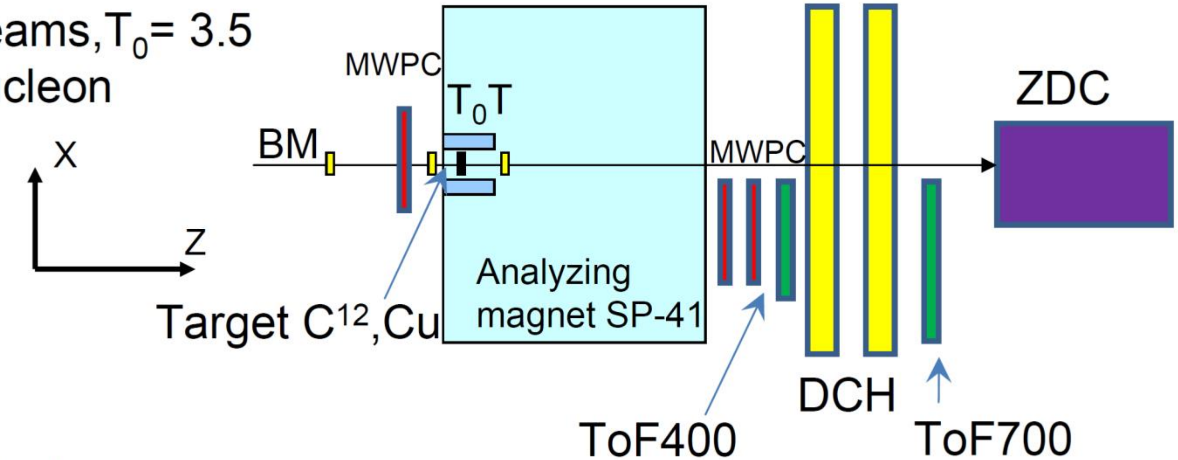


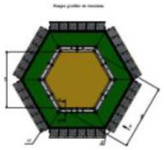
Tasks for BM@N technical run:

- deutron and C^{12} beams with T_0= 3.5 AGeV
- Trace beams, measure beam profile and time structure
- Test detector response: ToF-400, ToF-700, T0+Trigger, DCH-1,2, ZDC, ECAL modules, Beam monitors BM
- Test integrated DAQ and trigger system

BM@N technical run in February-March 2015

d, C^{12} beams, T_0= 3.5 GeV / nucleon





MWPC

Results of technical run:

- Deutron beam ($2\cdot10^4$ - 10^5 /cycle) and C^{12} (10^5 - 10^6/cycle) beams with T_0= 3.5 GeV / nucleon are delivered and used in BM@N experiment
- Functionality of integrated DAQ for detectors: ToF-400, ToF-700, T_0T, DCH-1,2, ZDC, ECAL modules, 3 MWPC is proven; → DAQ system showed reliable behavior
- Data with beam-target interactions are recorded using several trigger logics
- Deutron beam is traced through detectors at different values of magnetic field to test momentum reconstruction
- Resolution of T0T and ToF-400,700 detectors is tested
- Special runs are collected with different positions of ZDC to calibrate detector response

GEM detectors for central BM@N tracker

Tests of GEM detector 163 x 45 cm²

Set of 5 GEM detectors 66 x 41 cm² prepared for cosmic tests

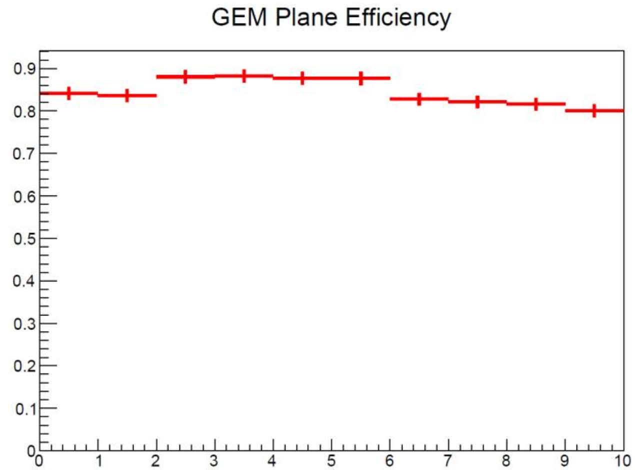
- GEM design and production at CERN workshop is slower than expected
- for tracking in BM@N technical runs in 2016 plan to use 5 detectors 66 x 41 cm² and 2 detectors 163 x 45 cm²
- for BM@N run in autumn 2017 plan to produce 6 more detectors 163 x 45 cm2 and design and produce 2 detectors 200 x 45 cm²

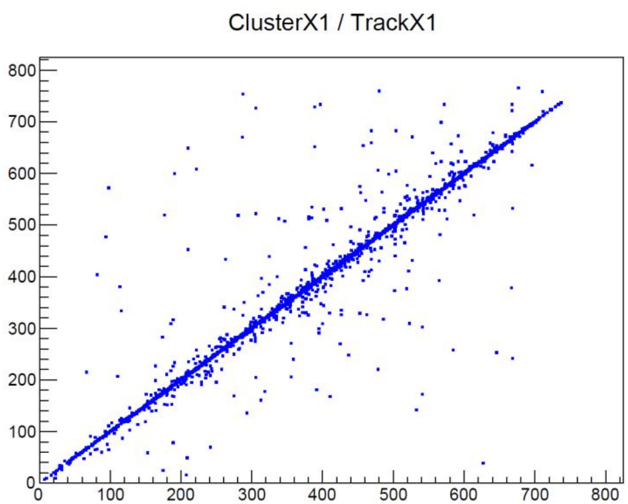
Tests of GEM detectors with cosmic particles

