MiniSPD stand for testing Si-detectors

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SPD (Spin Physics Detector) collaboration proposes to install a universal setup in the second interaction point of the NICA collider under construction (JINR, Dubna) to study the spin structure of the proton and deuteron. It plans to carry out research of spin-related phenomena with polarized proton and deuteron beams at a collision energy up to 27 GeV and a luminosity up to 10^{32} cm^{-2} s^{-1}.

MiniSPD stand is manufactured as a setup for testing SPD detector prototypes with cosmic muons at LHEP. It allows to carry out checkout of the Data Acquisition System (DAQ), the Detector Control System (DCS). Young physicists and students working at this test bench gain experience of work with real detectors of the future SPD setup.

In this report, we give some information about the basic tasks of SPD projects. The results of simulation and comparison with data on cosmic rays at this stand for three modules of silicon plates are also presented.

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I. INTRODUCTION

The Spin Physics Detector (SPD) is a universal facility for studying the nucleon spin structure and other spin-related phenomena with polarized proton and deuteron beams. It will be located in one of the two interaction points of the NICA (Nuclotron-based Ion Collider fAcility) collider that is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia [1].

At the heart of our project there is exceeding experience with polarized beams at JINR and Russian institutes. The central purpose of the proposed experiment is the comprehensive study of the unpolarized and polarized gluon content of the nucleon [2]. Spin measurements at the SPD-detector have attractive perspectives to make a unique contribution and challenge our understanding of the spin structure of the nucleon. One of the main unsolved problems of QCD is study of fundamental properties and structure of nucleon directly from the dynamics of its quarks and gluons based on the first principles.

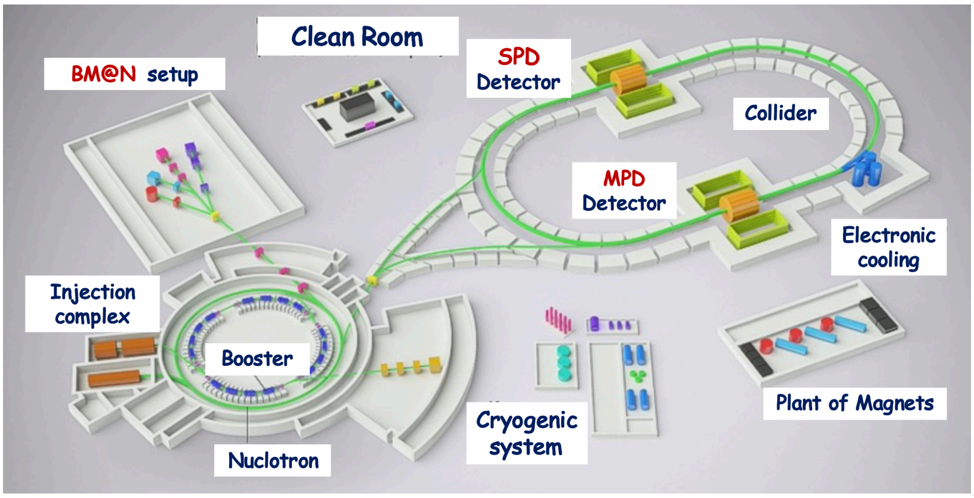

Figure 1: main accelerators and experimental facilities of the NICA complex.

Configuration of NICA aggregate is shown in Figure 1. It consists of the injection complex, the new superconducting Booster synchrotron (that is located inside the yoke of decommissioned Synchrophasotron), the existing superconducting heavy ion synchrotron Nuclotron (being developed presently to match the project specifications (see Figure 2, left). The NICA aerial view (April 2022) is shown in Figure 2, right. The collider will have two new superconducting storage rings and the new beam transfer channels.

Along the SPD setup, the NICA experimental complex includes the MPD (MultiPurpose Detector) and BM@N (Baryonic Matter at Nuclotron) setups. The MPD will study formation of dense baryonic matter at colliding of heavy ion beams; BM@N setup is already carrying out physical researches in the field of dense baryonic matter with Nuclotron extracted beams.

The international mega-science project “NICA complex” is aimed at the study of nuclear matter in the region of its maximum baryonic density at the MPD setup. Such a state of matter existed only at the early stages of evolution for our Universe. Lattice

QCD calculations and experimental data on hadron production at CERN predict that the MPD (Multi-Purpose Detector) setup allows to carry out the search for critical point and onset of deconfinement.

Figure 2: (Left) Nuclotron (Left). (Right) NICA aerial view, April 2022.

On 28 December last year, the first superconducting magnet was installed in the tunnel of the NICA accelerator complex (see Figure 3). Moreover, a testing system of the MPD solenoid was launched. The magnet factory produces superconducting magnets not only for the NICA project but also for the German project FAIR.

Figure 3: installation of the first superconducting magnet in the tunnel of the NICA accelerator complex by Director of JINR G. Trubnikov and Vice-Director of JINR V. Kekelidze.

