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Conceptual design of the Spin Physics Detector

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Contents

Chapter 1

Executive summary [A. Guskov]

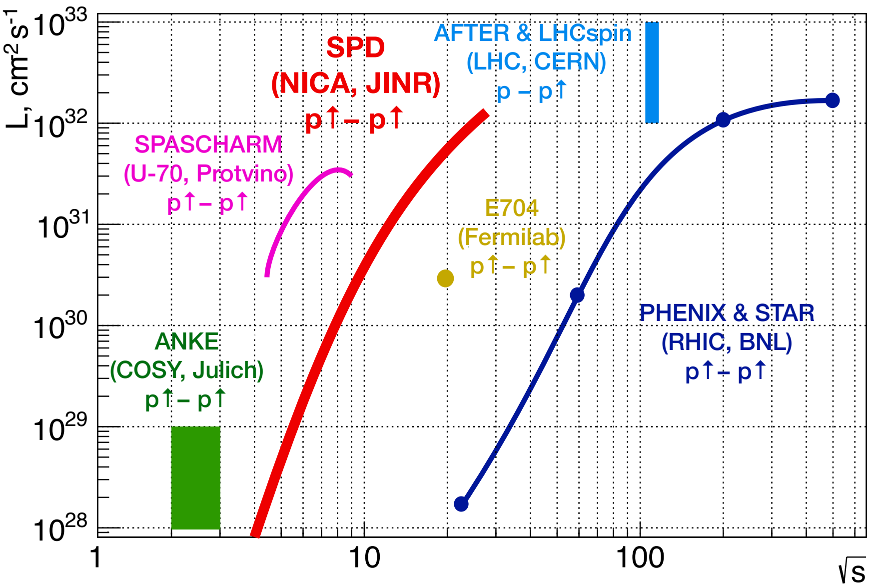


Figure 1.1

Chapter 2

Polarized and unpolarized partonic structure of proton and deuteron

1 Gluons in proton and deuteron [A. Guskov, O. Teryaev]

Gluons, together with quarks, are the fundamental constituents of the nucleon. They play a key role in generation of its mass and carry about half of its momentum in hard (semi)inclusive processes. The spin of the nucleon is also built up from the intrinsic spin of the valence and sea quarks (spin-1/2), gluons (spin-1), and their orbital angular momenta. Notwithstanding the progress achieved during the last decades in the understanding of the quark contribution to the nucleon spin, the gluon sector is much less developed. One of the difficulties is the lack of the direct probes to access gluon content in high-energy processes. While the quark contribution to the nucleon spin was determined quite precisely in semi-inclusive deep-inelastic scattering (SIDIS) experiments like EMC, HERMES, and COMPASS, the gluon contribution is still not well-constrained even so it is expected to be significant.

In recent years, the three-dimensional partonic structure of the nucleon became a subject of a careful study. Precise mapping of three-dimensional structure of the nucleon is crucial for our understanding of Quantum Chromodynamics (QCD). One of the ways to go beyond the usual collinear approximation is to describe nucleon content in the momentum space employing the so-called Transverse-Momentum-Dependent Parton Distribution Functions (TMD PDFs) [1–6].

The most powerful tools to study TMD PDFs are the measurements of the nucleon spin (in)dependent azimuthal asymmetries in SIDIS [1, 4, 5, 7] and Drell–Yan processes [8, 9]. Complementary information on TMD fragmentation process, necessary for the interpretation of SIDIS data, is obtained from e^+e^- measurements [10]. Being an actively developing field, TMD physics triggers a lot of experimental and theoretical interest all over the world, stimulating new measurements and developments in TMD extraction techniques oriented on existing and future data from lepton-nucleon, electron-positron and hadron-hadron facilities at BNL, CERN, DESY, FNAL, JLab, and KEK. For recent reviews on experimental and theoretical advances on TMDs see Refs. [11–15]. While a lot of experimental measurements were performed (and are planned) and theoretical understanding was achieved for Leading Order (LO) (twist-2) TMD PDFs such as Sivers, transversity and Boer-Mulders functions of quarks, only few data relevant for the study of gluon TMD PDFs are available [16–21].

The simplest model of the deuteron is a weakly-bound state of a proton and a neutron mainly in the S-wave with a small admixture of the D-wave state. This approach is not much helpful in the description of the deuteron structure at large Q^2 [1]. Possible non-nucleonic degrees of freedom in deuteron could play an important role in the understanding of the nuclear modification of PDFs (the EMC effect). Since the gluon transversity operator requires two-unit helicity-flip it does not exist for spin-1/2 nucleons [22]. Therefore, proton and neutron gluon transversity functions can not contribute directly to the gluon transversity of the deuteron. A non-zero deuteron transversity could be an indication of a non-nucleonic component or some other exotic hadronic mechanisms within the deuteron.

Most of the existing experimental results on spin-dependent gluon distributions in nucleon are obtained in the experiments at DESY (HERMES), CERN (COMPASS), and BNL (STAR and PHENIX). Study of polarized gluon content of the proton and nuclei is an important part of future projects in Europe and the United States such as AFTER@LHC and LHCSpin at CERN, and EIC at BNL [23–25]. Notwithstanding the fact that the gluons in nucleon were successfully probed in SIDIS measurements, hadronic collisions have an important advantage since they probe the gluons at the Born-level without involving the EM couplings.

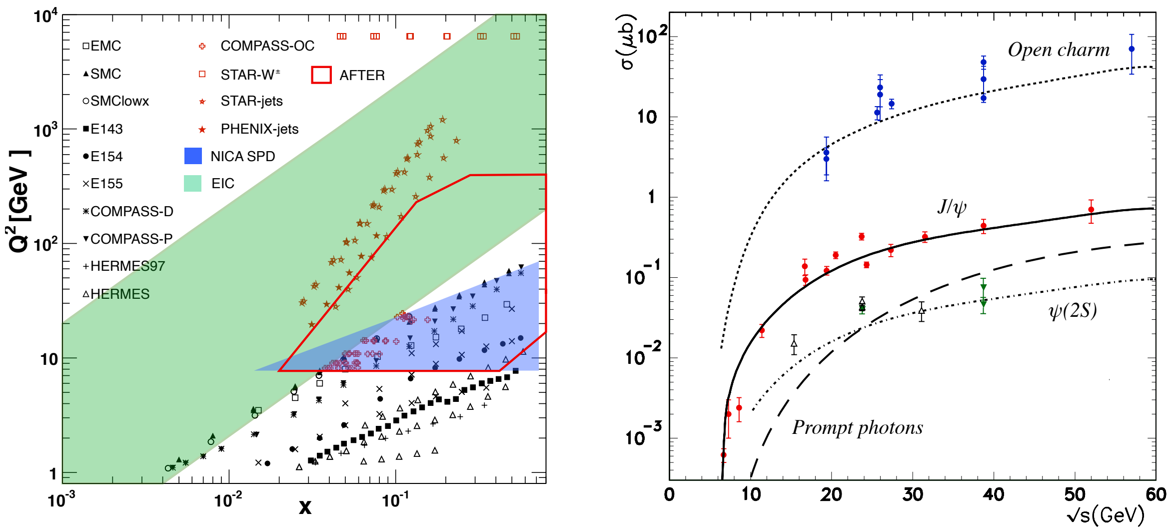
1.1 Gluon probes at NICA SPD

The polarized gluon content of proton and deuteron at intermediate and high values of the Bjorken x will be investigated using three complementary probes: inclusive production of charmonia, open charm, and prompt photons. 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 and the Drell-Yan process. Unfortunately, the latter one is unlikely to be accessible at SPD due to the small cross section and unfavourable background conditions. For effective registration of each aforementioned gluon probes, the SPD setup is planned to be equipped with a range (muon) system, an electromagnetic calorimeter, a time-of-flight system, straw tracker, and a silicon vertex detector. Nearly a 4π coverage of the setup and a low material budget in the inner part of the setup should provide a large acceptance for the detection of the desired final states. In Fig. 2.1(a) the kinematic phase-space in x and Q^2 to be accessed by the SPD is compared to the corresponding ranges of previous, present and future experiments. Parameters of the experimental facilities planning to contribute to gluon physics with polarized beams are listed in Tab. 2.1. Figure 2.1(b) illustrates the behavior of the cross sections for the inclusive production of J/ψ, ψ', D-mesons and high-p_T prompt photons in p-p collisions as a function of $\sqrt{s}$.

1.1.1 Charmonia production

From the experimental point of view, for considered energies, hadronic production of charmonia seems to be particularly suited to access gluon content in hadrons. Production of prompt J/ψ-mesons looks most attractive, since large data set of $J/\psi \to \mu^+\mu^-$ ($BF = 0.06$) events is accumulated in beam-dump experiments with proton and pion beams at $\sqrt{s}$ close to 20 GeV. However J/ψ-meson is not the cleanest probe of the proton structure, since a significant fraction (about 20% [30]) of J/ψ-mesons observed in hadronic collisions is produced indirectly through decays of χ_{cJ} and $\psi(2S)$ (the so-called feed-down contribution), and modeling of this contribution introduces additional uncertainties in theoretical calculations. Hence, to provide additional constraints to production models, it is important to study production of χ_{cJ} and $\psi(2S)$ separately, through their decays $\chi_{cJ} \to \gamma J/\psi$ ($BF = 0.014$, 0.343 and 0.19 for $J = 0, 1$ and 2) and $\psi(2S) \to \mu^+\mu^-$ ($BF = 0.08$). The latter state is of special interest, because it is essentially free from feed-down contamination from higher charmonium states, due to the proximity of $D^0\overline{D}^0$-threshold. However, the separation of the $\chi_{c0,1,2}$ signals is a challenging experimental task due to the small mass

[1] We use Q^2 (or μ^2) as a generic notation for the hard scale of a reaction: the invariant mass square of lepton pairs in Drell-Yan processes, Q^2, transverse momentum square p_T^2 of produced hadron or its mass square M^2.



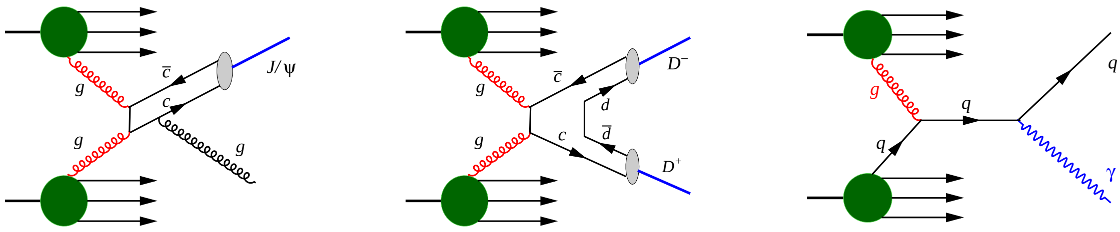
(a) (b)

Figure 2.1: (a) The kinematic coverage, in the (x, Q^2) plane, of the hadronic cross section data for the processes commonly included in global QCD analyses of polarized quark (black) and gluon (red) PDFs [26]. The kinematic domain expected to be covered by NICA SPD by charmonia, open charm and prompt-photon production is shown in blue. (b) Cross section for the processes of open charm, J/ψ, $\psi(2S)$ and prompt photons ($p_T > 3$ GeV) production as a function of center-of-mass energy (based on [27]).

Table 2.1: Main present and future actors in gluon spin physics.

Experimental facility	SPD @NICA [29]	RHIC [28]	EIC [25]	AFTER @LHC [23]	SpinLHC [24]
Scientific center	JINR	BNL	BNL	CERN	CERN
Operation mode	collider	collider	collider	fixed target	fixed target
Colliding particles & polarization	$p^{\uparrow}$-$p^{\uparrow}$ $d^{\uparrow}$-$d^{\uparrow}$ $p^{\uparrow}$-d, p-$d^{\uparrow}$	$p^{\uparrow}$-$p^{\uparrow}$	$e^{\uparrow}$-$p^{\uparrow}$, $d^{\uparrow}$, ^{3}He$^{\uparrow}$	p-$p^{\uparrow}$, $d^{\uparrow}$	p-$p^{\uparrow}$
Center-of-mass energy $\sqrt{s_{NN}}$, GeV	≤27 (p-p) ≤13.5 (d-d) ≤19 (p-d)	63, 200, 500	20-140 (ep)	115	115
Max. luminosity, 10^{32} cm^{-2} s^{-1}	∼1 (p-p) ∼0.1 (d-d)	2	1000	up to ∼10 (p-p)	4.7
Physics run	>2025	running	>2030	>2025	>2025

difference between the states and low energy resolution of the electromagnetic calorimeters for soft photons.



(a) (b) (c)

Figure 2.2: 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, (c) prompt photons.

Besides, 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 (Fig. 2.2(a)) and it's production can be calculated perturbatively, because the hard scale of the process is limited from below by the heavy quark mass, providing the direct access to polarized and unpolarized gluon distributions. However, the process of transition of the heavy quark-antiquark pair into a physical bound-state is not well understood at present and can become a source of significant theoretical uncertainties. We review modern status of the theory of quarkonium production in more detail in Sec. 1.5 to explain the latter point.

Therefore, quarkonium production can be used to study the structure of hadrons only with a great caution and only if the results consistent with other probes will eventually emerge. The studies of hadronic structure and heavy quarkonium production mechanism should become complimentary. But for now the most reasonable phenomenological strategy for measurements at SPD concerning quarkonia is to study yields and polarization of different quarkonium states in a wide kinematic range, at various energies, and in polarized as well as non-polarized hadronic collisions, to provide the development of the theory with more constraints allowing to exclude various models. When the theory of production of heavy quarkonia is firmly established – it will become an invaluable tool to study the details of hadronic structure.

1.1.2 Open charm production

It is well-known that the heavy flavor production offers direct probes of the gluon distributions in hadrons. The basic mechanism responsible for charm pair production in pp collisions is the gluon fusion (GF, see Fig. 2.2(b)). In the framework of pQCD, the GF contributes to the hadron cross section as $\mathscr{L}_{gg} \otimes \hat{\sigma}_{c\bar{c}}$, where the gluon luminosity $\mathscr{L}_{gg}$ is a convolution of the gluon densities in different protons, $\mathscr{L}_{gg} = g \otimes g$. At leading sorder in pQCD, $\mathscr{O}(\alpha_s^2)$, the partonic cross section $\hat{\sigma}_{c\bar{c}}$ describes the process $gg \to c\bar{c}$.

The GF contribution to the charmonia production in pp collisions has the form $\mathscr{L}_{gg} \otimes \hat{\sigma}_{(c\bar{c})+X} \otimes W_{c\bar{c}}$. At the Born level, the partonic cross section $\hat{\sigma}_{(c\bar{c})+X}$ is of the order of α_s^3 because its basic subprocess is $gg \to (c\bar{c}) + g$. Moreover, the quantity $W_{c\bar{c}}$, describing the probability for the charm pair to form a charmonium, imposes strong restrictions on the phase space of the final state.[2] For these two reasons, the α_s-suppression and phase space limitation, the cross sections for charmonia production are almost two orders of magnitude smaller than the corresponding ones for open charm, see Figs. 2.1 (b).

To analyze the kinematics of a DD pair, each of D-mesons has to be reconstructed. The decay modes $D^+ \to \pi^+ K^- \pi^+$ (BF=0.094) and $D^0 \to \pi^+ K^- \pi^+$ (BF=0.04) can be used for that. To suppress a combinatorial background SPD plans to use the search for a secondary vertex of a D-meson decay that is about 100 μm far from the interaction point (the $c\tau$ values are 312 and 123 μm for the charged and

[2]To form a charmonium, the momenta of the produced quark and antiquark should be sufficiently close to each other.

neutral D-mesons, respectively). Identification of a charged kaon in the final state by the time-of-flight system would also help to do that. Production and decay of D^*-mesons could be used as an additional tag for open-charm events. Singe-reconstructed D-mesons also carry reduced but still essential information about gluon distribution that is especially important in the low-energy region with a lack of statistics.

1.1.3 Prompt photon production

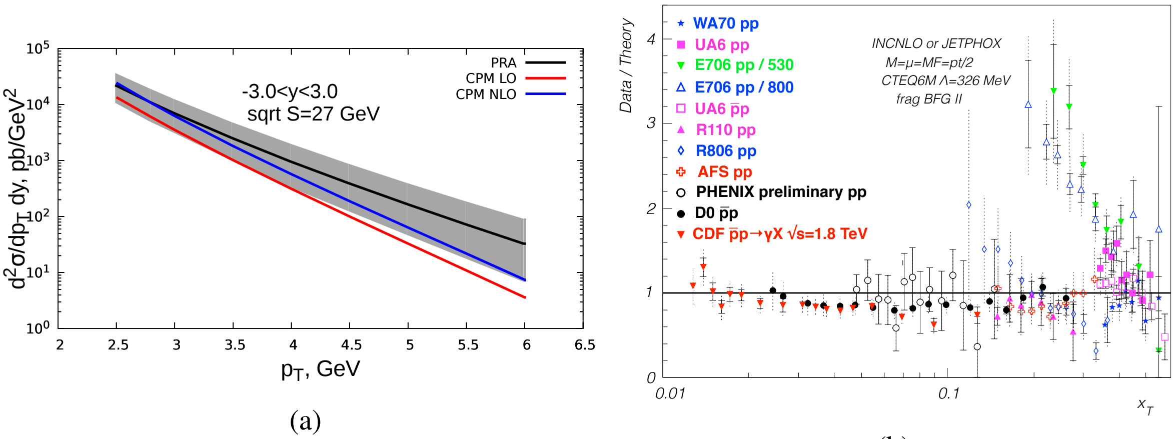
Photons emerging from the hard parton scattering subprocess, the so-called prompt photons, serve as a sensitive tool to access the gluon structure of hadrons and hadron-hadron collisions. Inclusive direct photon production proceeds without fragmentation, i.e. the photon carries the information directly from the hard scattering process. Hence this process measures a combination of initial k_T effects and hard scattering twist–3 processes. There are two main hard processes for the production of direct photons: gluon Compton scattering, $gq(\bar{q}) \to \gamma q(\bar{q})$ (Fig. 2.2(c)), which dominates, and quark-antiquark annihilation, $q\bar{q} \to \gamma g$. Contribution of the latter process to the total cross section is small.

Theoretical predictions for inclusive prompt photon production are shown in Fig. 2.3(a) as transverse momentum spectrum at the energy $\sqrt{s} = 27$ GeV. Calculations are performed in LO and NLO approximations of CPM, as well as in the Parton Reggeization Approach (PRA), which is a QCD and QED gauge-invariant version of k_T-factorization. They include direct and fragmentation contributions, the latter one is about 15-30 %. The K-factor between LO and NLO calculations in the CPM slightly depends on $p_{T\gamma}$ and equals about 1.8 [31]. LO prediction of PRA coincides with the result of NLO CPM calculation at moderate transverse momenta ($p_T < 4$ GeV) while at higher p_T PRA predicts somewhat harder p_T-spectrum.

In experiments prompt photons are detected alongside with a much larger number of photons from decays of secondary π^0 and η mesons (minimum-bias photons). The main challenge is to subtract these decay contributions to obtain the photons directly emitted from hard collisions. This kind of background is especially important at small transverse momenta of produced photons (p_T) and gives the lower limit of the accessible p_T range. Therefore the prompt-photon contribution with $p_T \leq 2-3$ GeV is usually unreachable in the experiment [32]. Figure 2.3(b) [33] presents the comparison of the p_T spectra ($x_T = 2p_T/\sqrt{s}$) measured in a wide kinematic range of $\sqrt{s}$ in different fixed-target and collider experiments and the theoretical NLO calculations performed within the JETPHOX package [34]. While high-energy collider results exhibit rather good agreement with expectations, situation at high-x_T is not pretty good. The results of the E706 ($\sqrt{s} = 31.6$ and 38.8 GeV) [35] and R806 ($\sqrt{s} = 63$ GeV) [36] experiments break out the trend an demonstrate some "slope". It could be an indication of possible systematic effects that have not been not fully understood.