BMN GEM and DAQ groups

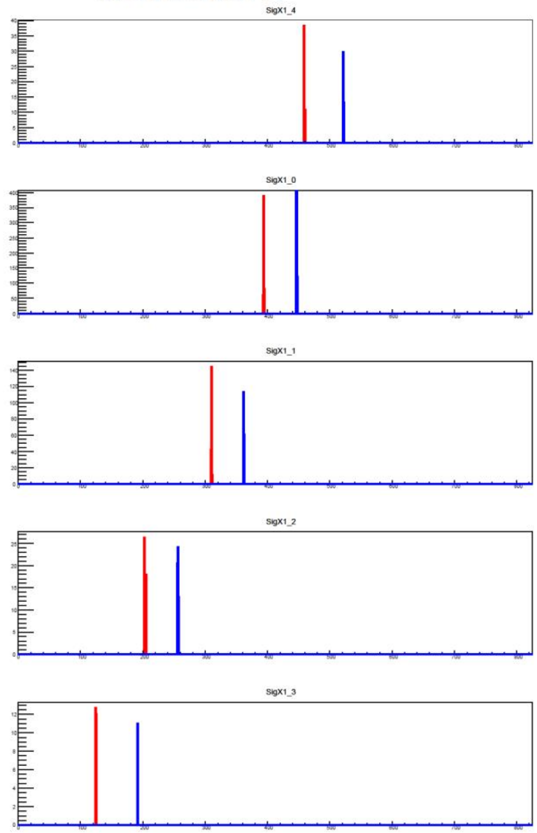
5 GEM detectors 66 x 41 cm^2

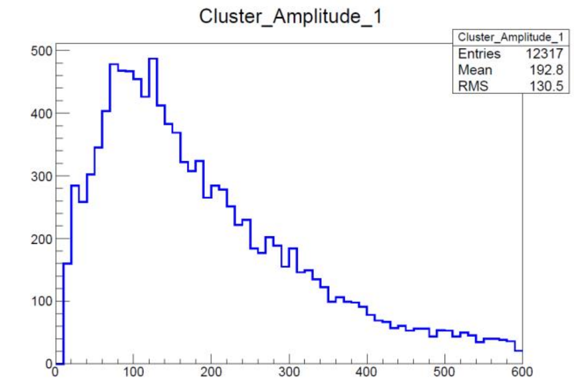
GEM plane Efficiency

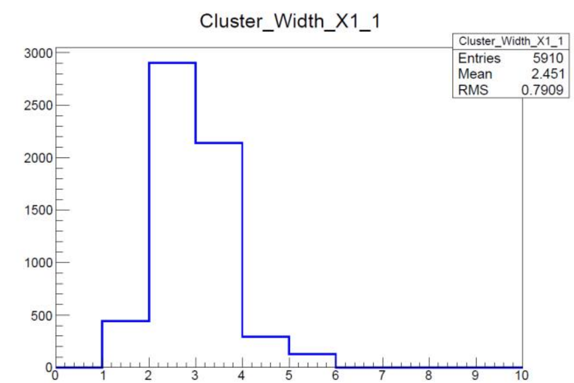




Cosmic event in 5 GEM detectors

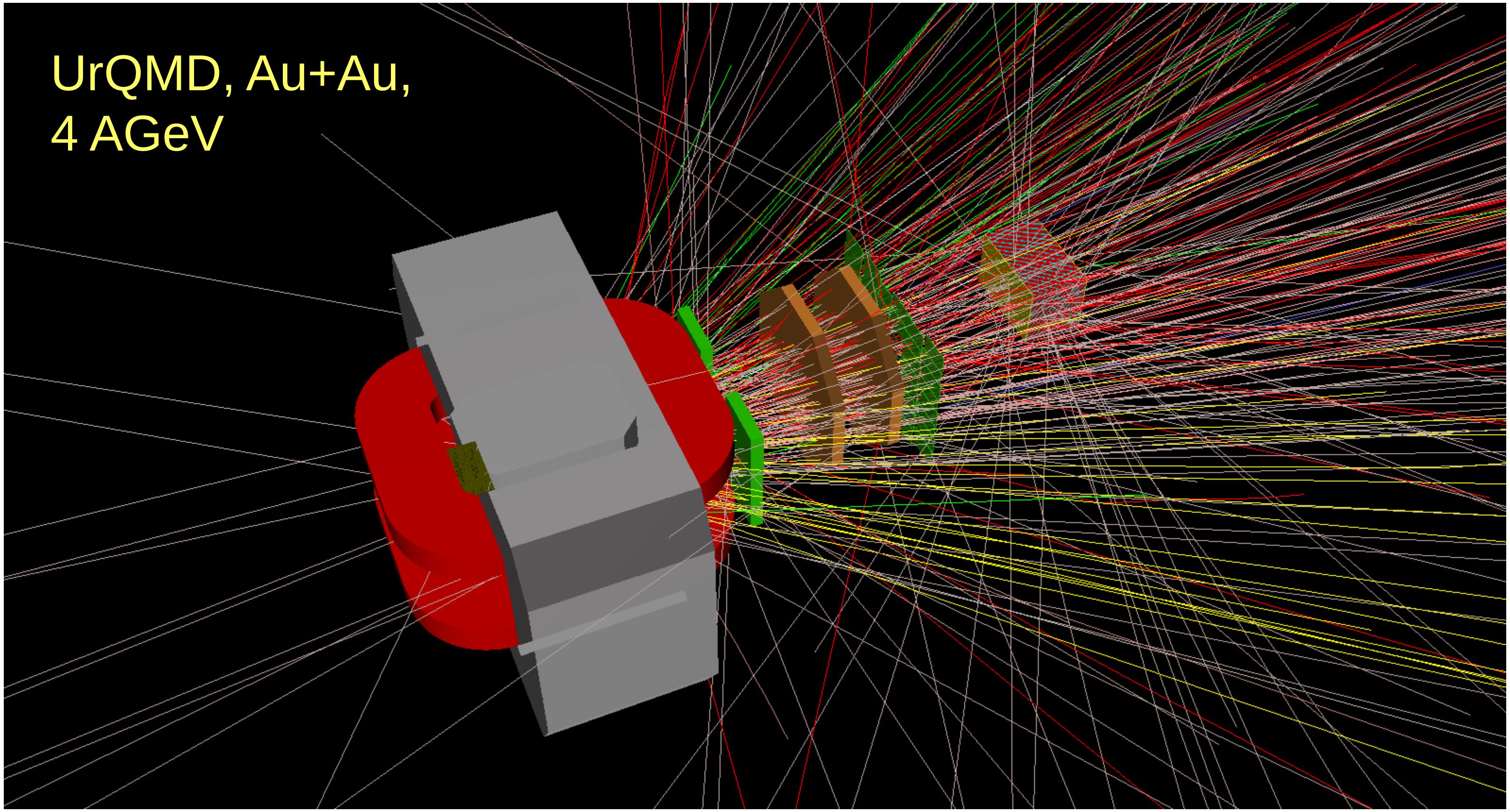




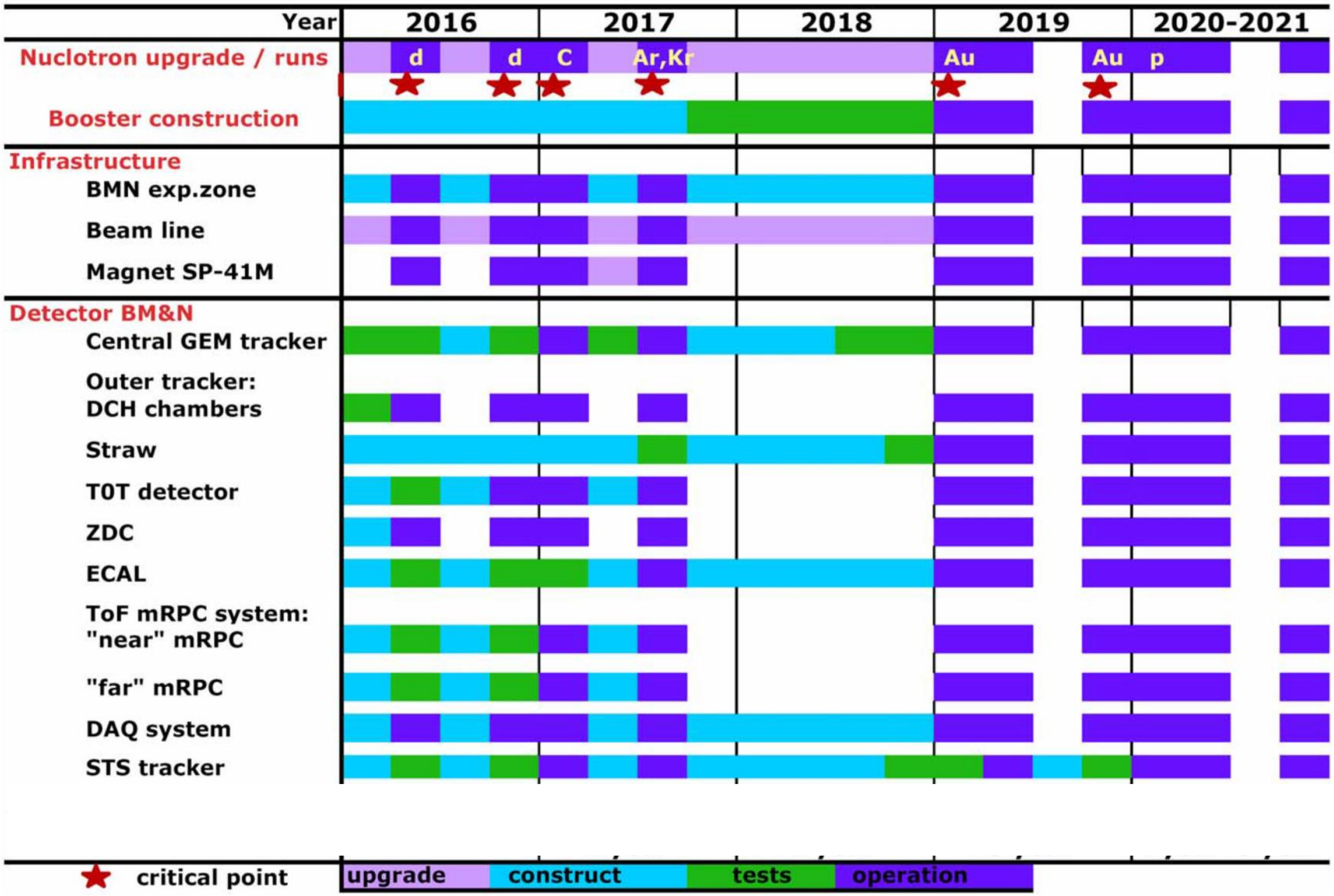


BMNROOT software framework

- Detector geometry
- A+A event generators
- GEANT simulation
- Track reconstruction
- Particle identification
- Physics analysis



Time schedule for BM@N project development



Another activity of the LHEP (at home)

Experiments (ongoing) at extracted beams:

1. ***HyperNIS*** (physics of hypernuclei, first of all – properties of loosely bound hypernuclei with neutron excess)
2. ***FAZA*** (nuclear multifragmentation and "liquid-to-fog" phase transition of the nuclear matter)
2. ***MARUSYA*** ("cumulative" production; currently – R&D of detectors for beam diagnostics)
4. ***ALPOM-2*** (needs polarized deuteron for calibrating of a polarimeter for new G_E / G_M experiment at JLAB).
5. ***Radiation biology*** (by LRB of JINR)
6. ***Applied physics (E&T RaW)***

Spin physics with polarized deuterons, protons and neutrons
at energies from $T_{kin} \geq 300$ MeV/nucl. to 5 GeV/nucl.
will again be continued from the 2-nd half of 2016.

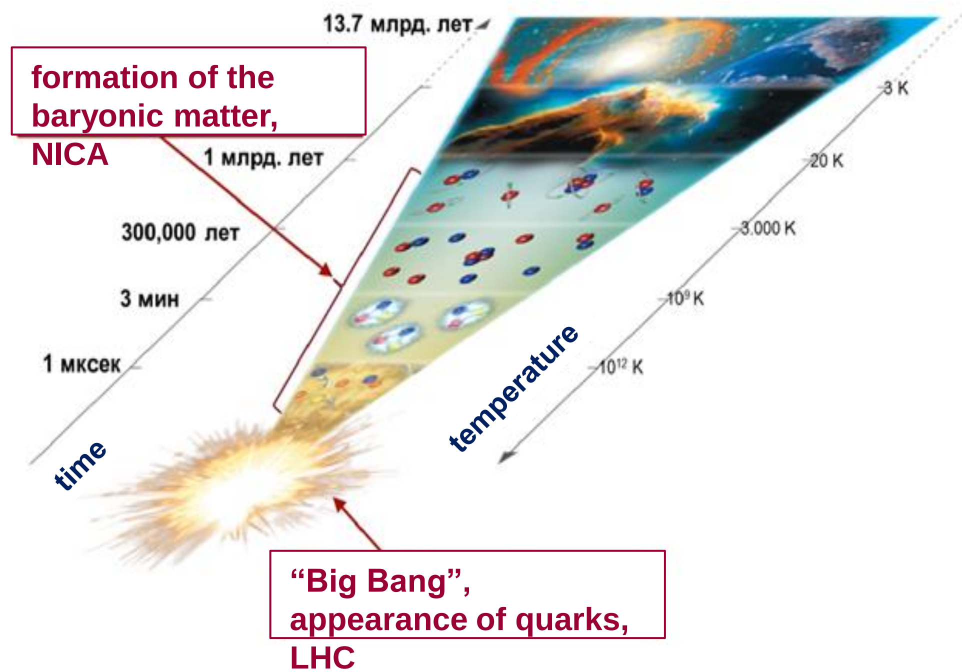
Summary

LHEP ЛФВЭ

L H E P J I N R

The main tasks of the NICA complex:

- ***study of hot and dense baryonic matter***
- ***study of the spin structure of nucleons and other polarization phenomena***



To do this, it is necessary:

- *to upgrade accelerator base in JINR, which is able to provide intensive beams from **p** to **Au** and polarized **protons and deuterons** with maximal energy up to* ***$\sqrt{S_{NN}}$= 11 GeV (Au^{79+})*** *and* ***=27 GeV (p)***

Physics at the Nuclotron/NICA facility

1. **High energy heavy ion (or relativistic nuclear) physics**
2. **Spin physics (polarization studies of nucleon structure, NN interactions, *few nucleon systems* and nuclear structure)**
3. **Flavour physics (physics of strange quarks, exotic hadrons, voilation of basic symmetries)**

Renewal of the instrumental basis: nuclear collider over the Nuclotron

- **Beam infrastructure for “fixed target” experiments will be kept;**
- **Nuclear collider (instrumented) will be built; $\sqrt{s} \approx$ (5-10) GeV per nucleon; luminosity ~ 10^{27} $cm^{-2}s^{-1}$ (U+U)**

Thank you!

Addendum
(remarks and backup slides)

Remarks to "strongly interacting matter" and "particle properties in a medium"

In experimental studies of the strongly interacting matter at least 3 stages can be considered:

- ***Formation*** **(creation) of this matter**
- ***Evolution*** **(for example, from hot and dense to cold and sparse matter where particles can appear)**
- ***Appearance of detectable objects*****: hadronization and/or condensing**

The general feature: unavoidable problems of a non-perturbative nature.

In different types of reactions one meets with different aspects of those stages, as well as with some new features, in particular:

modification of particle properties in "a medium"

NOTE: a particle must live "long enough" inside the medium!

(structure functions might be different in the cold and hot matter, dense and sparse; particle spectra; widths of resonances);

in fact, some examples are well known since long time (the free neutron lives $\approx$14.67$\pm$0.018 min while the bound neutron can live much longer!)

hadronization of quarks **(fragmentation functions)** ***occurs*** **also** ***in a different environments*****, etc.**

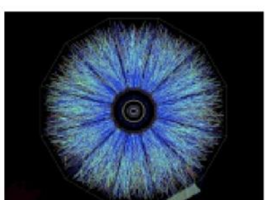
Strong external electromagnetic fields and other new aspects

(Also: Primakoff processes: $\gamma^*+A\rightarrow\ldots$; may be even $\gamma^*+\gamma^*\rightarrow\ldots$ etc.)

Comparison of magnetic fields

The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html



Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$eB(\tau=0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

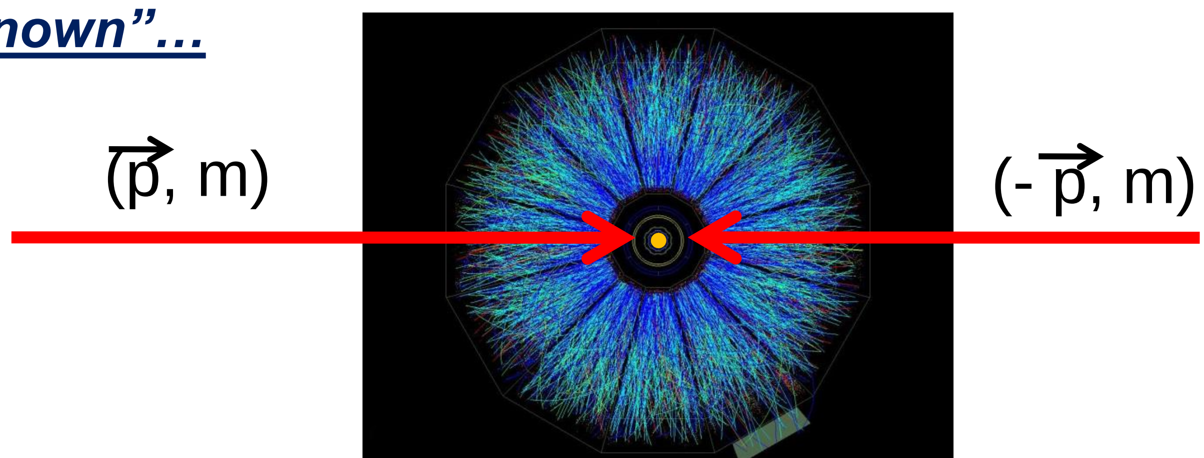
from D.Kharzeev (Nov. 5-6, 2008, in Dubna, "NICA round table" 3)

Types of the strong interacting environment

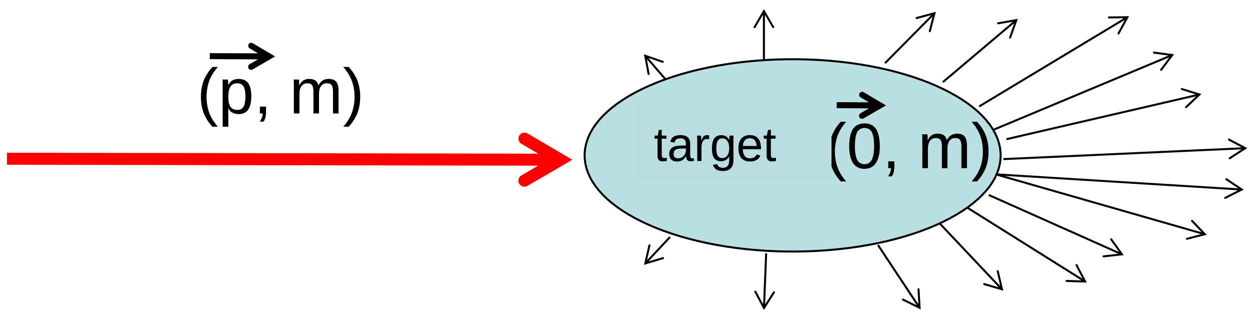
1. **The most used (up to now) environment is *the nuclear medium*: usual nuclei provide it. Well known examples: Λ-hypernuclei, Δ-excited nuclei. This environment is also in use in search for signatures about ω- (and ϕ) modification in nuclei as well as in search for η and η' nuclei.**

   Important feature: **<u>the environment is stable and "known"</u>*.***

2. ***The environment consisting from produced hadrons*** **(hadronic environment). The most known example – high multiplicity events at high energies or high multiplicity events in nuclei-nuclei collisions at small impact parameters (in collider experiments: at RHIC, at LHC with ALICE, at NICA with MPD). *<u>This environment is unstable and not so well "known"…</u>***



The "hadronic" environment can be produced in experiments with fixed targets when projectiles are nuclei; the particle under investigation can be either in the "central" region or in the "beam/target fragmentation" region.



