NICA accelerator complex at LHEP and proposal to study polarization phenomena with its beams (the SPD project)

Roumen Tsenov, for the SPD project team
From the Synchrophasotron to the NICA collider

1957
Synchrophasotron

10 GeV proton synchrotron - then the world leader in energy

Start up of the high energy era

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

1993
Nuclotron

The first superconducting accelerator of heavy ions based on Dubna type SC magnets

A.M. Baldin – pioneer of relativistic nuclear physics

2019
NICA

Superconducting collider of heavy ions

Study of nuclear matter under extreme conditions and spin physics

02 Sept. 2019
DSPIN-19 (JINR, Dubna)
Main targets of the NICA project:
- **study of hot and dense baryonic matter**
- **investigation of nucleon spin structure, polarization phenomena**

### NICA (Nuclotron based Ion Collider fAcility)

is the flagship project in high energy physics of the Joint Institute for Nuclear Research

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring circumference, m</td>
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<tr>
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<td>energy range for $\text{Au}^{79+}$: $\sqrt{S_{\text{NN}}}$, GeV</td>
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<td>r.m.s. $\Delta p/p$, $10^{-3}$</td>
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<tr>
<td>Luminosity for $\text{Au}^{79+}$, cm$^{-2}$ s$^{-1}$</td>
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<td><strong>polarized particles</strong></td>
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<tr>
<td>max. $\sqrt{S}$ for polarized $p$, GeV</td>
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<tr>
<td>Luminosity for $p$, cm$^{-2}$ s$^{-1}$</td>
<td>$1 \times 10^{32}$</td>
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</table>
JINR Nuclotron (45 Tm) injection bunch ~ 2 × 10^9 ions acceleration up to 1 - 4.5 GeV/u

Booster (25 Tm) storage of (2 ÷ 4) × 10^9 ions, acceleration up to 600 MeV/u

Stripping (80%) \( {^{197}}\text{Au}^{31+} \Rightarrow {^{197}}\text{Au}^{79+} \)

Linac LU-20

Linac HILac

KRION

Ion sources

Fixed Target Area

Structure and Operation Regimes

Nuclotron (45 Tm)

Two SC collider rings

~ 2 x 22 injection cycles

22 bunches per ring

IP-2

IP-1

02 Sept. 2019

DSPIN-19 (JINR, Dubna)
The NICA complex

Existing facilities

- PS & LU-20 (5MeV/u)
- Booster (600 MeV/u)
- NUCLOTRON 0.6-4.5 GeV/u
- KRION-6T+ HILac (3MeV/u)

To be constructed

- BM@N
- SPD hall
- Collider
- MPD hall
- SPD
Major milestones

• **2018** – start of **BM@N** experiment (min. configuration)
• **2018 – 2019** – **Booster** commissioning
• **2019** – readiness of **MPD Hall**
• **2019** – **MPD magnet** commissioning
• **2020** – completion of **civil construction** (build. 17)
• **2020** – **MPD** commissioning (**Stage I**)
• **2020 – 2021** – **Collider** commissioning
• **2020** – completion of “**NICA Center**” construction
• **2021** – commissioning of **Computer center**
• **2023** – **MPD** commissioning (**Stage II**)  
  
• **2025** – **SPD** commissioning (**Stage I**)
## Time-schedule

S. Kostromin, PAC June 2019

<table>
<thead>
<tr>
<th>Booster injection system</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
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<td>1</td>
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*ready for equipment mounting

Jan 2022
Nuclear collisions and the QGP expansion

Development in time, \(1 \text{ fm/c} = 3.3 \times 10^{-24} \text{ sec}\)

- \(\tau \sim 0 \text{ fm/c}\)
- \(\tau_0 \sim 1 \text{ fm/c}\)
- \(\tau \sim 10 \text{ fm/c}\)
- \(\tau \sim 10^{15} \text{ fm/c}\)

---

**JINR Development in time,** \(1 \text{ fm/c} = 3.3 \times 10^{-24} \text{ sec}\)

- Collision evolution
- Expansion and cooling
- Particle detectors
- Kinetic freeze-out
- Distributions and correlations of produced particles