A pair of prompt photons can be produced in hadronic interactions in $q\bar{q}$ annihilation, quark-gluon scattering, and gluon-gluon fusion hard processes (at the leading, next-to-leading, and next-to-next-leading orders, respectively). The double prompt photon production in nucleon interactions at low energies is not yet well-studied experimentally. The production cross section for proton-carbon interaction at $\sqrt{s} = 19.4$ GeV/c has been measured by the CERN NA3 experiment [37]. Based on this result we can expect the cross section of the double photon production with $p_T > 2$ GeV/c for each photon on the level of about 0.5 nb.

Estimations of the expected event rates are evaluated for p-p collisions at $\sqrt{s} = 27$ and 13.5 GeV for the projected integrated luminosity 1.0 and 0.1 fb^{-1}, respectively that corresponds effectively to one year of data taking (10^7 s). The results are listed in Tab. 2.2.



(a) (b)

Figure 2.3: (a) Prediction for prompt photon transverse momentum spectrum at $\sqrt{s} = 27$ GeV obtained in LO (red line) and NLO (blue line) approximations of CPM and LO of PRA (black line). Uncertainty bands for PRA predictions are due to factorization/renormalization scale variation only. (b) Data-to-theory ratio for the fixed-target and collider experiments [33].

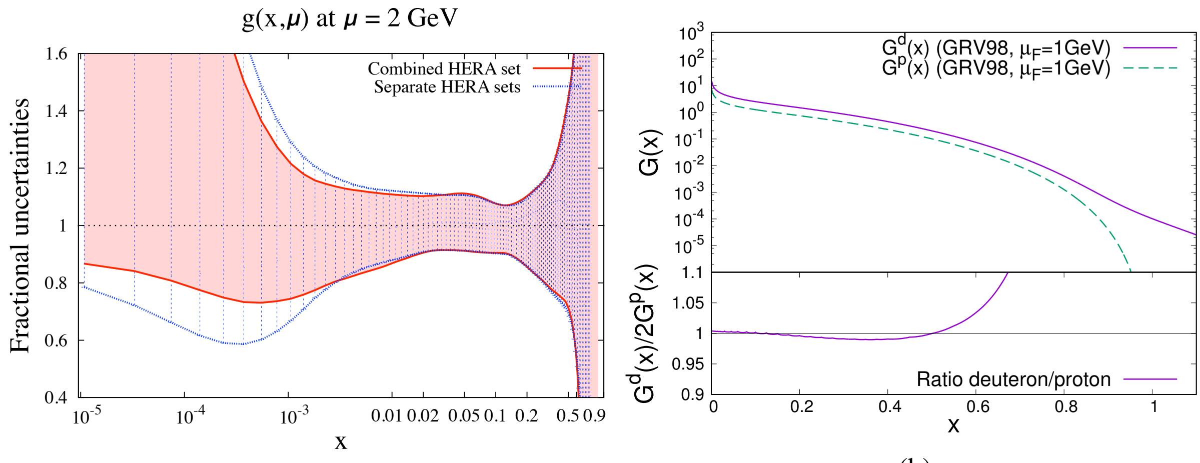
Table 2.2: Expected rates for each of the gluon probes (per one year of SPD running).

Probe	$\sigma_{27\,GeV}$, nb ($\times$BF)	$\sigma_{13.5\,GeV}$, nb ($\times$BF)	$N_{27\,GeV}$, 10^6	$N_{13.5\,GeV}$ 10^6
Prompt-γ ($p_T > 3$ GeV/c)	35	2	35	0.2
J/ψ	200	60		
$\rightarrow \mu^+\mu^-$	12	3.6	12	0.36
$\psi(3686)$	25	5		
$\rightarrow J/\psi\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$	0.5	0.1	0.5	0.01
$\rightarrow \mu^+\mu^-$	0.2	0.04	0.2	0.004
Open charm: $D\bar{D}$ pairs	1.5×10^4	1300	1.5×10^4	130
Single D-mesons				
$D^+ \rightarrow K^-2\pi^+$ and $D^- \rightarrow K^+2\pi^-$	1100	100	1100	10
$D^0 \rightarrow K^-\pi^+$ and $\bar{D}^0 \rightarrow K^+\pi^-$	730	65	730	6.5

1.2 Gluons at large x

The gluon PDF is one of poorly known parton distributions in the proton because available data constrain weakly the quantity $g(x,Q^2)$, particularly for x greater than 0.5 [40, 41]. In the high-x region, the gluon density is usually parameterized as $g(x,Q^2) \sim (1-x)^L$, and values of L extracted from global fits differ considerably from each other. In particular, obtained results for L vary from 3 to 11 at $Q^2 = 1.9$ GeV^2 [42].

To improve the situation with large x, one needs precise data on the heavy flavor production at energies not so far from the production threshold. Concerning the open charm production in pp collisions, the



(a) (b)

Figure 2.4: (a) Uncertainty of unpolarized gluon PDF based on HERA data ($\mu = 2$ GeV) [38]. (b) Gluon PDF in the deuteron in comparison with the nucleon [39].

corresponding cross sections are poorly known for $\sqrt{s} < 27$ GeV [43, 44].[3] Presently, the only available measurements for this region were performed by the E769 experiment, which corresponds three hundred events collected in pA collisions [45]. Unfortunately, E769 results have large uncertainties, which is enough to estimate only the order of magnitude for the $pp \to c\bar{c}X$ cross section at $\sqrt{s} \approx 20$ GeV. For this reason, future studies of the open charm production at SPD in pp and dd collisions for $\sqrt{s} \leq 27$ GeV are of special interest. In particular, they will allow to reduce significantly the present uncertainties in the gluon density (and α_s) at a GeV scale, especially for high x.

Detailed information on the gluon distribution at large x is very important for various phenomenological applications. For instance, it is of current interest to estimate the $b\bar{b}$ pair production cross section at NICA energies. Such predictions, however, are not presently reliable due to their strong dependence on the exponent L which is known poorly. Another example is the DGLAP evolution of the PDFs. Using precise data on $g(x,Q^2)$ (and α_s) at $Q^2 \sim m_c^2$ (m_c is the mass of the c-quark) as boundary conditions in DGLAP equations, one could reduce essentially the uncertainties in evolution of PDFs for higher values of Q.

From the theoretical point of view, the threshold behavior of cross sections is closely related to the so-called infrared renormalon problem. It is well known that radiative corrections to the production cross sections contain the mass (or threshold) logarithms whose contribution is expected to be sizable near the threshold. These logarithms are usually taken into account within the soft gluon resummation (SGR) formalism [46–50]. Formally resummed cross sections are, however, ill-defined due to the Landau pole contribution, and few prescriptions have been proposed to avoid the renormalon ambiguities [51–54]. Unfortunately, numerical predictions for heavy quark production cross sections can depend significantly on the choice of resummation prescription. Undoubtedly, anticipated data from SPD on the charm production not so far from the production threshold will provide an excellent test for these prescriptions.

Another interesting problem for NICA SPD is to probe the intrinsic charm (IC) content of the proton [55, 56]. The IC contribution to open charm production is expected to be sizable near the threshold because its PDF, $c(x,Q^2)$, is predicted to be harder than the gluonic one. As a result, the IC density in the proton can be dominant at sufficiently large x independently of its overall normalization [57]. To visualize the IC component, one needs to collect much enough events like $D\bar{D}$ pair produced in $pp \to D\bar{D}$ with a large overall x_F close to 1. That events are predicted to be very rare within the GF mechanism and would

[3] On the contrary, the J/ψ production cross section is known well enough practically down to the threshold, see Fig. 2.1(b).

directly indicate the five-quark component in the proton, $|uudc\bar{c}\rangle$

Investigation of the open charm production in pp, pd and dd collisions might be one of the key points in the NICA SPD programme. The motivation is twofold. On the one hand, production of D-mesons in pp collisions is practically unmeasured at NICA energies. On the other hand, these presently unavailable data on open charm production rates are strongly necessary for determination of the gluon density $g(x,\mu)$ at large x where this PDF is practically unknown.

Moreover, anticipated results on the open charm production are very important for many other current issues in particle physics: from infrared renormalon ambiguities in cross sections to intrinsic charm content of the proton.

1.3 Tests of TMD factorization with gluon probes

The description of hard inclusive processes in hadron collisions is based on factorization theorems. Formulation of factorization theorems in terms of the TMD PDFs of quarks and gluons is the most important step towards studying the 3D structure of hadrons and the nature of their spins. The conventional TMD-approach [58] can be applied for study of processes with colorless final states with transverse momenta much smaller than the relevant scale of hadron interactions, $q_T \ll Q$. In recent years a substantial success was achieved in the quark sector of TMD PDFs related with their correct theoretical definition and the connection with experimentally observed cross sections within the framework of factorization theorems [6]. In the case of unpolarized hadron collisions, in the leading twist approximation the production cross section is a function of two independent TMD PDFs, i.e. distribution functions of unpolarized quarks f_1^q and distribution functions of transversely polarized quarks $h_1^{\perp q}$ (referred to as Boer-Mulders function) in unpolarized nucleons. For description of cross sections in collisions of polarized hadrons, the number of TMD PDFs increases.

However, the situation with gluon TMD PDFs is significantly different. Until recently, gluon TMD PDFs were used only within the framework of phenomenological models of the type of the Generalized Parton Model (GPM), in which the factorization formula of the Collinear Parton Model is applied if small (non-perturbative-origin) transverse momenta of gluons from colliding hadrons are available.

The proof of the factorization theorem for processes with gluon TMD PDFs, as well as the formulation of evolution equations for them, have been presented relatively recently in [59], where it was applied to describe the Higgs boson production with small transverse momenta. However, hard processes in which detailed information on gluon TMD PDFs can be obtained primarily, include the processes of production of heavy mesons (D, B) and heavy quarkonia (J/ψ, Υ, η_c, η_b, $\ldots$). In these processes, there are two non-perturbative mechanisms to be factorized: the emission of soft gluons in the initial state and the formation of a colorless hadron in the final state. Even in the case of heavy meson production with small transverse momenta when their spectrum is determined only by a non-perturbative q_T-distribution of initial gluons, for factorization of hard and soft interactions it is not enough to use the TMD PDFs formalism, the introduction of new non-perturbative process-dependent hadron observables, the so-called TMDShFs (TMD shape functions) [60, 61] is needed. Moreover, the differential cross section for the process of production the state $\mathcal{Q}$ in a collision of unpolarized hadrons is written as

$$\frac{d\sigma}{dyd^2q_T} \sim f_1^g \otimes f_1^g \otimes S_{\mathcal{Q}} - w_{UU} \otimes h_1^{\perp g} \otimes h_1^{\perp g} \otimes S_{\mathcal{Q}},$$

where $S_{\mathcal{Q}}$ is the polarization-independent TMDShFs of this process and w_{UU} is the universal contribution weight function of linearly polarized TMD PDFs.

The factorization theorem contains three or more non-perturbative hadronic quantities at low transverse momenta: gluon TMD PDFs and TMDShFs. Thus, the phenomenological extraction of gluon TMDs from quarkonium production processes is still possible, i.e., a robust factorization theorem can potentially be obtained in any particular case of heavy meson production. However one also needs to model and extract the involved TMDShFs.

1.4 Linearly polarized gluons in unpolarized nucleon

Search for the polarized quarks and gluons in unpolarized hadrons is of special interest in studies of the spin-orbit couplings of partons and understanding of the proton spin decomposition. The corresponding intrinsic transverse momentum $\vec{k}_T$ dependent distributions of the transversely polarized quarks, $h_1^{\perp q}(x,\vec{k}_T^2)$, and linearly polarized gluons, $h_1^{\perp g}(x,\vec{k}_T^2)$, in an unpolarized nucleon have been introduced in Refs. [3] and [62]. Contrary to its quark version $h_1^{\perp q}$ the TMD density $h_1^{\perp g}$ is T- and chiral-even, and thus can directly be probed in certain experiments.

Azimuthal correlations in heavy quark pair production in unpolarized ep and pp collisions as probes of the density $h_1^{\perp g}$ have been considered in Refs. [63, 64]. For the case of DIS, the complete angular structure of the pair production cross section has been obtained in terms of seven azimuthal modulations. However, only two of those modulations are really independent; they can be chosen as the $\cos\varphi$ and $\cos 2\varphi$ distributions, where φ is the heavy quark (or anti-quark) azimuthal angle [65, 66].[4]

To probe the TMD distributions, the momenta of both heavy quark and anti-quark, $\vec{p}_Q$ and $\vec{p}_{\bar{Q}}$, in the process $pp \to Q\bar{Q}X$ should be measured (reconstructed). For further analysis, the sum and difference of the transverse heavy quark momenta are introduced,

$$\vec{K}_\perp = \frac{1}{2}\left(\vec{p}_{Q\perp} - \vec{p}_{\bar{Q}\perp}\right), \qquad \vec{q}_T = \vec{p}_{Q\perp} + \vec{p}_{\bar{Q}\perp}, \tag{2.1}$$

in the plane orthogonal to the collision axis. The azimuthal angles of $\vec{K}_\perp$ and $\vec{q}_T$ are denoted as $\phi_\perp$ and ϕ_T, respectively.

The angular structure of the $pp \to Q\bar{Q}X$ cross section has the following form:

$$\mathrm{d}\sigma_{pp} \propto A(q_T^2) + B(q_T^2)q_T^2\cos 2(\phi_\perp - \phi_T) + C(q_T^2)q_T^4\cos 4(\phi_\perp - \phi_T). \tag{2.2}$$

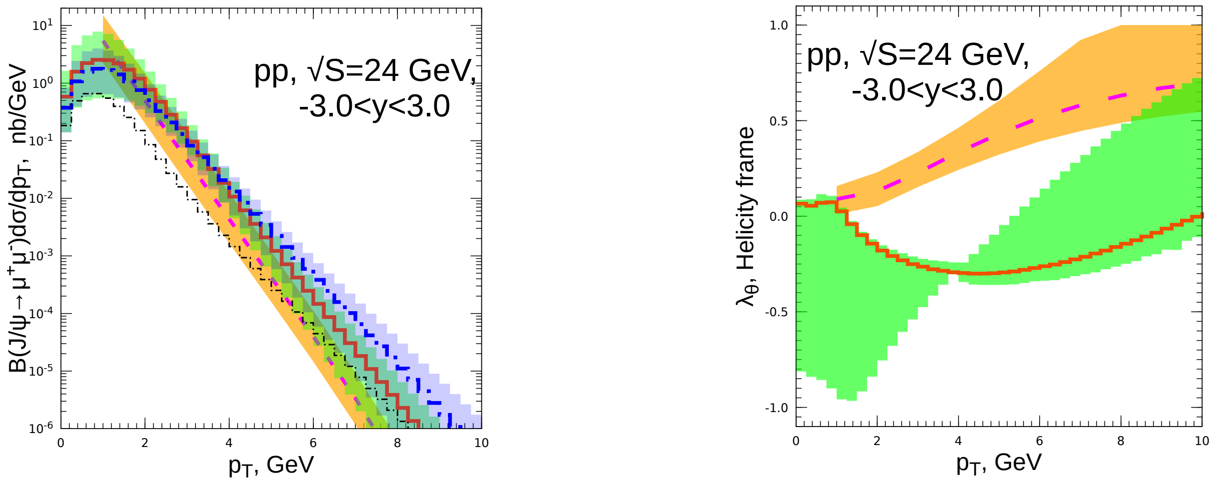
Assuming factorization for the TMD distributions, the terms A, B and C can schematically be written as the following convolutions [64]:

$$\begin{aligned} A &\propto f_1^q \otimes f_1^{\bar{q}} \otimes A_q + f_1^g \otimes f_1^g \otimes A_g + h_1^{\perp g} \otimes h_1^{\perp g} \otimes A_g^\perp, \\ B &\propto h_1^{\perp q} \otimes h_1^{\perp \bar{q}} \otimes B_q + f_1^g \otimes h_1^{\perp g} \otimes B_g, \\ C &\propto h_1^{\perp g} \otimes h_1^{\perp g} \otimes C_g. \end{aligned} \tag{2.3}$$

The order α_s^2 predictions for the coefficients A_i, B_i and C_i $(i = q, g)$ in Eqs.(2.3) are presented in Ref.[64]. Using these results, one can, in principle, extract the densities $h_1^{\perp q}(x,\vec{k}_T^2)$ and $h_1^{\perp g}(x,\vec{k}_T^2)$ from azimuthal distributions of the $D\bar{D}$ pairs produced in pp collisions.

Another processes proposed to probe the linearly polarized gluons in unpolarized proton are: pseudoscalar C-even quarkonia (such as η_c and χ_c) [68], di–gamma ($pp \to \gamma\gamma X$) [69] and J/ψ– pair ($pp \to J/\psi J/\psi X$) [70] production. These reactions are however strongly suppressed in comparison with $pp \to D\bar{D}X$.

[4]The function $h_1^{\perp g}$ can also be determined from measurements of the Callan-Gross ratio in DIS [67].



(a) (b)

Figure 2.5: Theoretical predictions for inclusive J/ψ p_T-spectrum (a) and p_T-dependence of polarization parameter λ_θ (b) in various models: NLO of Collinear Parton Model + NRQCD-factorization (thick dashed line with orange uncertainty band) [88, 89], LO of PRA [90] + NRQCD-factorization (thick solid histogram with a green uncertainty band) [91, 92], and LO PRA [90] + Improved Color Evaporation Model (thick dash-dotted histogram with blue uncertainty band) [93]. The contribution of $q\bar{q}$-annihilation channel to the central ICEM prediction is depicted by the thin dash-dotted histogram. Uncertainty bands are due to factorization/renormalization scale variation only.

1.5 Hadron structure and heavy charmonia production mechanisms

In this section we give a short review of modern status of the theory of heavy quarkonium production with an emphasis on possible applications of heavy quarkonium measurements for studies of the gluon content of hadrons.

Production of heavy quarkonia proceeds in two stages: first, a heavy quark-antiquark pair is produced at short distances, predominantly via gluon-gluon fusion but also with a non-negligible contribution of $q\bar{q}$ and qg-initiated subprocesses. The second stage is hadronization of quark-antiquark pair into a physical quarkonium state, which happens at large distances (low scales) and is accompanied by a complicated rearrangement of color via exchanges of soft gluons between the heavy quark-antiquark pair and other colored partons produced in the collision. Existing approaches, aimed to describe hadronization stage, such as Non-Relativistic QCD factorization (NRQCD-factorization) [71] and (Improved-) Color-Evaporation Model (CEM) [72–75] are currently facing serious phenomenological challenges (see e.g. recent reviews [76, 77]). NRQCD-factorization is challenged by the long-standing “polarization puzzle” [78, 79] and violation of Heavy-Quark Spin Symmetry relations between Long-Distance Matrix Elements (LDMEs) of η_c and J/ψ [80], while CEM usually rather poorly reproduces the detailed shapes of inclusive p_T-spectra of charmonia and bottomonia and, unlike NRQCD-factorization [81, 82], significantly under-predicts bulk of cross section for pair hadroproduction of J/ψ even at NLO in α_s [83]. Presently, the study of the heavy-quarkonium production mechanism is an active field of research, with new approaches, such as subleading-power fragmentation [84] and Soft-Gluon Factorization [85–87], being proposed recently.

