Prospects for the dense baryonic matter research at NICA

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Volga river
Main targets of the NICA project:

- *study of hot and dense baryonic matter*

- *investigation of nucleon spin structure, polarization phenomena*

- *development of accelerator facility for HEP @ JINR providing intensive beams of relativistic ions from p to Au polarized protons and deuterons with max energy up to $\sqrt{s_{NN}} = 11 \text{ GeV (Au}^{79+})$ and =27 GeV (p)*
Synchrotron **Nuclotron** is in operation since **1993**

*it is based on the superconducting fast cycling magnets developed in Dubna*

**Nuclotron** ring (C=251.5 m)

**Nuclotron** provides accelerated proton and ion beams (up to \( \text{Xe}^{42+}, A=124 \)) with energies up to 6 AGeV (Z/A = 1/2)
NICA complex
NICA complex

existing facility

PS & LU-20 (5MeV/u)

area of fixed target experiments

NUCLOTRON

0.6-4.5 GeV/u
NICA complex

existing facility
to be constructed

PS & LU-20 (5MeV/u)
KRION-6T HILac (3MeV/u)
area of fixed target experiments
Booster (600 MeV/u)
NUCLOTRON 0.6-4.5 GeV/u
NICA complex

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to be constructed

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0.6-4.5 GeV/u

MPD

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NICA complex

existing facility
to be constructed

PS & LU-20 (5MeV/u)
KRION-6T
HILac (3MeV/u)
area of fixed target experiments

Booster (600 MeV/u)

NUCLOTRON 0.6-4.5 GeV/u

contract for civil construction has been signed in 2015;
the works have started

MPD

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# NICA collider major parameters

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<tr>
<th><strong>Ring circumference, m</strong></th>
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<tr>
<td><strong>heavy ions</strong></td>
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<td>$\beta, , m$</td>
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<td>energy range for $\text{Au}^{79+}$: $\sqrt{S_{NN}}, , \text{GeV}$</td>
<td>4 - 11</td>
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<td>r.m.s. $\Delta p/p, , 10^{-3}$</td>
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<td>peak Luminosity for $\text{Au}^{79+}$, cm$^{-2}$ s$^{-1}$</td>
<td>$1 \times 10^{27}$</td>
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<td><strong>polarized particles</strong></td>
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<td>max. energy for polarized $p$, Gev</td>
<td>27</td>
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<tr>
<td>peak Luminosity for $p$, cm$^{-2}$ s$^{-1}$</td>
<td>$1 \times 10^{32}$</td>
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Physics objectives
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 H properties**;
- **Deconfinement (chiral), phase transition at high $\rho_B$ - enhanced strangeness production;**
- **QCD Critical Point - event-by-event fluctuations & correlations;**
- **Strangeness in nuclear matter - hypernuclei**
Present and future HI collider experiments

Interaction rate [Hz]

Collision energy $\sqrt{S_{NN}}$ [GeV]

Present and future HI collider experiments

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NICA/MPD will provide precise measurements exploring the whole phase space region in the energy range of max. baryonic density.
NICA White Paper – International Effort

Statistics of White Paper Contributions

111 contributions:
188 authors from 70 centers in 24 countries

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

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3 detectors

Baryonic Matter at Nuclotron (BM@N)

The fixed target experiment at the Nuclotron

Stage I 2017

MultiPurpose Detector (MPD) at the Collider

Stage I 2019

SPD (Spin Physics Detector) at the Collider

Project is under preparation
Experiments at NICA:
MultiPurpose Detector (MPD) at the Collider
MPD detector for Heavy-Ion Collisions @ NICA

Tracking: up to $|\eta|<2$ (TPC)
PID: hadrons, e, $\gamma$ (TOF, TPC, ECAL)
Event characterization:
  centrality & event plane (ZDC)

Superconducting solenoid:

high level ($\sim 3 \times 10^{-4}$) of magnetic field homogeneity

$B_0=0.66$ T

Correction coils (warm)

Stage 1: TPC, TOF, ECAL, ZDC, FD

Stage 2: IT + Endcaps (tracker, TOF, ECAL)

Magnet status:
technical design – completed;
Contracts under preparation

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TPC- technical project, preparation for fabrication

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

Cylinder C3 manufactured in Dec. 2013

FEC-64 prototype (ALTERA FPGA, ALTRO, PASA chips)

Cylinder C2, preparation for vacuum tests

$\varnothing 54$ cm, l=3.4 m

$R_{140}$ cm, L=3.4 m

4 mm thickness

0.1 mm precision
Time of Flight system (TOF)

Fast Forward Detector (FFD): production stage

Provides: \( T_0 \) for TOF, beam adjustment & collision L0-trigger

The achieved time resolution is better than required

\[ \sigma_{\text{FFD}} = \frac{54}{\sqrt{2}} = 38 \text{ ps} \]

\[ \chi^2 / \text{ndf} = 23.76 / 17 \]