---

**QGP phase**
- Quark and gluon degrees of freedom

---

**Lumpy initial energy density**

---

**Collision overlap zone**

---

**Quantum fluctuations**

---

**Development in time, 1 fm/c = 3.3 \times 10^{-24} sec**
QCD phase diagram

The Phases of QCD

Early Universe
Future LHC Experiments

Current RHIC Experiments

Future FAIR Experiments

Critical Point

Crossover

1st order phase transition

Hadron Gas

Vacuum

0 MeV

900 MeV

Baryon Chemical Potential

FAIR & NICA
Quark-Gluon Plasma

Lattice QCD
Perfect fluid

RHIC-BES
Critical point?

deconfinement transition

NICA

Hadrons

Quarks and Gluons

Proto-Neutron stars

Chiral transition

Net baryon density n/ n_o
n_o = 0.16 fm^-3

Color Superconductor

Quarkyonic phase

Compact Stars

Vacuum

0 MeV

n_o = 0.16 fm^-3
Physics at NICA

Quark-gluon 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 $\rho_B$ - enhanced strangeness production
- QCD Critical Point - event-by-event fluctuations & correlations
- Strangeness in nuclear matter - hypernuclei
Present and future HI experiments

Interaction rate [Hz]

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

2022 – 2025: SIS-100 FAIR

NICA/BM@N II

HADES

STAR F.T.

NA-61/SHINE

STAR BES II

energy region of max. baryonic density

02 Sept. 2019 DSPAN-19 (JINR, Dubna)
Collisions of polarized particles

Long tradition at the Synchrophasotron and Nuclotron

Polarization data has often been the graveyard for fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.

*J.D. Bjorken, 1987*
Polarized beams

A bunch crossing each 80 ns; crossing rate 12.5 MHz.

- 503 m, circumference
- 2, number of intersection points (IP)
- 0.35 m, \( \beta_{min} \) in the IP
- \( \approx 1 \times 10^{12} \), number of protons per bunch
- 22, number of bunches
- 0.5 m, RMS bunch length
- 0.027, incoherent tune shift, \( \Delta_{\text{Lasslett}} \)
- 0.067, beam-beam parameter, \( \xi \)
- 0.15, beam emittance \( \varepsilon_{nrm} \), \( \pi \) mm mrad

\( p \uparrow p \uparrow \) at \( \sqrt{s}_{pp} = 12 - 27 \) GeV,
\( L_{av} \approx 10^{32} \) cm\(^{-2}\)s\(^{-1}\)
\( d \uparrow d \uparrow \) at \( \sqrt{s}_{NN} = 4 - 13 \) GeV

longitudinal and transverse polarization at SPD and MPD
Physics tasks

► Nucleon spin structure studies

► Spin-dependent effects in elastic pp, pd and dd scattering;

► Spin effects in exclusive hadron production;

► Spin effects in production of hadrons with high $p_T$ in interaction of vector and tensor (d) polarized beams;

► Multiquark states and correlations
Spin dependent PDFs

Transversity Momentum Distributions: TMD \((x,k_T)\) probe the transverse parton momentum dependence

Generalized Parton Distributions: GPD \((x,b_T)\): probe the transverse parton distance dependence

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_{(q+g)}
\]
# Nucleon structure and PDFs

<table>
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<th>Quark</th>
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<th>L</th>
<th>T</th>
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<tr>
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<td>helicity</td>
<td>Sivers</td>
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<td>U</td>
<td></td>
<td>Boer-Mulders</td>
<td>Kohtzinian-Mulders worm-gear T</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>worm-gear L</td>
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</tr>
<tr>
<td>T</td>
<td></td>
<td>transversity</td>
<td>pretzelosity</td>
</tr>
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</table>