II. THE MAIN TASKS OF SPD PROJECT

Spin is one of the fundamental properties of elementary particles. Spin of a nucleon cannot be explained by a static view, where it is the simple sum of constitients: quarks and gluons with their orbital angular momenta:

total spin = spin(quark) + spin(gluon) + angular momentum (quark+gluon) = 1/2.

This value is not just the number 1/2. It is the result of interaction between quarks and gluons, more probably between gluons.

The origin of spin is a fundamental problem of physics. Our SPD project is aimed at study the spin properties of nucleons and light nuclei. We plan to pay considerable attention to the study of the gluon component of the nucleon. The progress achieved during the last decades in the understanding the gluon sector is much less developed than for the quark one. Basic difficulties are the lack of direct probes to access gluon content in high-energy processes.

In recent years, the three-dimensional partonic structure of the nucleon became a subject of careful study. Precise mapping of it is crucial for our understanding of Quantum Chromodynamics (QCD).

The main questions that arise in the study of the gluon structure are as follows: [1, 2, 4]:

- How are quarks and gluons, their spins distributed in space and on momentum inside the nucleon?
- What is the role of gluons in mass creation?
- How do the nucleon properties emerge from gluons and their interactions?
- How do the confined hadronic states emerge from quarks and gluons?

The polarized gluon content of proton and deuteron at intermediate and high values of the Bjorken x will be investigated using three complementary gluon probes: inclusive production of charmonia (Figure 4, (a)), open charm (Figure 4, (b)), and prompt photons (Figure 4, (c)) [2, 3]. The study of these processes is complementary to such proven approaches to access the partonic structure of the nucleon in hadronic collisions as the inclusive production of hadrons with high transverse momentum.

From the theoretical point of view, the task of accessing gluon distributions using heavy quarkonia is rather challenging. The heavy quark-antiquark pair couples directly to gluons from initial-state hadrons and charmonia production can be calculated perturbatively. However, this transition is not well understood at present and can become a source of significant theoretical uncertainties. Therefore, this probe can be used to study the structure of hadrons only with great caution.

Production of the open charm particles is the next direct probe of the gluon distributions in hadrons. The basic mechanism responsible for charm pair production in pp collisions is the gluon fusion (see Figure 4, (b)). The cross-sections for charmonia production are almost two orders of magnitude smaller than the corresponding ones for open charm. Our SPD setup will be able to register the open charm particles as $D\overline{D}$ and D^+D^- pairs, $D^\star$ meson, Λ_c hyperon.

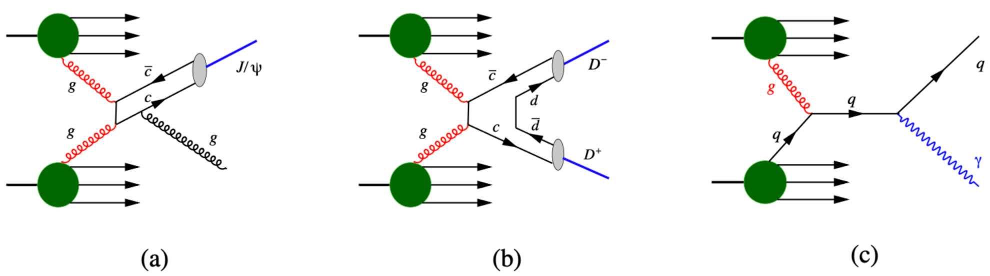

Figure 4: diagrams illustrating three probes to access the gluon content of proton and deuteron in polarized collisions at NICA SPD: production of (a) charmonium, (b) open charm particles, and (c) prompt photons.

Photons emerging from the hard parton scattering subprocess, the so-called prompt photons, serve as a sensitive tool to access the gluon structure of hadrons. Inclusive direct photon production proceeds without fragmentation, i.e. it carries the information directly from the hard scattering processes: $q+g \to q+\gamma$ and/or $q+\overline{q} \to g+\gamma$. The contribution of the latter process to the total cross-section is small.

Promt photons with energy smaller than 50 MeV (so-called soft photons) demonstrate experimentally excited yield in hadronic and ionic interactions at high energy [5]. Our SPD Collaboration manufactures an electromagnetic calorimeter to study soft photon yield.

The more detailed physical programme of the SPD project is presented in [2].

III. MINISPD SETUP

The general layout of the SPD setup is shown in Figure 5. The SPD Collaboration is doing a huge volume of work. Its groups create the necessary software for particle ID, testing future detector prototypes, develop theoretical models, and solving a lot of other tasks.