This is the case for experiments at BM@N at Nuclotron and CBM at FAIR, for example. *Important features:* <u>it is not stable,</u> short living, density is not constant (*expansion!*). A particle spends only part of its life inside the medium. (Therefore: <u>what are signatures for a possible change of the particle properties</u>?)

3. External electromagnetic field (as an environment).

Important features: **<u>it is short living</u>, depends upon the impact parameter. A particle spends only part of its life in this environment.**

(Again: *what are signatures for possible changes of the particle properties, if happen*?)

Complementarity between the collider-type and fixed-target type experiments

Collisions of elementary particles:

- **protons *(nucleus of hydrogen)***
- **heavy ions (for example, Au)**

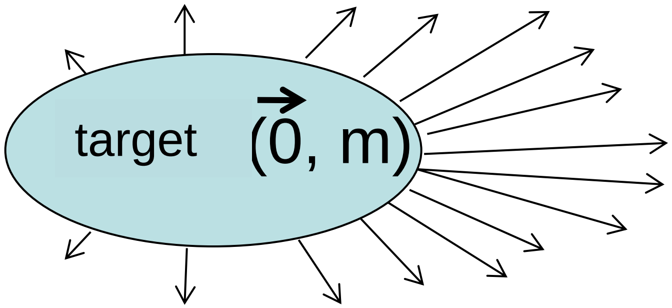
$$S_{NN} = (E_1+m)^2 - (\vec{p}+0)^2 \approx 2pm + 2m^2$$

Experiments:

✓ with fixed targets:

$p =$ **10** GeV

$(\vec{p}, m)$

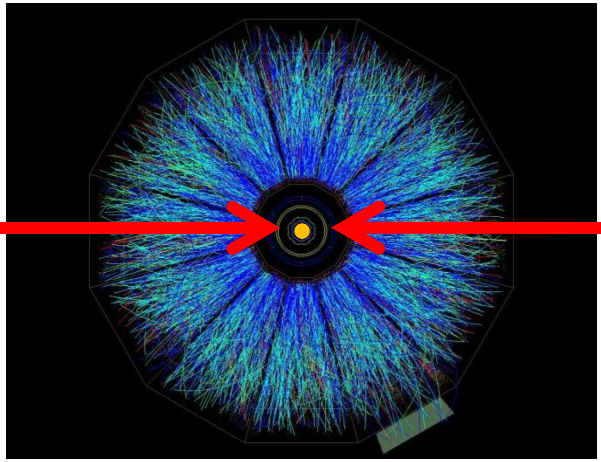


$\sqrt{S_{NN}} \approx$ **4,5** GeV

1eV	= **1.6 × 10^{-19}**J
1GeV=10^9 eV≈ m	

✓ at colliders:

$(\vec{p}, m)$ $(-\vec{p}, m)$



$\sqrt{S_{NN}} \approx 2p =$ **20** GeV

Particle properties in the nuclear matter: are they the same as in the “empty” space?

The topic "hadrons in a medium" has rather long history.

The *pre-historical* examples:
The life-time of neutron in stable nuclei drastically differs from its life-time in the empty space (*≈14.67±0.018 min*);
the life-time of the Λ-hyperon in free state differs *(apparently)* from its life-time in hypernuclei and depends *(apparently)* on an atomic number of a nucleus.

Next stage came with *pions in nuclei* and with the problem of *the pion condensate*.

Here the important contributions by A.Migdal, G.Brown, T.Ericsson and M.Ericsson, W.Weise, E.Oset must be mentioned.

Necessary conditions:
a particle must live "long enough" in the medium!

Good lessons were obtained in inclusive and exclusive experiments on

excitation of the Δ-isobar in nuclei

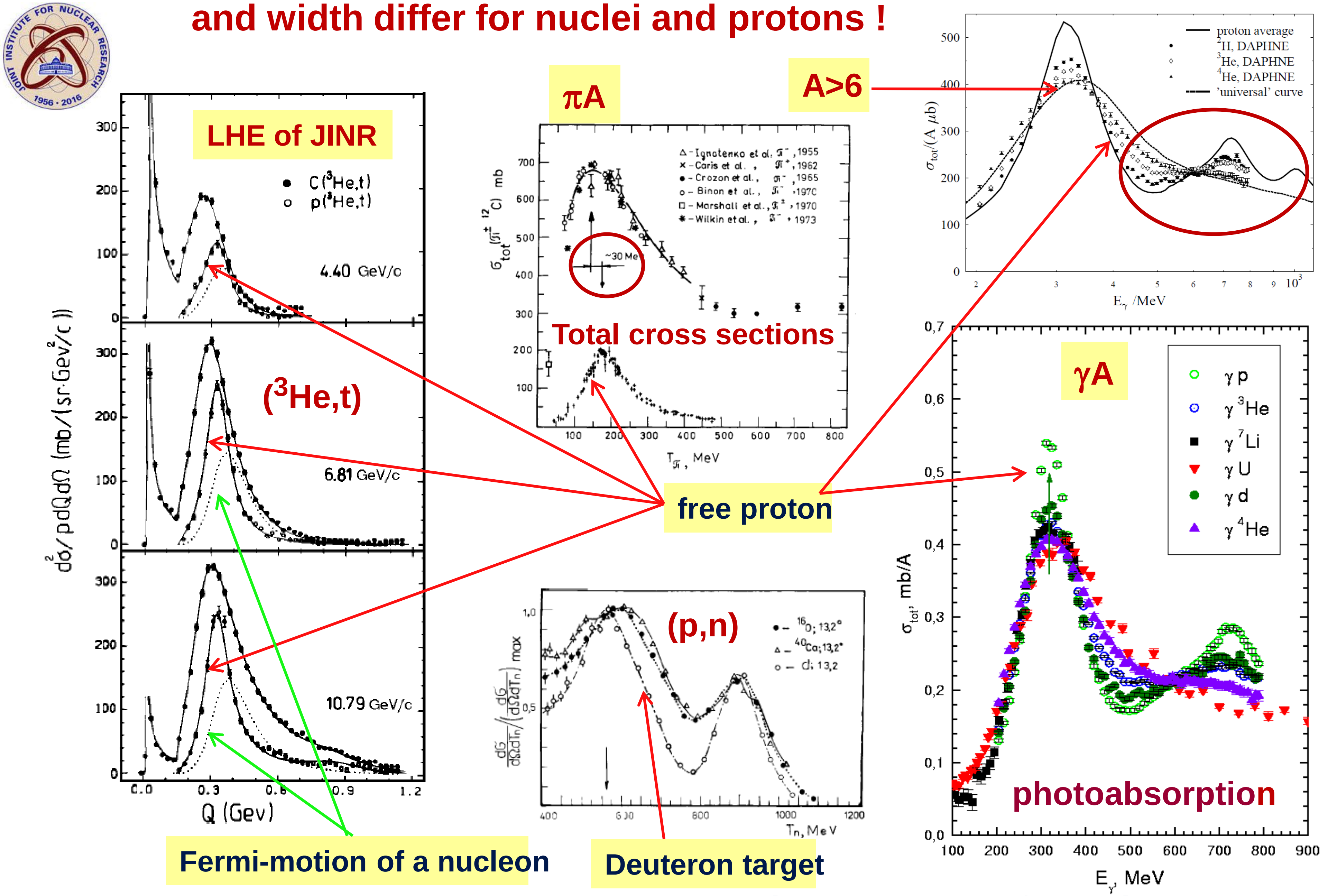
(end of '80-begin of '90, *pioneered in Dubna and Saclay*).

They stimulated theorists; contributions by E.Oset, V.Dmitriev, S.Fayans, S.Hirenzaki and others must be mentioned with respect to the topic under discussion. One of the approaches appeared at that time was *partial restoration of the SU(4) symmetry* in nuclear medium.

Another approach was based on *collective phenomena when pion propagates in a (finite !) nuclear medium.*

In the last decades new aspect was found by theorists and experimentalists. That was related with the *deeply bound pionic atoms* and with the *subthreshold (or cumulative) production of K^+ and K^-*. It resulted in concept of the *partial restoration of the chiral symmetry* in nuclear medium. It is this concept which is in use at modern discussions of the topic.

π- and Δ propagation in nuclear matter: the Δ-peak position and width differ for nuclei and protons !



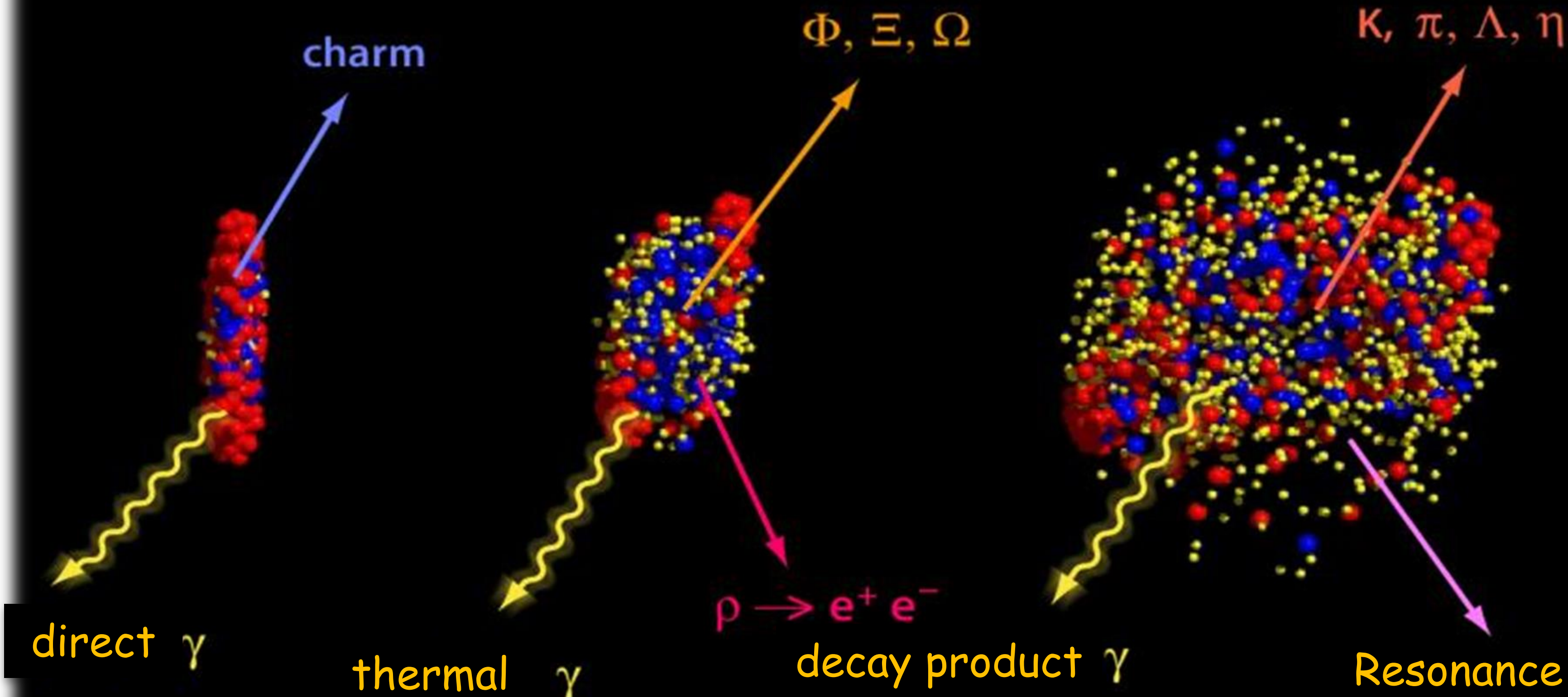
Here Q : the energy transfer to the target

