Mega-science project **NICA**
at Joint Institute for Nuclear Research, Dubna

V. Kekelidze

3 December 2014  V. Kekelidze, PF-China, Dubna
from the Synchrophasotron to the Collider NICA

1957
Synchrophasotron
10 GeV proton synchrotron – the world leader in energy
the start up of high energy era

1993
Nuclotron
the first superconducting accelerator of heavy ions

2019
NICA
The superconducting Collider of heavy ions

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

A.V. Baldin – the pioneer of relativistic nuclear physics

The study of nuclear matter at extremely high density

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Main targets of “NICA Complex”:

- **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 $\sqrt{s_{NN}} = 11 \text{ GeV} \ (Au^{79+}) \ \text{and} \ = 27 \ \text{GeV} \ (p)$
Synchrotron **Nuclotron** is in operation since **1993**

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

Nuclotron provides accelerated proton and ion beams (up to Xe$^{42+}$, $A=124$) with energies up to 6 AGeV ($Z/A = 1/2$)
The phases of nuclear matter

phase transition in nuclear matter could be compared with thermodynamic phases of water
Asymptotic freedom of quarks

The regime of “asymptotic freedom” is reached in hard processes at sufficiently high energies,

\[ \alpha_s, g^2 \]

asymptotic freedom; anti-screening of color charges

Yukawa coupling; charge screening, de-confinement

\[ \frac{1}{r} \sim \frac{1}{\ln(\frac{\alpha_f}{r})} \]

\[ R_0 \sim 1 \text{ fm} = 10^{-13} \text{ cm} \]

The super dense nuclear matter could be obtained in heavy ion interactions

D.J. Gross, H.D. Politzer, F. Wilczek
Nobel Prize in 2004

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Nuclear collisions and the QGP expansion

\[ \frac{\text{fm}}{c} = 3 \times 10^{-24} \text{s} \]

collision evolution
expansion and cooling

particle detectors

kinetic freeze-out

hadronization

distributions and correlations of produced particles

selection by spectators

QGP phase
quark and gluon degrees of freedom

collision overlap zone

quantum fluctuations

\[ \tau \sim 0 \text{ fm/c} \]
\[ \tau_0 \sim 1 \text{ fm/c} \]
\[ \tau \sim 10 \text{ fm/c} \]
\[ \tau \sim 10^{15} \text{ fm/c} \]

evolution in time

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charged particle collisions:

electrons, protons (hydrogen nucleus), heavy ions (nuclei)

Experiments:

✓ with fixed target

\[ p = 10 \text{ GeV} \]

\[ \sqrt{S_{NN}} \approx 4.5 \text{ GeV} \]

✓ at collider

\[ \sqrt{S_{NN}} \approx 2p = 20 \text{ GeV} \]

\[ S_{NN} = (E_1+m)^2 - (p+0)^2 \]

\[ \approx 2pm + 2m^2 \]

1 eV = \( 1.6 \times 10^{-19} \) J

1 GeV = \( 10^9 \) eV \( \approx m \)
Relativistic Heavy Ion Collider

Designed Energy $\sqrt{S_{NN}} = 200$ GeV

BNL 2000: RHIC ~ 4 km

PHENIX

STAR

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CERN 2009, LH Collider (7 000 GeV), experiments with fixed target at SPS

~ 27 km
The “Horn” effect observation.

The “Horn” effect observation.

One of the hypothesis: indication onset of deconfinement, requires more detailed study.

One of the hypothesis: indication onset of deconfinement, requires more detailed study.

The most interesting energy region (NICA / FAIR)

Non monotonic energy dependence of the yield ratio \( \frac{K^+}{\pi^+} \) ("Horn") in heavy ion collisions – indication on deconfinement?

Evidence in NA49 (SPS CERN)

Confirmed in: STAR (RHIC BNL)

ALICE (LHC CERN).