Due to above-mentioned problems and multitude of competing theoretical approaches and models available on the market, our lack of quantitative understanding of the mechanism of hadronization can become a source of significant theoretical uncertainties if quarkonium production is to be used as a tool to study the proton structure. The Fig. 2.5 provides an insight on this situation at NICA SPD. In this figure, predictions of three models for the p_T-spectrum (Fig. 2.5(a)) and p_T-dependence of the polarization parameter λ_θ (Fig. 2.5(b)) are compared. The first one relies on the NLO calculation in Collinear Parton Model (with LO being $O(\alpha_s^3)$, see Fig. 2.2(a)) to describe short-distance part of the cross section and uses the NRQCD-factorization formalism for the long-distance part, with LDMEs of the latter tuned to charmonium production data in hadronic collisions, DIS and e^+e^--annihilation [78, 79, 88, 89]. In the second prediction, the short-distance part of the cross section is calculated in the LO ($O(\alpha_s^2)$ for color-octet and P-wave contributions and $O(\alpha_s^3)$ for color-singlet S-wave ones) of PRA [90], while LDMEs in this calculation had been fitted to the charmonium hadroproduction data from RHIC, Tevatron and LHC [91, 92]. The third prediction is performed in the LO ($O(\alpha_s^2)$) of PRA with the same unintegrated PDFs as for the second one, but interfaced with an improved Color-Evaporation Model (ICEM) of Ref. [93] for description of hadronization. Non-perturbative parameters of the ICEM had been taken from the Ref. [93] where they had been fitted to charmonium hadroproduction data at Tevatron and LHC energies. Predictions of all three models for inclusive J/ψ p_T-spectrum at NICA SPD appear to be consistent within their uncertainty bands. However, the structure of this predictions is significantly different, with NRQCD-based predictions being dominated by gluon-gluon fusion subprocess, while ICEM prediction containing significant contamination from $q\bar{q}$-annihilation (thin dash-dotted histogram in the Fig. 2.5(a)), which reaches up to 50% at low $p_T < 1$ GeV and contributes up to 10% at higher $p_T > 3$ GeV. Also ICEM tends to predict significantly harder p_T-spectrum at $p_T > 5$ GeV, than NRQCD-based PRA prediction which was performed with the same unintegrated PDFs.

Discussion above shows, that J/ψ p_T-spectrum can be reliably predicted only in the limited range of transverse momenta, approximately from 3 to 6 GeV at $\sqrt{s} = 24$ GeV. At higher p_T the shape of the spectrum becomes highly model-dependent and at lower $p_T < M_{J/\psi}$ the TMD-factorization effects (including possible violation of factorization, see [60, 61]) come into the game and the contribution of $q\bar{q}$-annihilation subprocess becomes uncertain. Nevertheless, predictions and measurements of rapidity or x_F-differential cross-sections even in this limited p_T-range could help to further constrain the gluon PDF, e.g. to rule-out the extreme values of L in the $x \to 1$ asympthotics of the PDF $\sim (1-x)^L$.

Predictions of NLO CPM and LO of PRA for polarization parameter λ_θ (see the Fig. 2.5(b)) are significantly different, with PRA predicting mostly un-polarized production ($\lambda_\theta \simeq 0$) while CPM predicts transverse polarization ($\lambda_\theta = +1$) at high p_T. Disagreement of the predictions for polarization parameters mostly reflects the difference of LDMEs obtained in two fits and their large uncertainty bands are due to significant uncertainties of LDMEs. Measurements of heavy quarkonium polarization at NICA energies will provide additional constraints on models, however due to well-known problems with description of polarization at high energies [78, 79] constraints coming from polarization measurements should be interpreted with great care and one should try to disentangle conclusions for gluon PDF from the results related to heavy quarkonium polarization.

1.6 Non-nucleonic degrees of freedom in deuteron

The naive model describes the deuteron as a weakly-bound state of a proton and a neutron mainly in S-state with a small admixture of the D-state. However, such a simplified picture failed to describe the HERMES experimental results on the b_1 structure function of the deuteron [94]. Modern models treat the deuteron as a six-quark state with the wave function

$$|6q\rangle = c_1|NN\rangle + c_2|\Delta\Delta\rangle + c_3|CC\rangle, \tag{2.4}$$

that contains such terms as the nucleon $|NN\rangle$, Δ-resonance $|\Delta\Delta\rangle$ and the so-called hidden color component $|CC\rangle$ in which two color-octet baryons combine to form a color singlet [95]. Such configurations can be generated, for example, if two nucleons exchange a single gluon. The relative contribution of the hidden-color term varies from about 0.1% to 80% in different models [96]. The components other than

$|NN\rangle$ should manifest themselves in the high-Q^2 limit. Possible contributions of the Fock states with a valent gluon like $|uudddg\rangle$ could also be discussed [39, 97].

The unpolarized gluon PDF of the deuteron in the light-front quantization was calculated in the Ref. [39] under the approximation where the input nuclear wave function is obtained by solving the nonrelativistic Schrödinger equation with the phenomenological Argonne v18 nuclear potential as an input. Gluon PDFs calculated per nucleon are very similar for the proton one in the range of small and intermediate x values while for $x > 0.6$ the difference becomes large due to the Fermi motion (see Fig. 2.14(a)). A similar work was performed in Ref. [98] for determination of spatial gluon distribution in deuteron for low-x that could be tested in the J/ψ production at EIC. Today the gluon content of deuteron and light nuclei becomes the matter of interest for the lattice QCD studies [99]. Apart from the general understanding of the gluon EMC effect, the measurement of the gluon PDF at high-x for deuteron could provide a useful input for high-energy astrophysical calculation [39].

SPD can perform an explicit comparison of the differential inclusive production cross sections $d\sigma/dx_F$ for all three gluon probes: charmonia, open charm, and prompt photons using p-p and d-d collisions at $\sqrt{s_{NN}} = 13.5$ GeV and possibly below. Such results could be treated in terms of the difference of unpolarized gluon PDFs in deuteron and nucleon.

1.7 Gluon polarization Δg with longitudinally polarized beams

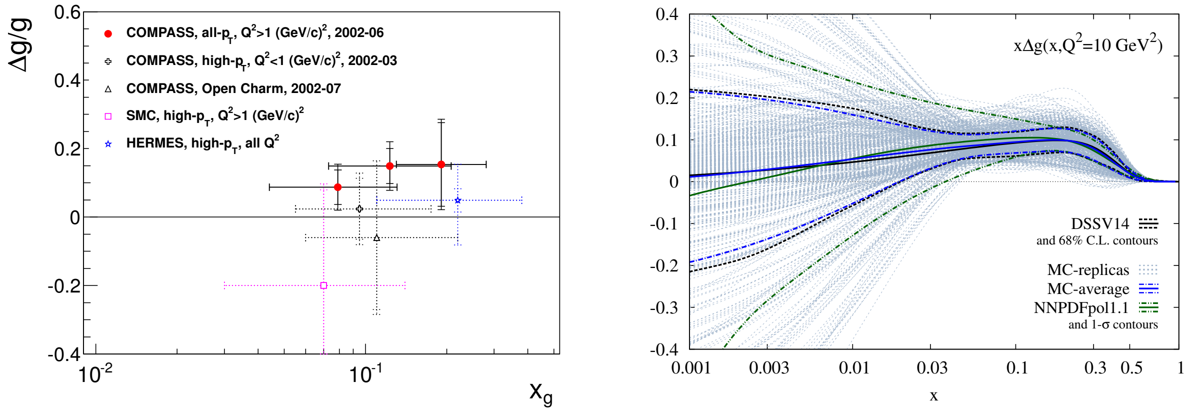
The gluon helicity distribution function $\Delta g(x)$ is a fundamental quantity characterizing the inner structure of the nucleon. It describes the difference of probabilities to find in the longitudinally polarized nucleon a gluon with the same and opposite spin orientations. The integral $\Delta G = \int \Delta g(x)dx$ can be interpreted as the gluon spin contribution to the nucleon spin. After the EMC experiment discovered that only a small part of proton spin is carried by the quarks [100], the gluon spin was assumed to be another significant contributor. So ΔG is a key ingredient of the nucleon helicity sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g, \tag{2.5}$$

where $\Delta\Sigma \approx 0.25$ [15] is the net contribution from the quark spin and L_q, L_g represent contribution of the orbital angular momenta of quarks and gluons, respectively.

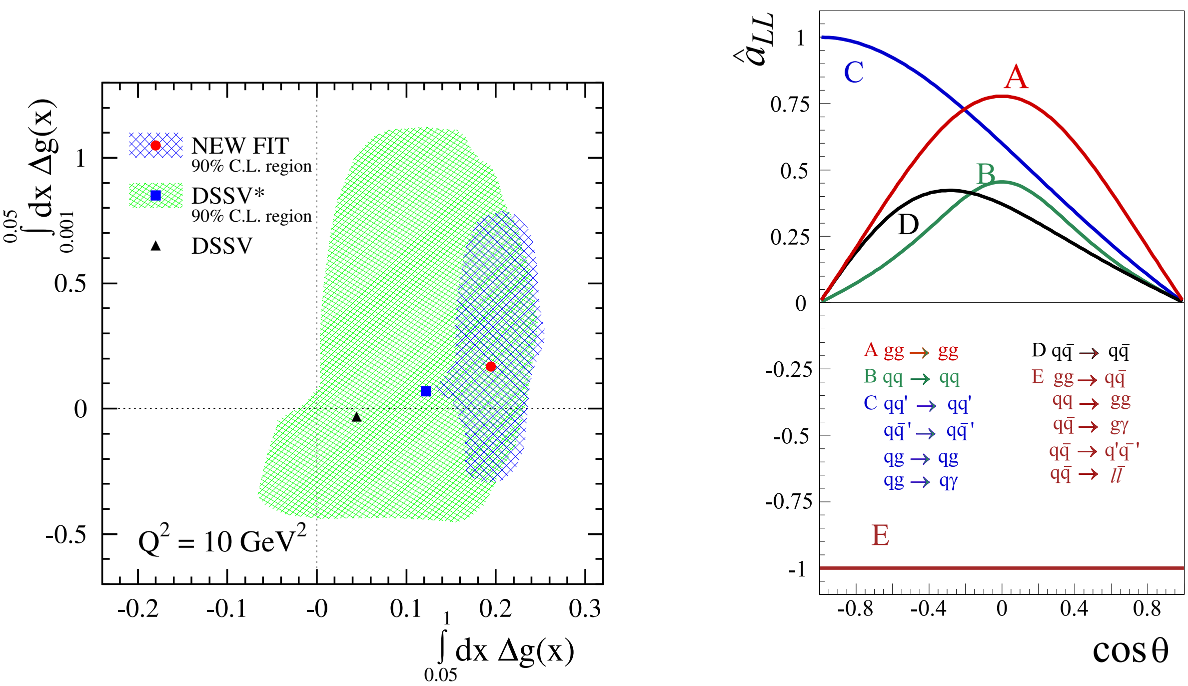
The first attempt to measure the gluon polarization in the nucleon was made by the FNAL E581/704 Collaboration using a 200 GeV polarized proton beam and a polarized proton target [101]. They measured the longitudinal double-spin asymmetries A_{LL} for inclusive multi-γ and $\pi^0\pi^0$ production to be consistent with zero within their sensitivities. In the following years a set of SIDIS measurements was performed by the HERMES [102], SMC [103] and COMPASS [104–108] experiments. The production of hadron pairs with high transverse momenta and the production of the open charm where the photon-gluon fusion mechanism dominates were studied. It was figured out that with a large uncertainty the value of ΔG is close to zero. Nevertheless, for gluons carrying a large fraction x of the nucleon momentum, an evidence of a positive polarization has been observed, see Fig. 2.6(a). New results for ΔG were obtained from the measurement of the A_{LL} asymmetries in the inclusive production of high-p_T neutral pions [109–111], η-mesons [109], jets [112], heavy flavors [113] and, recently, J/ψ-mesons [114] in polarized p-p collisions at RHIC. The new data in general are in agreement with SIDIS measurements, which demonstrates the universality of the helicity-dependent parton densities and QCD factorization.

At the moment the most recent sets of polarized PDFs extracted in the NLO approximation are LSS15 [115], DSSV14 [116, 117], NNPDF-pol1.1 [26], and JAM17 [118]. To obtain them, different approaches, parameterizations, and sets of experimental data were used, see Ref. [119] for more details. Fit results for $\Delta g(x)$ from DSSV14 and NNPDF–pol1.1 are presented in Fig. 2.6(b) [117]. The RHIC p-p data put a strong constraint on the size of $\Delta g(x)$ in the range $0.05 < x < 0.2$ but cannot determine its sign as soon as



(a) (b)

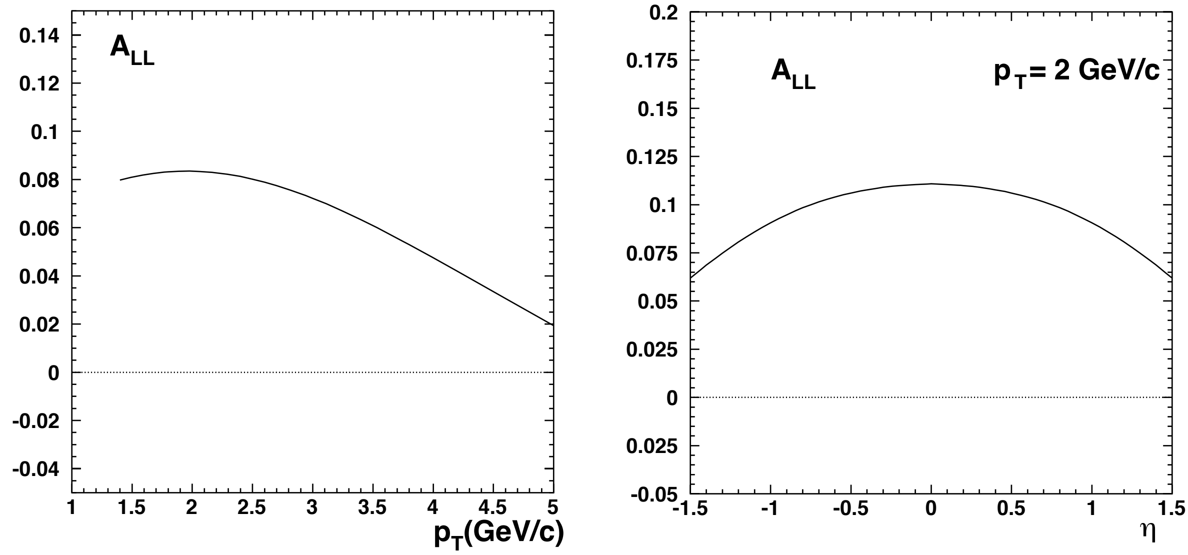
Figure 2.6: (a) SIDIS data on $\Delta g(x)/g(x)$ extracted in LO [108]. (b) Global fit results for the gluon helicity distribution $\Delta g(x)$ [117].



(a) (b)

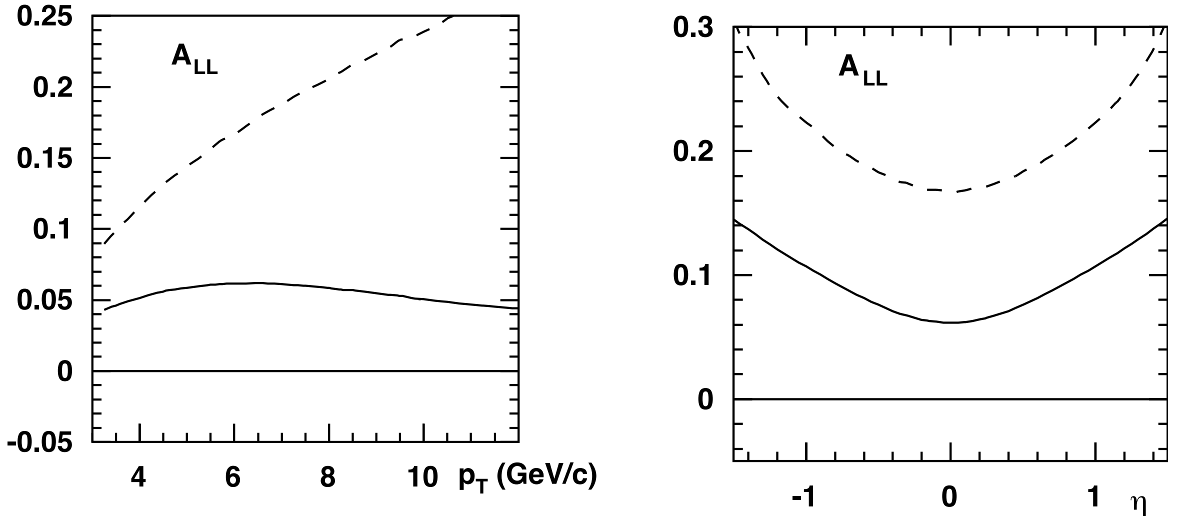
Figure 2.7: (a) Estimates of contributions of low-x and high-x kinematic ranges into ΔG for the DSSV series of the global fit. The 90% C.L. areas are shown [116]. (b) Partonic longitudinal double-spin asymmetries A_{LL} for different hard processes as a function of center-of-mass scattering angle [121].

they mainly probe Δg squared (see details below). The small x region remains still largely unconstrained and could be covered in future by measurements at EIC [25]. Region of high x is covered at the moment only by SIDIS measurements which still lack a proper NLO description [120]. The uncertainty of the contribution to Δg from the kinematic range $0.001 < x < 0.05$ vs. the corresponding contribution from the range $x > 0.05$ for the DSSV global fits is shown in Fig. 2.7(a) [116].



(a) (b)

Figure 2.8: Longitudinal double spin asymmetry A_{LL} for inclusive J/ψ production calculated for p-p collisions at $\sqrt{s} = 39$ GeV in the LO approximation as a function of a) transverse momentum p_T and b) pseudorapidity η [122].



(a) (b)

Figure 2.9: Longitudinal double spin asymmetry A_{LL} for inclusive prompt-photon production calculated for p-p collisions at $\sqrt{s} = 39$ GeV in the LO approximation as a function of a) transverse momentum p_T and b) rapidity η ($p_T = 6$ GeV/c) [122].

In case of the longitudinally polarized p-p collisions the asymmetry A_{LL} is defined as

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}, \tag{2.6}$$

where σ^{++} and σ^{+-} denote the cross sections with the same and opposite proton helicity combinations, respectively. For the prompt photons produced via the gluon Compton scattering

$$A_{LL}^{\gamma} \approx \frac{\Delta g(x_1)}{g_(x_1)} \otimes A_{1p}(x_2) \otimes \hat{a}_{LL}^{gq(\bar{q})\to\gamma q(\bar{q})} + (1 \leftrightarrow 2). \tag{2.7}$$

Here $A_{1p}(x)$ is the asymmetry well-measured in a wide range of x and $\hat{a}_{LL}^{gq(\bar{q})\to\gamma q(\bar{q})}$ is the asymmetry of the corresponding hard process. The Fig. 2.7(b) shows the behavior of $\hat{a}_{LL}$ for different hard processes as a function of the center-of-mass scattering angle. For charmonia and open charm production via the gluon-gluon fusion process the expression for the corresponding asymmetry reads

$$A_{LL}^{c\bar{c}} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g_(x_2)} \otimes \hat{a}_{LL}^{gg\to c\bar{c}X}. \tag{2.8}$$

This asymmetry on the one hand is more sensitive to the gluon polarization than the corresponding one for the prompt photons due to the quadratic dependence on Δg. On the other hand the sign of the Δg value can not be determined from it. So the measurements with prompt photons and heavy-quark states are complementary. The contribution of $q\bar{q}$ annihilation processes to the above-mentioned asymmetries is negligible despite $\hat{a}_{LL} = -1$ because of the smallness of the sea-quark polarization in the nucleon.

It is important to emphasise that a sizable systematic uncertainty of A_{LL} measurements in the inclusive J/ψ production comes from our limited knowledge of charmonia production mechanisms including the feed-down contribution. Each of them has different partonic asymmetries $\hat{a}_{LL}$ [123]. For the Δg estimation in Ref. [114] the value of $\hat{a}_{LL}^{J/\psi}$ has been forced to -1. The SPD setup will have the possibility to reconstruct $\chi_c J$ states via their radiative decays and resolve J/ψ and $\psi(2S)$ signals in a wide kinematic range and disentangle contributions of different production mechanisms. The quality of the Δg estimation could be significantly improved by measuring A_{LL} separately for each charmonium state.