**PDFs describe different properties:**

3 PDFs are needed to describe nucleon structure in collinear approximation.

8 PDFs are needed if we want to take into account intrinsic transverse momentum $k_T$ of quarks.

\[ f_1 \] -- density of partons in non-polarized nucleon;

\[ g_1 \] -- helicity, longitudinal polarization of quarks in longitudinally polarized nucleon;

\[ h_L \] -- Boer-Mulders, transversely polarized quarks in non-polarized nucleon;

\[ f_{1T} \] -- Sivers, correlation between the transverse polarization of the nucleon (transverse spin) and the transverse momentum of non-polarized quarks; etc…
Physical probes

- Inclusive and exclusive Drell-Yan pair production;

- Direct photons;

- Nucleon PDFs by $J/\psi$ production;

LO $c\bar{c}$ production diagram:
A quark-antiquark pair creates a lepton ($e/\mu$) pair through a virtual photon.

\[ \propto PDF_{nucl1} \otimes PDF_{nucl2} \]

We can use this “virtual photon microscope” to look into nucleons and obtain access to PDFs.
Asymmetries in DY pair production

\( Q^2 = 4 \text{ GeV}^2 \)

\( Q^2 = 15 \text{ GeV}^2 \)

\( s = 400 \text{ GeV}^2 \)

\[ A_{UT} \frac{q_T}{M_N} = \sin(\phi - \phi_s) \]

\[ A_{UT} \frac{q_T}{M_N} = \sin(\phi + \phi_s) \]

Sivers

Boer-Mulders

J.C. Collins et al., PRD73 (2006)014021
**Kinematical ranges and statistics**

**COMPASS-2015 data**

- $4.3 \text{ GeV/c}^2 < M_{\mu\mu} < 8.5 \text{ GeV/c}^2$
- $q_T > 0.4 \text{ GeV/c}$
- $\langle f \rangle \approx 0.18$
- $\langle P_{\text{Target}} \rangle \approx 0.73$
- $t \approx 1.08864 \times 10^7 \text{s (18 weeks, 126 days)}$

$N_{DY} = 35 \times 10^3$

**SPD**

- $4.0 \text{ GeV/c}^2 < M_{\mu\mu} < 9.0 \text{ GeV/c}^2$
- $\langle P_{\text{beam 1,2}} \rangle \approx 0.6$
- $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- $t = 10^7 \text{s (16.5 weeks)}$
- $\sigma_{DY[4-9]} = 0.074 \text{ nb}$

\[ N_{DY} = \sigma_{DY} \times L \times t \]

$N_{DY} = 88.8 \times 10^3$

\[ dA = \frac{1}{P_{b1}P_{b2}} \times \frac{1}{\sqrt{N}} \]
COMPASS 2015 NH$_3$ data
$4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

SPD

$02\text{ Sept. 2019}$

DSPIN-19 (JINR, Dubna)
Unpolarised Drell-Yan

\[
\frac{d\sigma}{d\Omega} \propto (F_U^1 + F_U^2) \times \left[ 1 + A_U^1 \cos^2 \theta_{CS} + \sin 2\theta_{CS} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2 \varphi_{CS}} \cos 2\varphi_{CS} \right]
\]

\[
\lambda = A_U^1, \mu = A_U^{\cos \varphi_{CS}}, \nu = 2A_U^{\cos 2 \varphi_{CS}}
\]

- "Naïve" Drell-Yan model
  Collinear \((k_T = 0)\) LO pQCD no rad. processes
  \(\lambda = 1, \mu = \nu = 0\)

- Intrinsic transverse motion + QCD effects
  \(\lambda \neq 1, \mu \neq 0, \nu \neq 0\), but \(1 - \lambda = 2\nu\) (Lam-Tung)

- Experimentally observed large \(\nu\) and violation of the LT-relation
  \(\lambda \neq 1, \mu \neq 0, \nu \neq 0\)

Boer-Mulder

\[
A_U^{\cos 2 \varphi_{CS}} \propto h_{1,\pi}^{\perp} \otimes h_{1,p}^{\perp}
\]
NA10 vs SPD

\[ \langle P_{\text{beam } 1,2} \rangle \approx 0.6 \]

In 6 bins

\[ \text{SPD } dA \approx 0.02 \]

\[ \text{with } \langle P_{\text{beam } 1,2} \rangle = 1.0 \text{ SPD } dA \approx 0.008 \]
Prompt (direct) photon production

Gluon Compton scattering
Quark-antiquark annihilation

The gluon Compton scattering mechanism dominates...

\[ qg \rightarrow q\gamma \quad 85\% \]
\[ qqbar \rightarrow g\gamma \quad 15\% \]

...so we can obtain access to the contribution of gluon to spin of the nucleon.