Backup slides (MPD)

MultiPurpose Detector (MPD)

the observables in AA, pA and pp collisions:

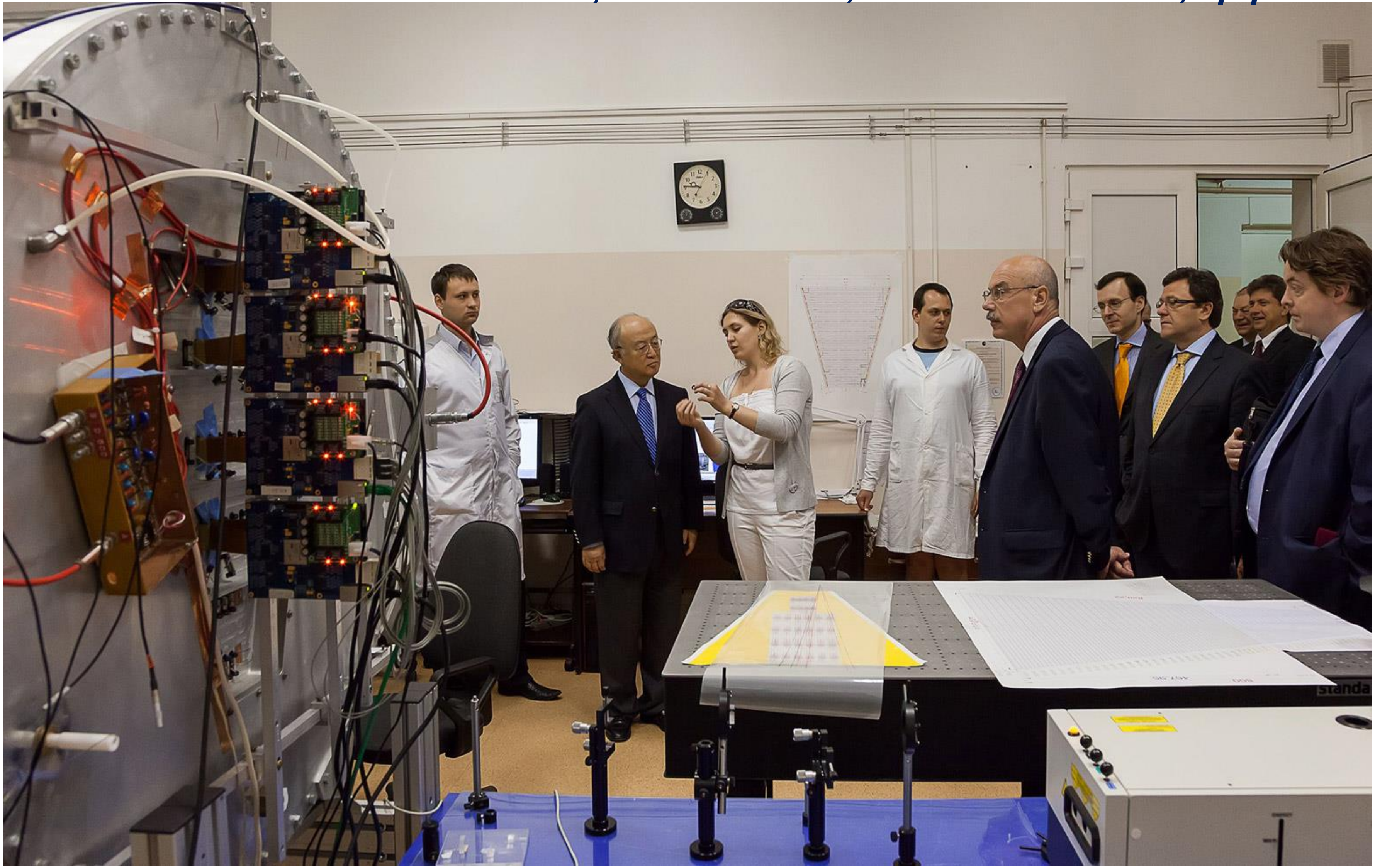
- *multiplicity of produced hadrons (π, K, p, Λ, Ξ, Ω)*
- *electromagnetic probes: electrons, gammas, vector meson decays,*



- *event-by-event fluctuations*
- *femtoscopy of π, K, p, Λ*
- *…..*

TPC prototype

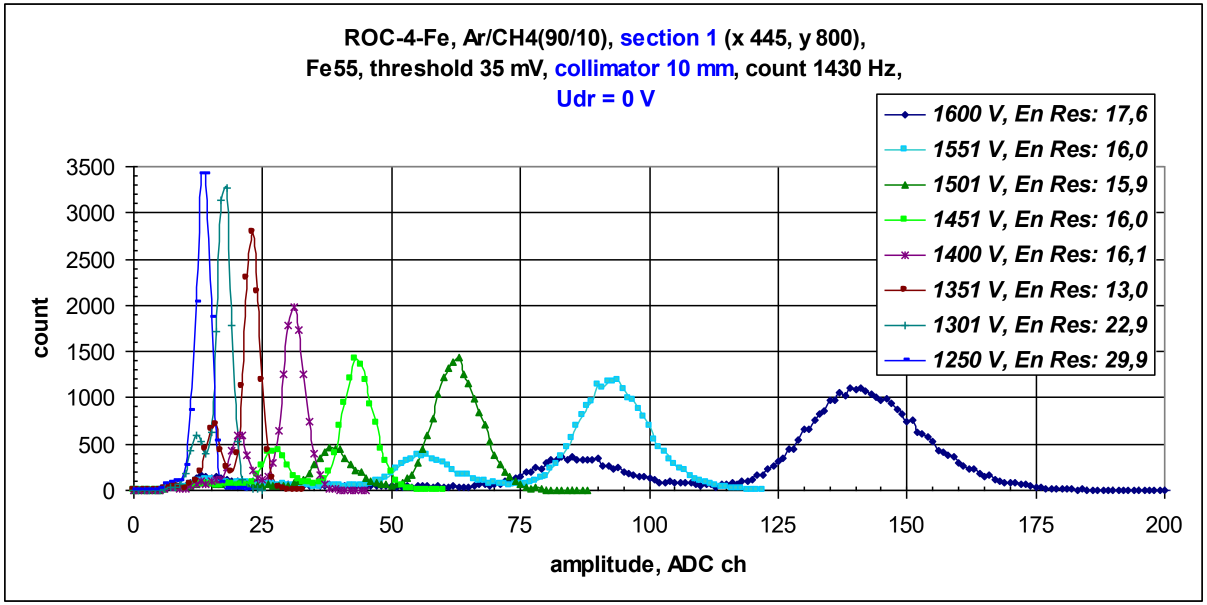
Dia. =3000 mm, L = 3400 mm, FEE = 120 000 ch, $\delta p/p < 2\%$



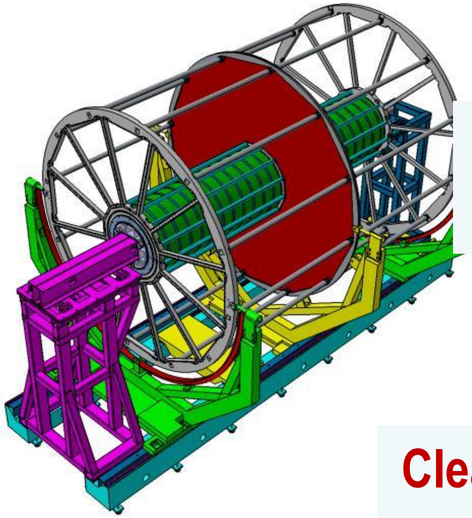
Presentation of the TPC prototype to the IAEA Director General, Prof. *I.Y. Amano*

TPC : mass-production of ROC chambers

ROC test procedure:
- counting plateau
- dark current
- energy resolution (Fe-55)
- uniformity of gas gain



TPC: tooling, clean room, service



Design of the tooling for TPC assembly is ready, waiting of the green light for manufacturing

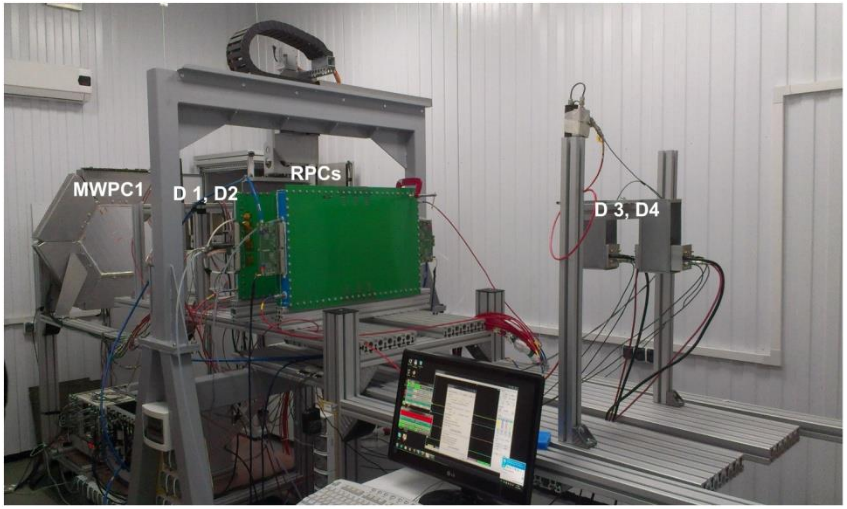
Clean room for TPC assembling - readiness in August 2016

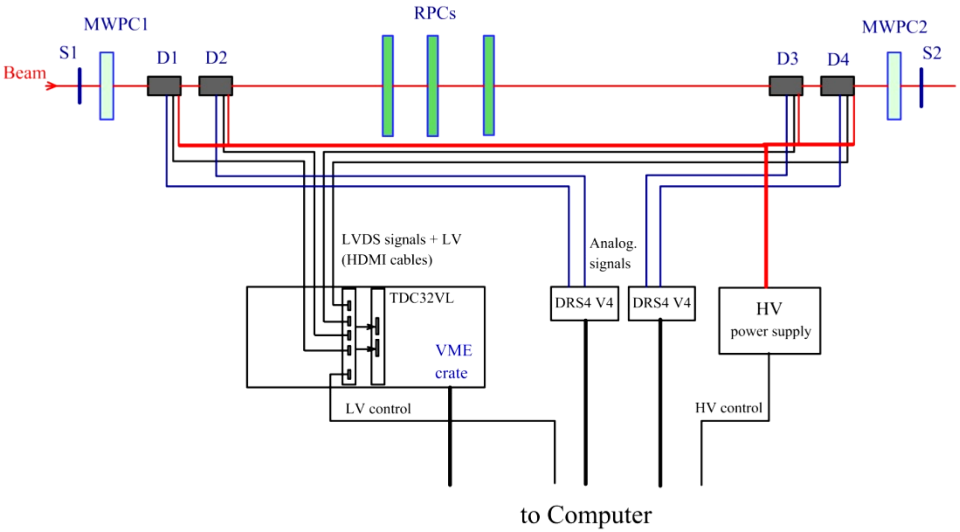
Time scale for the TPC gas system:

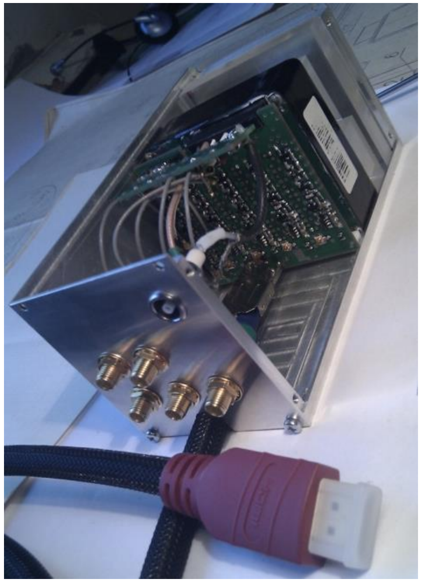
- Purification system tests with the TPC imitator – November 2016
- TPC gas system delivery to JINR – beginning of 2017

An example.