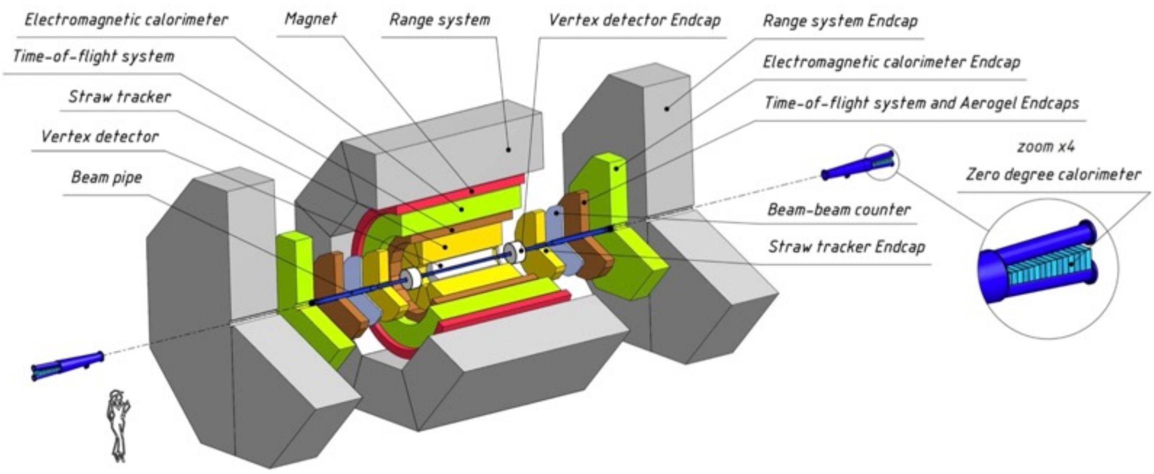

Figure 5: general location of elements for the SPD setup.

One of the most important directions of our activities was the manufactoring of the test bench, MiniSPD stand. This test bench registers cosmic muons and allows to check the prototype work of the basic elements of SPD setup. It includes in miniature the following detectors (see Figure 6, the left and right pictures): the trigger subsystem (scintillators), two-sided silicon plates, Gem detectors, drift (straw) tube stations and modules of "shashlik" type.

Using the MiniSPD stand is extremely valuable, since:

- MiniSPD is a setup for testing SPD detector prototypes with cosmic muons;
- MiniSPD is used to test the Data Acquisition System (DAQ) of SPD detector;
- MiniSPD is used to test the Detector Control System (DCS) of SPD setup;
- MiniSPD is used to teach students how to work with real detectors.

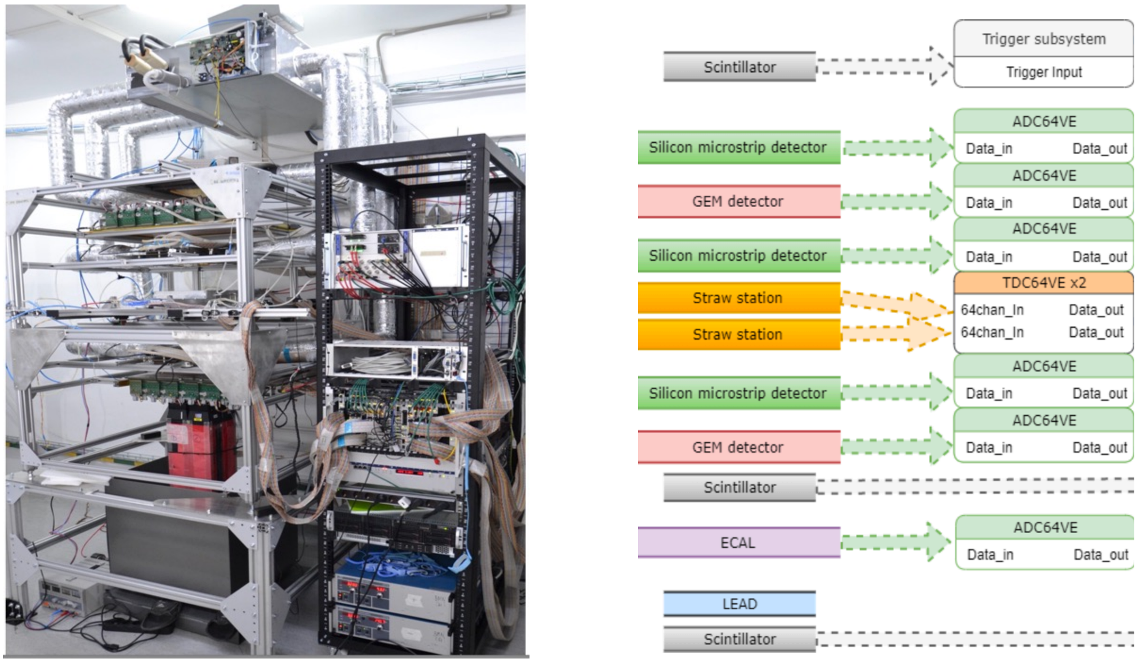

Figure 6: test bench MiniSPD and its functional structure.

By now, our group carried out the study of Si-detector work. It includes the Monte Carlo simulation and comparison of these results to cosmic ray data. In Figure 7, three silicon modules are arranged horizontally, although in reality they are located vertically, one after the other. The first (top) module consists of parts 1 and 2. The third (bottom) module looks like the first one (parts 7 and 8). The second module consists of four parts. We enumerate them 3, 4, 5 and 6.