02 Sept. 2019 DSPIN-19 (JINR, Dubna)
The gluon Compton scattering gives access to the gluon content of proton:

Transverse beam polarization: access to the Sivers function for gluons

\[ \sigma^\uparrow - \sigma^\downarrow = \sum_i \int_{x_{\text{min}}}^{1} dx_a \int d^2k_{Ta} d^2k_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s}) e y} [q_i(x_a, k_{Ta})\Delta_N G(x_b, k_{Tb}) \times \frac{d\hat{\sigma}}{dt}(q_i G \rightarrow q_i \gamma) + G(x_a, k_{Ta})\Delta_N q_i(x_b, k_{Tb}) \frac{d\hat{\sigma}}{dt}(G q_i \rightarrow q_i \gamma)] \]

Longitudinal beam polarization: access to gluon polarization \( \Delta g/g \)

\[ A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \cdot \left[ \sum_q e_q^2 \left[ \Delta q(x_2) + \Delta \bar{q}(x_2) \right] \right] + (1 \leftrightarrow 2) \]
Expected asymmetries in prompt photon production


Charmonium ($J/\psi$) production

Applicability of the method is limited due the lack of understanding $J/\psi$ production mechanism.

Proton-proton collisions at SPD provide ideal opportunity for verification of theoretical approaches to $J/\psi$ production.

Studying of $J/\Psi$ production gives us access to the gluon PDFs.

Quark annihilation

NRQCD

Gluon fusion
Asymmetries in high $p_T$ hadron production

- Diquark properties;
- Confinement laws;
- Nature of the huge spin effects;
- Deuteron spin structure;
- Properties of the bare $N\Lambda$- and $NK$-interactions;
- Nature and properties of the cold super dense baryonic matter (CsDBM) ($pA$ and $AA$);
- Dilepton production puzzle in $np$-interaction.
Cross section is integrated over $s_1$ and $s_2$ was calculated at NICA energies
Preliminary result for cross section of $pp \rightarrow pp l^+ l^-$ process at NICA energies

Preliminary results for cross section of exclusive Drell-Yan process over $t_1$ and $t_2$ at NICA energies. $\frac{d\sigma}{dQ^2 dt_1 dt_2}$ -in pb/GeV$^6$. Estimations show that such contribution might be visible.

Both final protons should be detected

Integrated over $t_1$ and $t_2$ cross section $d\sigma/dQ^2 \sim 5.5$ pb/GeV$^2$ at $Q^2 = 5$GeV$^2$ (NICA energies)
GPD through vector meson exclusive production

\[ p + p \rightarrow p + p + VM \]

\[ q' = q - \Delta \]

\[ k = \bar{k} - \frac{\Delta}{2} \]

\[ k' = \bar{k} + \frac{\Delta}{2} \]

\[ p = \bar{p} - \frac{\Delta}{2} \]

\[ p' = \bar{p} + \frac{\Delta}{2} \]

Vector meson production via photoproduction mechanism or odderon exchange.
Unravelling the spin puzzle

- TMDs
- GPDs

Direct photons ($\Delta G$)
- Inclusive $\pi, \rho, \omega$
- Exclusive $J/\psi$

Inclusive DY
- Inclusive $J/\psi$

Exclusive DY
- Exclusive $\pi^0, \rho, \omega$

$\text{DY, } J/\psi$ with tensor polarized deuteron beam

Twist 2 and 3 collinear parton distributions and correlators
Minimum biased events