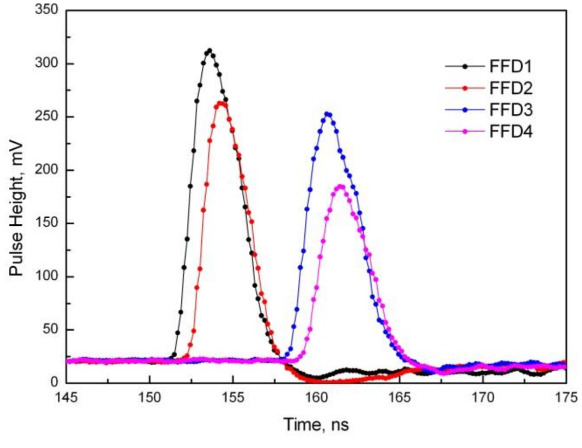
MPD test beamline: tests of the T_0 detector prototype

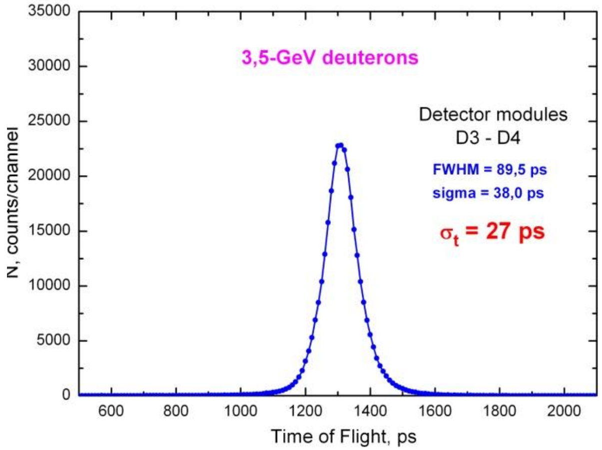






Time resolution for 3.5 GeV deuteron beam ~30 ps
(note that light passes distance of ~0.9 cm for the time ~30 ps)





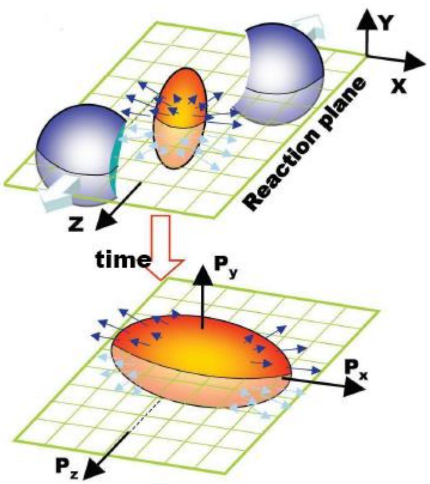
Backup slides (BM@N)

Heavy-ions A+A: in-medium effects

➔ BM@N can study the „in-medium“ effects for strangeness by measurements of a variety of observables at different energies and centralities in heavy-ion collisions in order to find an „anomalous“ behaviour in comparison with theory

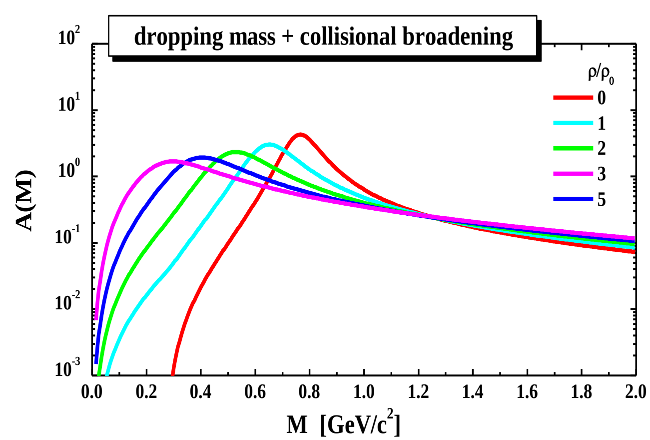
Observables sensitive to the „in-medium“ effects:

particle yields and ratios ;
p_T - (m_T)- spectra ;
rapidity distributions;
angular distributions;
collective flow (v_1,v_2,…)



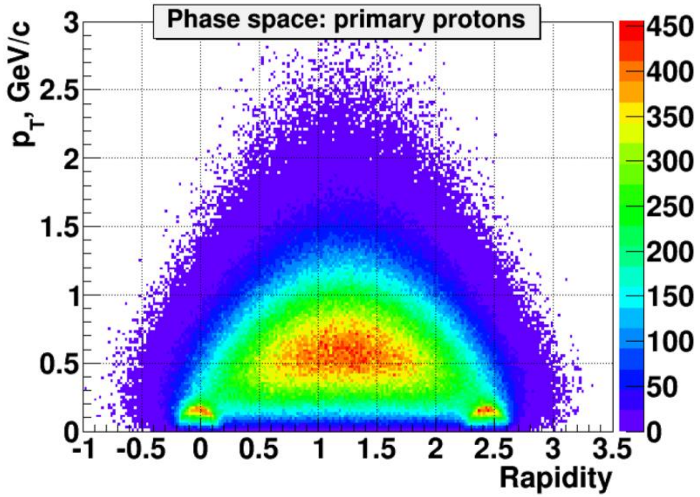
➔BM@N (perspectives): measurements of the „in-medium“ effects for vector mesons (V= ρ, ω, ϕ)

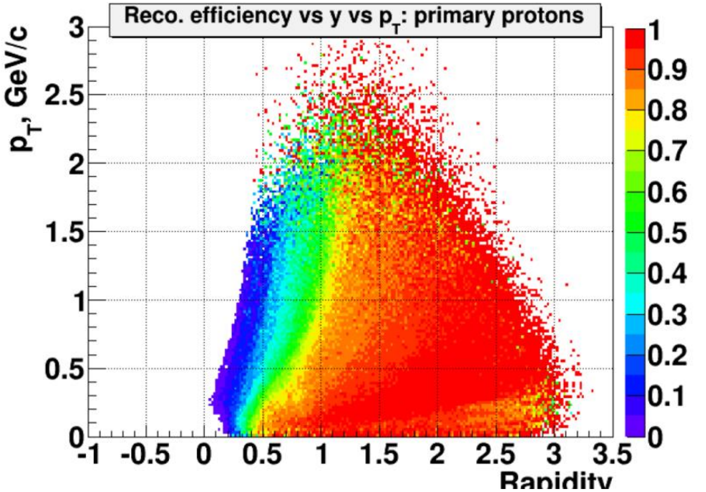
Optimal way – use “dilepton“ mode: V➔e+e- or photon mode: $\omega \to \gamma\pi^0$.
Possible alternative: $\phi \to K^+K^-$ strong decay



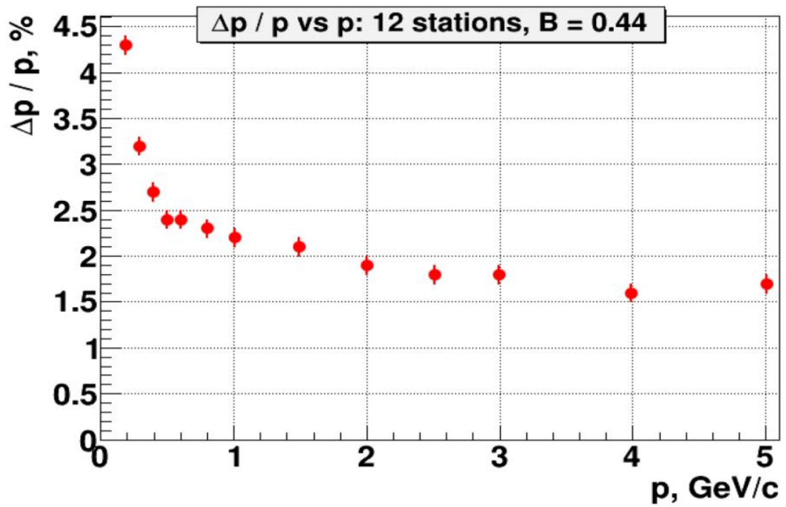
GEM tracker: acceptance / momentum resolution / detection efficiency

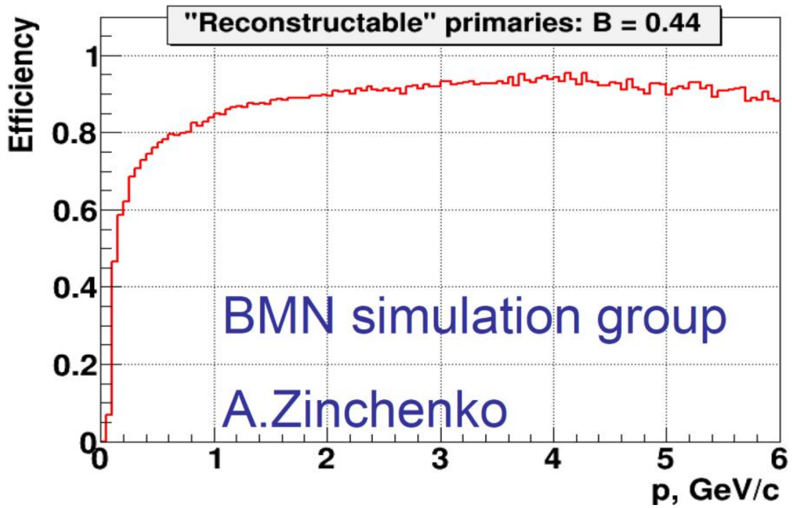
Phase space / acceptance to primary protons:





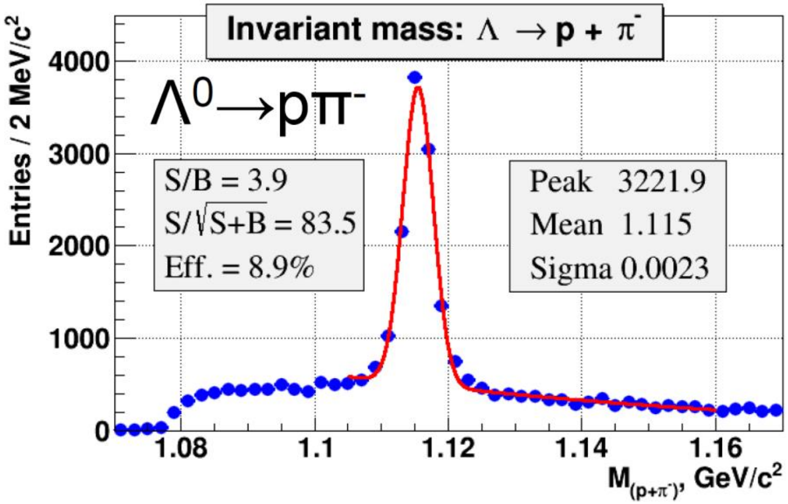
Momentum resolution / detection efficiency