Predictions for the longitudinal double-spin asymmetries A_{LL} in p-p collisions can be found in Refs. [124] (J/ψ) and [125] (prompt photons). They mostly cover the kinematic range of the RHIC experiments. Some estimates for A_{LL} in charmonia [122] and prompt-photon [122, 126, 127] production at $\sqrt{s}$ = 39 GeV (see Figs. 2.8 and 2.9, respectively) have been done in preparation of the unrealized HERA-$\vec{N}$ project.

The authors of the Ref. [128] proposed to extract information about the gluon helicity Δg via studying of the production of high-p_T prompt photons accompanied by Σ^+ hyperons. To do that the single longitudinal spin asymmetry $A_L^{\gamma\Sigma}$ and the polarization of the produced Σ^+ hyperons should be measured. However, further elaboration of this method is needed.

1.8 Gluon-related TMD and twist-3 effects with transversely polarized beams

One of the promising ways to investigate the spin structure of the nucleon is the study of transverse single-spin asymmetries (SSAs) in the inclusive production of different final states in high-energy interactions. The SSA A_N is defined as

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}, \tag{2.9}$$

where $\sigma^{\uparrow}$ and $\sigma^{\downarrow}$ denote the inclusive production cross sections with opposite transverse polarization of one of the colliding particles. At the moment, more than forty years after the transverse spin phenomena were discovered, a wealth of experimental data indicating non-zero A_N in the lepton-nucleon and nucleon-nucleon interactions was collected. However, our understanding of the SSA phenomenon is not yet conclusive.

Theoretically two dual approaches are used to explain the transverse single-spin asymmetries: the collinear twist-3 formalism and the transverse momentum dependent (TMD) factorization approach. In the first one at large transverse momenta $p_T \gg \Lambda_{QCD}$ of a produced particle, the collinear factorization involving twist-3 contributions for three-parton (Efremov-Teryaev-Qiu-Sterman) correlations [129–132] are used. Here $\Lambda_{QCD} \approx 200$ MeV is the QCD scale. An alternative approach assumes the TMD factorization, valid for $p_T \ll Q$, where the SSAs come from the initial-state quark and gluon Sivers functions or the final-state Collins fragmentation functions. The Sivers function $f_{1T}^{\perp,q(g)}(x,k_T)$ is a TMD PDF that describes the left-right asymmetry in the distribution of the partons w.r.t. to the plane defined by the nucleon spin and momentum vectors. Originating from the correlation between the spin of the nucleon and the orbital motion of partons, it is an important detail of the three-dimensional picture of the nucleon. This function is responsible for the so-called Sivers effect (for both quarks and gluons) that was first suggested in [133] as an explanation for the large single transverse spin asymmetries A_N in the inclusive production of the nucleon. More on the theoretical and experimental status of the transverse spin structure of the nucleon can be found in Refs. [13, 134]. The first attempt to access the gluon Sivers function (GSF) studying azimuthal asymmetries in high-p_T hadron pair production in SIDIS of transversely polarised deuterons and protons, was performed by COMPASS [20]. Using neural network techniques the contribution originating from Photon–Gluon Fusion (PGF) subprocess has been separated from the leading-order virtual-photon absorption and QCD Compton scattering subprocesses. The measured combined proton-deuteron PGF-asymmetry was found to be negative and more than two standard deviations below zero, which supports the possible existence of a non-zero Sivers function. In the meantime, COMPASS did not see any signal for the PGF Collins asymmetry, which can analogously be related to the gluon transversity distribution. COMPASS studied GSF also through Sivers asymmetry in the J/ψ-production channel [21], again obtaining an indication of a negative asymmetry.

Recently, in Ref. [135] a first estimate of the GSF was obtained using the midrapidity data on the A_N SSA, measured in π^0 production at RHIC [16]. The extraction was performed within the GPM framework using GRV98-LO set for the unpolarized PDF and available parameterizations for the quark Sivers functions (SIDIS1 from Ref. [136] and SIDIS2 from Ref. [137]). The two parameterizations were obtained using different options for fragmentation functions, namely Kretzer [138] and DSS07 [139] sets, which give significantly different results for gluons. The latter point has a strong impact on the extracted GSF especially in low-x region. First k_T-moments of the GSF $\Delta_N^{q(g)}(x,k_T)$ for the SIDIS1 and SIDIS2 sets are shown in Fig. 2.10 (a) and (b), respectively.

The gluon Sivers function is expected to satisfy the positivity bound defined as two time the unpolarized TMD gluon distribution. Although, some theoretical expectations are that the gluon Sivers function at relatively high x is about 1/3 of the quark one [134].

Several inclusive processes were proposed to access the gluon-induced spin effects in transversely polarized p-p collisions. Single spin asymmetries for production of charmonia [140] (RHIC, AFTER), open charm [141–144] (RHIC) [144] (AFTER), and prompt photons [131, 145] (E704), [146] (RHIC) were estimated using both approaches for the experimental conditions of the past, present, and future experiments.

The SSA $A_N^{J/\psi}$ in the J/ψ production was measured by PHENIX in the p-p and p-A collisions at $\sqrt{s_{NN}} =$ 200 GeV/c [17, 18]. The obtained values for $A_N^{J/\psi}$ are consistent with zero for negative and positive x_F. Theoretical predictions [140] based on the Color Evaporation Model with TMD approach and the gluon Sivers function from Ref. [147] for different center-of-mass energies are shown in Fig. 2.11(a) as functions of rapidity y. Since the J/ψ production mechanism is not well understood, the measurement of the $A_N^{J/\psi}$ may bring a valuable input to that matter as well. Predictions for $A_N^{J/\psi}$ in proton-proton collisions at NICA energy $\sqrt{s} = 27$ GeV, obtained in GPM + NRQCD approach, as function of x_F and p_T are shown in the Figure (2.12). For comparison, results are presented for SIDIS1 [136] and D'Alesio et al. [148, 149] parameterizations of proton Sivers function.

A measurement with open-heavy hadrons (both D- and B-mesons) was performed at RHIC (PHENIX, $\sqrt{s} = 200$ GeV) [19] using high-p_T muons from their semileptonic decays. Obtained results are affected by relatively large statistical uncertainties and do not exhibit any significant non-zero asymmetry. Nevertheless, the results do not contradict the predictions of the twist-3 approach from Ref. [142]. The Sivers effect contribution to the A_N^D asymmetry calculated within the Generalized Parton Model for $\sqrt{s} = 27$ GeV is presented in Fig. 2.11(b).

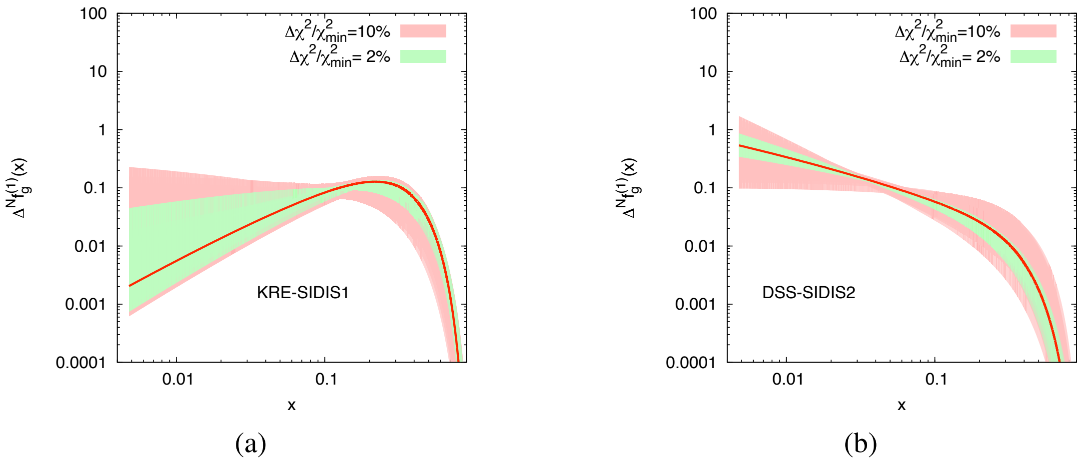


Figure 2.10: The first k_T-moment of the gluon Sivers function for SIDIS1 [136] and SIDIS2 [137] extractions of the quark Sivers functions [135].

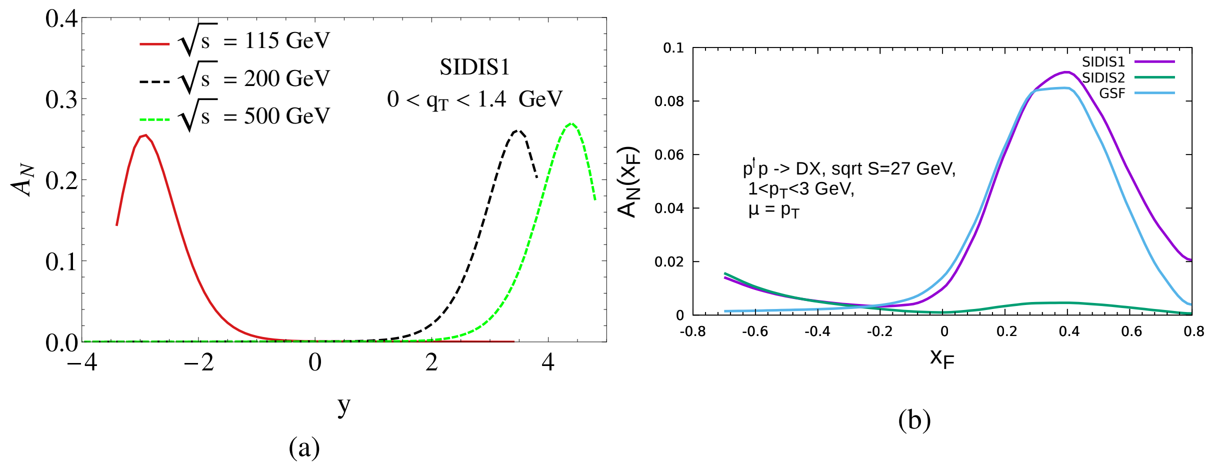
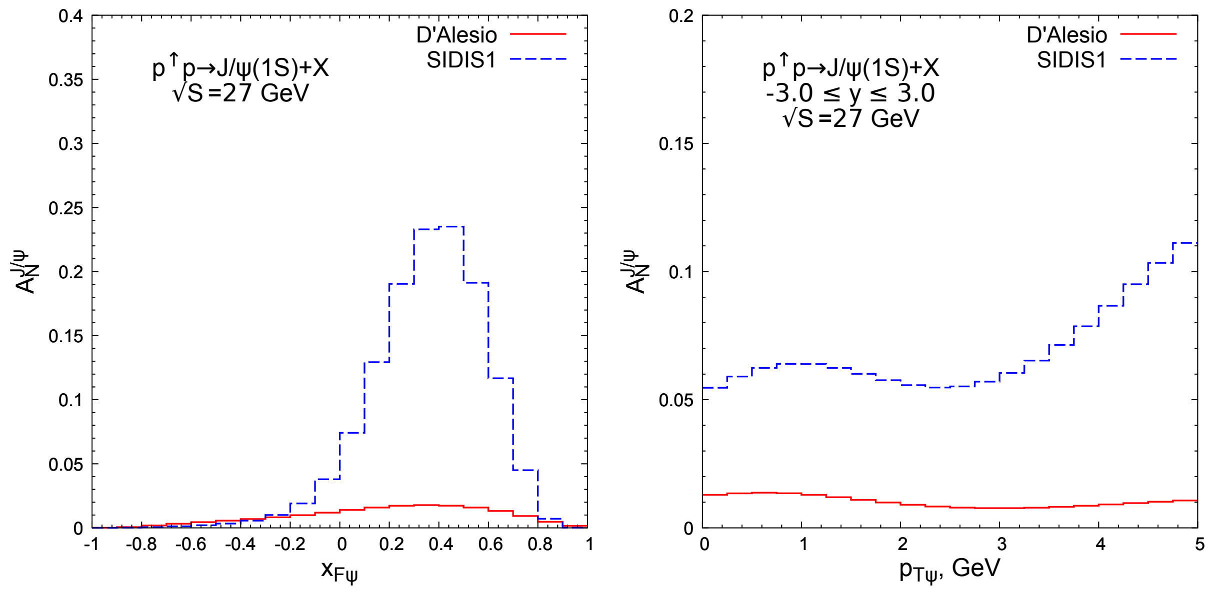


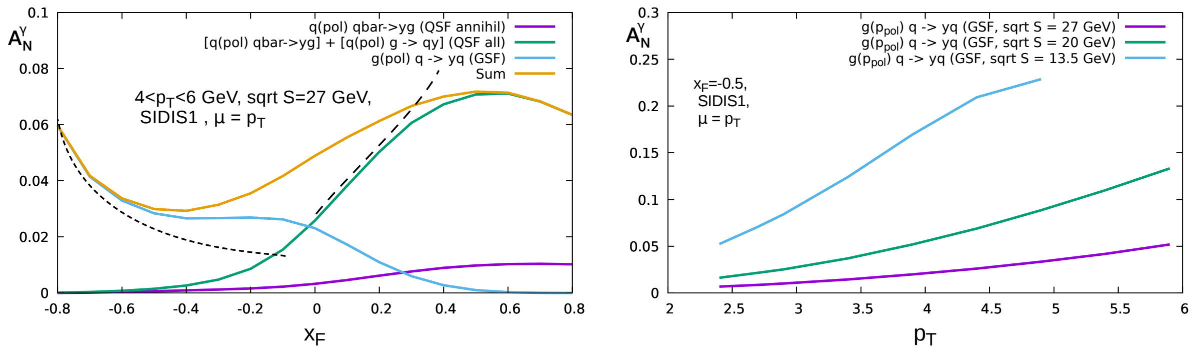
Figure 2.11: (a) Predictions for $A_N^{J/\psi}$ for $\sqrt{s} = 115$ GeV (AFTER), 200 GeV and 500 GeV (RHIC) as a function of rapidity y[140]. (b) Sivers effect contribution to the A_N^D asymmetry calculated within the Generalized Parton Model.

Measurement of the A_N^γ SSA with prompt photons provides a unique opportunity to study the Sivers PDF and twist-3 correlation functions , since the corresponding hard process does not involve fragmentation in the final state and thus is exempt from the Collins effect. The first attempt to measure A_N^γ at $\sqrt{s} = 19.4$ GeV was performed at the fixed target experiment E704 at Fermilab in the kinematic range $-0.15 < x_F < 0.15$ and 2.5 GeV/$c < p_T <$ 3.1 GeV/c. The results were consistent with zero within large statistical and systematic uncertainties [150]. Figure 2.13(a) shows the expected A_N^γ asymmetry as a function of x_F for $\sqrt{s} = 27$ GeV based on the SIDIS1 extraction of the gluon Sivers function. Quark and gluon contributions from the gluon Compton scattering, dominating at positive and negative values of x_F, respectively, are shown separately. The $q\bar{q}$ annihilation contribution is also presented. Dashed lines illustrate the twist-3 predictions for $\sqrt{s} = 30$ GeV and $p_T = 4$ GeV/c for negative [145] and positive [131] values of x_F. The p_T dependence of the A_N^γ asymmetry at $x_F = -0.5$ is shown for different values of $\sqrt{s}$ in Fig. 2.13(b).



(a) (a)

Figure 2.12: Predictions for $A_N^{J/\psi}$ as function of x_F (a) and p_T (b) in p-p collisions at the energy $\sqrt{S} = 27$ GeV obtained in GPM + NRQCD approach.



(a) (a)

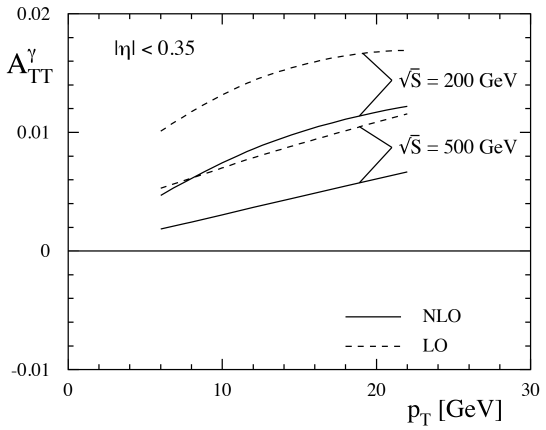
Figure 2.13: (a) x_F dependence of the asymmetry A_N^γ calculated basing on the SIDIS1 Sivers function for $\sqrt{s} = 27$ GeV and $4 < p_T < 6$ GeV. Gluon and quark contributions are shown separately by color solid lines. Dashed lines illustrate the twist-3 predictions for $\sqrt{s} = 30$ GeV and $p_T = 4$ GeV for negative [145] and positive [131] values of x_F. (b) p_T dependence of the A_N^γ asymmetry for different values of $\sqrt{s}$ at $x_F = -0.5$.

1.9 Gluon transversity in deuteron

The transversity function $\Delta_T q(x)$ is defined for partons as the difference of probabilities to find in a transversely polarized nucleon a parton with the same and opposite spin orientations. In spite of the definition is similar to the helicity function $\Delta q(x)$, the transversity describes a completely different aspect of the nucleon spin structure. This function is known quite well after a series of SIDIS and Drell-Yan experiments. As soon as the transversity is related with the spin flip, for the spin-1/2 nucleon only a quark contribution ($\Delta s = 1$) is possible while $\Delta s = 2$ for the spin-1 gluons is forbidden in the twist-2.

Nevertheless, a tiny nonzero gluon transversity is allowed due to higher-twist effects and possible physics beyond the Standard model like electric dipole moment of the neutron [151]. The transverse double spin asymmetry A_{TT} defined for interaction of transversely polarized hadrons by the similar manner as A_{LL} is a way to access the transversity. But due to the absence of a gluonic contribution in the leading order in the case of the nucleon interactions $A_{TT} \ll A_{LL}$. As an example, the asymmetry A^{γ}_{TT} for the prompt-photon production at 200 and 500 GeV coming from the $q\bar{q}$ annihilation process calculated in LO [152] and NLO [153] is shown in Fig. 2.14(b).

Situation changes [154] for the spin-1 deuteron where a gluon component not embedded into the nucleons is possible. So in the collision of transversely polarized deuterons a nonzero contribution of the gluon transversity $\Delta_T g(x)$ to A_{TT} asymmetries is possible already in the twist-2. At the moment there is no any experimental data on the gluon transversity in the deuteron. The gluon-induced (NLO) Drell-Yan process $qg \to q\gamma^* \to q\mu^+\mu^-$ was proposed in Ref. [151] as a way to access it in the polarized *p*-*d* collisions at the SpinQuest experiment at Fermilab. A measurement of the double transverse spin asymmetries A_{TT} in the gluon-induced processes at polarized *d*-*d* collisions at NICA SPD could be an alternative way to access the $\Delta_T g(x)$.



(a)

Figure 2.14: (a) A^{γ}_{TT} asymmetry for the prompt-photon production at 200 and 500 GeV coming from the $q\bar{q}$ annihilation process calculated in LO [152] and NLO [153].

1.10 Deuteron tensor polarization and shear forces

The availability of tensor polarized deuteron beam opens a possibility to study shear forces generated by quarks and gluons [155]. The natural way to get the traceless part of the energy-momentum tensor related to shear is provided just by tensor polarization, as the relevant tensor $S^{\mu\nu}$ is a traceless one by construction. The contribution of the ”tensor polarized” parton distribution C^T [156, 157] (introduced as an ”aligned” one [158]) is constrained by the zero sum rule [158] for its second moment (complementing the Close-Kumano sum rule [157])which may be decomposed into quark and gluon components [159]:

$$\sum_{i=q,\bar{q}} \int_0^1 C_i^T(x) x dx = \delta_T(Q^2), \tag{2.10}$$

$$\int_0^1 C_G^T(x) x dx = -\delta_T(Q^2). \tag{2.11}$$

As a result, the matrix elements of energy momentum tensors of quarks and gluons look like

$$\sum_i \langle P,S|T_i^{\mu\nu}|P,S\rangle_{Q^2} = 2P^\mu P^\nu (1-\delta(Q^2)) + 2M^2 S^{\mu\nu}\delta_T(Q^2) \tag{2.12}$$

$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^\mu P^\nu \delta(Q^2) - 2M^2 S^{\mu\nu}\delta_T(Q^2), \tag{2.13}$$

where the second terms describe the average (integrated over transverse distance) shear force. Here M is the nucleon mass.