PYTHIA 6, $\sqrt{s_{\text{pp}}} = 26$ GeV; 4 MHz event rate
- Average charged particle multiplicity $\approx 7.8$
- Average neutral particle multiplicity $\approx 6.5$

from A. Guskov

02 Sept. 2019

DSPIN-19 (JINR, Dubna)
Requirements for the SPD

- close to $4\pi$ geometrical acceptance;
- high-precision ($\sim 50 \, \mu m$) and fast vertex detector;
- high-precision ($\sim 100 \, \mu m$) and fast tracker;
- good particle ID capabilities;
- efficient muon range system,
- good electromagnetic calorimeter,
- low material budget over the track paths,
- trigger and DAQ system able to cope with event rates at luminosity of $10^{32} \, (cm.s)^{-1}$,
- modularity and easy access to the detector elements, that makes possible further reconfiguration and upgrade of the facility.
• Length: 9.2 m;
• Diameter: 6.8 m;
• Mass: 1800 t;
• Consists of three modules;
• Easy way to rearrange.
Dimensions
$\frac{1}{2}$ model symmetry

$B^{(c)}(x, y, 0) = 0.$

$J_T = 40 \frac{A}{mm^2},$

$J_{T,1,2}^{(1,2)} = n80 \frac{A}{mm^2},$

$S = 200 \times 20 mm^2,$

$I_T = J_T \cdot S = 160 kA,$

$I_{T,1,2}^{(1,2)} = J_{T,1,2}^{(1,2)} \cdot S = n80 kA.$

Hybrid magnetic system

- Backward coils
- Forward coils
- Toroid coils

1. NbTi/Cu 33/33/33%
2. stainless steel tube
3. insulation epoxy layer, 0.3 mm
4. copper shield
5. multilayer thermal shield
6. outer cover, 1mm stainless steel

$B_{max} = 1.0 T$

$\Omega = \{(r, \varphi, z) : 0 \leq r \leq 3500, \varphi = 0, 0 \leq z \leq 3500\}$

$B_{min} = 0 T$

$Z = 1600 mm$

$Z = 2800 mm$

Integral = 636.455
Integral = 469.525
Integral = 384.218
Integral = 341.424
Integral = 298.62
Vertex detector (Inner tracker)

- Silicon vertex detector around the beam pipe;
- Several layers of double sided silicon strips and MAPS;
- Optimized number of layers w.r.t. material budget;
- Goal: few tens of µm resolution for the vertex reconstruction.

Charged particle creates electron/hole pairs, which migrates to electrodes creating signal in the nearest strips.
- Six particles from the vertex
- Vertex detector with 5 layers
- Silicon resolution: 50 mkm (blue) and 25 mkm (red)
Central tracker

- Minimum material on the particle tracks ($X_0 \sim 0.1$);
- Time (~100 ns) and spatial resolution (~100 $\mu$m);
- Expected particle rates (DAQ rates) ~ MHz;
- Technology developed also in JINR, production workshops available.
Momentum resolution

**Hybrid magnetic system**

**Vertex Det.**: 5 silicon layers of 300 μm thickness each;

**Barrel TS**: 8 straw-tube layers, two planes of 1 cm thickness in each.

**Pseudo-solenoidal or 3→3**
Electromagnetic calorimeter

- Photon energy range 0.1 - 10 GeV;
- Due to space limitations the total length of the ECAL module should be less than 50 cm;
- Required energy resolution <10.0%/√E (GeV) and energy threshold below 100 MeV;
- Design ("shashlik") similar of that for KOPIO ECAL

About 6500 modules

Shashlik
It should provide good (>95%) muon identification for momenta above 1 GeV.

Combination of responses from the ECal and RS could give additional lever for rejecting of pions and protons in a wide energy range.

The RS also provides additional coordinate measurement.