In Figure 7 dark side corresponds to oblique strips (U-coordinate, $\pm 2.5°$), and the light side corresponds to vertical (X-coordinate) strips. For convenience, we denote the sides of the corresponding part k (k=1, 2, ..., 8) as Xk or Uk. The numbering of strips is chosen from left to right or vice versa. The thickness of a silicon plate is 300 μm, a strip width is 95 μm for X-side (103 μm for U), and the number of strips on each part is equal to 640.

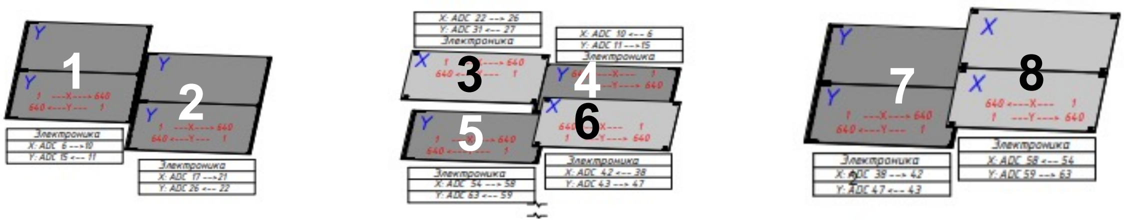

Figure 7: shcheme of the silicon plates at the MiniSPD stand.

Coordinates for all eight parts of the three silicon modules are given in Table I. They define the location of first strip on every side.

Table I: Locations of silicon detectors

Coordinate plates	X, mm	Y, mm	Z, mm	Size, mm^2
X1, U1	-28.55	0	35.0	63 $\times$ 126
X2, U2	31.55	0	50.3	63 $\times$ 126
X3, U3	-32,55	-27.55	387.8	63 $\times$ 63
X4, U4	27.55	-32.55	395.1	63 $\times$ 63
X5, U5	-27.55	32.55	395.1	63 $\times$ 63
X6, U6	32.55	27.55	387.8	63 $\times$ 63
X7, U7	-28.55	0	893.5	63 $\times$ 126
X8, U8	31.55	0	886.2	63 $\times$ 126

In this report, we present the basic results of Monte Carlo simulation of all silicon modules of MiniSPD and its comparison with data obtained at this stand. We carry out a simulation by GEANT4. It takes into account the operation of our trigger subsystem (the top and bottom scintillator wafers). We also carried out a simulation without its operation. This modelling includes the detailed description of strips presented in Strip-Stepping.C file. It executes the following commands in sequence:

- for the X-plane, by the number of a triggered strip, its X-coordinate is determined. Then the U-coordinate of the corresponding strip on the opposite side is found. It allows us to restore its number and get energy deposition in it;
- sorting numbers of triggered strips in ascending order for their subsequent merging without repetition (separately for X and U coordinates);
- accounting for the border crossing of the triggered strip at the making of a stepping.

We simulate cosmic muons with the average energy of 170 MeV, the polar angle Θ distrubuted according to the cosine law and with the uniform distribution for the azimuth angle ϕ. Locations of their initial points are evenly distributed on the circle of 10 cm radius. These distributions are given in Figure 8 for $-20° < \Theta < 20°$, initial points and $0 < \phi < 360°$ (from left to right).

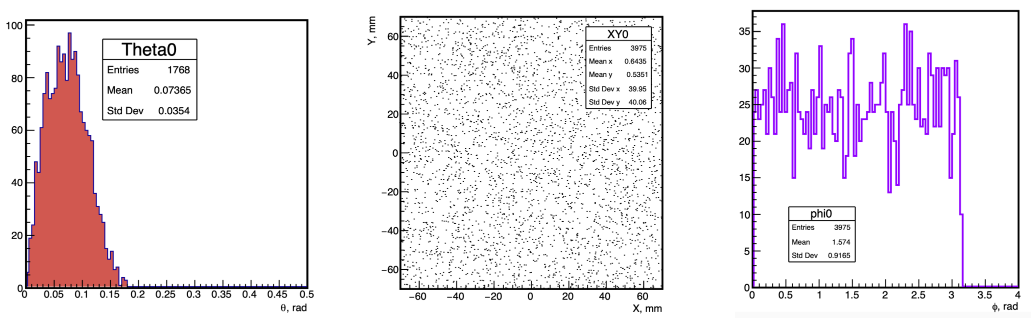

Figure 8: distributions of Θ (left), intial locations of muons (in the middle) and ϕ (left).

The common view of the MiniSPD scheme irradiative by positive muons taken from GEANT4 window is shown in Figure 9. Events were selected when the trigger subsystem of the upper and lower scintillators fired. At that, one, two or three Si-modules can trigger. Our simulation shows the scintillator response efficiency is close to 99 %. Distributions on the number of triggered strips for simulation events and results on cosmic rays (data from MiniSPD) are given in Figures 10 -13. They are alternate in pairs (Monte Carlo – data).