The zero sum rules (2.10) were later interpreted [160] as yet another manifestation of Equivalence Principle (EP), as it was done earlier [161] for Ji sum rules. In turn, the smallness of δ_T, compatible with the existing HERMES data, was suggested [160] to be the new manifestation of Extended Equivalence Principle (ExEP) [162–164] valid separately for quarks and gluons in non-perturbative QCD due to the confinement and chiral symmetry violation. It was originally suggested for anomalous gravitomagnetic moments [162, 164]. In particular, it provides the rotation of spin in the terrestrial experiment with the angular velocity of Earth rotation. Let us stress, that it may seem trivial if spin is considered just as a vector. However, it became highly non-trivial if the measurement of spin by the device rotating together with Earth is taken into account. This is a particular example of the practical importance of the quantum theory of measurement. Another example may be represented by the Unruh radiation in heavy-ion collisions [165], which implies that the particles production may be also considered as a quantum-mechanical measurement in the non-inertial hadronic medium.

Recently, ExEP was also discovered for the pressure [166].

To check ExEP for shear force one may use future studies of DIS at JLab and of Drell-Yan process with tensor polarized deuterons [167] [5].

Note that tensor polarized parton distribution may be also measured in *any* hard process with the relevant combination of deuteron polarizations, in particular, for large p_T pions production, providing much better statistics. The correspondent quantity can be the P-even Single Spin asymmetry

$$A_T = \frac{d\sigma(+) + d\sigma(-) - 2d\sigma(0)}{d\sigma(+) + d\sigma(-) + d\sigma(0)} \sim \frac{\sum_{i=q,\bar{q},g} \int d\hat{\sigma}_i C_i^T(x)}{\sum_{i=q,\bar{q},g} \int d\hat{\sigma}_i q_i(x)}, \tag{2.14}$$

where the differential cross section with definite polarization of deuteron appear.

Note that due to the tensor polarization tensor being traceless the sum rule for the three mutually orthogonal orientations of coordinate frame is valid [158]:

$$\sum_i S_{zz}^i = 0. \tag{2.15}$$

As a result, the leading twist kinematically dominant ”longitudinal” tensor polarization can be obtained by accelerating *transverse* polarized deuterons which will be accessible at NICA.

[5] Complementary probes are provided by vector mesons [163].

2 Quarks in proton and deuteron

2.1 SSA for pions and kaons

2.2 Drell-Yan pair production

Production of Drell-Yan (DY) pairs in polarized hadronic collisions $pp \to \gamma^* \to \mu^+\mu^-$ is a promising way to touch TMP PDFs of valence quarks and sea antiquarks via the measurement of azimuthal asymmetries. A tiny DY cross section and huge combinatorial background coming from decays of secondary pions and kaons into muons make this task rather difficult. A typical detector configuration for such kind of studies at $\sqrt{s} \sim 20$ GeV is a fixed-target beam-dump setup where due to the Lorentz boost the most of secondary pions and kaons are stopped in a thick absorber before their decay. At the moment only the COMPASS experiment at CERN has presented the results for the three azimuthal asymmetries measured in pion-induced polarized DY [168, 169]. The observed glimpse of the sign change in Sivers asymmetries is found to be consistent with the fundamental prediction of QCD that the Sivers TMD PDF extracted from DY has a sign opposite to the one extracted from SIDIS data. Unique results for the Sivers functions of $\bar{u}$ and $\bar{d}$ are expected from the SpinQuest experiment at Fermilab [170, 171].

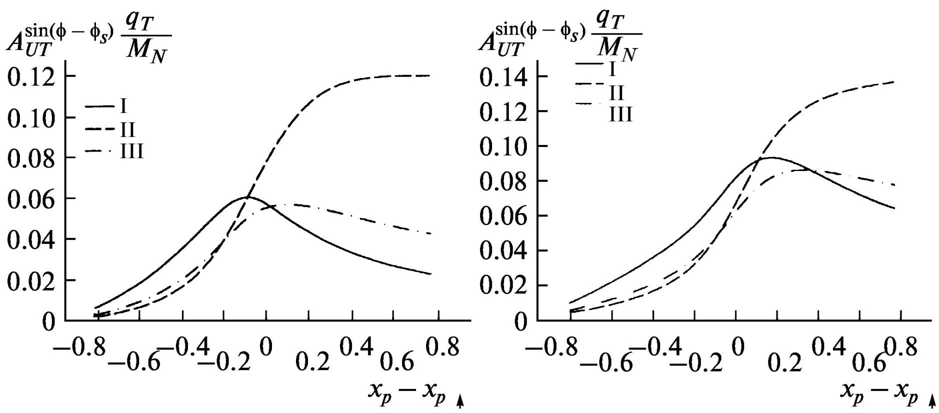


Figure 2.15: Estimated Sivers asymmetries for NICA conditions $s = 20\ GeV$, $Q^2 = 4\ GeV^2$ (left) and $s = 20\ GeV$, $Q^2 = 15\ GeV^2$ (right). Fits for Sivers functions are taken from [172].

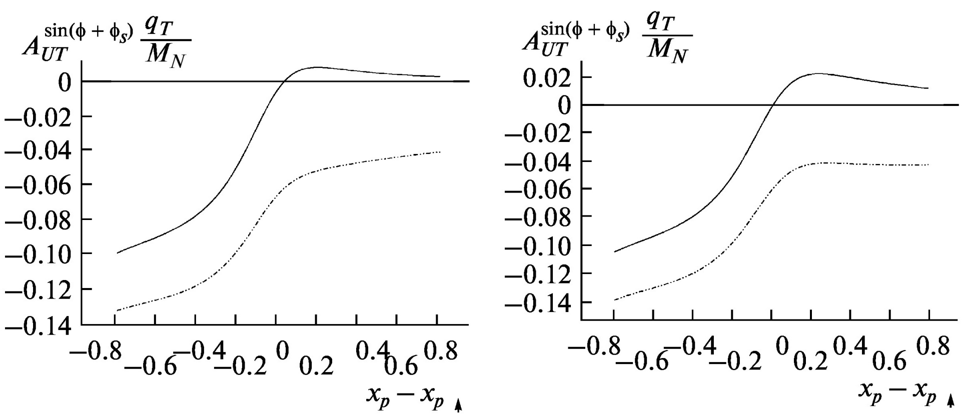
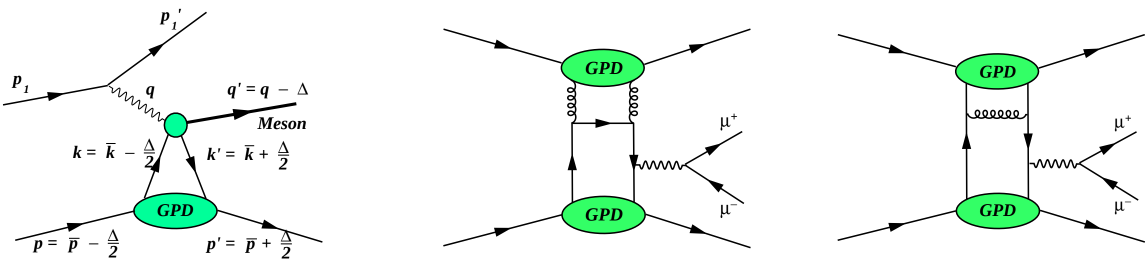


Figure 2.16: Estimated Boer-Mulders asymmetries for NICA conditions.

Unfortunately the Spin Physics Detector cannot use the advantage of fixed-target beam-dump setups and expected background conditions for the Drell-Yan measurements are rather untoward. However further improvement of experimental techniques and analysis procedures could give a chance to access polarized DY at SPD. Estimated Sivers and Boer-Mulders asymmetries for SPD conditions are presented at Fig. 2.15 and 2.16, respectively.

2.3 Generalized parton distributions

The concept of Generalised Parton Distributions (GPDs) is a complementary to TMD PDFs approach to describe the three-dimensional structure of hadrons. Study of the deeply virtual meson production (DVMP) is one of the proven ways to access GPDs. This process has been investigated at [] ... using lepton and photon beams. An exclusive electromagnetic process $pp \to ppM$ Fig. 2.17(a) where the first proton radiates a photon with low virtuality that interacts with the other proton and produce the meson, could be used to access Generalised Parton Distributions at SPD. At SPD energies the meson photoproduction amplitude can be presented in a factorized form as a convolution of the hard scattering part which can be calculated perturbatively and the GPDs [173, 174]. In case of vector mesons production the odderon exchange (that could be described as exchange by at least 3 gluons) is also possible and the interference of these two channels is the matter of special interest. Ultraperipheral p-A collisions at SPD which enhance the photoproduction contribution by several orders of magnitude could also be considered. Ultraperipheral processes could be also used for test of the most general non-perturbative concept of the Generalized Transverse Momentum dependent Distributions (GTMD). This possibility was explored for high energies in Ref. [175] but the approach could be extended down to the SPD energies.



(a) (b) (c)

Figure 2.17: (a) Vector meson production at NICA via photoproduction mechanism or odderon exchange. (b) Drell-Yan process with gluon and quark GPDs.

The exclusive production of the J/ψ meson can be studied at SPD at energies $W = \sqrt{(q+p)^2} \sim 5-15$ GeV. Here q and p are the 4-momenta of a virtual photon (odderon) and a proton, respectively. Large meson mass makes possible to perform perturbative calculations at sufficiently low Q^2 where the the photon exchange should dominate. The corresponding cross section is estimated to be of about $\sigma_{J/\psi} \sim 10$ nb. The main contribution to the cross section is coming from the gluon GPDs.

The exclusive Drell-Yan (exDY) process was proposed for study of GPDs in p-p collisions in Ref. [176]. The kinematics of this process is defined by convolution of two GPDs. Both quark and gluon GPDs contribute to the exDY cross section via the diagrams shown schematically at Fig. .

Investigation of the cross section determined by two-GPDs effects is in progress now [177]. It is shown that the gluon and sea quark GPDs lead to the cross section which does not decrease with the grows of energy. The exDY cross section $d\sigma/dQ^2$ at NICA kinematics $\sqrt{s} = 24$ GeV and $Q^2 = 5$ (GeV/c)^2 is estimated as 3 pb/(GeV/c)^2 thst is much smaller with respect to the inclusive Drell-Yan cross section.

Nevertheless exclusivity requirement applied in the analysis of future SPD dimuon data could increase the signal-to-background ratio. It should be mentioned that J/ψ could also be produced exclusively in the similar way.

2.4 Polarized fragmentation functions

3 Tests of QCD basics at low energies [U. Uzikov, A. Guskov]

3.1 Elastic *pp* and *dd* scattering

3.2 Multiquark correlations and systems

3.3 Central nucleon-nucleon collisions [Komarov]

The main experimental basis for clarification of the non-perturbative QCD (NPQCD) baryon structure is the baryon spectroscopy and the short-range nucleon-nucleon interaction. The more the nucleons are overlapped during collision, the higher sensitivity of the latter to the NPQCD structure. Maximum sensitivity can be reached in conditions of overlapping of the quark core of nucleons and sufficiently long time of this overlapping. Unfortunately, these conditions practically are not met in the available nucleon-nucleon experimental data: at relatively low energies the effective momentum transfers are not sufficiently high, and at high energies the contents of colliding nucleons diverge too quickly. This circumstance explains why the region of the *NN* collisions at distances smaller than the radius of the nucleon core still remains unexplored. Access to this area is possible through the central collisions (CC) of the nucleons at adequate energies. The collisions are usually named central if the corresponding impact parameter R is small, $R < r_{core} \approx 0.4 fm$.

Overlapping of the nucleon cores can be achieved at the center-of-mass (CM) energies $\sqrt{s}_{min} = U_{rep}(0) + 2m_N$, where $U_{rep}(0)$ is the repulsive potential of the *NN* interaction at zero distance, $U_{rep}(0) \approx 1$ GeV. Then the minimal energy of interest is $\sqrt{s}_{min} \approx 2.9$ GeV. At the energies less than 7.5 GeV (corresponding the chiral symmetry breaking momentum $\Lambda_{\chi SB} \approx 1.2$ GeV/c [178, 179]) the resulting intermediate state is an excited (6q)* system of six chiral constituent quarks interacting via goldstone boson, gluon exchange and confinement potential. This interaction is supposed to be much more intensive than in the perturbative quark-gluon system, and provides therefore relatively long lifetime of the system, sufficient for manifestation of the NPQCD structure. In some conditions, it can even produce quasi-bound states, resonance dibaryons. It should be stressed that the (6q)* system under consideration is characterized by very high baryon and energy densities since two baryons and the whole CM energy is concentrated in a small volume of about $4/3\pi(r_{core})^3$ size.

Decay of the (6q)* system leads to reconstruction of hadronic states in the form

$$p + p \to (6q)^* \to N + N + Mesons, \tag{2.16}$$

where *Mesons* denotes the system of light mesons, predominantly pions.

Peripheral *NN* collisions proceed mainly via production of excited baryons N^* in the intermediate state

$$p + p \to \{(N + N^*)\text{or}(N^* + N^*)\} \to N + N + Mesons \tag{2.17}$$

and have, in general, the final states similar to that in the central collisions (2.16). Therefore, in order to distinguish the central collision process (2.16) from the peripheral (2.17), one needs special centrality criteria. According to [180, 181], there are two such criteria: A) using of the reaction

$$N + N \to d(90^\circ) + Mesons, \tag{2.18}$$

where $d(90^\circ)$ is a deuteron emitted at the angle close to 90° [6]; B) smallness of the interaction region size $r_{int} < r_{core}$, where $r_{int} = 1/(-Q^2)^{1/2}$ with $Q = P_1 - D/2$. Here P_1 is the four-momentum of one of the initial nucleons and D is the four-momentum of the final joined nucleon pair.

[6] or reaction $N + N \to \{pp\}_{S_0}(90^\circ) + Mesons$, where $\{pp\}_{S_0}$ is a proton pair in the $^1S_0$ state

Evaluation of feasibility of experiments with the above centrality criteria shows [181] that at the expected luminosity [29] the event rate in SPD will be at the level of tens events per second. Hence, rather large amount of information about the processes of interest can be obtained in a reasonable time.

The following goals can be aimed, in particular, in experiments with central collisions:

- study of known and search for new dibaryon resonances in the region of $\sqrt{s} \approx 2.5 - 7.5$ GeV;
- search for the predicted dominance of the σ-meson production [182];
- search for the expected effects caused by the chiral symmetry partial restoration (drop of mass and width of mesons) [183, 184];
- study of the energy dependence of the reaction (2.18) cross section, what is sensitive to the strength of the confinement forces and the value of the chiral symmetry breaking momentum;
- first measurement of the analyzing power of the reaction (2.18) for transverse and longitudinal beam polarization.

It is worth to mention that experiments of this kind have never been carried out systematically. There exists a possibility to observe new unexpected effects that can induce new approaches in solving the fundamental problems of the non-perturbative QCD.

3.4 Exclusive hard processes with deuteron [M. Strikman]

Questions involved in studies of the short-range / high momentum nuclear structure and understanding microscopic nucleon structure and dynamics of large momentum transfer processes are delicately intertwined: understanding of hard dynamics of two body processes is also necessary for precision studies of the short range nuclear structure. Exclusive large t reactions like $p^2H \to ppn$ process can address many of these questions. Advantages of such reaction is a good knowledge of the nonrelativistic deuteron wave function and ability to choose both kinematics sensitive to dynamics of elastic NN scattering and the kinematics sensitive to short range deuteron structure.The collider kinematics presents a number of advantages as all particles in the reactions in question have large momenta and hence can be easily detected.

3.4.1 Probing dynamics of NN interaction

The simplest kinematics is production of two nucleons approximately back to back large transverse momenta and spectator nucleon with longitudinal momentum $p \sim p_{^2H}/2$ and transverse momentum $\geq$ 200 MeV/c [185, 186].

In the impulse approximation this process corresponds to elastic scattering of the projectile proton off a quasifree nucleon of the target. Inn this kinematics soft rescatterings of the initial and final nucleons, which accompany the hard $pp(pn)$ reaction are large. The eikonal approximation, which accounts for relativistic kinematics as dictated by the Feynman diagrams, reveals the important role played by the initial and final state interactions in the angular and momentum dependences of the differential cross section in well defined kinematics. The condition for the applicability of the generalized eikonal approximation [187] is that the c.m. scattering angle and invariant mass of the two nucleon system are large enough so that $-t, -u \geq 2$ GeV^2.

It was suggested in [188, 189] that nucleons in the elementary reaction interact in small size configurations with a small cross section - so called color transparency phenomenon. This effect is suppressed by the space - time evolution of nucleon wave packets [190, 191]. However effect of evolution is very small for the deuteron where typical distances between nucleons in the rescattering amplitude are is ≤ 1.5 fm. Hence the discussed process allows *to measure the wave packet size of a nucleon practically right in the interaction point.*

It was pointed out that the hard dynamics in pp and pn elastic scattering may be rather different [192]. Hence it would be instructive to compare the channels where pp and pn are produced with large p_t.

Experiments with polarized beams would greatly add to this program: due to a better separation of kinematic domains where impulse approximation, double and triple scattering dominate, while the studies $\vec{p}\vec{d} \to pNN$ processes will allow both to study spin structure of pp and pn elastic scattering at large t (the later is practically not known). Also, it would be possible to find out whether the a strong difference between the cross sections of elastic scattering of protons with parallel and antiparallel spins[193] involves collisions of protons in configurations with sizes depending on the spin orientation.

It would be possible also to study effects of coherence in the channels where exchange by gluons in t-channel is not possible, for example $pd \to \Delta NN$. In particular, it would be possible to test the effect of chiral transparency suggested in [194] - suppression of the pion field in the nucleons experiencing large $-t$ scattering.

3.4.2 Probing microscopic deuteron structure

It is established now that the dominant source of the short range/ high momentum correlations (SRC) in nuclei are proton - neutron correlations with the same quantum numbers as the deuteron and with high momentum tail similar to that in the deuteron, see review in [195, 196]. Hence the deuteron serves as a kind of the hydrogen atom of the SRC physics. Only after it would be tested experimentally that approximations currently used for the description of the p^2H reaction work well, it would be possible to perform high precision studies of SRC in heavier nuclei.

It was demonstrated in Ref.[185, 186] that under specific kinematical conditions (in particular low transverse momenta of a slow nucleons in the deuteron rest frame)) the effect of initial and final state interactions can be accounted for by rescaling the cross section calculated within the plane wave impulse approximation. In this kinematics it would be possible to check universality of the wave function - in particular its independence on the momentum transfer in the elementary reaction. Such factorization is expected to break down at sufficiently large $-t$ and $-u$ where scattering involves interaction of nucleons in the small size configurations (the color transparency regime) since the small size configurations are suppressed in bound nucleons with suppression growing with the nucleon off shellness [191].

Studies of the nonnucleonic configurations in the deuteron as well as relativistic effects. in the scattering off a polarized deuteron are of separate interest. In particular, it would be possible to a search for non-nucleonic degrees of freedom like 6 quark, two Δ isobars via production reaction $p^2H \to \Delta^{++} + p + \Delta^-$ with Δ^{++} and proton back to back and Δ^- being slow in the deuteron rest frame.