Our design will follow closely the design of the PANDA experiment range system (at FAIR, GSI) being developed now at the DLNP of JINR.
The SPD DAQ may be developed *a la* upgraded DAQ of the COMPASS experiment;

- Event rate 3.0 MHz (at $L=10^{32} \text{ cm}^{-2}\text{s}^{-1}$, $\sqrt{s}=27 \text{ GeV}$);

- Rough preliminary estimation of the total data flux from the detectors (Si tracker + straw tracker + PID + ECal + Range system): 10-20 GBytes/s (no detailed simulation results available yet);

- Triggered or trigger-less DAQ: to be decided.
Software and computing
SPD advantages:
- measurements with pp, pd and dd beams,
- possibility to perform energy scan with small steps,
- measurements via muon and electron-positron pairs,
- operations with non-polarized, transverse and longitudinally polarized beams and their combinations,
- possibility to extract all first order PDFs in one experiment.

<table>
<thead>
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<th>HOME INSTITUTE, EXPERIMENT</th>
<th>RHIC, STAR</th>
<th>RHIC, fsPHENIX</th>
<th>NICA, SPD</th>
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<td>pp, pA, pHe³, dHe³</td>
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<td>(0.8-6)×10³²</td>
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<td>yes</td>
</tr>
<tr>
<td>Worm-Gear</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Flavour separation</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Exclusive DY</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Deuteron quadrupole structure</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>
Collaborating institutions – 25 so far

- National Science Laboratory, Armenia
- Institute of Applied Physics of the Belarus Academy of Sciences;
  - Gomel State Technical University, Belarus;
  - Institute for Nuclear Problems of BSU – Minsk;
- Chilean cluster of universities, Chile
- Tsinghua University, Tsinghua, China
- Instituto Superior de Tecnologías y Ciencias Aplicadas (INsTEC), Havana University;
- Charles University, Prague;
- Technical University, Prague
- INFN section of Turin and University of Turin;
- CEA, Saclay, France;
- Warsaw University of Technology;
- Tomsk State University;
  - Tomsk Polytechnic University;
- Lebedev Physics Institute of the RAS, Moscow;
  - Institute for High Energy Physics, Protvino;
- Institute of Nuclear Physics of the Moscow State University;
  - Institute for Nuclear Research of the RAS, Troitsk;
  - Institute for Theoretical and Experimental Physics, Moscow;
- St. Petersburg Nuclear Physics Institute, Gatchina;
- St. Petersburg State University;
- St. Petersburg Polytechnic University;
- Samara National Research University;
- Belgorod National Research University;
- Kharkov National University, Kiev, Ukraine

Protocols for joint research within the SPD project signed.

- EoI letters received

Bilateral agreements on NICA exist.
Start of the SPD project

- **Letter of Intent** presented at the JINR PAC in summer 2014, where:
  - the physics program of the experiment was developed;
  - requirements to NICA polarized beams were formulated;
  - desired detector characteristics and sketch of the facility were given;
- A few presentation at international conferences about the physics potential and program of the SPD were given;
- Several workshops on spin physics at NICA were organized:
  - NICA-SPIN-2013, Дубна, 17-19.03.2013
  - SPIN-Praha-2013, 7-13.07.2013
  - SPIN-Praha-2015, 26-31.07.2015
  - DSPIN2013, DSPIN2015, DSPIN2017

**arXiv: 1408.3959**

Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beams.

Compiled by the Drafting Committee:

(Letter of Intent presented at the meeting of the JINR Program Advisory Committee (PAC) for Particle Physics on 25–26 June 2014.)

In 2017 a new stage of the project started: *From Lol to CDR (Conceptual Design Report)*
Roadmap

- JINR project for the SPD design (Jan. 2019);
  *Conceptual and technical design of the Spin Physics Detector (SPD) at the NICA collider*
- Setting up of the collaboration, MoU (2020);
- Preparation of the Conceptual Design Report (2019);

*Construction of the detector would take at least three years (2022-2025) and first measurements could be expected as early as close to the end of 2025...*
SPD/NICA will provide a unique opportunity not available at other facilities to study all of the PDFs in one experiment and obtain comprehensive information on the nucleon spin structure at high statistical level with minimal systematic uncertainties.