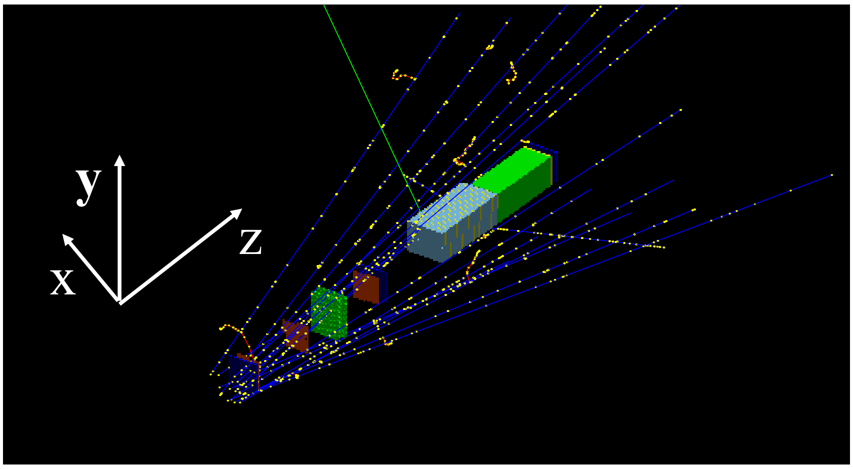

Figure 9: scheme of MiniSPD from GEANT4 window. Three Si-modules is depicted in brown.

We can analyze the strip work for every plane and its both sides (for X and U coordinate). In some cases, the numbering of strips in the simulation and in the experiment at MiniSPD test bench does not match, so there is a difference in the distributions. We observe a good work of sides X1, U1, U2, U4, X5, X6, X8 and U8; availability of noise channels for X2, X4, U3, U5, X7 and U7 and dead channels of X3, U4 sides. For side X3, only half of the channels work. Sides X2, U5, U7, X7 possess increased noise.

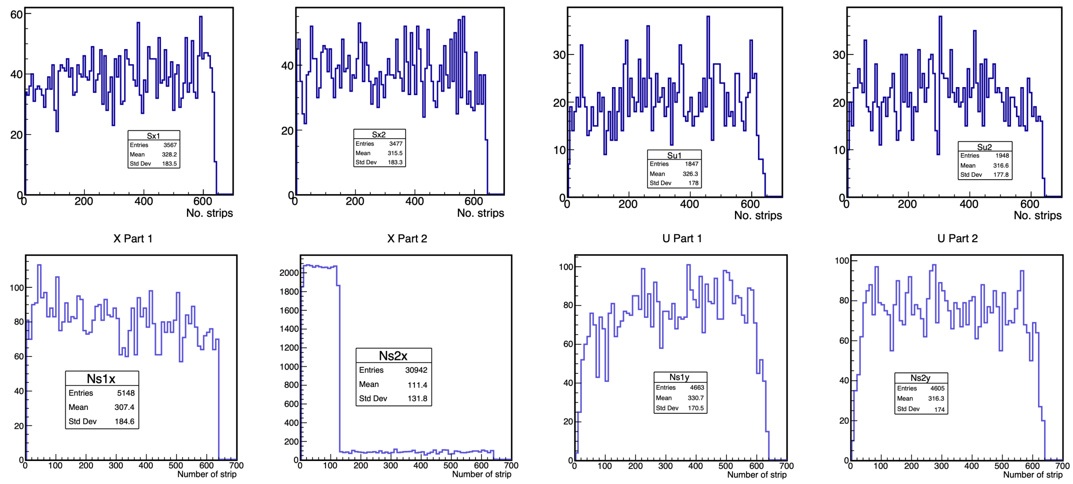

Figure 10: distributions according to the number of triggered strips for Monte Carlo events and cosmic rays for X1, X2, U1 and U2 sides of the first Si-module.

At MiniSPD, energy deposition in the single strip E_{dep} is measured in ADC units. At Monte Carlo simulation we use for that MeV. Considering the existence of linear dependence between these quantities, and also their average values $< ADC >$ and $< E_{dep} >$, we can estimate the lower registration threshold E_{cut} in MeV units. Using good working sides (X1, X6, U2, U8) we get the interval 30 keV $< E_{cut} <$ 60 keV and estimate its average value ∼ 55 keV. Energy depositions obtained by simulation and from experimental data are presented in Figure 14.