3.5 Polarized pd elastic scattering within the Glauber model and pN spin amplitudes [Yu. Uzikov]

Nucleon-nucleon elastic scattering contains fundamental information on the dynamics of the NN interaction and constitutes a basic process in physics of atomic nuclei and hadrons. Full information about spin amplitudes of pp and pn elastic scattering can be obtained, in principle, from complete polarization experiment, which, however, requires to measure dozen independent observables at given collision enegy that constitutes too complicated experimental task. A systematic reconstruction of these amplitudes from scattering data is provided by the SAID data base [197] and covers laboratory energies up to 3 GeV ($p_{lab} \approx 3.8$ GeV/c) for pp and 1.2 GeV ($p_{lab} \approx 1.9$ GeV/c) for pn scattering. At higher energies there are only non-complete data on pp scattering, whereas information about the pn system is very scarse. In the literature there are some models and corresponding parametrizations for pN amplitudes, obtained in the eikonal approach [198] for the lab momentum 6 GeV/c and within the Regge phenomenology [199] for 3-50 GeV/c (corresponding to $2.77 < \sqrt{s} < 10$ GeV). Another Regge-type parametrization for values of s above 6 GeV^2 ($p_{lab} \geq 2.2$ GeV/c) was presented in Ref. [200]. A possible way to check existing parametrizations is to study spin effects in proton-deuteron (pd) and neutron-deuteron (nd) elastic and quasi-elastic scattering. At high energies and small four-momentum transfer t, pd scattering can be described by the Glauber diffraction theory of multistep scattering, which involves as input on-shell pN elastic scattering amplitudes. Applications of this theory with spin-dependent effects included [201] indicate a good agreement with the pd scattering data at energies about 1 GeV if the SAID data on pN scattering amplitudes are used as starting point of the calculations [202, 203].

The spin-dependent Glauber theory [201, 202] is applied recently [204] to calculate spin observables of pd elastic scattering at 3-50 GeV/c utilizing the pp elastic scattering amplitudes f_{pp} established and parametrized in Ref. [199] within the Regge formalism. As a first approximation, for the pn amplitudes was used likewise the ones for pp from [199]. The Regge approach allows one to construct pn (and $\bar{p}N$) amplitudes together with the pp amplitudes. However, in view of the scarse experimental information about the spin-dependent pn amplitudes and taking into account that the spin-independent parts of the pp and pn amplitudes at high energies are approximately the same, it was assumed in [204] that $f_{pn} = f_{pp}$.

The differential cross section of pp- elastic scatetring and vector anayzing power A_y in the interval of transferred four momentum $0 < -t < 1.5$ GeV^2 are reasonable reproduced with the parameters from Ref. [199]. Numerical results for the observables of pd elastic scattering obtained at $p_l = 4.85$ GeV/c and 45 GeV/c using pN amplitudes from [199] As shown in Ref. [204] available data on pd-elastic differential cross section in forward hemisphere are well described by this model. Vector analyzing power A_y^p decreases in absolute value with increasing energy and similar behaviour demonstrates the A_y^d. In contrast, the spin correlaion coefficients $C_{x,x}$ and $C_{y,y}$ show an oppisite tendency. One should to note, that tenzor analysing powers A_{xx} and A_{xx} are weakly changed with increasing energy, moreover these observables are not changing qualitatively in forward direction if all spin-dependent amplitudes are excluded and only the spin-independent pN amplitude is taken into account. On the hand, spin correlation parameters $C_{x,x}$, $C_{y,y}$ vaninshing in this case. The calculated in [204] polarization observables of the pd-elastic scattering can be measured at SPD NICA that will provide a serious test of the used pN amplitudes. The corresponding differential cross section is rather large in the considered region $p_{lab} = 3-50$ GeV/c and $|t| = 0-2$ GeV^2 being $d\sigma/dt > 0.1$ mb/GeV^2. Expected counting rate N at $p_{lab} = 50$ GeV/c ($q_{pp}^{cm} = 5$ GeV/c) for the luminosity $L = 5\times 10^{30} cm^{-2}s^{-1}$ and for the solid angle $\Delta\Omega = 0.03$ is $N \geq 10^2 s^{-1}$.

3.6 Single-spin physics [V. Abramov]

A systematic study of such single-spin phenomena as the transverse single-spin polarization of hadrons (A_N) and the polarization of hyperons (P_N) in p+p, d+d, C+C and Ca+Ca collisions is proposed. A systematic study means a detailed study of the dependence of the observed A_N and P_N for dozens of reactions on variables such as collision energy ($\sqrt{s}$), Feynman variable ($x_{\rm F}$), transverse momentum (p_T), the atomic weights of the colliding particles (A_1 and A_2), the multiplicity of charged particles (N_{ch}) in the event, and the centrality of collisions. The study of a large number of reactions will reveal the dependence of A_N and P_N on the quantum numbers (spin, isospin, flavor, etc.) of the hadrons participating in the reaction. A systematic study also implies a global analysis of all available single-spin data within a single model in order to identify general behavior and the mechanism of the origin of polarization phenomena.

One of such models is the model of chromomagnetic quark polarization (CPQ) developed by the author [205]. The CPQ model assumes the presence of an inhomogeneous circular transverse chromomagnetic field $\mathbf{B}^a$ in the interaction region of colliding hadrons. The interaction of the chromomagnetic moments of test quarks, which later form the observed hadron, with the field $\mathbf{B}^a$ leads, as a result of the Stern-Gerlach effect, to the appearance of spin effects (with nonzero A_N and P_N). The spin precession of test quarks leads to the phenomenon of oscillations $A_N(x_F)$ and $P_N(x_F)$ depending on the Feynman variable x_F, and the frequency of these oscillations depends on the number of spectator quarks, color charges of quarks and antiquarks, and the direction of their motion in the c.m. of reactions. The frequency of these oscillations is a linear function of the number of quarks and antiquarks - spectators interacting in pairs with each of the test quarks, taking into account the color state of the pair. The highest oscillation frequencies are expected in the case of antibaryon production in baryon collisions and in ion collisions.

The CPQ model also predicts for a number of reactions such a phenomenon as the resonance dependence of A_N and P_N on energy ($\sqrt{s}$), which occurs if the sign of the color charge of the test quark and spectators is opposite. The most interesting reaction in this respect is the production of anti-lambda in various initial states of the beams of the NICA collider, for which the resonance energy is close to 7 GeV in the c.m.

The threshold dependence of A_N on the hadron production angle in the c.m. is also predicted. An example of the manifestation of the threshold dependence A_N is the reaction $p^{\uparrow}p(A) \to \pi^- X$, for which the threshold angle is 74^o, since the test quark is the d-quark, which is heavier than the u-quark.

An important advantage of hyperons is the ability to measure A_N and P_N for them, which makes it possible to compare them with each other and with model predictions.

The rate of pion production in pp collisions varies from $3 \cdot 10^7/s$ at 23 GeV to $2 \cdot 10^5/s$ at 7 GeV. In C + C and Ca + Ca collisions, it will be three orders of magnitude lower. The rate of production of hyperons is two orders of magnitude lower than that of pions. Antihyperones are produced 5 to 10 times less frequently than hyperons.

3.7 Scaling onset in exclusive reactions with lightest nuclei and spin observables [Yu. Uzikov, V. Ladygin]

The structure of the lightest nuclei at short distances $r_{NN} < 0.5$ fm or high relative momenta ($q > \hbar/r_{NN} \sim$ 0.4 GeV/c constitues a fundamental problem in nuclear physics. One of the most important questions is related to search for onset of transiton region from meson-baryon to quark-gluon picture on nuclei. A definite signature for transition to the valence quark region is given the constituent counting rules (CCR) [206, 207]. According the dimensional scaling the differential cross section of a binary reaction at enough high incident energy can be parametized as $d\sigma/dt \sim s^{-(n-2)} f(t/s)$, where n is the sum of costituent quarks in all participants, s and t are Mandelstam variables. Many hard processes with free hadrons are consistent with CCR at energies of several GeV. The CCR propetrties of the reactions with the lightest nuclei were observed in photodisintegration of the deuteron $\gamma d \to pn$ at $E_\gamma = 1 - 4$ GeV and ^3He nucleus $^3He(\gamma, pp)n$, $\gamma^3He \to dp$. More earlier data on the reaction $dd \to^3 Hp$,$dd \to^3 Hen$ [208] and $pd \to pd$, as was show in Ref.[209] also follow CCR behavior s^{-22} and s^{-16}, respectively, at surprising low energies, 0.5 GeV. Recently the CCR behaviour of the reaction $pd \to pd$ was observed in [210, 211] at higher energies. On the other hand, the reaction with pion production $pp \to d\pi^+$ does not follow CCR rule demostrating the differential cross section $\sim s^{-9}$ instead of s^{-12}. One possible way to explain this is a partial restortaion of chiral symmetry at enough high excitaion energy [212]. However, systematic study of these properties of the reactions with lightest nuclei are absent. So, important to know whether reaction $pn \to d\rho^0$ follows the CCR behavior and at what minimal energy there is the CCR onset. Assuming the model of the vector meson dominance and taking into account the observed CCR behavior of the $\gamma d \to pn$ reaction, one may expect the $\sim s^{-12}$ dependence of the cross section of the reaction $pn \to d\rho^0$. Furthermore, possible relation between CCR behavior of the upolarized cross section and spin observables of the same reaction are practically not known. The SPD NICA facility provides a good opportunity for this study using polarized beams in pp, dd and pd collisions.

The tensor A_{yy} and vector A_y analyzing power in dp- elastic scattering obtained at 60°, 70°, 80° and 90° in cms versus transverse momentum p_T [213, 214] demonstrates the negative and positive asymptotics, respectively. Note, that negative sign of A_{yy} is observed also in deuteron inclusive breakup at large p_T [**?**].It would be interesting to extend the range of the measurements to larger p_T, where the manifestation of non-nucleonic degrees of freedom is expected. New precise measurements with small statistical and systematic uncertainties at the energies higher than $\sqrt{s}$ $\geq$3.3 GeV and at different scattering angles are required to make a conclusion about the validity of CCR [206, 207] in dp - elastic scattering. We propose to measure also different vector and tensor analyzing powers in dp- elastic scattering at SPD energies.

The measurements of dp- elastic scattering can be performed either with polarized deuterons and unpolarized protons, or with unpolarized deuterons and polarized deuterons. The dp- elastic scattering events can be selected using cuts on the azimuthal and polar scattering angles correlations. The vector A_y and tensor A_{yy} and A_{xx} analyzing powers will be measured simultaneously in the case of the vertically polarized deuteron beam. The precision on the tensor ΔA_{yy} $\sim$0.09 and ΔA_{xx} $\sim$0.09 and on the vector ΔA_y $\sim$0.03 analyzing powers can be achieved for the scattering angle $\sim 90^\circ \pm 5^\circ$ at $\sqrt{s}$ $\sim$4.5 GeV (p_T $\sim$1.7 GeV/c) for 30 days of the beam time at the luminosity $\mathscr{L} \approx 10^{29} cm^{-2} \cdot s^{-1}$. We assume $\sim$75% of the beam polarization from the ideal values of polarization for different spin modes. The spin correlations can be obtained in quasi-free dp- elastic scattering using dd- collisions.

3.8 Yield of antiprotons in hadronic collisions for astrophysical dark matter search

Chapter 3

Polarized beams [A. Kovalenko]

1 Available species and types of collisions

Basic specification to available polarization states and combinations is the following:

- protons: vector polarization, longitudinal and transverse direction in respect to a particle velocity;
- deuterons (possibly helium-3 ions at the second stage): vector and tensor polarization, vertical direction of polarization, changing of the polarization direction at 90° up to about 4 GeV/c momentum;
- possibility to collide any available polarized particles: proton – deuteron, proton – helium-3, deuteron – helium-3 with the luminosity of 10^{30} cm^{-2} s^{-1} at the collision energy equivalent to the proton-proton collisions;
- possibility of asymmetric collisions should be considered as an option for the future development of the facility;
- for efficient estimates of systematic error it is desirable (or necessary) to realize rotation of a bunch polarization direction on 90° within one turn;

Technical realization of the above mentioned conditions is feasible [215].

2 Beam structure, intensity and luminosity

Beam structure of polarized proton and deuteron beams at the first stage will be corresponded to that was optimized for the NICA heavy ion regime. Some of the important, for the SPD, operation parameters in case of bunched beam are the following: bunch number 22, bunch length $\sigma = 60$ cm, the collider orbit length - 503 m, bunch velocity $v \approx c = 3 \times 10^8$ m/s, revolution time $\tau = 1.67 \times 10^{-6}$ s, bunch revolution frequency $f \approx 0.6$ MHz, time gap between bunches $\Delta\tau = 76.0 \times 10^{-9}$ s. The dependence of the pp-collision luminosity on the energy and number of protons is presented in Fig. 3.1.

As it is clear from the calculations the luminosity level of 1×10^{30} cm^{-2}s^{-1} is reached at a bunch intensity of 10^{11} polarized protons, whereas to obtain the level of 1×10^{32} cm^{-2}s^{-1} multi-bunch storage mode should be used [216].

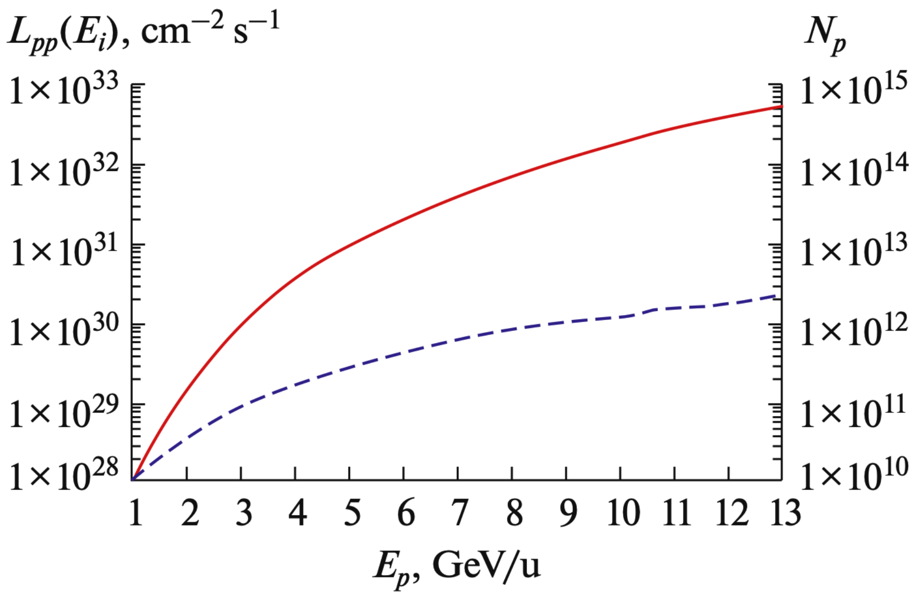


Figure 3.1: Normalized dependence of the pp-collision luminosity L and the beam intensity N on proton kinetic energy.

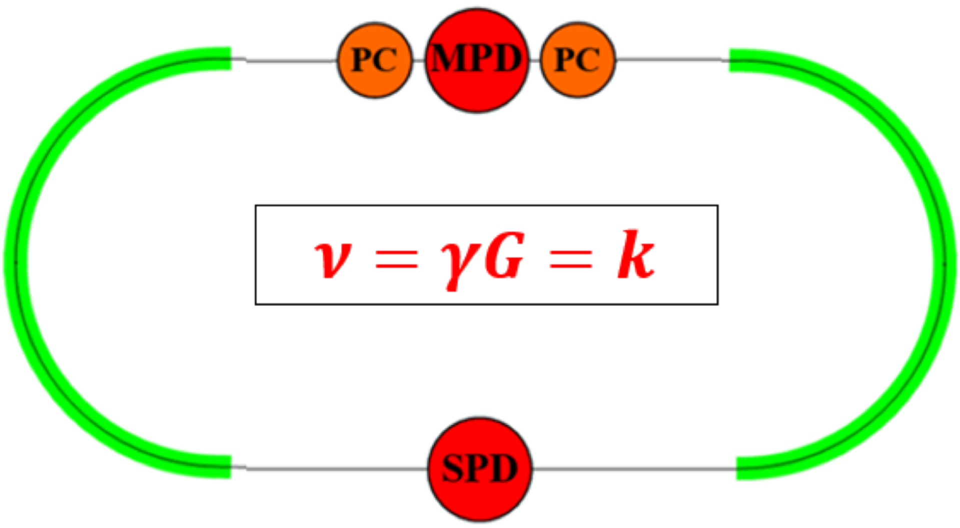


Figure 3.2: General scheme of the polarization control at integer spin resonance points.

3 Polarization control and monitoring

3.1 Transportation of polarized ions in the complex

Polarized protons and deuterons from the source SPI are accelerated first in the linac LU-20M and after that are injected and accelerated in the Nuclotron to the specified energy and extracted to the collider via long transfer line. The maim tasks at this stage are the following: i) preservation of the ion polarization during acceleration in the Nuclotron (and in the collider also) and ii) the polarization control in the collider mode. Moreover, it is necessary to adjust the polarization direction at the beam transfer between the Complex elements.

3.2 Operation modes of the NICA collider at polarized ions

From the spin dynamics point of view, NICA collider can operate in two regimes (modes), namely: in a Preferred Spin mode (PS-regime) and in the Spin Transparency mode (ST-regime) In the PS - regime periodic motion of the spin along the particle orbit is the only possible, i.e. – stationary magnetic structure select the only one stable direction of the polarization vector in any point of the particle orbit, non-integer part of the spin tune is not equal to zero, whereas in the ST – regime the direction of the spin vector is reproduced in any point at every turn, i.e. magnetic structure of the accelerator (or storage ring) is transparent for the spin – non-integer part of the spin tune is equal to zero.

The main difference between the PS- and ST- regimes is occurred at the manipulations of the spin direction during physics data taken. In the ST- regime the spin motion is very sensitive to the magnetic field changes, because particles are moved in the vicinity of the integer resonance In this case the use of additional "weak" magnetic field, rotating spin at small angles $\Psi \ll 1$ provides the needed polarization direction at any specified point of the collider. It is possible to use a pair of solenoids with the field integral of 1 $T \cdot m$, introduced negligible distortions of the particle closed orbit, to produce necessary variation of the spin angle in the NICA collider over the momentum range up to 13.5 GeV/c. In the case PS regime similar procedure will require spin rotators base on a strong fields, rotating the spins at the angles of $\Psi \sim 1$. Thus, in the case of the changing the polarization direction from the longitudinal to the transverse one, it would be necessary to apply the transverse field with the total integral of 20-30 $T \cdot m$, which would be resulted in a strong distortions of the particle close orbit. The amplitude of the distortions can reach of tens of centimeters at low energies. Thus, efficient polarization control of ions, deuterons especially, by means of quasi-stationary weak fields is possible the only if the ST- regime is used.

3.3 Specifications to the polarized beams in the collider

Different experiments are planning with polarized proton, deuteron and helium-3 (in the future) particles to identify and study different observables for different physics tasks: Drell-Yan, J/ψ, high hadron physics, exotic states etc. The polarization control system should be satisfied to the following main conditions:

- to obtain both longitudinal and transverse polarization in the MPD and SPD detectors with the polarization degree not less 70% and the polarization lifetime not less than the beam lifetime;
- to provide the collision luminosity of $\sim 10^{30} - 10^{32}$ cm^{-2}s^{-1} over the particle momentum range from 2 to 13.5 GeV/c;
- to provide the particle energy scan with a step of 1.0 GeV (Drell-Yan, J/ψ) and 0.3 MeV (high-p_T hadron physics, exotic states);
- to adopt operation in asymmetric on the particle momentum mode;
- make simultaneous spin-flips for all bunches in the case of the Spin Flipping experiments (SF system).

