Nuclotron based Ion Collider fAcility (NICA) & Multi Purpose Detector (MPD) to study properties of hot & dense baryonic matter
Introduction

- The NICA/MPD project is aimed to study of hot & dense baryonic matter at $A=1$-$197$, $\sqrt{S_{NN}} = 4$ - 11 GeV/u, $L = 10^{27}$cm$^{-2}$s$^{-1}$

- This Project was initiated and led by A.N. Sissakian

Physics motivation

- The study of hot & dense baryonic matter would provide us with relevant information on
  - in-medium properties of hadrons & nuclear matter equation of state
  - de-confinement and/or chiral symmetry restoration,
  - phase transition, mixed phase & critical end-point
  - possible strong P- & CP violation

- It is indicated in series of theoretical works
  - A. Sissakian, A. Sorin, V. Toneev, G. Zinovjev, M. Gazdzicki,
  - M. Gorenstein, J. Cleymans and others

  that an optimal way to reach the highest possible baryon density in the lab is heavy ion collision at $\sqrt{S_{NN}} = 4$ - 11 GeV/u

V. Kekelidze at Blois 2010 18 July 2010
Creation of the deconfined QGP state in heavy-ion collisions, study of fundamental properties of QCD (confinement, QCD vacuum, phase transition) in hot and dense strongly interacting matter

**QCD phase diagram**

**Baryon density in A+A collisions**

J. Randrup & J. Cleymans

V. Kekelidze at Blois 2010

18 July 2010
The Nuclotron

- accelerator facility of JINR in HEP based on the unique technology of superconducting fast cycling magnets developed in JINR (put in operation in 1993).
-- provides proton, polarized deuteron & multi charged ion beams

On energy $H=1.8T$ corresponds:
- $d$ ($A=2$, $Z=1$) - 5.2 GeV/u
- $Xe$ ($A=124$, $Z=42$) - 3.3 GeV/u
- $Au$ ($A=197$, $Z=79$) - 4.05 GeV/u

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>working</th>
<th>planned</th>
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<tbody>
<tr>
<td>Accelerated particles</td>
<td>$1&lt;Z&lt;36$</td>
<td>$1&lt;Z&lt;92$</td>
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<tr>
<td>Max Energy (GeV/n)</td>
<td>4.2</td>
<td>6($A/Z=2$)</td>
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<td>Magnetic field (T)</td>
<td>1.5</td>
<td>2.0</td>
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<td>Slow extraction system</td>
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<td>Time extraction (sec)</td>
<td>Up to 10</td>
<td>up to 10</td>
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<td>Energy range (GeV/n)</td>
<td>0.2-2.3</td>
<td>0.2-6.0</td>
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V. Kekelidze at Blois 2010
**Injector:** 2\times10^9 \text{ ions/pulse of } ^{197}\text{Au}^{32+} at energy of 6.2 \text{ MeV/u}

**Nuclotron (45 Tm)**
Injection of one bunch of \(1.1 \times 10^9\) ions, acceleration up to 1\div4.5 \text{ GeV/u max.}

**Collider (45 Tm)**
Storage of 32 bunches \(\times 1\cdot10^9\) ions per ring at 1\div4.5 \text{ GeV/u}, electron and/or stochastic cooling

**Booster (25 Tm)**
1(2-3) single-turn injection, storage of 2 \((4-6)\times10^9\), acceleration up to 100 \text{ MeV/u}, electron cooling, acceleration up to 600 \text{ MeV/u}