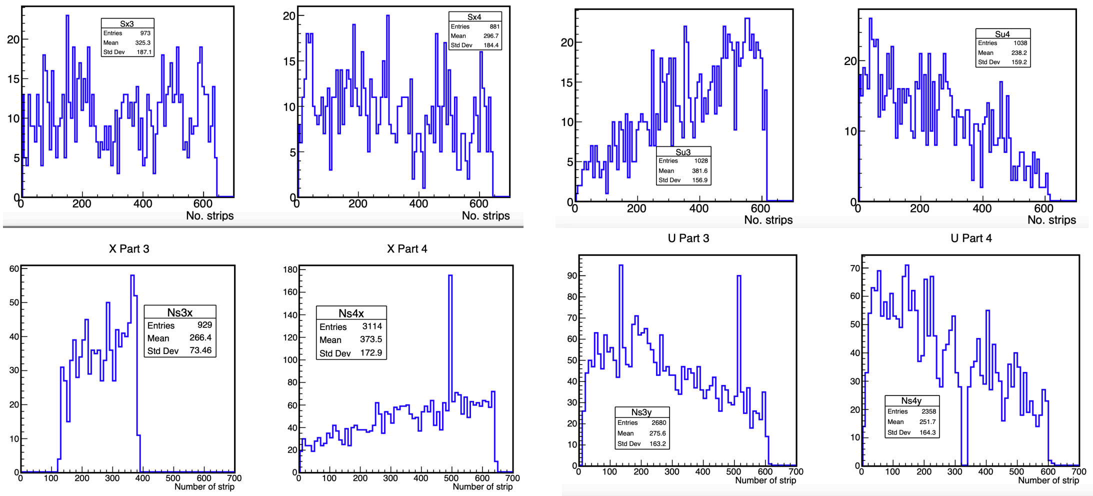

Figure 11: same as in Figure 10 for X3, X4, U3 and U4 sides of the second Si-module.

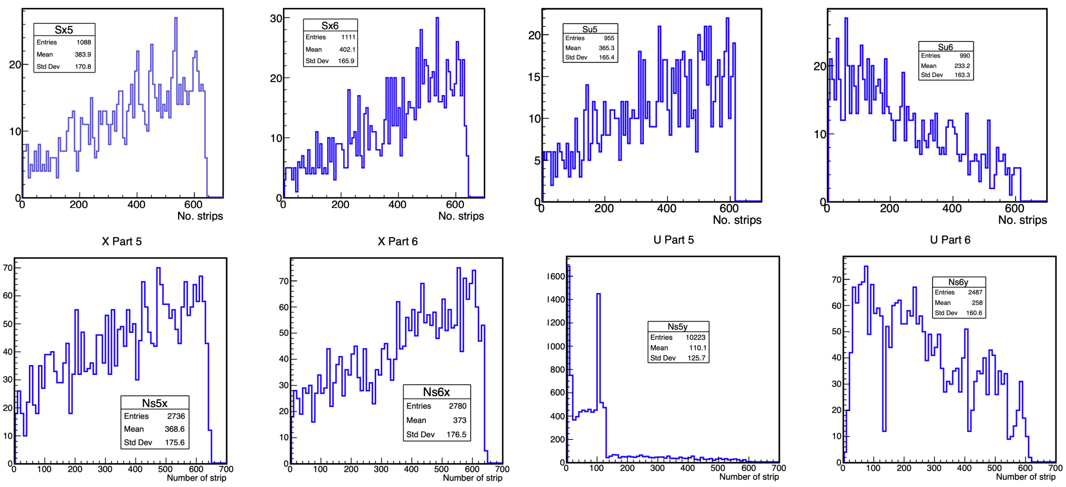

Figure 12: same as in Figure 10 for X5, X6, U5 and U6 sides of the second Si-module.

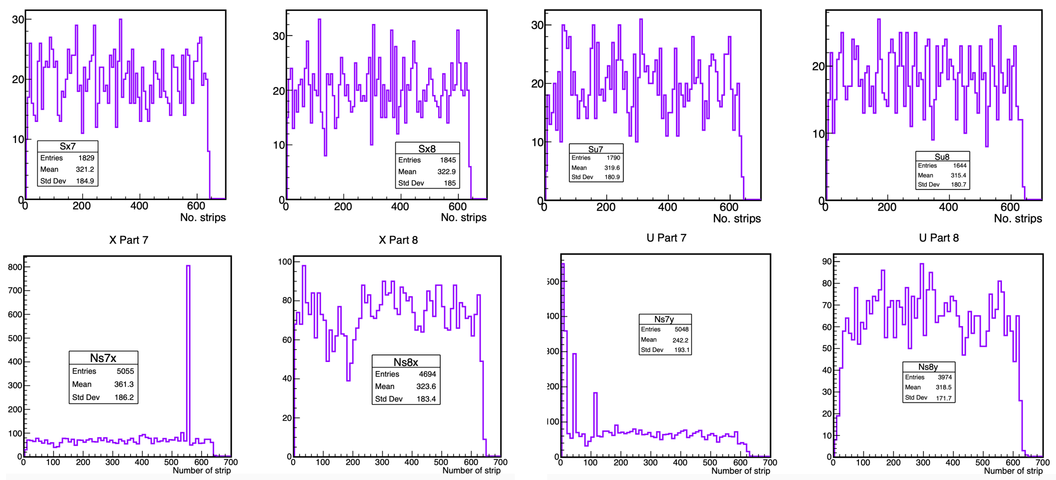

Figure 13: same as in Figure 10 for X7, X8, U7 and U8 sides of the third Si-module.