STAR: QM2011 proceedings

ALICE: QM2011 proceedings
The freeze-out condition (of phase transition)

\[ T \text{ (MeV)} \]

\[ \rho_B \text{ (fm}^{-3}) \]

- RHIC
- FAIR
- SPS

E1+E2: colliders
E: fixed targets

J. Randrup & J. Cleymans
Te most interesting Energy range
- the region of maximum density of nuclear matter, which had not been ever reached in the Lab conditions (the early Universe, neutron stars)

$$\sqrt{s_{NN}} \sim 10 \text{ GeV}$$

Two International projects are targeting to this issue:

✓ **FAIR** (*Darmstadt, Germany*)
  - experiments with fixed target

✓ **NICA** (*JINR, Dubna*) – **collider** experiments
Complex FAIR: experiments with fixed target

1.0 AGeV

Darmstadt, Germany
Collider basic parameters:

\[ \sqrt{s_{NN}} = 4-11 \text{ GeV}; \text{ beams: from } p \text{ to } Au; \text{ } L \sim 10^{27} \text{ cm}^{-2} \text{ c}^{-1} (Au), \sim 10^{32} \text{ cm}^{-2} \text{ c}^{-1} (p) \]
Existing & future accelerators for heavy ions

The region of max. baryonic density

20??

2019

2019

Existing

2019

SIS-300 (FAIR)

SIS-100 (FAIR)

NICA (JINR)

Nuclotron-M (JINR)

SIS-18 (GSI)

AGS (BNL)

SPS (NA-49/61, CERN)

BES

RHIC (BNL)

fixed targ. exp.: L- limited by detectors

Colliders:

scale for L, in cm$^{-2}$s$^{-1}$

10$^{23}$

10$^{25}$

10$^{27}$

$\sqrt{S_{NN}}$, GeV

for Au+Au

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The NICA complex construction has been approved in 2010

- accelerator complex 2010 – 2019
- MPD (MultiPurpose Detector) (at Collider) 2010 – 2019
- experiment with fixed target BM@N (I stage) 2012 - 2017

The project preparation for Spin Physics Detector (SPD) is in progress
Detectors and observables
the observables in AA, pA and pp collisions:

- multiplicity of produced hadrons ($\pi, K, p, \Lambda, \Xi, \Omega$)
- electromagnetic probes: electrons, gammas, vector meson decays,
- event-by-event fluctuations
- femtoscopy of $\pi, K, p, \Lambda$
- ....
Lepton pair production

- In-medium modification of vector meson properties may signal on partial chiral symmetry restoration in heavy ion collisions
- Dileptons as penetrating probes of the fireball interior – no FSI
- Existing experimental data underestimated by the vacuum spectral functions for $0.3 \text{ GeV} < M_{ee} < 0.7 \text{ GeV}$

The detector relevant features:

- Low material budget
- Electron reliable ID & hadron extra suppression by ECAL
- High event rate allowing studying of dielectron continuum at high pT

Required mass resolution $\sim 10 \text{ MeV}$

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<tr>
<td>$\omega$</td>
<td>23</td>
<td>783</td>
<td>8</td>
</tr>
<tr>
<td>$\phi$</td>
<td>44</td>
<td>1019</td>
<td>4</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.3</td>
<td>768</td>
<td>149</td>
</tr>
</tbody>
</table>
Collective motion: “elliptic flow”

Initial coordinate-space anisotropy

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)] + 2v_4 \cos[4(\phi - \Psi_R)] + \ldots$$

Final momentum-space anisotropy

Elliptic flow establishes there is strongly interacting matter at \( t \sim 0 \)
one of the most interesting subject of research: estimate of ability to measure charge asymmetry w.r.t. reaction plane as a possible signature of strong $P$ violation

Electric dipole moment of QCD matter!


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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

[Diagram showing percentage contributions from various countries, with Russia being the largest contributor with 63% and Germany contributing 28%.]