Constant: \( 1143 \pm 18.1 \)
Mean: \( -0.001697 \pm 0.000680 \)
Sigma: \( 0.05421 \pm 0.00052 \)

mRPC – TDR has been prepared, ready for mass production

required efficiency, rate capability & time resolution are reached

\[ \sigma_{\text{PRPC}} = \frac{89}{\sqrt{2}} = 63 \text{ ps} \]

\[ \text{Sigma} = 0.08862 \pm 0.00044 \]


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ECAL – TDR - in preparation

$L \sim 35 \, \text{cm} \, (~ 14 \, \text{X}_0)$, Pb+Scint. $(4 \times 4 \, \text{cm}^2)$
read-out: WLS fibers + MAPD

Energy resolution $2.5\% / \sqrt{E}$

ZDC coverage: $3.2 < |\eta| < 4.8$

Energy resolution $2.5\% / \sqrt{E}$

Preparation for tests with electron beams at DESY (December’13)

Zero Degree Calorimeter (ZDC):
TDR stage

$\sigma(E)/(E) = 53\% / \sqrt{E} \, (\text{GeV}) + 10\%$

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ZDC provides required resolution
### MPD (l-stage) detector status

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<td>1. Magnet</td>
<td>– survey for producers</td>
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<td>2. Integration</td>
<td>– project in preparation</td>
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<td>3. ECAL</td>
<td>– TDR in preparation</td>
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<td>4. ZDC</td>
<td>– TDR close to completion</td>
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<td>5. TOF</td>
<td>– TDR close to completion</td>
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<td>6. FFD</td>
<td>– TDR close to completion</td>
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<td>7. TPC</td>
<td>– TDR close to completion:</td>
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<td>assembly area preparations</td>
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<td>fabrication of basic elements</td>
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<td>readout chambers – production + R&amp;D (alternative)</td>
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<td>ALTRO-based Front-End card prototype</td>
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<td>- preproduction stage</td>
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MPD I stage

feasibility study
MPD simulation framework

- Software repositories
- Software tests
- Forum
- Information, etc.

Event generators

- UrQMD 2.3
- LA QGSM
- SHIELD on fly
- PHSD
- UrQMD 3.4
- 3FD + particlization

- inherits basic properties from FairRoot (*developed at GSI*), C++ classes;
- extended set of event generators for heavy ion collisions;
- detector composition and geometry; particle propagation by GEANT3/4;
- advanced detector response functions, realistic tracking and PID included.

presentation of S. Merts
MPD tracking performance:

Fig. 1: Track reconstruction efficiency
- low acceptance down to 100 MeV/c;

Fig. 2: Momentum resolution
- \( \frac{\Delta p}{p} < 2\% @ p_T < 1.5 \text{ GeV/c} \)

Fig. 3: Primary vertex resolution
- \( \sigma_x \) & \( \sigma_z < 0.15 \text{ mm in central collisions} \)
  (track multiplicity in TPC > 500)
**MPD performance: hyperons**

Production of multi-strange hyperons to study the properties of the strongly interacting system and signal for QGP

- Central Au+Au @ 9A GeV (UrQMD), TPC+TOF barrel
- Realistic tracking and PID, secondary vertex reconstruction

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**Yields for 10 weeks of running**

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<tr>
<th>Particle</th>
<th>Expected yield</th>
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<td>$\Lambda$</td>
<td>$5.8 \times 10^9$</td>
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<tr>
<td>$\bar{\Lambda}$</td>
<td>$7.3 \times 10^7$</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$2.9 \times 10^7$</td>
</tr>
<tr>
<td>$\bar{\Xi}^+$</td>
<td>$1.6 \times 10^6$</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>$1.4 \times 10^6$</td>
</tr>
<tr>
<td>$\bar{\Omega}^+$</td>
<td>$2.9 \times 10^5$</td>
</tr>
</tbody>
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Momentum anisotropy (elliptic flow) originates from initial spatial anisotropy. $V_2$ depends on matter properties and EOS.

- Min. bias Au+Au @ 11A GeV (UrQMD), TPC+TOF barrel
- Realistic tracking & PID, secondary vertex reconstruction
- Event plane from TPC tracks
**Motivation:**
* The lightest bound state of hidden strangeness
* Low cross-section in nuclear matter and early freeze-out

**Data set and analysis**
- Central Au+Au collisions, at $\sqrt{s_{NN}} = 11$ GeV (UrQMD)
- Channel of decay: $\phi \rightarrow K^+K^-$, realistic tracking and PID (TOF + dE/dx)

**Measured values:**
- Width = $4.96 \pm 0.25$ (MeV/c$^2$)
- $M_{inv} = 1019.03 \pm 0.12$ (MeV/c$^2$)
- close to ones generated (PDG)
**Good probes to indicate medium modifications of spectral functions due to chiral symmetry restoration in A+A collisions; effect is proportional to baryon density**