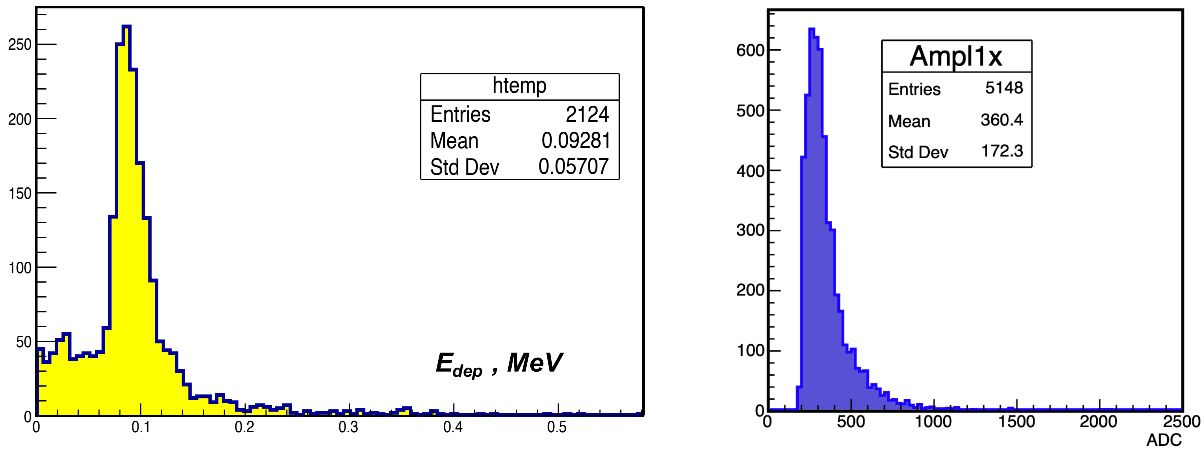

Figure 14: energy deposition in a one strip at the X1-side for simulation events (left) and experimental data (right)

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The important procedure of any experimental project is the alignment. Geometric position of the Si-modules differs from their estimated values. It can be stipulated by inaccuracy in the given position of the planes and their dimensions. The alignment compensates this misalignment in a mathematical way. For that goal, we worked out program packets based on the Millepede's approach of V. Blobel [6] and used them to define the linear and nonlinear parameters of direct muon tracks.

We solve the alignment task by minimizing of the function $F = \Sigma_{events}\Sigma_{tracks}\Sigma_{hits}\left(\frac{d_i}{\sigma_i}\right)^2$ where $d_i = u_{fit} - u_{mes}$, u_{fit} and u_{mes} are the fitting (expected) and measured (observed) values of u-coordinate. We use four parameters $(x_0,\ t_x,\ y_0, t_y)$ described any track in projections on X and Y planes to fit it in space by a straight line

$$u_{fit} = u_j(z_i) = (x_0 + t_x z_i)\cos(\alpha_i) + (y_0 + t_y z_i)\sin(\alpha_i) + \Delta_i\,. \tag{1}$$

where Δ_i is the shift. We find shifts and subtract them from corresponding coordinates of i-detector. Angle α_i can be 0 or 2.5^o (strip orientations). Experimental data are divided into 4 groups depending on the part numbers of every modules through which they pass. The first group contains "vertical" tracks, two others are "oblique" and the last group includes "false" tracks. For example, if the track passes through parts 2, 4 and 8 we call it "vertical" ("oblique" for parts 1, 5, 8). The first group is the most numerous.

Figures 15-16 illustrate well the noticeable improvement of chi-squares and minimization of residuals for X3 and U3 sides of the third part. A significant reduction of residuals is observed for U3-coordinate in comparison to X3. This is due to the fact that half channels of the X3 side do not work (see Figure 11).

We carried out the alignment for all possible choices of track passing through three modules and determined the misalignment parameters (shifts in equation 1). At that, we significantly improved the chi-squares for all real variants. The theoretical resolution for our Si-planes is about 28 μm. Data MiniSPD give shift values for tracks passing through parts 1, 4, 8 equal to 3 μm (X4 side) and 408 μm (U4 side). The same for parts 1, 5 and 8, we have 28 μm (X5) and 976 μm (U5). In the most cases, shifts for X-coordinates are turned out less than those for U-coordinates.