**Stripping (80%)** \(^{197}\text{Au}^{32+} \Rightarrow ^{197}\text{Au}^{79+}\)

**Two superconducting collider rings**

**IP-1**

**IP-2**

**2 x 32 injection cycles (\sim 6 \text{ min})**

**Nuclotron (45 Tm)**
Injection of one bunch of \(1.1\times10^9\) ions, acceleration up to 1\div4.5 \text{ GeV/u max.}

**Option:** stacking with BB and S-Cooling
\sim 2 x 300 injection cycles (\sim 1 \text{ h})

**Bunch compression (RF phase jump)**
# Collider—general parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Ring circumference, [m]</td>
<td>~ 400</td>
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<tr>
<td>( B_p ) max [ T·m ]</td>
<td>45.0</td>
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<tr>
<td>Ion kinetic energy (Au79+), [GeV/u]</td>
<td>1.0 ÷ 4.56</td>
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<tr>
<td>Dipole field (max), [ T ]</td>
<td>2.0</td>
</tr>
<tr>
<td>Free space at IP (for detector)</td>
<td>9 m</td>
</tr>
<tr>
<td>Beam crossing angle at IP</td>
<td>0</td>
</tr>
<tr>
<td>Vacuum, [ Torr ]</td>
<td>( 10^{-11} )</td>
</tr>
<tr>
<td>Luminosity per one IP, cm(^{-2})·s(^{-1})</td>
<td>0.75( \div 11 ) · 10(^{26} )</td>
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# NICA: works schedule

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V.Kekelidze at Blois 2010
List of Tasks for MPD

To measure a large variety of signals systematically changing collision parameters (energy, centrality, system size).

Reference data (i.e. p+p) will be taken at the same experimental conditions.

- bulk observables (hadrons): $4\pi$ particle yields (OD, EOS)
- multi-strange hyperon production: yields & spectra (OD, EOS)
- electromagnetic probes (CSR, OD)
- azimuthal charged-particle correlations (LPV)
- event-by-event fluctuation in hadron productions (CEP)
- correlations involving $\pi$, K, p, $\Lambda$ (OD)
- directed & elliptic flows for identified hadron species (EOS, OD)
- ....

OD – Onset of Deconfinement
CEP – Critical End Point
CSR – Chiral Symmetry Restoration
LPV – Local Parity Violation in strong interaction
EOS – Equation Of State

V. Kekelidze at Blois 2010  18 July 2010
# Particle yields in Au+Au collisions

$\sqrt{s_{NN}} = 7.1$ GeV (10% central)

<table>
<thead>
<tr>
<th>Particle (mass)</th>
<th>Multiplicity</th>
<th>decay mode</th>
<th>BR</th>
<th>$\varepsilon$ (%)</th>
<th>yield (s$^{-1}$)</th>
<th>yield 10w</th>
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<tbody>
<tr>
<td>$K^+$ (494)</td>
<td>55</td>
<td>--</td>
<td>--</td>
<td>20</td>
<td>$7.7 \cdot 10^3$</td>
<td>$4.6 \cdot 10^{10}$</td>
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<tr>
<td>$K^-$ (494)</td>
<td>16</td>
<td>--</td>
<td>--</td>
<td>20</td>
<td>$2.2 \cdot 10^3$</td>
<td>$1.3 \cdot 10^{10}$</td>
</tr>
<tr>
<td>$\rho$ (770)</td>
<td>23.6</td>
<td>$e^+e^-$</td>
<td>$4.7 \cdot 10^{-5}$</td>
<td>2</td>
<td>$1.6 \cdot 10^{-2}$</td>
<td>$9.4 \cdot 10^4$</td>
</tr>
<tr>
<td>$\omega$ (782)</td>
<td>14.2</td>
<td>$e^+e^-$</td>
<td>$7.1 \cdot 10^{-5}$</td>
<td>2</td>
<td>$1.4 \cdot 10^{-2}$</td>
<td>$8.6 \cdot 10^4$</td>
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<tr>
<td>$\varphi$ (1020)</td>
<td>2.7</td>
<td>$e^+e^-$</td>
<td>$3 \cdot 10^{-4}$</td>
<td>2</td>
<td>$1.1 \cdot 10^{-2}$</td>
<td>$6.8 \cdot 10^4$</td>
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<tr>
<td>$\Xi^-$ (1321)</td>
<td>2.4</td>
<td>$\Lambda\pi^-$</td>
<td>1</td>
<td>4</td>
<td>67</td>
<td>$4.0 \cdot 10^8$</td>
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<tr>
<td>$\Omega^-$ (1672)</td>
<td>0.16</td>
<td>$\Lambda K^-$</td>
<td>0.68</td>
<td>2</td>
<td>1.5</td>
<td>$9.2 \cdot 10^6$</td>
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<tr>
<td>$D^0$ (1864)</td>
<td>$7.5 \cdot 10^{-4}$</td>
<td>$K^+\pi^-$</td>
<td>0.038</td>
<td>1</td>
<td>$2.0 \cdot 10^{-4}$</td>
<td>1200</td>
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<tr>
<td>$J/\psi$ (3097)</td>
<td>$3.8 \cdot 10^{-5}$</td>
<td>$e^+e^-$</td>
<td>0.06</td>
<td>5</td>
<td>$8.0 \cdot 10^{-5}$</td>
<td>480</td>
</tr>
</tbody>
</table>