3.4 Spin flipping system

The SF system makes it possible to carry out the spin physics experiments at much higher level of the accuracy [217]. Being equipped by such system the SPD set-up will have real privileges, in particular:

- revers of the polarization direction at the polarized ion source is not necessary;

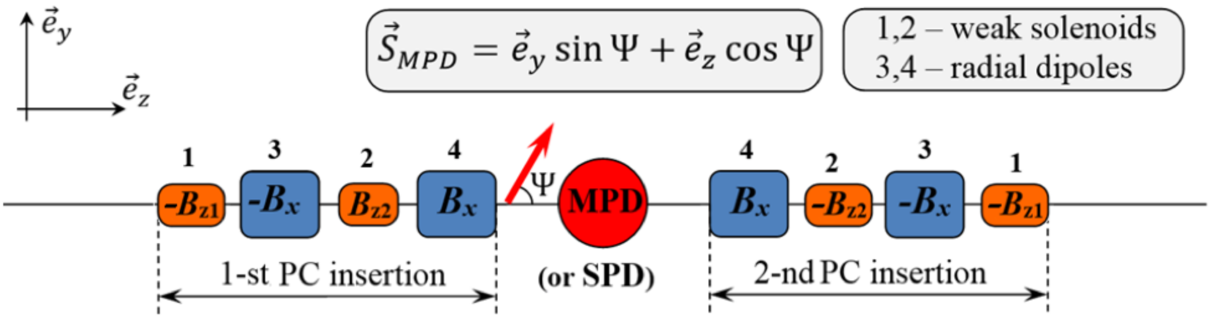


Figure 3.3: Detail scheme of the PC's insertions in the collider in the ST regime.

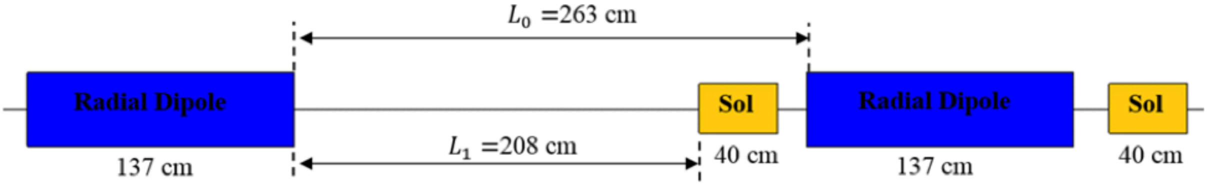


Figure 3.4: Placement of weak control solenoids in horizontal plane.

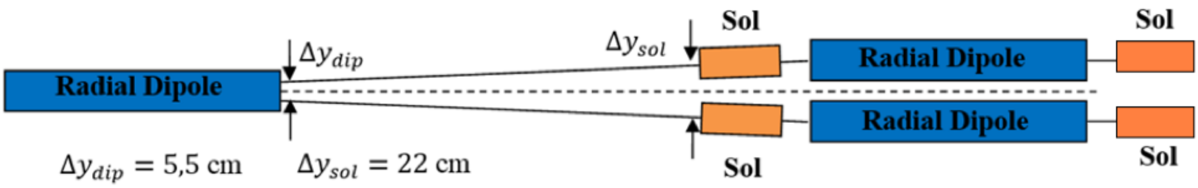


Figure 3.5: Placement of weak control solenoids in vertical plane together with radial dipoles.

– no necessity of a bunch-to-bunch luminosity measurements and bunch monitoring system;

– the possibility of comparison collisions of bunches with any directions of the particle spin (vertical-longitudinal, vertical – radial, radial – longitudinal, etc.). The SF system based on quasi-stationary fields is naturally realized in the ST collider regime. The pair of "weak" controlled solenoids provides simultaneous influence on the polarization direction and the spin tune. Thus, possibility of the spin tune stabilization during the spin flipping is occurred, preventing both as the zero spin tune and higher order spin resonances crossing. The polarization degree will be kept with an exponential accuracy, if the field of "weak" controlled solenoids will be changed slowly. For realization of SF system in the collider operating in a PS regime it would be necessary to introduce in the lattice RF-field of a MHz's range and the field total integral of 1 T×m, that's not so easy technical task.

3.5 On-line control of the polarization in the collider

The unique possibility of the on-line polarization control is occurred if the collider operates in the ST-regime. Because the field ramp in a "weak" solenoids ($t_{change} \sim 0.2$ s) is much larger of the spin precession period around the induced spin field ($t_{rev} \sim 10^{-4}$ s), any manipulations with the spin direction at spin tune will be occurred adiabatically and the polarization degree during the experiment time will be supported constant with the exponent accuracy. The direction of polarization vector will be a function of the weak solenoids field and can be defined by mean of the field measurements. The comparison of the ST- and PS- regimes in the NICA collider is presented in Table 3.1. Thus, the ST-regime makes it possible to carry out the experiments at the NICA collider at the new level of the accuracy.

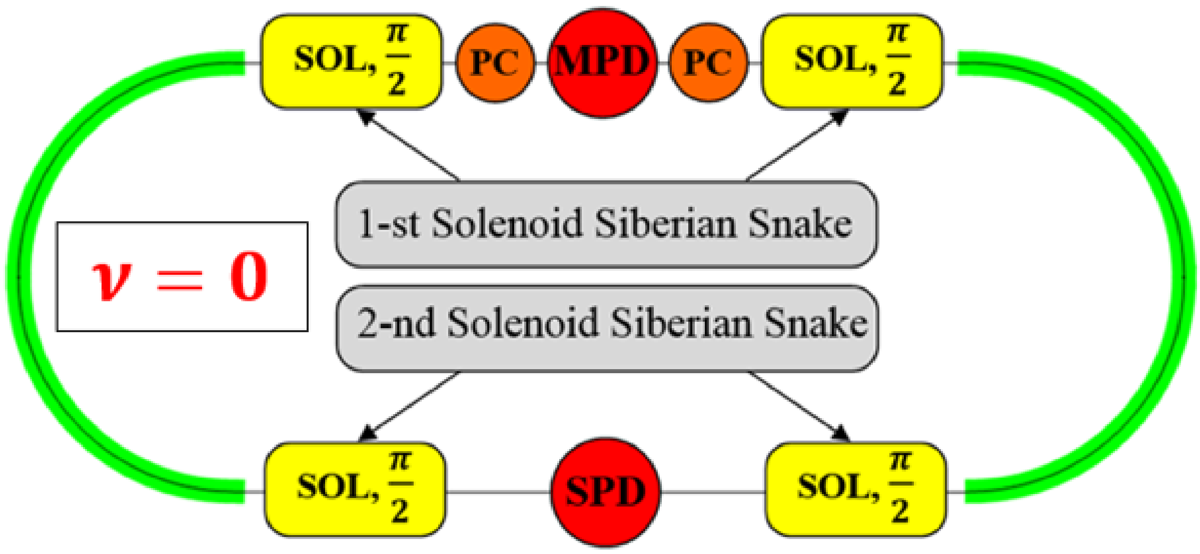


Figure 3.6: Scheme of realization ST regime in NICA collider.

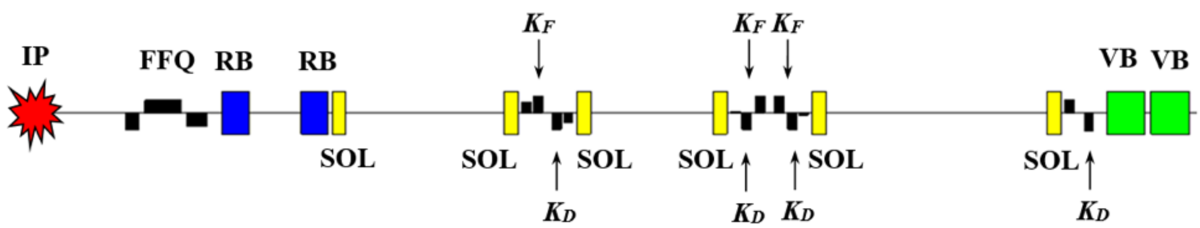


Figure 3.7: Distributed snake (one half) based on short 6 T SC solenoids.

Table 3.1: Comparison of two regimes.

Possibility of realization	PS regime	ST regime
Stationary longitudinal/transverse polarization in the detectors	yes	yes
Polarization control in any point of the orbit	no	yes
Spin Flipping systems based on quasi- static fields	no	yes
on-line polarization control	no	yes

3.6 Polarization control in the collider NICA in ST regime

Use of integer spin resonances in ST-regimes. Stable polarization direction in the NICA collider is vertical (orthogonal to the particle orbit), whereas the spin tune is proportional to the particle energy: $\nu = \gamma G$, where G is anomalous part of the gyromagnetic ratio. The collider is operated in the PS- regime practically over the total energy range because $\gamma \neq k/G$, where k is an integer. The ST regime is realized at discrete energy points corresponding to integer spin resonances: $\gamma = k/G$. For protons the number of points corresponding to ST- regime is 25 starting from minimal energy $E_{kin}^{min} = 108$ MeV with the step of $\Delta E = 523$ MeV. There is only one point $E_{kin} = 5.63$ GeV/u, corresponding to the momentum 13 GeV/c i.e. the ST-regime for deuterons in the Nuclotron/NICA complex.

Possible scheme of ion polarization control in the collider at the integer spin resonances is presented in Fig. 3.2. Two PC-insertions (marked with orange circles in Fig. 3.2) placed near MPD are used to stabilize the needed polarization direction at any point of the collider ring, including the collision

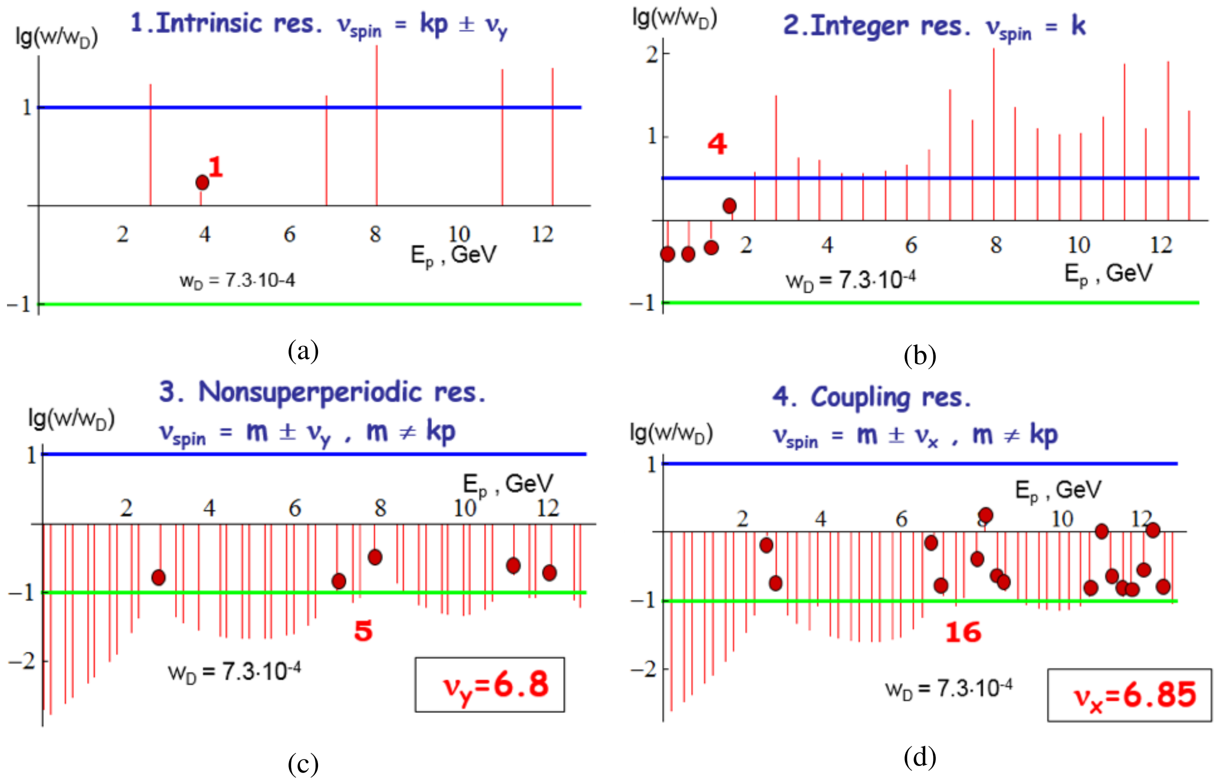


Figure 3.8: Linear spin resonances in the Nuclotron at polarized proton mode.

points, at injection, etc. Detail scheme of the PC's is presented in Fig. 3.3. Weak solenoids (B_{z1} and B_{z2} generated longitudinal magnetic field $\pm B_{z2}$ are placed between the collider structural magnets, generated radial field $\pm B_x$ (marked as 3 and 4), providing deflection the beams to the collision plane of the MPD.

The scheme make it possible the ion polarization control in vertical plane (yz) in the MPD (or SPD) (Ψ is angle between polarization and particle velocity vectors). The scheme provides necessary spin rotation for all discrete points over NICA energy range if integral magnetic field will reach 0.6 T×m in each of four solenoids. If we limit the field maximum to 1.5 T, the magnetic length of the solenoid unit of 40 cm. Real relative scale of the control solenoid (40 cm long), radial dipole and distances between them is shown in Fig. 3.4.

The scheme of installation weak control solenoids in vertical plane together with the collider lattice elements is presented in Fig. 3.5. The beam convergence angle in vertical plane, defined by the dipoles with transverse to the beam axis magnetic fields is: $a_x = 0.04$ rad. The distance between the collider rings in vertical is 32 cm. The distances in vertical plane between the particle closed orbits are $\Delta y_{dip} = L_x a \approx 5.5$ cm. and $\Delta y_{sol} = \Delta y_{dip} + 2L_1 a \approx 22$ cm. at the output of common radial dipole and at the exits of control solenoids respectively.

3.7 Ion polarization control in ST regime by means of two snakes

Two solenoidal snakes installed symmetrically in respect to both MPD and SPD set-ups will provide ST regime in NICA collider (Fig. 3.6).

The configuration make it possible to turn the spin in vertical plane (yz) of MPD or SPD detector, whereas in the collider magnet arcs the polarization vector is moving in the median plane (xz) [218]. The ST scheme with two snakes provides the zero spin tune at any point of the particle energy. It is very important for optimization of the NICA effective operation at the highest possible luminosity of pp - collisions, due to necessity of the particle store at an energy level that gives proper conditions for electron cooling of stored beam. Only in this case it is possible to form particle bunches with high number of particles and high degree of the polarization at low energy (about 1 GeV) with further acceleration up to the experiment energy. The total integral of longitudinal solenoidal field should reach 4×25 T×m per ring at the proton momentum of 13.5 GeV/c and 4×80 T×m for deuterons respectively. The distributed system consisting of a short solenoids is possible, i.e. In the case of 6 T solenoids the total length of 4.2 m is sufficient to form a half-length snake. It is possible to adopt the collider lattice structure optimized for heavy ion beam for the case of ST regime at the protons mode over the total energy range. Weak control solenoids don't disturb practically orbital motion in the collider whereas, strong solenoids of the snakes led to a strong betatron tunes coupling. Because longitudinal field of the snakes is changed proportionally to the particle momentum, the collider magnetic optics will stay adequate to the polarized particle stable motion during the beam acceleration phase. Matching of the solenoids with the collider structure is provided by means of proper choice of the work point by means of structural KF (focusing) and KD (defocusing) quadrupole lenses. Possible scheme of the distributed snake (one half) based on short 6T superconducting solenoids (SC) is shown in Fig. 3.7. The elements are the following: SOL-SC solenoid, FFQ - final focus triplet of the collider, VB - structural dipole magnets; RB - bending dipoles with transverse field for converging the bunches in the collision point IP.

3.8 Stability of spin motion

In the ST regime precession of the polarization vector is caused by the field of solenoids, by the field imperfections of the collider lattice elements, by a finite beam emittance and depends on a power of zero spin tune resonance. To stabilize the polarization during acceleration process or during control the polarization direction in the ST regime it will be necessary to provide spin tune level caused by the control solenoids much higher of a power of zero spin tune resonance: The calculations have showed that the level of 10^{-2} for protons and 10^{-4} for deuterons would be sufficient. These values put limitations on the minimum field integral in each of weak control solenoids – 0.6 T×m.

Table 3.2: Polarization in the SPD and MPD detectors in PS and ST regimes.

Snake SPD	Snake MPD	Spin tune	Control regime	Polarization in SPD	Polarization in MPD
off	off	$\nu \neq \gamma G$	PS	vertical	vertical
off	off	$\nu = \gamma G$	ST	any	any
off	on	1/2	PS	longitudinal	in the collider median plane, direction angle depends on energy
on	off	1/2	PS	in the collider median plane, direction angle depends on energy	longitudinal
off	off	$\nu = \gamma G$	ST	any	any

3.9 Polarized beams dynamics in NUCLOTRON

Stable polarization direction in the Nuclotron is vertical, and the spin tune is proportional to the beam energy: $\nu = \gamma G$ (G is anomaly part of the gyromagnetic ratio of the particle, γ is Lorentz factor) that definitely lead to crossing of spin resonances during the particle acceleration and, as consequence, to resonance depolarization of the beam. There is no problem with deuterons: the only one integer spin resonance can be excluded by means of weak solenoid (0.1 T×m) inserted into the accelerator lattice.

Table 3.3: Polarization in the SPD and MPD detectors in PS and ST regimes.

Snake SPD	Snake MPD	Spin tune	Control regime	SF system	Online polarization control	Possibility of acceleration in collider	Influence of RF modulation on polarization lifetime
off	off	$\nu \neq \gamma G$	PS	no	no	no	reduce
off	off	$\nu = \gamma G$	ST	yes	yes	no	reduce
off	on	1/2	PS	no	no	yes	no influence
on	off	1/2	PS	no	no	yes	no influence
off	off	$\nu = \gamma G$	ST	yes	yes	yes	no influence

The number of different spin resonances in the proton mode is much larger. Logarithmic graphs of linear spin resonances power scaled to the specific power corresponding to complete depolarization of the beam are presented in Fig. 3.8 [219, 220]. The proton energy range Ep corresponds to the available at Nuclotron. Each graph is divided onto three areas that correspond to intermediate crossing (between horizontal lines), fast crossing (below green line) and adiabatic crossing (upper blue line). The lines of a fast and adiabatic crossing are corresponding to 1% loose of the polarization degree.

The parameters taken for calculation of the resonances power were the following: the magnetic field ramp - 1 T/s; beam emittance (horizontal and vertical) at the injection energy - 45π mm$\times$mrad; quadrupole misalignment errors – 0.1 mm; errors of angular alignment of structural dipole and quadrupole magnets - 0.01 rad; and the relative error of the quadrupole gradients - 0.001. The resonances marked with red circles are dangerous and lead to the beam depolarization after their crossing. To keep the polarization of proton beam at proper level, partial Siberian snake based at a solenoid will be used. Two options have been considered: 1) The use of a weak 5% snake with the field integral of 0.65 T$\times$m, which can save the proton beam polarization up to 3.4 GeV/c and 2) The use of 25% snake ($\sim$ 12 T$\times$m). The first one is efficient if the collider operates in the ST regime with two snakes and injection of the beam is provided at low energy (around 1 GeV), whereas strong enough snake that is used in option 2 could save the polarization over the total energy range in the NUCLOTRON and is suitable to the operation at integer resonances. The choice of energy points is limited to the points of integer resonances.

3.10 Operation modes of the NICA collider at polarized beams

Collider NICA with two solenoidal snakes will make it possible the following operation configurations (see Table 3.2) [221].

If the snakes installed in SPD and MPD sections are switched off, the PS regime with vertical polarization at any point of the collider orbit is occurred. Some narrow energy gaps which the ST regime at integer resonances is exists in, gives possibility to have any direction of the polarization in the both detectors. After switching one of the snakes on, the collider will operate in PS regime with the spin tune 1/2. The snake transform completely spin motion providing stable longitudinal direction of the polarization in opposite respect to the snake section of the collider orbit.