**Received MPD performance for dileptons**

**Yields, central Au+Au at $\sqrt{s_{NN}} = 8.8$ GeV/u**

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<tr>
<th>meson</th>
<th>Yields</th>
<th>Yield/1 w</th>
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<tbody>
<tr>
<td>$4\pi$</td>
<td>$y=0$</td>
<td>$7 \cdot 10^4$</td>
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<tr>
<td>$\rho$</td>
<td>31</td>
<td>17</td>
</tr>
<tr>
<td>$\omega$</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>$\phi$</td>
<td>2.6</td>
<td>1.2</td>
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</table>

$\sigma_\omega \approx 14$ MeV/c$^2$
Hypernuclei @ MPD

Hypernuclei production enhanced at high baryon densities (NICA)

Hypertritons (central Au+Au @ 5A GeV (DCM-QGSM)

\[ ^3\Lambda H \rightarrow ^3He + \pi^- \]

Entries / 3 MeV/c^2

| p0   | 61.07 |
| p1   | 2.992 |
| p2   | 0.00192 |
| p3   | 3.781 |
| p4   | 361.3 |
| p5   | -4039 |
| p6   | 1.175e+04 |

S/S+B = 8.4
S/B = 2.9
eff. = 0.8%

\[ ^3\Lambda H \rightarrow p + d + \pi^- \]

Entries / 3 MeV/c^2

| p0   | 74.19 |
| p1   | 2.993 |
| p2   | 0.002272 |
| p3   | -7.633 |
| p4   | 587.7 |
| p5   | -7000 |
| p6   | 2.464e+04 |

S/S+B = 10.9
S/B = 11.8
eff. = 1.0%

\(~ 10^6 ^3\Lambda H \) are expected in 10 weeks

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Experiments at NICA:

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

*at the Nuclotron extracted beams*
# Nuclotron Beams

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Project (2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field, T</td>
<td>2.0 ($B_r = 42.8$ T·m)</td>
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<tr>
<td>Field ramp, T/s</td>
<td>1.0</td>
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<tr>
<td>Repetition period, s</td>
<td>5.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy, GeV/u</th>
<th>Ions/ cycle</th>
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<tbody>
<tr>
<td>Light ions ♞ d</td>
<td>7.0</td>
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<tr>
<td>Heavy ions</td>
<td>With KRION-6T &amp; Booster</td>
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<tr>
<td>$^{40}\text{Ar}^{18+}$</td>
<td>5.9</td>
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<tr>
<td>$^{56}\text{Fe}^{26+}$</td>
<td>6.4</td>
</tr>
<tr>
<td>$^{124}\text{Xe}^{48/42+}$</td>
<td>5.0</td>
</tr>
<tr>
<td>$^{197}\text{Au}^{79+}$</td>
<td>5.5</td>
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<tr>
<td>Polarized beams</td>
<td>With SPI</td>
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<tr>
<td>p↑</td>
<td>12.9</td>
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<tr>
<td>d↑</td>
<td>6.6</td>
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</tbody>
</table>

(*) With the Siberian snake
Nuclotron to BM@N beam line

26 elements of magnetic optics:
→ 8 dipole magnets
→ 18 quadruple lenses

Requirements for Au beam:
• minimum dead material
  → need to replace air intervals /foils with vacuum

Building 205

Nuclotron

~160 m
**BM@N (Baryonic Matter at Nuclotron): the 1st stage**

**Expression of interest from scientists:**
IN, SINP MSU, IHEP + S-Ptr Univ. (RF);
GSI, Frankfurt U., Gissen U. (Germany):
+ CBM-MPD IT-Consortium,

**Physics:**
- hyperon production
- hadron femtoscopy
- in-medium effects for strange & vector mesons
- electromagnetic probes (optional)

**BM@N schematic view**

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GEM tracker (12 planes)

Phase space / acceptance to primary p

Momentum and vertex resolutions

Δp / p vs p: 12 stations, B = 0.44

σ_X(Y) at Z_1 vs p: 12 stations, B = 0.44

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

12 planes of GEM tracker

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

- $S/B = 3.9$
- $S/\sqrt{S+B} = 83.5$
- Eff. = 8.9%

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

- $S/B = 3.6$
- $S/\sqrt{S+B} = 14.0$
- Eff. = 0.8%

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

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

- $S/B = 1.6$
- $S/\sqrt{S+B} = 22.4$
- Eff. = 1.0%

$E_{kin} = 4.5A$ GeV, $2 \times 10^6$ events;

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# BM@N Milestones

- **ZDC** complete configuration, **2016**
- **DAQ** complete config., **end 2017**
- **GEM** 8 planes, **end 2017**
- **TOF** complete config., **end 2017**
- **GEM** 12 planes, **end 2018**
- **ST** 4 planes, **2019**

- technical runs with **d, C, Li**, **2015 - 2017**
- physics run **BM@N (I stage) with p, Xe**, **Nov 2017**
- physics run **BM@N (II stage) with Au**, **Feb 2019**
## NICA schedule

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**Legend**: running
Concluding remarks

- NICA complex has a potential for competitive research in the fields of dense baryonic matter

- The construction of both detectors BM@N & MPD is progressing

- The international collaboration around the NICA is growing

- New partners are invited to join the BM@N & MPD
Thank you!