*Luminosity* $L = 10^{27}$ cm$^{-2}$s$^{-1}$

*Event rate (central)* 700 Hz

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18 July 2010
NICA Physics. Electromagnetic probes (dileptons)

Changes of the particle properties (broadening of spectral functions) in hot and dense medium. NICA is well situated to study in-medium effects due to highest baryon densities.

Energy range (NICA):
- Onset of the low-mass pair enhancement.
- Study the effect under highest baryon density conditions.
**NICA physics. CEP (experimental signatures)**

**K/π-ratio: event-by-event dynamical fluctuations**

\[ \sigma_{\text{dyn}}^2 = \sigma_{\text{data}}^2 - \sigma_{\text{mixed}}^2 \]

Better precision than fixed target experiments provide! (factor of ~3 compared to existing data)

- NA49
- UrQMD
- STAR
- MPD (estim.)

**NICA:**
- Large acceptance (close to $4\pi$, total $\phi$-coverage)
- Excellent tracking and PID
- Better precision for fluctuation measurements (CEP search)

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18 July 2010
# STAR Run10 Physics Programs

<table>
<thead>
<tr>
<th>Beam Energy (GeV)</th>
<th>29 cryo-week</th>
<th>STAR BUR In days</th>
<th>Physics</th>
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<tbody>
<tr>
<td>200</td>
<td>11</td>
<td>56</td>
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<td>62.4</td>
<td>4</td>
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<td>39</td>
<td>1.5</td>
<td>5 (24M)</td>
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<td>27</td>
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<td>15 (33M)</td>
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<td>18</td>
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<td>16 (15M)</td>
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<td>11.5</td>
<td>2</td>
<td>19 (5M)</td>
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<td>7.7</td>
<td>4</td>
<td>56 (5M)</td>
<td>BES programs</td>
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<tr>
<td>5.5</td>
<td>0.5</td>
<td>5 (0.1M)</td>
<td>(1) QCD T_e (2) QCD phase boundary</td>
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</tbody>
</table>

Femtoscopy correlation studies @ NICA

play a crucial role in the study of space-time aspects of the system:
- high statistics, uniform acceptance, excellent PID required
- multidimensional fit technique has to be applied

**STAR**
- $4 \cdot 10^6$ min. bias events (200k central) in 2010 LES run
  - $10\%$ precision for $\pi \pi$ correlation

**MPD/NICA**
- $10^9$ min. bias events/week (10$^8$ central)
  - best precision for:
    - femtoscopy with respect to RP
    - correlation of multistrange particles

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Table 1.3: Two-particle systems which, in principle, can be measured in the NICA energy range.

<table>
<thead>
<tr>
<th></th>
<th>$\pi^+$</th>
<th>$\pi^-$</th>
<th>$\pi^0$</th>
<th>$K^+$</th>
<th>$K^-$</th>
<th>$K^0$</th>
<th>$p$</th>
<th>$n$</th>
<th>$\Lambda$</th>
<th>$\Lambda$</th>
<th>$\Xi$</th>
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<td>$\pi^+$</td>
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V.Kekelidze at Blois 2010
18 July 2010
MPD Collaboration

+ Nuclotron-M/NICA/MPD/SPD cooperation

Members of the Collaboration – 100:
- JINR
- Other institutes – 54

Institutions:
- JINR
- 12 institutes from 7 countries

The Collaboration is permanently growing

New participants – are welcome!
3 stages of putting into operation

1-st stage
barrel part (TPC, Ecal, TOF) + ZDC, FFD, BBC, magnet, ...