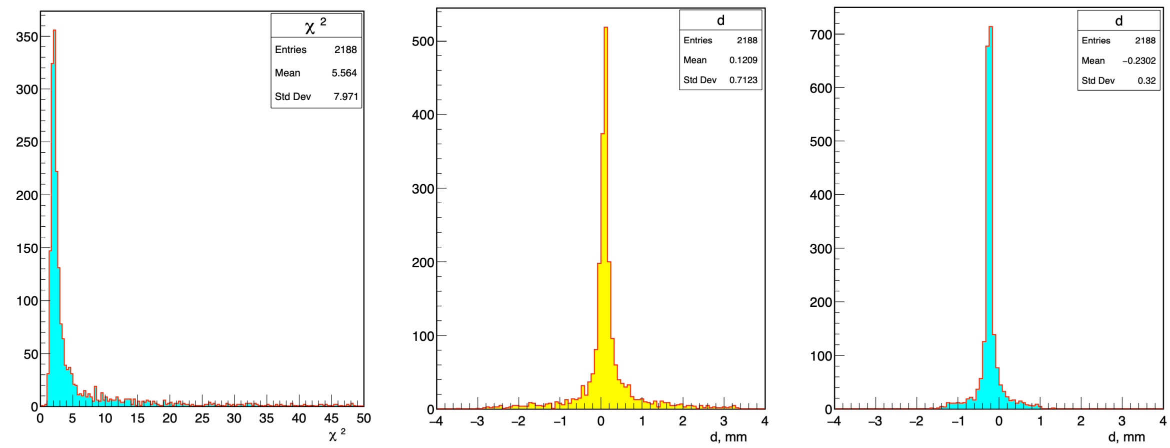

Figure 15: χ^2 and resifual distributions of tracks passing through parts 1, 3 and 7 for X3 (yellow) and U3 (blue) before alignment.

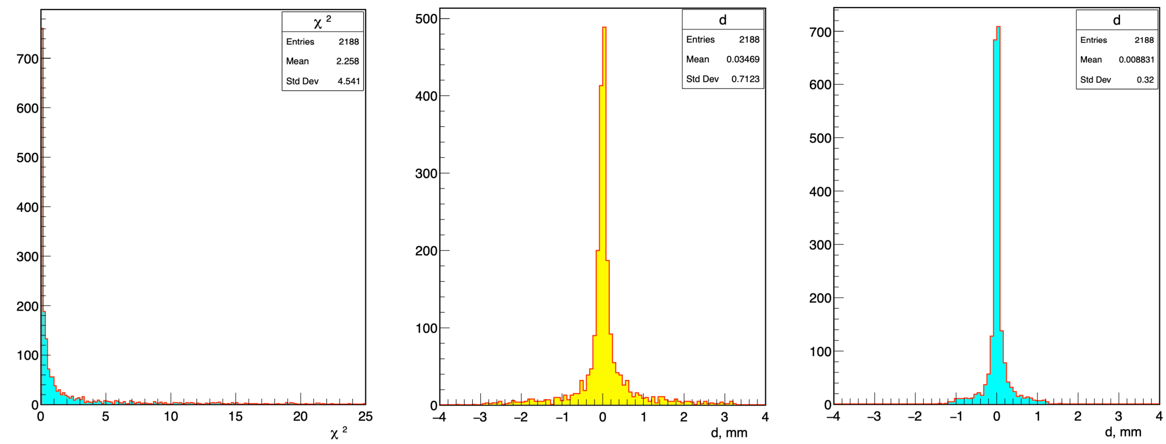

Figure 16: χ^2 and residual distributions of tracks passing through parts 1, 3 and 7 for X3 (yellow) and U3 (blue) planes after alignment.

IV. CONCLUSION

Monte Carlo simulation of two-sided silicon plates of miniSPD stand is carried out for two cases: with and without taking into account operation of the scintillator triggers. Comparison Monte Carlo simulation with experimental data allows to estimate the lower threshold on energy for a single strip operation. It is about 55 keV.

Work of all parts (1-8) and their sides (X and U) of MiniSPD Si-detectors was analyzed and compared with Monte Carlo simulation. Noisy and dead channels are seen directly from the distributions according to the numbers of triggered strips. The alignment task is solved for parts of the middle (II) module. The distributions on residuals of its parts and χ^2 on tracks are obtained.

We continue carrying out MC simulation of straw (drift) tubes to compare it with experimental data obtained at MiniSPD stand. We also plan to carry out Monte Carlo simulation of the electromagnetic calorimeter work having 16 "shashlik" modules. It will allow us to prepare for solving of our basic task [7] soft (direct) photon yield and the pionic condensate formation (restoration of π^0) in pp (pd, dd) interactions at high multiplicity.

Acknowledgments

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[1] SPD web site http://spd.jinr.ru.

[2] The SPD collaboration. Conceptual design of the Spin Physics Detector. version1.1. arXiv:2102.00442v3 [hep-ex] 2 Feb 2022

[3] V.V. Abramov et al. Possible Studies at the First Stage of the NICA Collider Operation with Polarized and Unpolarized Proton and Deuteron Beams. SPD Collab. Phys.Part.Nucl. **52** (2021) 1044.

[4] Elke C. Aschenauer(Brookhaven Natl. Lab.), Markus Diefenthaler(Jefferson Lab). ICFA Beam Dyn.Newslett. **74** (2018) 10 – 23.

[5] Elena Kokoulina et al. Study of soft photon yield in pp and AA interactions at JINR, EPJ Web Conf. **235** (2020) 03003.

[6] V. Blobel. Version 0.999-17.10 2000 (Universitat Hamburg).

[7] E Kokoulina et al. Soft photon study at NICA's facilities. J. Phys.: Conf. Ser. **1690** (2020) 012035.