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<table>
<thead>
<tr>
<th>Beam</th>
<th>Current</th>
<th>Ion source type</th>
<th>New Injector + booster</th>
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<tbody>
<tr>
<td>p</td>
<td>$3 \cdot 10^{10}$</td>
<td>Duoplasmotron</td>
<td>$1 \div 5e10^{12}$</td>
</tr>
<tr>
<td>d</td>
<td>$5 \cdot 10^{10}$</td>
<td>---, ---</td>
<td>$1 \div 5e10^{12}$</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>$8 \cdot 10^8$</td>
<td>---, ---</td>
<td>$0.5 \div 1e10^{12}$</td>
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<tr>
<td>d↑</td>
<td>$2 \cdot 10^8$</td>
<td>SPI</td>
<td>$0.5 \div 1e10^{10}$</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>$8 \cdot 10^8$</td>
<td>Laser</td>
<td>$1 \div 5e10^{11}$</td>
</tr>
<tr>
<td>$^{11,10}\text{B}$</td>
<td>$1 \cdot 10^{9,8}$</td>
<td>---, ---</td>
<td>---</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$1 \cdot 10^9$</td>
<td>---, ---</td>
<td>$1 \div 2e10^{11}$</td>
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<tr>
<td>$^{24}\text{Mg}$</td>
<td>$2 \cdot 10^7$</td>
<td>---, ---</td>
<td>---</td>
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<tr>
<td>$^{14}\text{N}$</td>
<td>$1 \cdot 10^7$</td>
<td>ESIS (&quot;Krion-6T&quot;)</td>
<td>$1 \div 5e10^{10}$</td>
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<tr>
<td>$^{40}\text{Ar}$</td>
<td>$1 \cdot 10^9$</td>
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<tr>
<td>$^{56}\text{Fe}$</td>
<td>$2 \cdot 10^6$</td>
<td>---, ---</td>
<td>$1 \div 5e10^{10}$</td>
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<td>$^{84}\text{Kr}$</td>
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<td>---, ---</td>
<td>$0.5 \div 1e10^9$</td>
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<td>$^{124}\text{Xe}$</td>
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<tr>
<td>$^{197}\text{Au}$</td>
<td>$-$</td>
<td>---, ---</td>
<td>$1e10^9$</td>
</tr>
</tbody>
</table>
Bld. 205: planned structure of research zones

beam polarimeters

Polarization studies area

R&D p,d, A

R&D p,d, A

BM@N area

HyperNIS

Baryonic Matter at Nuclotron (DBM@N)

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

**Collaboration of scientific centers:**
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**

modernized magnet СП-41

area prepared for detector installation
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)

Stage 1: TPC, TOF, ECAL, ZDC, FD
Stage 2: IT + Endcaps (tracker, TOF, ECAL)

Status: technical design and detector R&D – completed;
Preparation for the mass production

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MPD Solenoid

\[ B_0 = 0.66 \, \text{T} \]

weight \( \sim 900 \, \text{t} \)

Packages:

1. Cold Mass + Cryostat + Vacuum System
2. Trim Coils
3. Yoke + Support Struct
4. Control System
5. Cryogenic System
6. PS + Cooling + other system + tests

\( \delta B/B \sim 10^{-4} \)

magnetic field simulation

TPC region

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TPC- technical project approved, fabrication stage

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

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

Cylinder C3 manufactured in Dec. 2013

Cylinder C2, preparation for vacuum tests

\( \varnothing 27 \text{ cm}, \ L = 3.4 \text{ m} \)

R140 cm, L=3.4 m
4 mm thickness
0,1 mm precision

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Time of Flight system (TOF)

Fast Forward Detector (FFD):
production stage

Provides: $T_0$ for TOF, beam adjustment & collision $L_0$-trigger

mRPC – TDR has been prepared, ready for mass production


The achieved time resolution is better than required

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

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

Constant $= 1143 \pm 18.1$

Mean $=-0.001697 \pm 0.000680$

Sigma $= 0.05421 \pm 0.00052$

$\sigma_{PRPC1} = \frac{89}{\sqrt{2}} = 63 \text{ ps}$

$\sigma_{PRPC2}$

required efficiency, rate capability & time resolution are reached

Sigma $= 0.08862 \pm 0.00044$

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ECAL – TDR - in preparation

L ~35 cm (~ 14 $X_0$), Pb+Scint. (4x4 cm$^2$) read-out: WLS fibers + MAPD

**Energy resolution** 2.5% / $\sqrt{E}$
**Time resolution** 80 psec / $\sqrt{E}$

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

Zero Degree Calorimeter (ZDC): TDR stage

ZDC coverage: 2.2<$|\eta|$< 4.8

Pb-scintillator sampling (5\lam)
Read-out: fibers + AvalanchePD

Energy resolution
\[ \sigma(E)/(E) = 55%/\sqrt{E}\text{(GeV)} + 2% + 16%/4\sqrt{E}\text{(GeV)} \]

ZDC provides required resolution
**MPD performance for dileptons**

**Hadron suppression up to $10^{-5}$**

![PID](image)