2-nd stage
IT, EC-subdetectors

Forward spectrometer-B

3-d stage
F-spectrometers (optional?)
Angle coverage of MPD

Acceptance (B=0.5 T):
- Full azimuthal TPC ($|\eta| < 2$)
- ECAL ($|\eta| < 1.2$)
- FD ($2 < |\eta| < 4$)
- TOF ($|\eta| < 3$)
- IT ($|\eta| < 2.5$)
- ZDC ($|\eta| > 3$)

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Time Projection Chamber (TPC)

**Challenges**
- low material budget, max. transparency for forward tracking
- high event rates (up to ~ 7 kHz)
- small distortions, stable conditions, $B_r/B_z < 5\times10^{-4}$

**TPC parameters**
- Size: 3.4 m (length) x 2.2 m (diameter)
- Drift Length: 150 cm
- # of samples: 50
- Electric field: 140 V/cm
- Magnetic field: 0.5 T (max.)
- Gas: 90% Argon + 10% Methane (atm+2 mbar)
- Readout: 2x12 sectors (MWPC+pads or GEM)
- Pad size – 4x10 mm in inner sector area
  6x12 mm in outer sector area
- Total # of pads: ~80000

**Performance required (MWPC option)**
- Spatial resolution: $\delta_r \sim 300$ mm, $s_z \sim 2$ mm
- Two track resolution < 1 cm
- Momentum resolution $\Delta p/p < 3\%$ (0.2 < $p$ < 1 GeV/c)
- dE/dx resolution < 8%
Readout Chamber

Pad Plane:
- Two sets of 4x10 mm and 6x12 mm pads
- 256 channels of readout electronics

FEE:
- Amplifier/Shaper – PCA16/ILC and PASA
- 12 bits ADC – ADC12EU050
- FPGA VIRTEX5
Time Of Flight (TOF) system

**Basic requirements**
- Coverage: barrel > 30 m\(^2\),
- Endcap covers down to |\(\eta| < 3\)
- \(\sigma \sim 80\) ps (100 ps overall)

**Dimensions**
- **Barrel**: 5 m (length), 2.5 m (diameter)
- **Endcap**: 2 x 2.5 m (diameter) disks
- **Gas**: 90% C\(_2\)H\(_2\)F\(_4\) + 5% iC\(_4\)H\(_{10}\) + 5% SF\(_6\)

**Segmentation (barrel)**
- 12 sectors
- Module: 10-gap RPC, 48 pads 2.5x3.5 cm\(^2\)
  or 30-50 cm long and 1-2 cm wide strips

**Endcaps**
- 24 mRPC 53,37,21x80-100 cm\(^2\)
  - Pad size: 4x4 cm\(^2\)
  - Geom. efficiency \(\sim 95\)%
ECAL – “shashlyk” type modules with APD readout

(Lead plates (0.275 mm) and plastic scintillator (1.5 mm), the radiation length of tower $18X_0$ (40 cm))

The active area of APD - 3x3 mm; density of pixels in APD – $10^4$/mm$^2$

Energy resolution $\frac{\sigma_E}{E}$, %

Time resolution $80$ psec/$\sqrt{E}$
Feasibility studies
TPC Simulation

Tracking efficiency

Energy loss distribution in the MPD TPC

Particle transverse momentum resolution

Primary vertex resolution with TPC and TPC+IT

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V0 performance (TPC+IT)

