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SPD Range (Muon) System

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Abstract—The range system (RS) is one of the essential detectors of the spin physics detector (SPD) which is currently under preparation for the second interaction point of the NICA collider. RS provides identification of muons and can also be used as a coarse hadronic calorimeter. The SPD range system design and geometry modeling are presented as well as the main results of RS prototype tests.

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1. INTRODUCTION

The spin physics detector [1, 2] is a projected specialized detector at the second interaction point of the Nuclotron-based Ion Collider fAcility (NICA) designed at the Joint Institute for Nuclear Research (Dubna, Russia). The proposed colliding modes of the NICA complex include collisions of high intensity polarized pp, pd, and dd beams. The polarization system is going to be able to keep longitudinal and transverse polarization degree up to 70% with the collision luminosity up to 10^{32} cm^{-2} s^{-1} over the beam particle momentum range of 2–13.5 GeV/c. The above specification offers unique prospects to investigate a wide range of polarized phenomena.

Since the unpolarized gluon content of hadrons is widely investigated in collider and fix-target experiments, the understanding of the polarized parton distribution functions (PDFs) strongly needs experimental input. The measurement of specific single and double spin asymmetries provides access to the gluon helicity, gluon Sivers and Boer–Mulders PDFs in the nucleon, as well as the gluon transversity distribution tensor PDFs in the deuteron. Polarized quark PDFs and fragmentation functions can be accessed via the production of high-p_T hadrons. Studies of the direct photon production processes allow access to information on the nucleon's gluon structure [3]. Another promising probe of polarized gluon content of hadrons is the inclusive charmonia production. It has a relatively large cross section, clear experimental signature in the dimuon decay mode ($J/\psi \to \mu^+\mu^-$) (making the muon identification one of the relevant tasks), and looks attractive taking into account the large datasets collected by beam-dump experiments at comparable $\sqrt{s}$.

The main purpose of the SPD is the study of the nucleon spin structure which remains one of the key topics of modern high-energy physics. The proposed detector design should have close to 4π geometrical acceptance, high-precision tracking system, advanced particle identification capabilities, good electromagnetic calorimeter, efficient muon system, and data acquisition system capable of handling event rates at 10^{32} cm^{-2} s^{-1} luminosity.

2. SPD RANGE SYSTEM

The SPD range (muon) system concept is based on a technique of detecting charged particles in a laminated structure of gaseous detectors alternating with iron absorber plates. Mini-drift tubes (MDT) [4, 5] with two-coordinate readout (the wires and the orthogonal strips) will be used for particle registration in the RS. The MDT tracking detector is a type of Iarocci streamer tubes that consists of an array of aluminum cells with anode wires in the center of each cell but uses proportional mode of operation instead of a streamer one.

The eight-wires MDT detector is comprised of the following parts: metallic cathode (aluminum extruded comb-like profile), anode wires and plastic envelope for gas tightness. The gas used in the detector is a mixture of Ar : CO_2 (70 : 30 proportion) at atmospheric pressure. A chamber with various number of MDTs up to few meters long can be assembled to have hundreds of cells in a detecting plane.

The main purpose of the SPD range system is primary muon identification with optimal separation from background contamination originating mostly from primary pions and secondary decay muons in the full SPD energy range $\sqrt{s_{pp}}$ = 12–27 GeV. The resolution of the muon system is enough to use it as a coarse

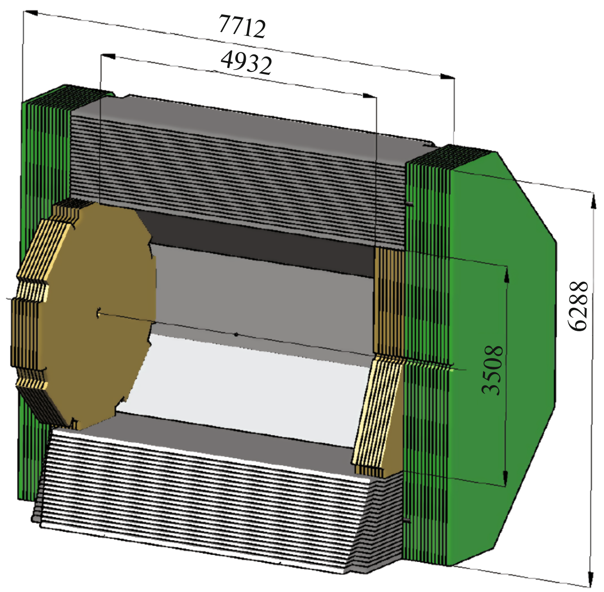

Fig. 1. 3D schematic view and main dimensions (in mm) of the SPD range system.

hadron calorimeter (sampling has mostly 30 and 60 mm iron absorber plates). It is worth mentioning that the muon system is the only one for neutron registration in the SPD setup.