You are welcome to join the SPD/NICA project!
Web site: spd.jinr.ru.
Contact person: Roumen Tsenov (tsenov@jinr.ru)
baryonic density $\rho / \rho_0$

$\rho_0 = 0.16 \text{fm}^{-3}$
Spin and magnetic moment

\[ \vec{\mu} \]

\[ \vec{\mu}_S = g \frac{q}{2m} \vec{S} = \gamma \vec{S} \]

nuclear magneton:

\[ \mu_N = \frac{e\hbar}{2m_p} \]

\[ \begin{align*} 
\mu_p &= 2.79\mu_N \\
\mu_n &= -1.91\mu_N \\
\mu_d &= 0.86\mu_N 
\end{align*} \]

for the electron:

\[ \vec{\mu}_S = -\frac{g\mu_B\vec{\sigma}}{2} \]

\[ \mu_B = \frac{e\hbar}{2m_e} \]
Before 1988

\[
\frac{1}{2} = \frac{1}{2} \Delta \sum \text{quarks}
\]

The quark model says: the nucleon spin is carried only by quarks.

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Magnetic moment of quark model</th>
<th>Computed ($\mu_N$)</th>
<th>Observed ($\mu_N$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$4/3 \mu_u - 1/3 \mu_d$</td>
<td>2.79</td>
<td>2.793</td>
</tr>
<tr>
<td>$n$</td>
<td>$4/3 \mu_d - 1/3 \mu_u$</td>
<td>-1.86</td>
<td>-1.913</td>
</tr>
</tbody>
</table>
**Experiment:** (EMC, Nucl. Phys. B 328 (1989) 1)

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma \text{ quarks}
\]

**PROBLEM:** According to the experimental data, only 30% of the nucleon spin is carried by quarks. Where does the rest of the spin come from?
Spin puzzle: small contribution of quarks (may be fractional because of density matrix rather than wave function description) to the proton spin

The deficit may be due to:
1. Gluon average spin $\Delta G$, and
2. Orbital motion $L$ related to transverse (completing 3D) structure of proton

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g
\]

All ingredients can be explored at SPD!

Main instrument: transverse spin asymmetries

The simplest transverse asymmetry: left-right; more involved: azimuthal modulations
Prompt photon asymmetries: accuracy

Statistics: $3 \times 10^7$ prompt photons with $p_T>4$ GeV/c for one year of data taking ($10^7$ s). It could keep statistical uncertainty of $A_N$ and $A_{LL}$ asymmetries measurement below 0.001 level.

Main contribution to systematics comes from MC-dependent subtraction of background from decay photons, charged particles etc. The expected total error does not exceed $(1-2) \times 10^{-2}$.

Similar accuracy is expected for $A_{LL}$ while the expected asymmetry is between $\pm 0.05$

SPD data for $A_N$ and $A_{LL}$ at $\sqrt{s} \sim 20$ GeV will be complementary to the expected results from RHIC ($\sqrt{s} \sim 200$ GeV) and corresponds to the region of typically larger values of $\Delta G/G$. 
Problems for NICA