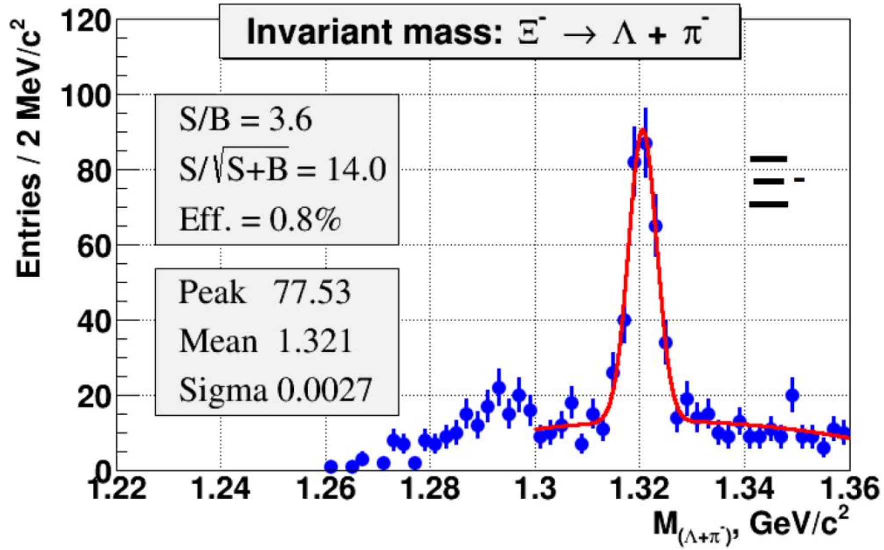


GEM tracker: Λ^0, Ξ^-, $^3H_\Lambda$ reconstruction

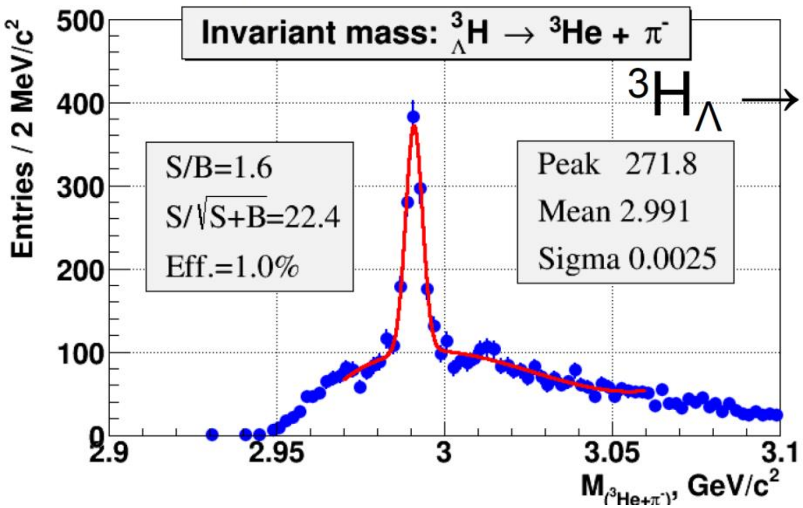
Au+Au, URQMD,10k central events



Au+Au, 4.5 AGeV, 900k central events
→ 7.5M Ξ^- for 1 month, 20 kHz trigger

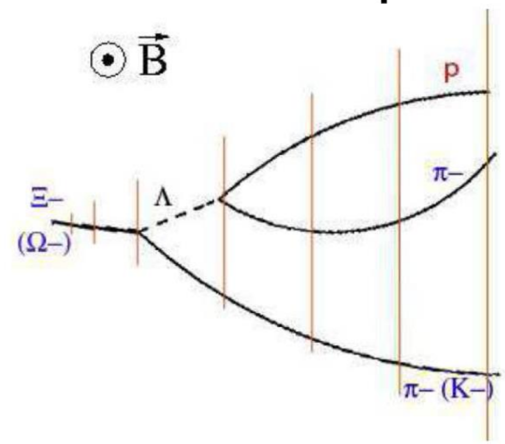


Au+Au, 4.5 AGeV, 2.6M central events
→ 8.5M $^3H_\Lambda$ for 1 month, 20 kHz trigger



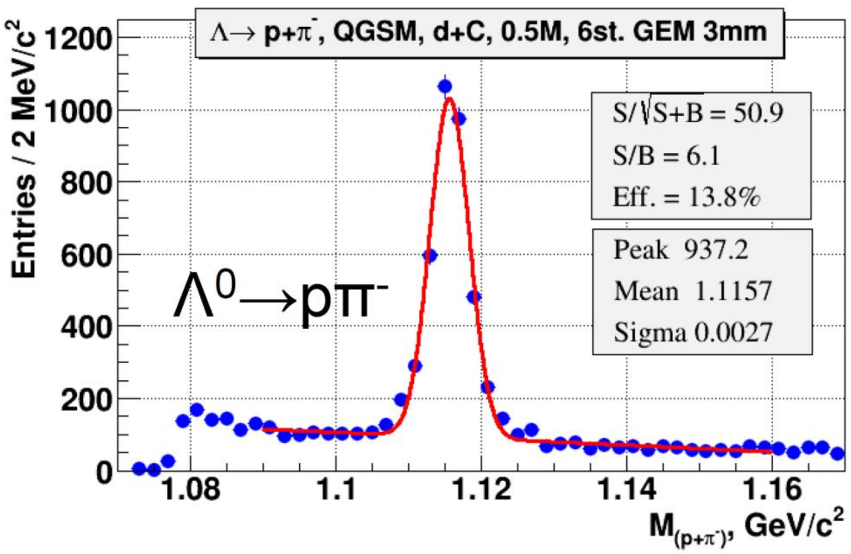
$^3H_\Lambda \rightarrow {}^3He\ \pi^-$

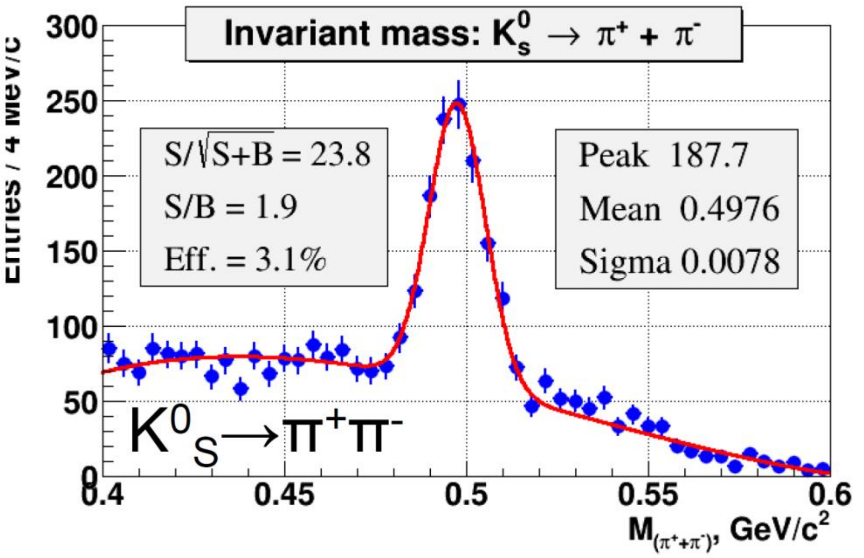
$\Xi^- \rightarrow \pi^- + \Lambda^0 \rightarrow p\pi^-$