The range system is a proven solution for detecting muons either stopped by the absorber or the ones crossing the iron. In the former case, the muon energy can be roughly estimated keeping in mind the stopping power of the iron absorber (about 1.5 GeV/m) for relativistic muons with $dE/dX = 2$ MeV cm^2/g. The muon system consists of eight barrels, two endcap-plugs, and two endcap-disk modules. A cross section of the RS 3D-model is shown in Fig. 1.

The granularity of the main iron absorber layers is 30 mm with two 60 mm for the inner and outer layers. Nineteen 30 mm layers of absorber with 35 mm gaps for MDT detectors in between and two 60 mm wrapping layers give about 4 nuclear interaction length of material (λ_I) in the barrel part. The forward RS detector consists of endcap-plugs (60 mm + 7 × 30 mm layers) and endcap-disks (12 × 30 mm + 60 mm layers). The above RS composition of modules is chosen mainly due to technical requirements of the collision hall. The SPD muon system weighs around 810 ton considering the designed 7.7 m length and 6.3 m height. A preliminary range system model for Monte Carlo (MC) studies was created and used for simulation with Geant4. Being encapsulated within the SPDRoot framework it has an almost uniformly distributed thickness ~$4\lambda_I$ representing a reasonable model of the current constructional RS design.

3. RANGE SYSTEM R&D PROGRAM

3.1. Range System Prototype

The range system prototype (RSP), constructed for testing and optimizing various aspects of the range system performance, has 22 detecting layers of MDTs alternating with 30 and 60 mm thick iron absorber plates (for comparison of different samplings). Figure 2 shows the RSP installation on the T9/PS test beam at CERN. The prototype is equipped with 288 (1 m long) MDT detector units, 22 strip boards (1 × 1 m^2 size, 3 cm wide strips), and corresponding readout electronics (2160 channels for wire readout and 764 for strip readout) weighing 10 ton in total. The R&D program

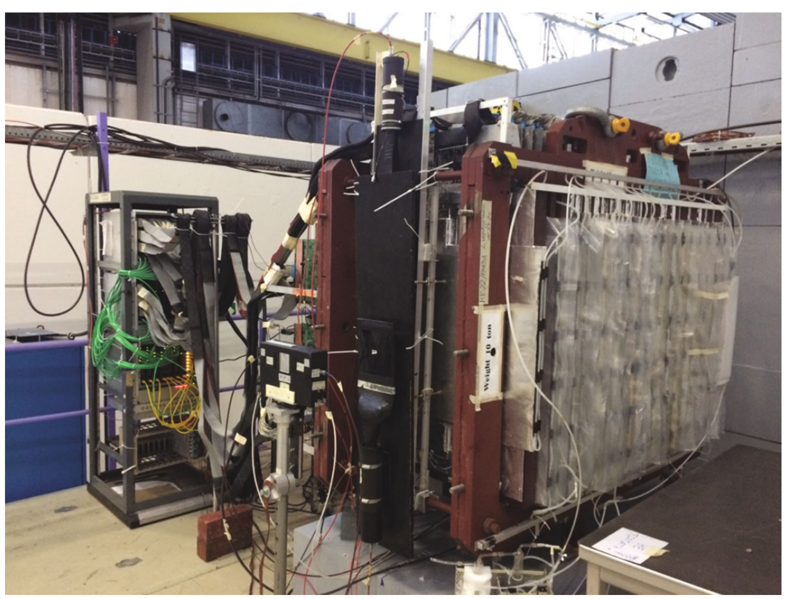

Fig. 2. Range system prototype in the beam position installed at the T9/PS beam line.

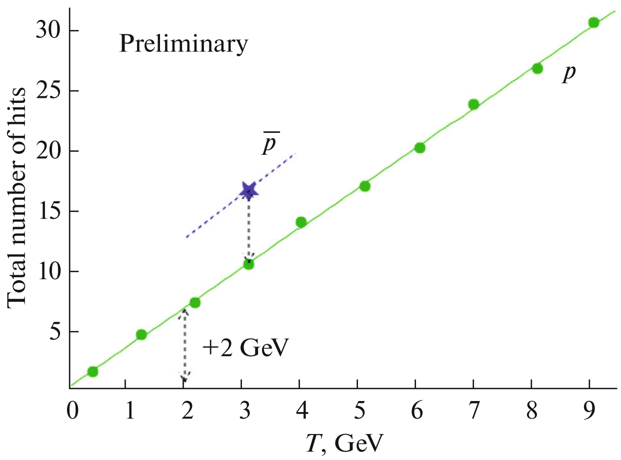

Fig. 3. Hit multiplicities for protons (green circles) and antiprotons (blue stars) at various particle kinetic energies.

includes calibration of the system response to a variety of particles at different energies, muon/hadron separation performance, pattern recognition algorithm testing as well as tuning of the Monte Carlo simulation parameters.