- SPD LoI: TMDs@DY
- TMDs – $J/\psi$, $\gamma$
- GPDs: Exclusive DY-type (smaller x-section but lower background)
- GPDs from TMDs (pressure?!)
- Fracture – SSAs with extra hadrons
- Relation of HIC/hadronic spin (MPD/SPD) – polarization for hadrons, light and heavy ions
<table>
<thead>
<tr>
<th>Experiment</th>
<th>CERN, COMP.-II</th>
<th>FAIR, PANDA</th>
<th>FNAL, E-906</th>
<th>SPAS-CHARM</th>
<th>RHIC, STAR</th>
<th>RHIC, PHENIX</th>
<th>NICA, SPD</th>
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</thead>
<tbody>
<tr>
<td><strong>mode</strong></td>
<td>FixTar</td>
<td>FixTar</td>
<td>FixTar</td>
<td>FixTar</td>
<td>collider</td>
<td>collider</td>
<td>collider</td>
</tr>
<tr>
<td><strong>Beam/target</strong></td>
<td>π-, p</td>
<td>anti-p, p</td>
<td>π-, p</td>
<td>π±, pol.p</td>
<td>pp</td>
<td>pp</td>
<td>pp, pd, dd</td>
</tr>
<tr>
<td><strong>Polarization:b/t</strong></td>
<td>0; 0.8</td>
<td>0; 0</td>
<td>0; 0</td>
<td>0; 0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>2·10^{33}</td>
<td>2·10^{22}</td>
<td>3.5·10^{35}</td>
<td>5·10^{22}</td>
<td>5·10^{32}</td>
<td>10^{32}</td>
<td></td>
</tr>
<tr>
<td>√s, GeV</td>
<td>19</td>
<td>6</td>
<td>16</td>
<td>8</td>
<td>200, 500</td>
<td>200, 500</td>
<td>10-26</td>
</tr>
<tr>
<td><strong>x_1(beam) range</strong></td>
<td>0.1-0.9</td>
<td>0.1-0.6</td>
<td>0.1-0.9</td>
<td>0.1-0.3</td>
<td>0.03-1.0</td>
<td>0.03-1.0</td>
<td>0.1-0.8</td>
</tr>
<tr>
<td><strong>q_T, GeV</strong></td>
<td>0.5 -4.0</td>
<td>0.5 -1.5</td>
<td>0.5 -3.0</td>
<td>1.0 -10.0</td>
<td>1.0 -10.0</td>
<td>0.5 -6.0</td>
<td></td>
</tr>
<tr>
<td><strong>Lepton pairs,</strong></td>
<td>μ-μ+</td>
<td>μ-μ+</td>
<td>μ-μ+</td>
<td>μ-μ+</td>
<td>μ-μ+</td>
<td>μ-μ+</td>
<td>μ-μ+, e+e-</td>
</tr>
<tr>
<td><strong>Data taking</strong></td>
<td>2014</td>
<td>&gt;2018</td>
<td>2013</td>
<td>&gt;2016</td>
<td>&gt;2016</td>
<td>&gt;2016</td>
<td>&gt;2018</td>
</tr>
<tr>
<td><strong>Transversity</strong></td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Boer-Mulders</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Sivers</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Pretzelosity</strong></td>
<td>YES (?)</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Worm Gear</strong></td>
<td>YES (?)</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>J/Ψ</strong></td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Flavour separ.</strong></td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
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<td><strong>Direct γ</strong></td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
Reconfigurable design
JINR participation:
112 authors, 37.7 FTE

- Laboratory of High-Energy Physics
  - authors: 74
  - FTE: 24.4

- Laboratory of Nuclear Problems
  - authors: 30
  - FTE: 11.3

- Laboratory of Theoretical Physics
  - authors: 6
  - FTE: 2

- Directorate (1), Laboratory of Information Technologies (1)
COMPASS data, pion beam

Figure 4: COMPASS data on Drell–Yan pair production spin asymmetries related to Sivers, transversity and pretzelosity TMD PDFs (top to bottom).
Systems that have not been thought out yet...

- **System for particle ID** (multigap glass RPCs, Micromegas, Aerogel Cherenkov?);

- "Zero degree" system (fine grained hadron calorimeter?)

- Front-end electronics of the different subsystems;
Beam test facility

<table>
<thead>
<tr>
<th>P, MeV/c</th>
<th>d</th>
<th>p,n</th>
<th>π±</th>
<th>K⁺</th>
<th>K⁻</th>
<th>μ±</th>
<th>e±</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>$10^3$</td>
<td>$10^5$</td>
<td>$10^5$</td>
<td>$10^3$</td>
<td>$10^2$</td>
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<tr>
<td>800</td>
<td>$10^3$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^3$</td>
<td>$10^2$</td>
<td>$10^3$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>1500</td>
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<td>$10^2$</td>
<td>$10^2$</td>
<td>$10^2$</td>
</tr>
</tbody>
</table>