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

<table>
<thead>
<tr>
<th>Particle</th>
<th>Yields</th>
<th>BR</th>
<th>Effic. %</th>
<th>Yield/1 w</th>
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<tbody>
<tr>
<td>$\rho$</td>
<td>31</td>
<td>4.7 $\times$ 10^{-5}</td>
<td>35</td>
<td>7.3 $\times$ 10^{4}</td>
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<tr>
<td>$\omega$</td>
<td>20</td>
<td>7.1 $\times$ 10^{-5}</td>
<td>35</td>
<td>7.2 $\times$ 10^{4}</td>
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<tr>
<td>$\phi$</td>
<td>2.6</td>
<td>3 $\times$ 10^{-4}</td>
<td>35</td>
<td>1.7 $\times$ 10^{4}</td>
</tr>
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</table>

**3 December 2014**

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Hypernuclei @ MPD

Hypernuclei production enhanced at high baryon densities (NICA)

Hypertritons

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

Entries: 826
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: 537
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%

$\sim 10^6 \ ^3\Lambda H$ are expected for 10 weeks @ 5A GeV

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NICA computing request

**BMN Data Flows, 2017**

- **80 kB/event**
- **10 kHz trigger rate**
- **60% beam on time**
- **20% DAQ standby time**
- **950 MB/s readout rate**
  - (4800 MB/s peak)
- **25 TB RAW data per day**
- **Up to 5 PB RAW data / year**

Together with MPD (2020)

> **> 10 PB RAW data / year**

**Needs:**

- **Comp. CPU** – **5 000 GHz**
- **Cpmp. CPU cores** – **1600**
- **Comp. RAM** – **10 000 GB**
- **Disc storage** – **2 200 TB**
- **Mass storage** – **20 PB/year**

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## NICA plans

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<td>Nuclotron development</td>
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<td>BM@N I stage</td>
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<td>Collider civil engineering</td>
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<td>MPD Hall</td>
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</table>

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

The issues to be studied:

- MMT-DY processes
- $J/\Psi$ 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 forming
Project is under preparation

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International Cooperation on the NICA project

The signed agreements:

**Germany** (BMBF, GSI) — SC magnet and SI tracker assembly workshops;

**China** (ASIPP, Singua & Hefei Un-ts) — HTSC current leads, SC magnets, RPC chambers;

**USA** (FNAL) — stochastic and electron cooling;

**CERN** — parts of BM@N and MPD set-ups;

**RSA** — cryostats, diagnostic of ion sources.

Australia

Azerbaijan

CERN

France

Georgia

Greece

India

Republic of South Africa

UCT (Cape Town)

UJ (Johannesburg)

iThemba Labs

Bulgaria

INRNE BAS (Sofia)

TU-Sofia

SU

ISSP BAS

LTD BAS

SWU

PU (Plovdiv)

TUL (Blagoevgrad)

Italy

Japan

Moldova

Mongolia

Romania

Serbia

Slovak

Republic

USA

3 December 2014

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Meeting at ASIPP in Hefei, China
V.A. Matveev – the JINR Director
and Dr. Beatrix Vierkorn-Rudolph - the BMBF Directorate 71 Director
signed the document

recognizing the NICA complex as the large-scale project on the Russian territory
and appreciating the selection of NICA as one of the “Mega science” projects

Parties agreed to join their efforts in the construction of both FAIR & NICA in:

- construction of cryogenic facility at LHEP JINR to provide the assembly
  & the cold tests of superconducting magnets for the NICA synchrotrons
  & 175 quadrupole modules for FAIR SIS100

- preparation of clean area at LHEP JINR for the assembly and test of silicon tracking detectors for BM@N, MPD & CBM

- stimulation of joint research & educational programs for young scientists

3 December 2014
On August 8, 2013, the representatives of 13 countries met in Dubna to discuss possible participation in the megaproject «Complex NICA».

The representatives of 6 countries—Belarus, Bulgaria, Germany, Kazakhstan, Russia and Ukraine, together with the JINR, signed the Protocol of intention. Recently Egypt has joined this protocol.
The expert group (EG) recommends to take into account the NICA project in the updated Road Map ESFRI.

EG encourages active cooperation of JINR with European partner Institutions

HORIZON - 2020

The fact that NICA/JINR is a part of European research infrastructure has been already recognized by ESFRI.
Concluding remarks

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

- Construction of the accelerator complex and both detectors BM@N & MPD are progressing well.

- The SPD project is in preparation.

- The international collaboration around the NICA is growing.

- China Institutions play an essential role in project development.

New partners are invited to join NICA.
Thank you
谢谢