3.2. Hadron Calorimetry

Hadron calorimetry is implemented by measuring the total number of hits (hit wires) in an event (proton and antiproton data are presented in this paper). The prototype's trigger system is equipped with two time-of-flight scintillation counters (for protons selection momenta below 5 GeV/c) which fixes also the beam entrance spot, and Čerenkov counters (for protons momenta above 5 GeV/c) with CO_2 variable gas pressure. This composition of trigger counters permits to separate electrons/pions/muons in different momentum ranges. The range system prototype was calibrated for proton/antiproton responses using the full thickness of RSP ~$5\lambda_I$. The proton and antiproton hit multiplicities as a function of particle kinetic energy are shown in Fig. 3. When proton and antiproton annihilate the energy deposition of the products adds up to twice the rest mass of the proton (~2 GeV). This effect is clearly visible in Fig. 3. Few additional measurements at different momenta of antiprotons will allow to estimate the entire calibration line, which should be parallel to the proton line. This measurement is planned for future RSP runs.

3.3. Neutron Registration

Another very important feature of the proposed SPD range system is the possibility to identify neutrons and estimate their energy. During the RSP beam tests it was demonstrated using the same charged particle monochromatic (5 GeV/c) beam at T9/PS with a carbon target as a neutron source installed in front of the first prototype's detecting layer along with scintillators for vetoing protons. A distinctive feature of the neutron hit profile is the absence of an incoming charged track in the first few layers of the prototype. Figure 4 illustrates an example of a neutron response in the range system prototype as compared to a proton's one.

3.4. Muon/Hadron Separation

The hit profile in the range system corresponding to a particular kind of particles with a certain momentum has a specific pattern. For example, low momentum pions ($p < 1$ GeV/c) are in a remarkable percentage almost indistinguishable from muons with the same momentum. The increasing energy of hadrons

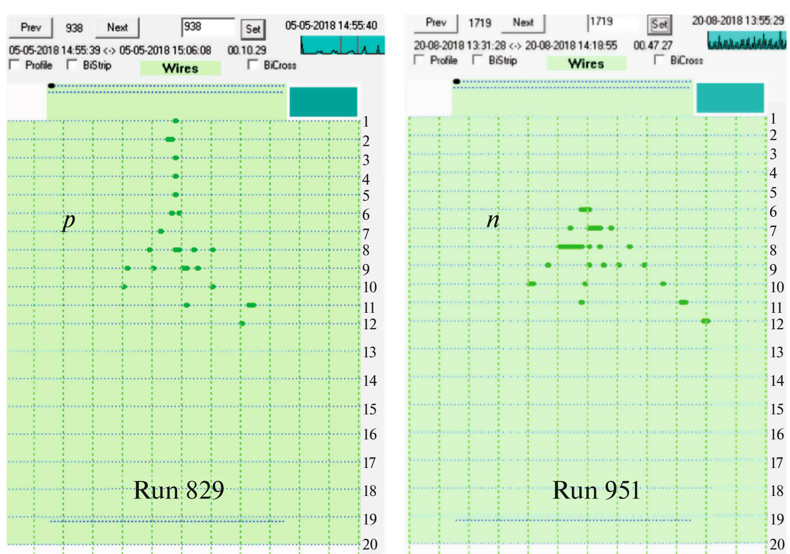

Fig. 4. Comparison of hit profiles in the RSP for a proton (left) and a neutron (right) with the same momentum 5 GeV/c.