Central Au+Au @ 9 GeV

Improved Signal-to-Background ratio (S/B) with the vertex IT detector

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Hyperon reconstruction

Au+Au 9 Gev

Eff. $\approx 3.8\%$

$\frac{S}{B} \pm 3\sigma = 245 / 18 \approx 13.7$

$\frac{S}{\sqrt{S+B}} \approx 15.1$

Eff. $\approx 2.1\%$

$\frac{S}{B} \pm 3\sigma = 286 / 59 \approx 4.9$

$\frac{S}{\sqrt{S+B}} \approx 15.4$

Excellent capabilities
for hyperon measurements!
TOF performance study

- **Coverage:**
  - $|\eta| < 1.4$, $p_t=0.1$-2 GeVc  
  - $|\eta| < 2.6$, $p_t=0.1$-2 GeVc

- **Matching eff.:** > 85% at $p_t > 0.5$ GeV/c

- **PID:** $2\sigma$ $\pi/K \sim 1.7$ GeV/c, $(\pi,K)/p \sim 3$ GeV/c
n/γ separation efficiency
by using information on X-Y(transverse) and Z (longitudinal) shapes of profiles of the cluster in the ECal

Efficiency of neutron identification - 95% with 3% admixture of photons
Electron identification (MPD simulation)

- Efficient electron selection up to \( p = 1.2 \) GeV/c (black points)
- Negligible hadron contamination in electrons (red symbols)

- Combined \( dE/dx + \text{TOF} \) information improve \( e/\pi \) separation substantially!
- ECAL provides extra suppression factor (detailed MC simulation in progress)
Dielectrons at NICA/MPD

- Au+Au collisions at $\sqrt{s_{NN}} = 7$ GeV/u (UrQMD)
- Pluto (ver. 4.12) hadron cocktail generator
  - meson yields from HSD model + data
  - only lepton branches are activated
- MpdRoot simulation framework
  - realistic track reconstruction
  - particle identification via dE/dx and TOF

10⁷ Au+Au events

V. Kekelidze at Blois 2010

18 July 2010
# Timetable MPD

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The NICA/MPD project to study hot & dense baryonic matter is well progressing at JINR

The 1st stage of MPD conception is completed

R&D for major sub-detectors - close to completion

Prototyping plans for MPD are well defined

Construction schedules are estimated for NICA & MPD

The Collaboration is growing
New members are welcome!
Spares

V. Kekelidze at Blois 2010   18 July 2010
Introduction: NICA Layout & Main Elements

- Collider 32T
  - $C = 336 \text{ m}$
- Synchrophasotron yoke
- "Old" linac
- KRION-6T & HILac
- Beam transfer line
- MPD
- Existing beam lines (Fixed target exp-s)
- Nucloton
- Spin Physics Detector (SPD)
- Booster
- 2.3 m
- 4.0 m

V. Kekelidze at Blois 2010
Relativistic Nuclear Physics

Colliders & Synchrotrons: Luminosity vs Energy ($\sqrt{s}$)

Synchrotrons: SIS100, SIS300, SPS, Nuclotron, U-10, U-70, NICA, RHIC (Au$^{79+}$), LHC (Pb$^{82+}$)

L(E)

$10^32, 10^30, 10^28, 10^26, 10^24$

$0.1, 1.0, 10, 100, 1000, 10000$

$\sqrt{s}$, $\eta$, $\rho$, $\omega$, $\phi$, $J/\Psi$, $Y$, $W^{\pm}Z^0$, $t$

V. Kekelidze at Blois 2010
18 July 2010
Particle multiplicities in hadronic model (HSD)

The main dimensions of the Central part of MPD

V. Kekelidze at Blois 2010  18 July 2010
TPC prototype №1

Electric field – 140 V/cm
Drift distance – 40 cm

V. Kekelidze at Blois 2010
18 July 2010
Di-electron simulation

~ 8 hours of NICA/MPD running time equivalent to the entire data set volume for STAR (< 10^7 events)
Electron identification

Rejection of protons, kaons and most of pions by TOF

$\pi$ contamination in the $e^{+}$ sample < 0.3%

ECAL provides extra suppression factor

V. Kekelidze at Blois 2010

18 July 2010
## NICA: works schedule

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### R & D
- Design
- Manufacture
- Mounting
- Mount+Com
- Commis/Opr
- Operation

V.Kekelidze at Blois 2010  
18 July 2010