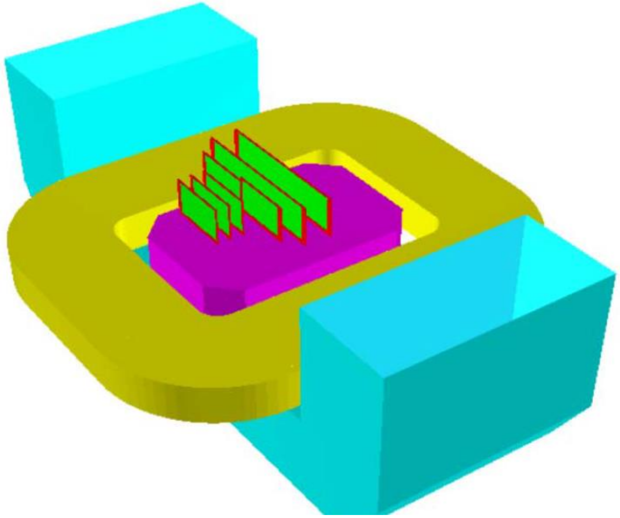
GEM tracker: Λ^0, K^0_S reconstruction

d+C, 4 AGeV, 500k events

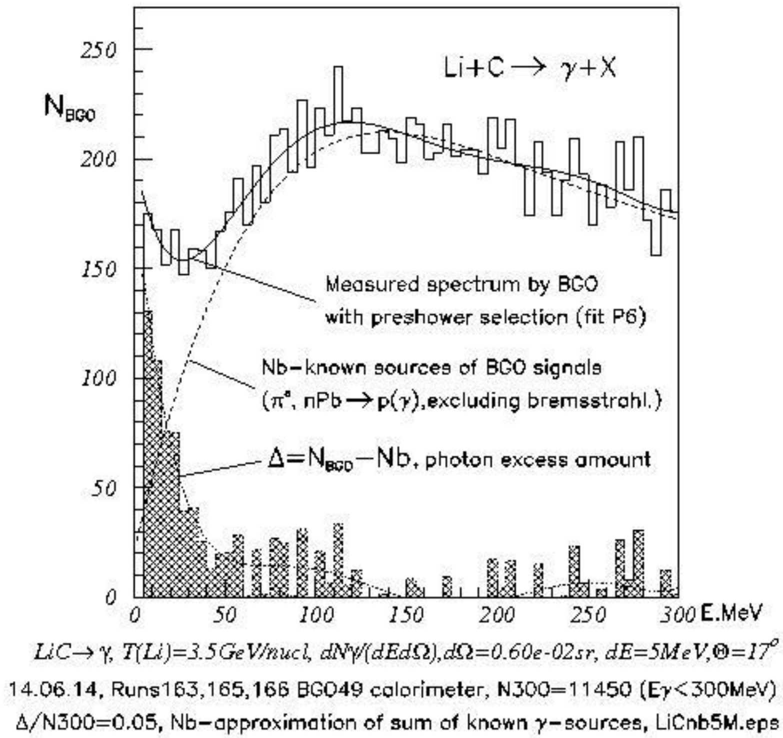


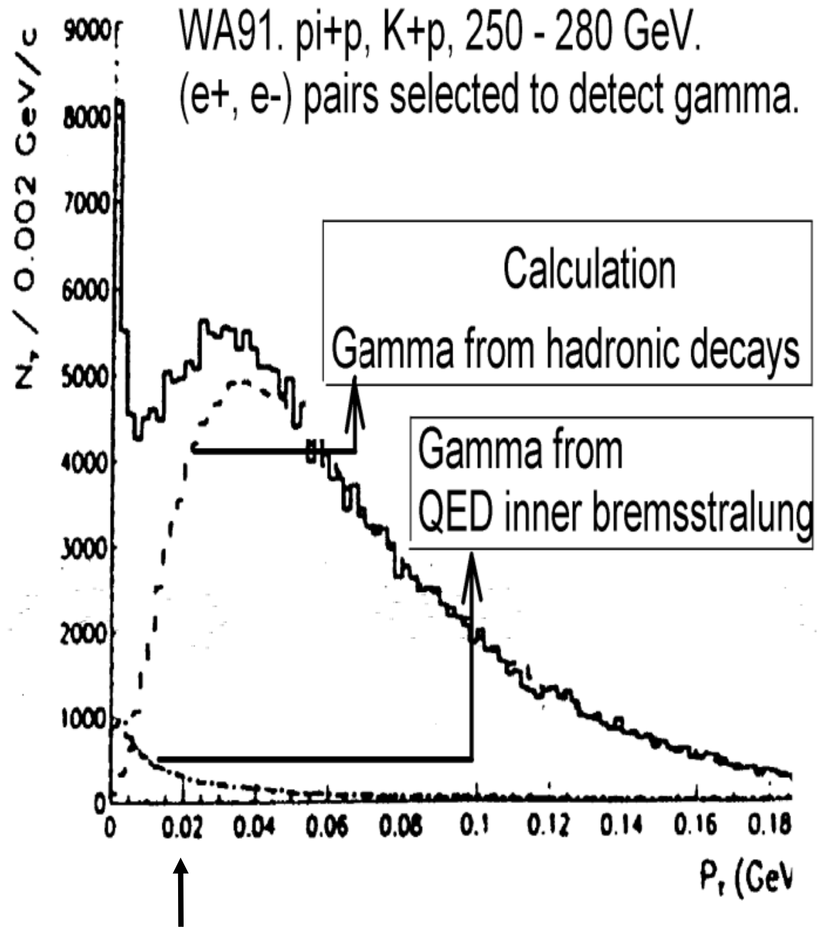


Configuration with 6 GEM stations for next BM@N runs in 2016



Complementary studies: Spectrum of "soft" photons



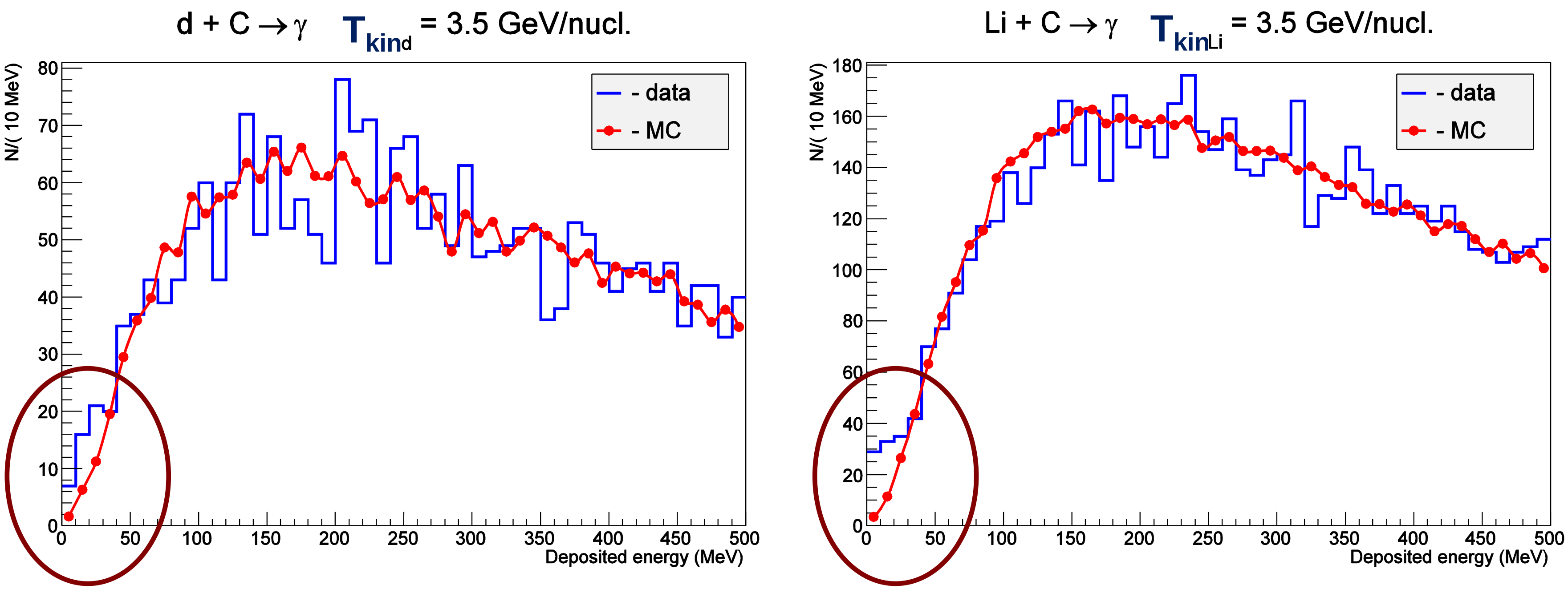


P_T = 20 MeV

- Result from 7x7 modules of BGO calorimeter, NIS-GIBS setup, June 2014
- To check feasibility of soft photon studies needs full simulation of BGO calorimeter in the BM@N setup

SPECTRA of “SOFT” PHOTONS in d+C and Li+C INTERACTIONS AT NUCLOTRON

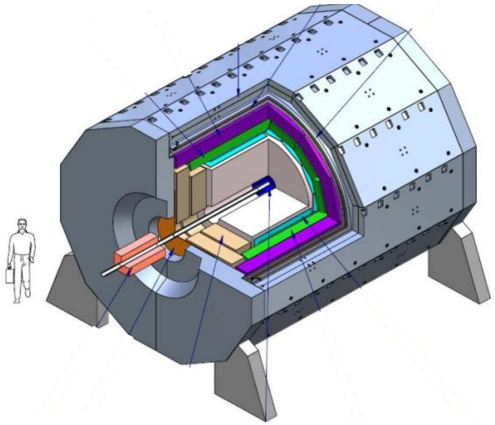
Results from the Nuclotron runs 49 and 50.



d+C and C+C data from run 51 are being analyzed.

Backup slides to “physics at LHEP”

Relativistic Heavy Ion Physics at NICA



The MPD experiment:

to study in-medium properties of hadrons,
& search for phase transition, mixed phase
& critical end-point

in collisions of ***heavy ion*** *(over atomic mass range A = 1-238)*
by scanning of the ***energy region*** $\sqrt{S_{NN}}$ **= 3-9 GeV**

a program of corresponding R&D's is foreseen including
ones in the framework of experiments
carried out at ***Nuclotron***

Relativistic Heavy Ion Physics at Nuclotron & at higher energies

BM@N at Nuclotron ***M.Kapishin***
to study in-medium properties of hadrons, strangeness production etc. (complementary to the MPD)

FAZA at Nuclotron ***S.Avdeev***
effects of the phase transition in the thermal multifragmentation

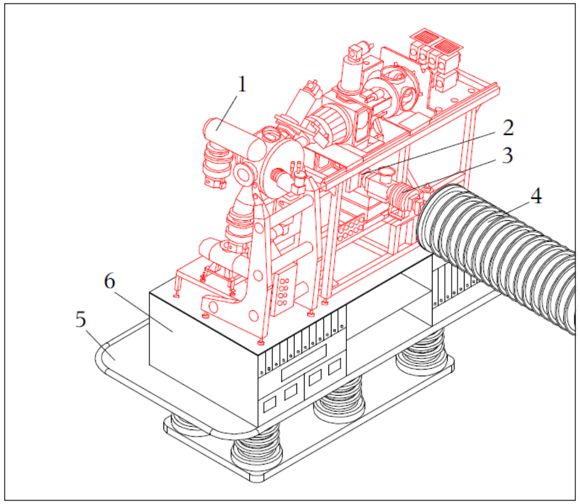
HADES & CBM ***V.Ladygin, Yu.Murin***
at SIS 18, 100/300 **GSI**

NA49 -> NA61 *at SPS* **CERN** ***G.Melkumov***

STAR *at RHIC* **BNL** ***R.Lednicky, Yu.Panebratsev***

ALICE *at LHC* **CERN** ***A.Vodopianov***

Spin Physics



Source of Polarized Deuterons
for Nuclotron-M / NICA complex
will provide ~ 10^{10} **d↑** */pulse from Nuclotron-M*

MPPT *(movable* **p↑**⊥*target) for f.t. experiments*

Spin physics (NN and and few nucleon systems) ***A.Kovalenko***

- **pp (np)** *elastic scattering (analyzing powers & correlation coefficients)*
- *meson production in* **pp** *near thresholds*
- **pd** *(3-nucleon forces, analyzing powers & correlation coefficients) etc.*

Nucleon Spin structure ***A.Nagaitsev, I.Savin***

- **COMPASS (SPS CERN)**
- **SPD** *at* **NICA** *(pp, pd –polarized, $\sqrt{S}$ = 20 GeV)* ***LoI*** *:in preparation*

Particle Physics

Physics at LHC CERN *(CM tests, Higgs, SUSY, …)*

- **CMS** — **A.Zarubin, A.Golutvin**
- **ATLAS** — **V.Kukhtin, A.Cheplakov**

Flavor Physics

- **NA48- NA62 (SPS CERN)** — **V.Kekelidze, Yu.Potrebenikov**
  Precise check of the CM & CPV in Kaon very rare decays

- **HyperNIS (Nuclotron)** — ***E.Strokovsky, Yu.Lukstins***
  exotic nuclei (hypernuclei)

Ongoing projects
(*accelerators*, *experiments*)

at home:

***Nuclotron-NICA*, *MPD*, *BM@N*,**

HyperNIS, ALPOM-2, DSS, FAZA-3, "E&T RaW"

at CERN:

ALICE, CMS, ATLAS, NA62, COMPASS-II, NA61

at GSI/FAIR:

HADES, CBM, PANDA

at BNL:

STAR

Accelerators, R&D:

ILC, *FEL*,

IREN (*FLNP*)

Activities: *SPD*, *NA48/2, NA49, Termalization, Becquerel, Marusya,…*

The physics program
(high energy heavy ion Physics):

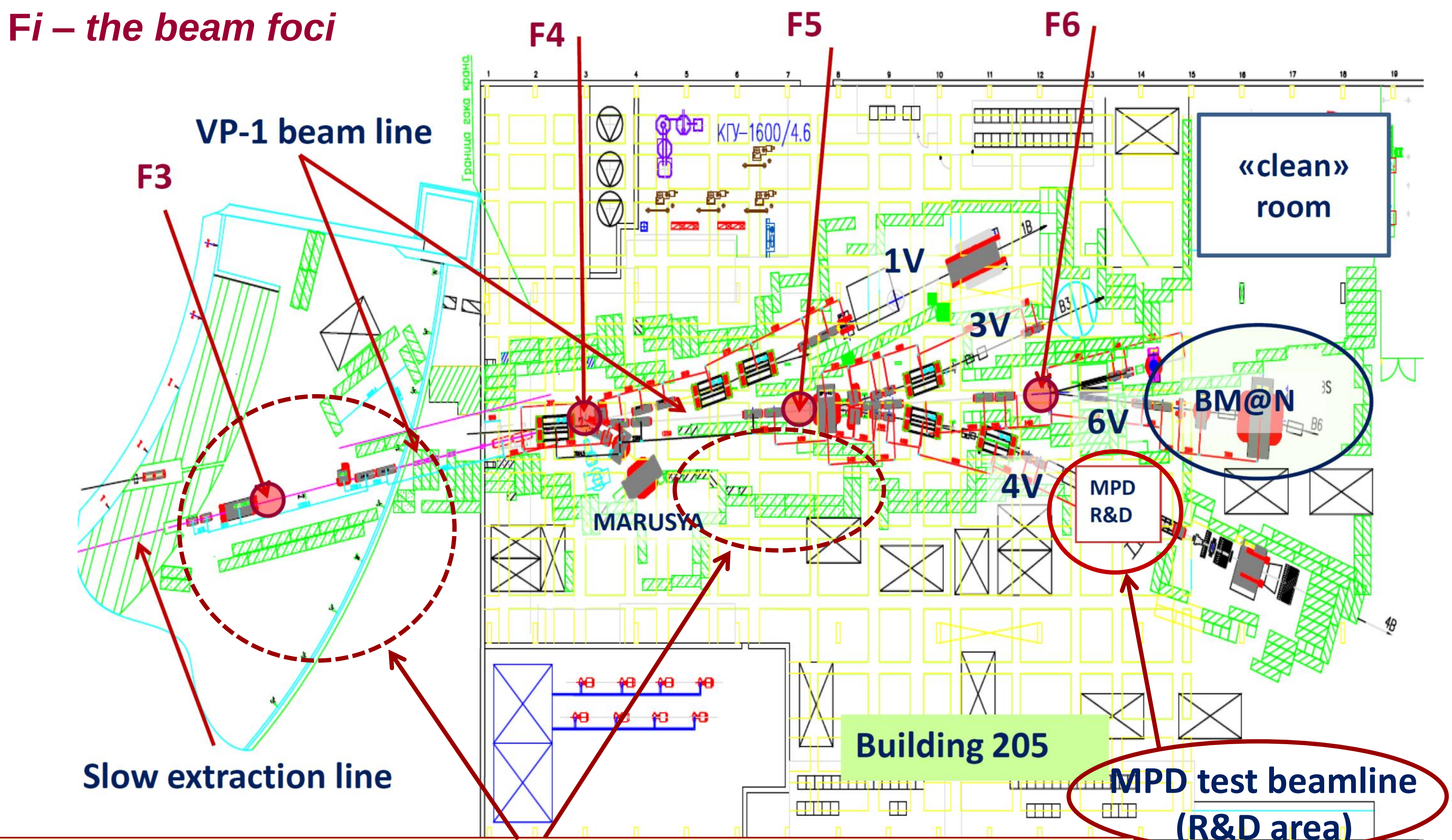
1. The equation-of-state of nuclear matter at high densities. Search for the mixed phase.
2. In-medium properties of hadrons.
3. Space-time evolution of nuclear interaction.
4. The first order deconfinement and/or chiral symmetry restoration phase transitions.
5. The QCD critical endpoint.