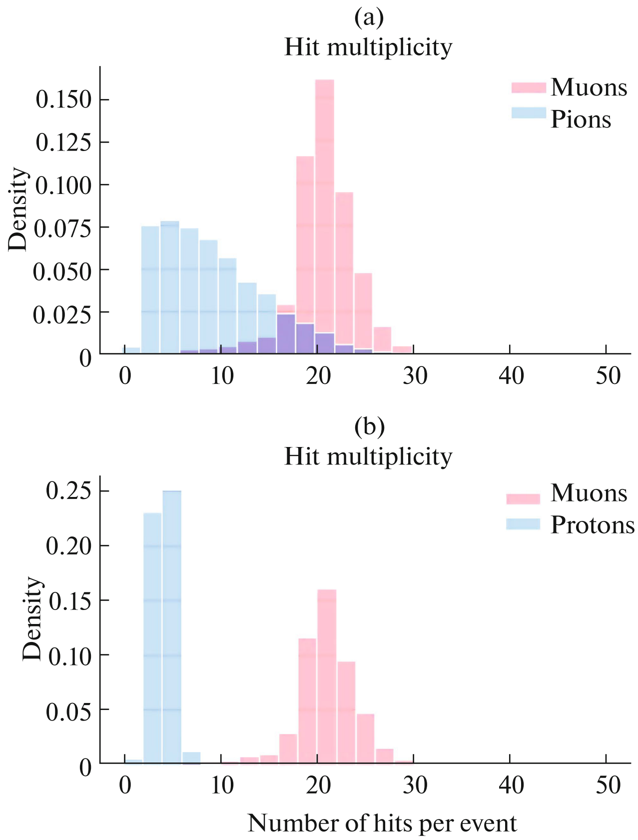

Fig. 5. Normalized distributions of the hit multiplicity per event for (a) muons compared to pions and (b) muons compared to protons with momentum $p = 1$ GeV/c in the SPD range system (MC).

(up to 10 GeV/c) significantly changes the profile of hits, forming a cascade of secondary particles. Finding variables sensitive to differences in such patterns is directly related to the possibility of separation between muons and hadrons (in fact the main task of the muon system). It can be used as an input to various machine learning techniques.

As a starting point, a decision tree classification algorithm is used to separate between signal (muon) and background (protons and pions) samples in data and MC. The chosen technique is a well-known solution for binary classification (DecisionTreeClassifier from *scikit-learn* library). The main advantages of the algorithm are its robustness, transparency, and limited number of hyper-parameters for optimization. Events (data) in both samples were labeled using time-of-flight detectors only. The following variables are chosen as an input to the decision tree: hit multiplicity in an event, first and last fired layers, splitting layer number (the lowest number of a layer having ≥2 hits), and number of hits in the last layer. The normalized distributions of the hit multiplicity per event for muons compared to pions and muons compared to protons with momentum $p = 1$ GeV/c obtained with SPD range system (MC) are shown in Fig. 5. The hit multiplicity is found to be the most powerful discriminative variable while the last fired layer number and splitting layer number variables also showed high importance for muon/hadron separation. The applied technique allows to differentiate between the classes with 97% accuracy for muons/pions and 99% for muons/protons. An analogous method was applied to the RSP dataset and showed less accuracy of 93% for muons/protons separation mainly due to the impurity of the signal muon sample, since the events in data were labeled using time-of-flight detectors only. Later the Čerenkov counter tags will be used to fix better the muon data sample.

4. CONCLUSIONS

A concept of the SPD muon range system, being based on mini-drift tubes as detector, iron plates as absorber, followed by robust analogue amplifier/discriminator electronics, supplemented by a digital end-stage for data transfer to the data acquisition system is discussed. In order to study the response of the system in Monte Carlo, a Geant4 geometrical model of the SPD/NICA RS was implemented and used for preliminary estimates of muon/hadron separation using decision tree technique. In order to test and optimize various aspects of the range system performance a fully equipped and functional RS prototype was used. Test beam and cosmic runs performed between 2017–2019 have sufficient amount of experimental data containing the RSP response to a variety of particles ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $p/\bar{p}$, n) and will be used to search for the optimal π/μ separation algorithm in a wide range of particle momenta (0.5–10 GeV/c), hadron calorimetry ($\pi^{\pm}$, $p/\bar{p}$, n) as a function of hadron momentum, and tuning MC signal digitization parameters using real test beam data.

REFERENCES

1. I. A. Savin et al., "Spin physics experiments at NICA-SPD with polarized proton and deuteron beams," EPJ Web Conf. **85**, 02039 (2015); arXiv: 1408.3959 [hep-ex]
2. A. Guskov, "SPD—the spin physics project with polarized proton and deuteron beams at the NICA collider," JPS Conf. Proc. **26**, 021018 (2019); arXiv: 1904.04779 [hep-ex]
3. A. Guskov, "Physics with prompt photons at SPD," J. Phys. Conf. Ser. **1435**, 012035 (2020); arXiv: 1910.07838 [hep-ex]
4. V. M. Abazov, G. D. Alexeev, Y. I. Davydov, V. L. Malyshev, V. V. Tokmenin, and A. A. Piskun, "Comparative analysis of the performance characteristics of mini-drift tubes with different design," Instrum. Exp. Tech. **53**, 356-361 (2010).
5. V. M. Abazov, G. D. Alexeev, Y. I. Davydov, V. L. Malyshev, A. A. Piskun, and V. V. Tokmenin, "Coordinate accuracy of mini-drift tubes in detection of an induced signal," Instrum. Exp. Tech. **53**, 648–652 (2010).