Backup slides to

"fixed-target experiments at LHEP"

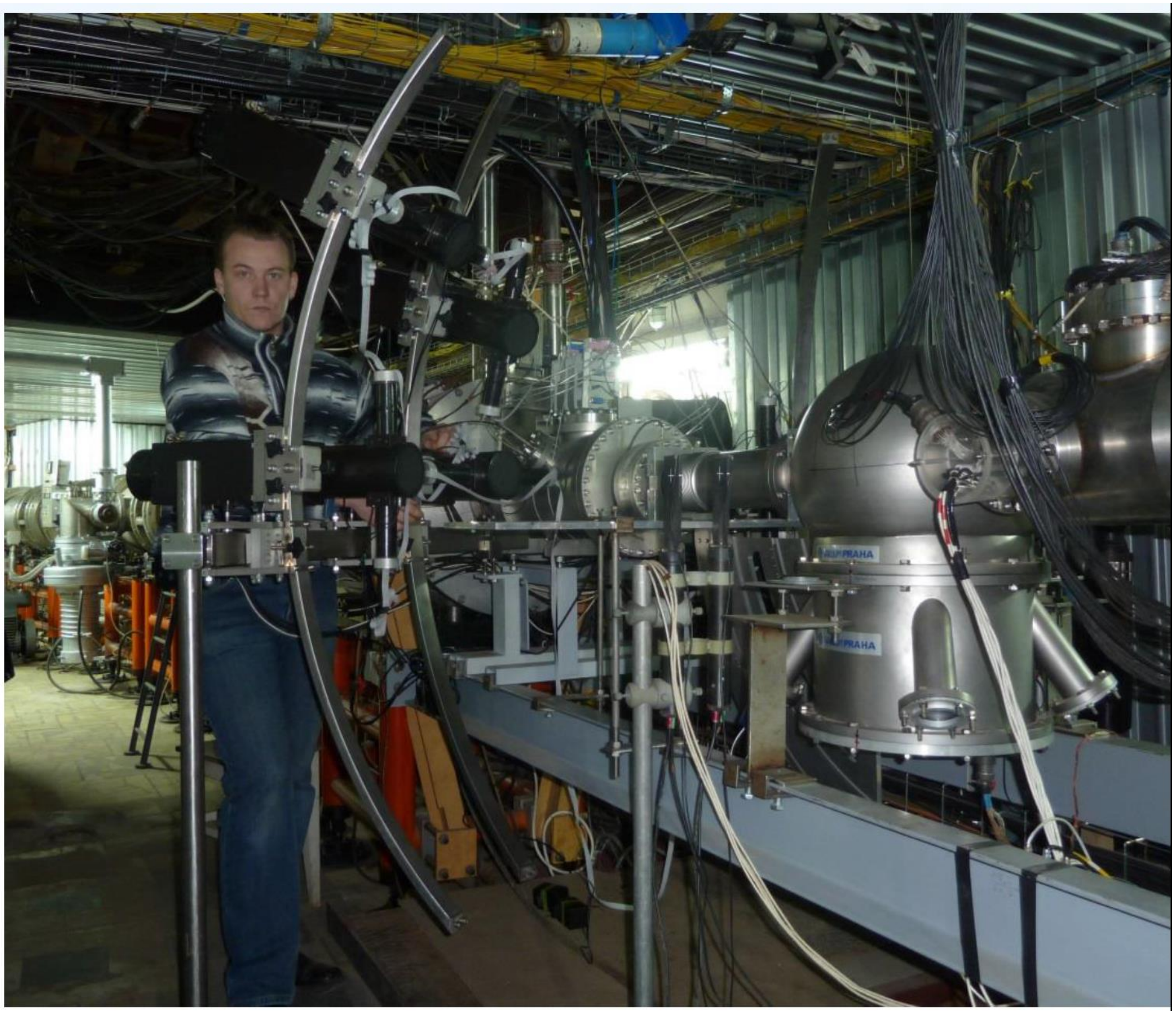
Extracted beams.

Map of beam lines for fixed target experiments at Nuclotron beams



Areas suitable (potentially) for applied and R&D experiments

Internal Target Station.

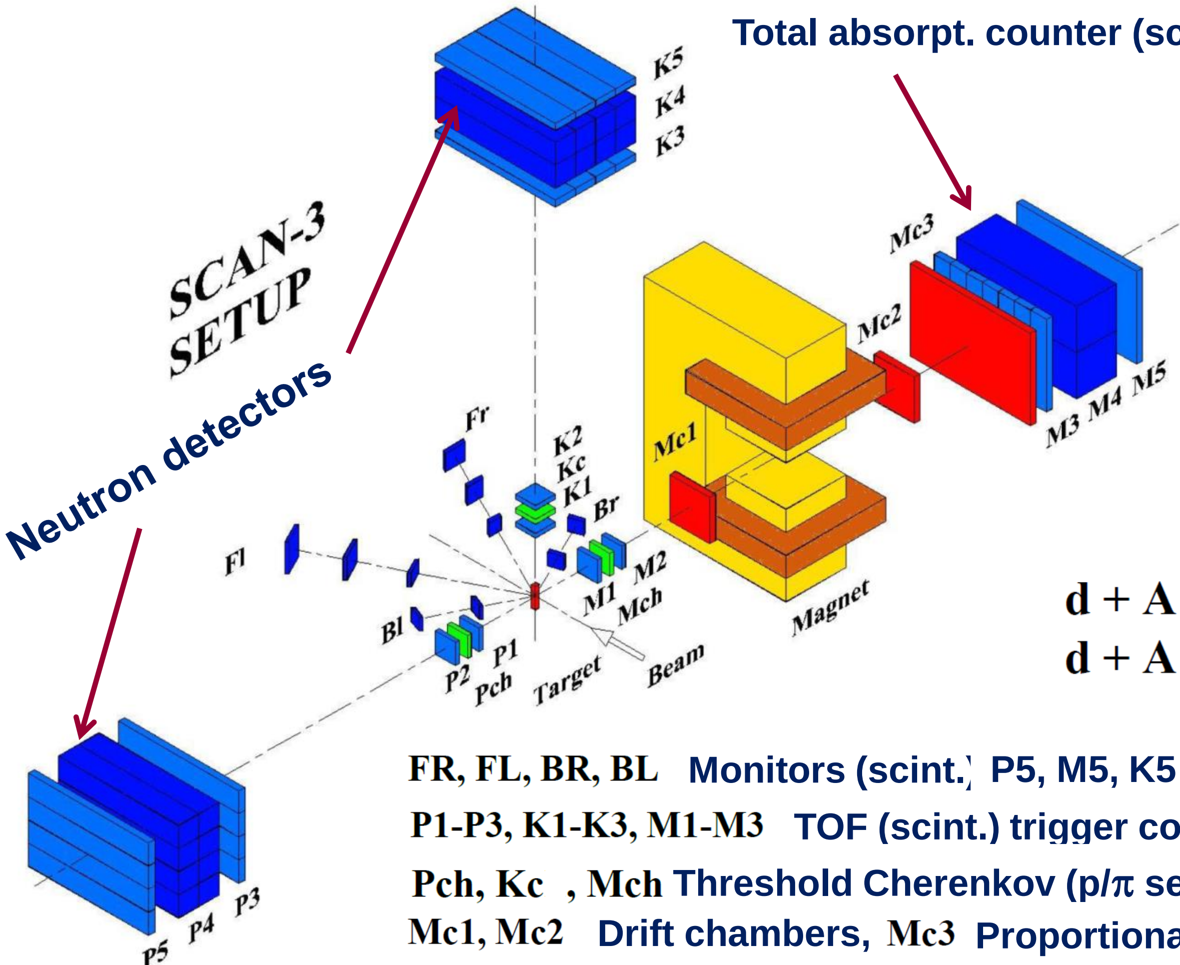


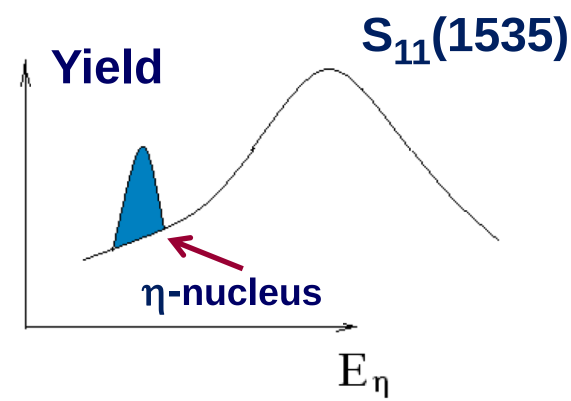
SCAN-3 (*new project*, *approved, under preparation*):

search for nuclei with η-meson as a constituent;

and study of *np* and *pp* pair production…

the Internal Target Station will be used.





"back-to-back"

ηN→ πN

$$d + A \to {}_\eta(A-1) + X \to \pi + N + X',$$
$$d + A \to {}_\eta(A-1) + X \to N + N + X'.$$

ηNN→ NN

FR, FL, BR, BL Monitors (scint.; P5, M5, K5 – veto counters)

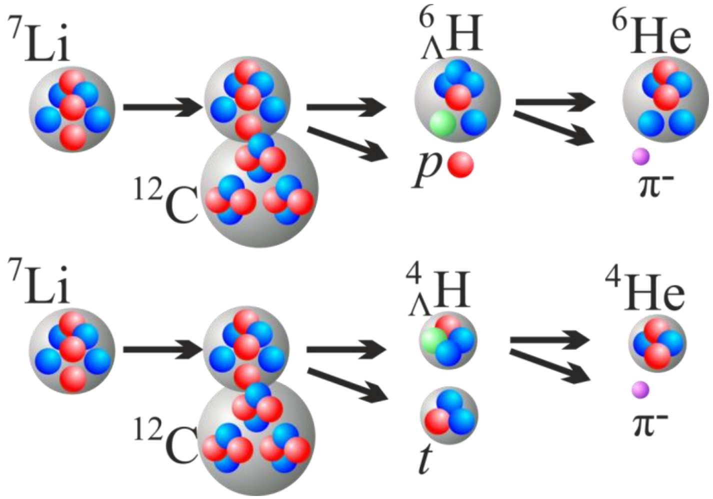
P1-P3, K1-K3, M1-M3 TOF (scint.) trigger conters

Pch, Kc , Mch Threshold Cherenkov (p/π separ.)

Mc1, Mc2 Drift chambers, Mc3 Proportional chamber

HyperNIS (physics of hypernuclei, first of all – properties of loosely bound hypernuclei with neutron excess)

The nearest goal:



Z_b=3 Z_{prod}=1+1 Z_{final}=2+1

$$^{7}Li + {}^{12}C \rightarrow {}^{6}_{\Lambda}H + p_{frag} + K^{+}$$
$$\quad\quad \Lsh\ {}^{6}He + \pi^{-}$$

$$^{7}Li + {}^{12}C \rightarrow {}^{4}_{\Lambda}H + t_{frag} + K^{+}$$
$$\quad\quad \Lsh\ {}^{4}He + \pi^{-},$$

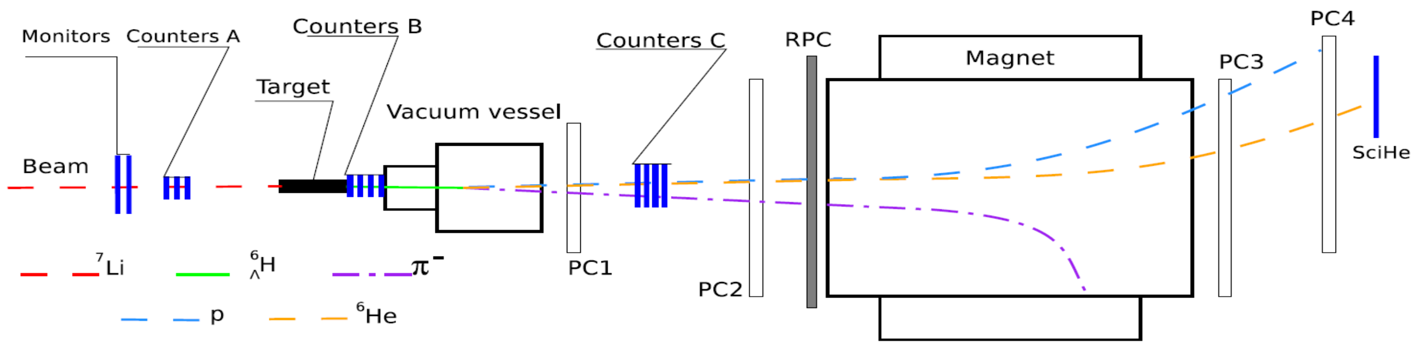


Figure 3: Configuration of the NIS-GIBS spectrometer adapted for the first-stage of the hypernuclear experiments, in particular for the search of $^{6}_{\Lambda}H$ hypernuclei with the ^{7}Li beam (not in scale). Target – carbon 12×3×3 cm, 20.4 g/cm^{2}; beam monitors; A,B,C – trigger counters; vacuum decay vessel of 55 cm length; the analyzing magnet of 0.9T; PC_{1-4} – proportional chambers, RPC – TOF stations, SciHe – Scintillation counter to confirm registration of He nuclei.