If two dynamic solenoid snakes are switching on, the unique spin transparency (ST) regime is realized. The spin tune don't depend on particle energy and equal to zero that's gives possibility to obtain any direction of the polarization at any point of the collider orbit. The features of the collider operation in polarized modes are shown in Table 3.3.

It is very important to realize the possibility of polarized beam acceleration in the NICA collider without loose the polarization degree. The problem of reaching the highest possible luminosity of polarized proton collisions is connected with the particle multi-bunch storage in the collider and electron cooling of the stored beam during the process. The optimal proton beam kinetic energy at the beam injection into the collider is about 1 GeV [222, 223].

3.11 Zero Degree Calorimeter [S. Shimansky]

3.12 Conclusion and outlook

The proposed scheme of the ion polarization control in the NICA collider is adopted easily to the collider magnetic optics at any regimes of the polarization control. Important advantages could be obtained with the applying spin transparency regime. Polarization degree of about 70% is provided at the collision points. The polarization life time is expected to be at the level of hours comparable with the beam life time. We didn't describe some specific measurement and monitoring systems should be designed at the stage of preparation technical project. In particular: precise measurement of the luminosity (bunch-to-bunch?), absolute polarimeter based on a gas jet, targeting stations etc.

Chapter 4

Detector layout

1 General design [A. Guskov]

The physics tasks represented in the Chapter 2 impose general requirements to the concept of the Spin Physics Detector. Unlike a case of high-energy collisions where the collision energy $\sqrt{s}$ is a few orders of magnitude larger than a typical hard scale Q of the studied reactions, at SPD energies for all the probes planned to be used for access gluon content of the colliding particles $Q \sim M_{J\psi} \sim 2M_D \sim p_{T\gamma\ min}$ is just a few times less that $\sqrt{s}/2$. Therefore one should expect quite uniform distribution of all signal particles (muons from the J/ψ decay, prompt photons, products of D-mesons decay etc.) over the kinematic range. In other words, there is no preferable range in rapidity could be specified for each probe for the optimal overall performance. Together with relatively small cross sections of the discussed probes, this fact leads one to a requirement of $\sim 4\pi$ coverage of the SPD setup.

The Spin Physics Detector must have sufficient tracking capabilities and a magnetic system for spectrometric purposes for the most of the addressed physics tasks. It has to be equipped with a thick enough muon system for effective separation of muons and hadrons to be able to deal with the decay $J/\psi \to \mu^+\mu^-$. Precision vertex detector is needed for recovering of the secondary vertices from decays of $D^{\pm/0}$ mesons and other short-lived particles. Electromagnetic calorimeter ensures capability to detect signal and background photons. Low material budget and general transparency of the setup should also provide favorable conditions for the photon physics. Hadron identification capability is needed for any physics task with protons and/or kaons in the final state, in particular, to enforce a signal-to-background ratio for D-mesons selection, and also to improve tracking at low momenta. Since tiny effects are intended to be investigated, a triggerless DAQ system is planned in order to minimize possible systematic uncertainties of the measurements.

Strict limitations to the SPD detector layout are coming from an external conditions such as the maximal possible load to the floor of the SPD experimental hall (1500 tons together with a lodgement and a detector moving system). Together with a requirement to have overall thickness of the muon system not less than 4 nuclear interaction lengths (Λ_I) this limits an outer size of the SPD detector and a size of an inner part of the detector. Location of the collider infrastructure, in particular, focusing elements also defines the size of the SPD setup along the beam axis. More details could be found in Chapter 3.

General layout of the SPD is shown schematically in Fig. 4.1. The detailed description of each subsystem could be found below. Table 4.1 brings together the elements of the SPD physics program and the requirements to the experimental setup.

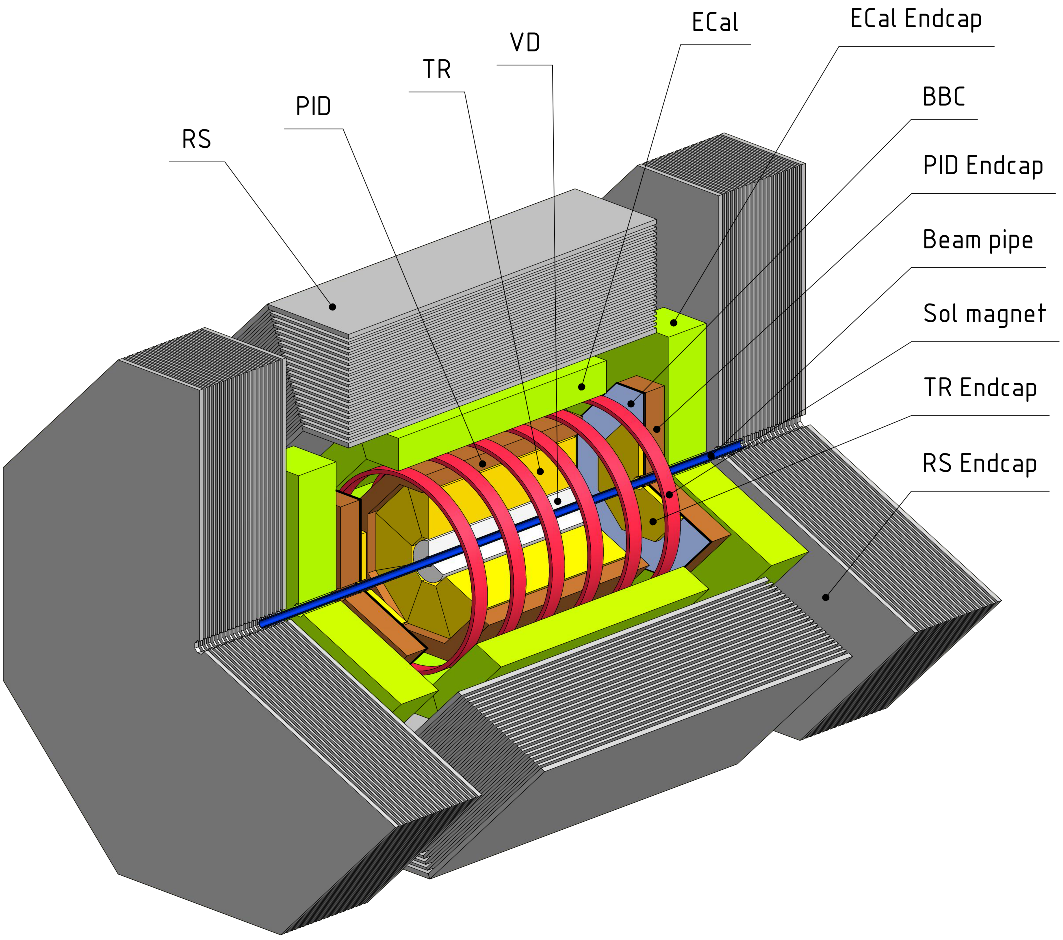


Figure 4.1: General layout of the Spin Physics Detector.

Table 4.1: Required setup configuration for each point of the SPD physics program. (+++) - absolutely needed, (++) - extremely useful, (+) - useful, (-) - not needed.

Program	Vertex detector	Straw tracker	PID system	Electromagnetic calorimeter	Beam-beam counter	Range system
Gluon content with:						
charmonia (and DY)	+	++	-	++	-	+++
open charm	+++	++	++	-	-	+
prompt photons	+	+	-	++	-	-
SSA for π and K	+	++	+++	++	-	-
Light vector meson production	+	++	-	+	-	-
Elastic scattering	+	++	-	-	++	-
$\bar{p}$ production	+	++	+++	++	-	-

2 Magnetic system [A. Kovalenko]

The SPD Magnetic System (MS) should satisfy to the following criteria:

- minimization of the material inside the detector inner part;
- the magnetic field integral of (1-2) T m along the particle tracks, whereas the peak value of the field should be limited to 0.8T over the straw tacker volume;
- minimization of the total weight, cross section of the current coil (coils) and overall amount of the MS material, i.e. the MS should have perfect mechanics.

Several options of the MS's were considered:

1. Solenoid - uniform multi-turn coil placed between the ECAL and the muon range (RS) systems;
2. Toroidal MS (inside ECAL): $3 \times 8 = 24$ coils forming toroidal distribution of the field in the detector volume only,
3. Hybrid system consisting of toroidal coil composition in a barrel and solenoidal in a forward/backward parts. Both as room and cryogenic temperatures were considered;
4. System of a 4 separate coils inside the ECAL: a) all coils are connected in series, and b) right and left hand pairs are connected opposite to each other;
5. Hybrid system consisting of 8 toroidal coil composition in a barrel and 2 pairs of separate solenoidal coils in a forward/backward parts. Both as room and cryogenic temperatures were considered;
6. System of a 6 separate coils placed between the ECAL and RS system of the reduced diameter.

Thus, more then10 different options of the 3D configurations of the magnetic fields were analyzed, calculated field maps were presented to the collaboration and part of them have been used for the SPD simulation [. . . .]. Conceptual analysis of the considered MS systems was performed also. Some data were reported at the European Conference on Apply Superconductivity EUCAS2019 [. . .]. General conclusion are briefly summarized below.

1. The most well-known system is classic solenoid. The experience of design and construction of superconducting solenoids have been collected by many groups in the world including MPD NICA. The MPD solenoid manufacturing is completed and the assembling is started in the experimental

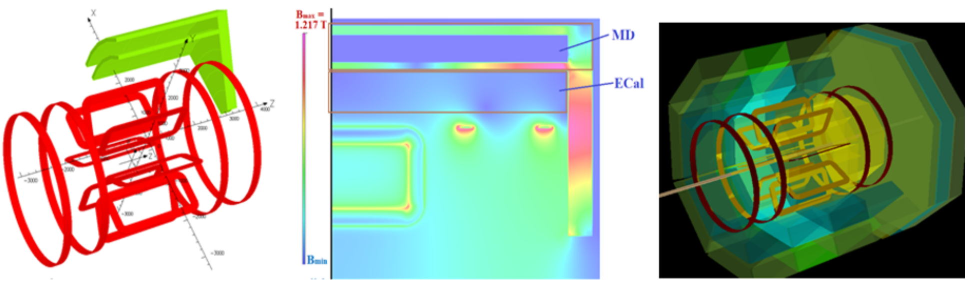


Figure 4.2: Hybrid MS: toroidal magnet consisting of 8 coils in barrel part and double coil system in forward and backward parts of the detector.

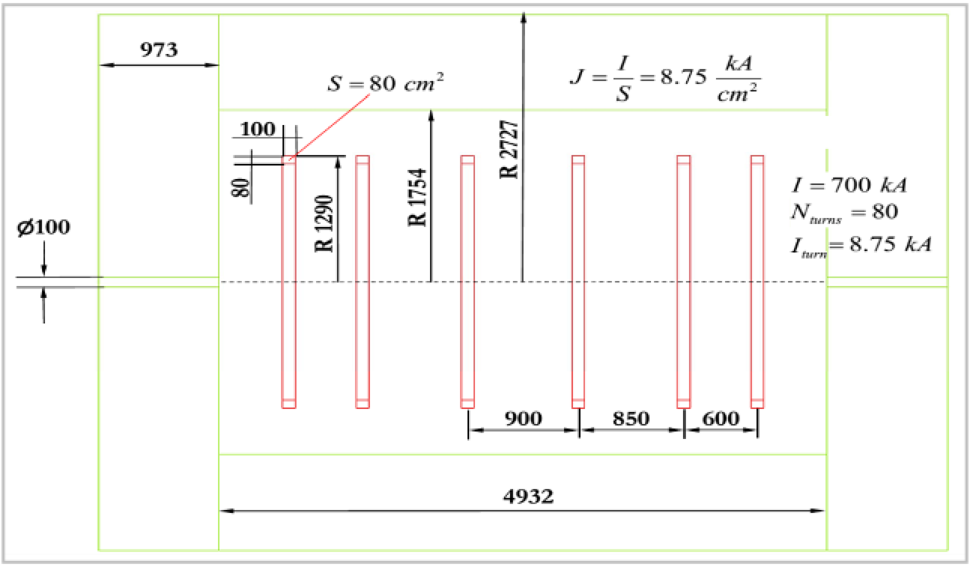


Figure 4.3: Geometrical model of the 6-coil magnetic system

hall. Main disadvantage of similar solenoid as the SPD MS would be a lot of material front of the ECAL and high cost as well. Moreover, fixed geometry of the field gives no any universality of the SPD experimental program.

2. The toroidal MS was considered in "warm" and "cold" options. The warm one was rejected due to the material budget: necessary ampere-turns led to unacceptable cross section of the coils that means amount of copper. The problem is solved partially in the case of superconducting coils, nevertheless the complexity of construction of the coil system is very high in any case. The most important negative effect can occur due to concentration of the coil material closer to the bunch crossing area.

3. The MS consisting of separated coils is transparent absolutely for the particles passing through inner volume of the detector and contain "target" material for the secondary particles in limiting volume at the ECAL inner part. The amount of material depends directly on necessary amper.-turns of the coil and achievable current density. The last point gives evidence in favor of a superconducting approach. The magnetic field radial and axial distribution is not so uniform in comparison with a solenoid especially in the area close to the coils. Nevertheless, the accuracy of modern 3D calculation codes for a nonlinear magnetic fields and precise magnetic measurements can guarantee necessary accuracy of real field mapping. Optimization of the coil cross section is very important also.

4. Hybrid MS consisting of toroidal system in barrel part of the SPD and two pairs of separate coil was considered as some compromise, namely: minimization of the magnetic field near the polarized particles interaction zone and solenoidal-type distribution in front and backward parts of the SPD. The MS scheme is shown schematically in Fig. 4.2.

More advanced analysis of the detector and the collider system have shown that partial compensation of the magnetic field at the axis will give not so much advantages. It would be positive, somehow, if there was no the spin control system in the collider lattice. The NICA collider will be equipped with such one. The elements aimed at the particle spin control at NICA collider was proposed and under technical design now. General description of the spin control system is presented in section 3. Thus, the condition

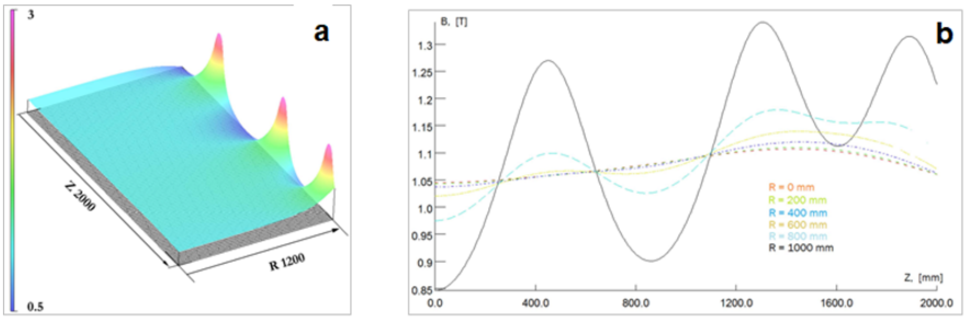


Figure 4.4: The field calculation results: (a) B_z as function of r, z; (b). B_z as function of z at different r.

of "zero" magnetic field along the beam axis is not a critical issue in our case. Updated choice of the SPD MS was made in favor of a separate 6-coil design. Geometrical model of the coil system is presented in Fig. **??**, whereas the field calculation data in Fig. 4.4.

As it clear from Fig. 4.4, longitudinal variation of an axial magnetic field is varied from about 5% at the beam axis to about 12% at the radial distance of 2 cm from the coil inner turns. The number of 12% can be further improved by the coils system optimization. We consider the technology of a superconducting coils manufacturing based on a hollow high current cable similar to that is used for the Nuclotron magnet or that is used in ITER systems. Manufacturing technology of a hollow cable made of NbTi/Cu composite wires cooled at 4.5 K with forced He flow is well developed at the Laboratory. The magnets of NICA booster and collider are manufacturing at our Laboratory magnet facility. The coil containing 80 turns will provide 800 kA $\times$ turns and generate necessary magnetic field in the detector volume. Some of the SPD 6 coil MS are presented in the Table 4.2 in comparison with the other detectors.

Table 4.2: Comparison of the SPD (NICA) and CMS (LHC) [] magnetic systems.

Parameter	SPD/NICA	CMS/LHC
Size (diam./length), m/m	3.6/6.0	6.5/12.7
Magnetic system	6 coils	solenoid
Peak magnetic field, T	2.0	4.5
Coil average diam., m	∼3.6	∼ 6.5
Field volume, m^3	∼65	∼414
Stored energy, MJ	∼100	∼2800
Coil turns	6×40	2112
Operating current, kA	10	20
Total inductance, H	∼2	12.6

3 Beam pipe [A. Guskov]

A beam pipe separates the detector and high vacuum of the accelerator. It must be mechanically sturdy on the one hand and thin enough in terms of number of radiation lengths to minimize multiple scattering and radiation effects. The beam pipe is also protects the closest detectors from soft particles produced in the interaction point. A diameter of the beam pipe is a compromise between a radial size of the beams and a requirement to put coordinate detectors as close as possible to the interaction point for the better reconstruction of primary and secondary vertices. A beryllium beam pipe of 6 cm diameter and 0.5 mm of thickness is proposed to be used.

A construction of the beam pipe and its positioning inside the SPD is shown in Fig. 4.5. ...

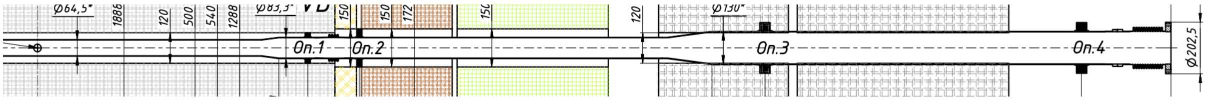


Figure 4.5: SPD beryllium beam pipe [DUMMY PLOT].

At the first stage of SPD running a cheap steel beam pipe could be used.

4 Vertex detector [N. Zamyatin]

4.1 General overview

The SPD Vertex Detector (VD) is a silicon-based part of the spectrometer responsible for precise determination of a primary interaction point and measurement of secondary vertices from the decays of short-lived particles (first of all *D*-mesons). The Vertex Detector is divided into the barrel and two end-cap parts (Fig. 4.6). Two different versions of the VD design are discussed: 1) five layers based on double side silicon detectors (DSSDs) and 2) three inner layers based on Monolithic Active Pixel Sensors (MAPS) and two outer layers based on DSSDs. The Barrel of VD consists of five layers based on double side silicon detectors (approximately 4.2 m^2). The end-cap regions are each consists of five disks (approximately ? m^2). The Barrel of VD covers a radius an area between 96 mm and 500 mm (Fig. 4.7). All five cylindrical layers set with rectangular two-coordinate silicon strip detectors and give information on coordinates of the tracks (r,ϕ,z) (enable to measure a point in each layer). The end-cup regions detect particles in the radial region between 96 mm and 500 mm. Each of the five disks set with DSSD with concentric (r) strips and radial (ϕ) strips. The VD has length about 1.1 m and covers the region of pseudo-rapidity up to $|\eta| < 2.0$. Each DSSD has 300 μm thickness and strip pitch in the range from 95 μ m to 281.5 μm. The DSSDs are assembled into detector modules by two detectors per module, forming strips 18 cm long. Detectors and Front-end electronics boards (FEE-PCB) connected via low-mass polyimide microcabels and assembled low-mass on mechanical supports with cooling system.

From general conditions of SPD VD performance requirements are 1) close to 4π geometry; 2) track reconstruction efficiency for muons greater than 99% at $p \leq 13$ GeV/c (for $0 \leq |\eta| \leq 2.5$); 3) low material budget less than ?X_0 per layer; 4) coordinates resolutions for vertexing: $\sigma_{r,\phi} < 50$ μm, $\sigma_z < 100$ μm. The lifetime of Vertex Detector is required to be not less than 10 years of NICA running.

Table 4.3: Relevant numbers of the barrel VD.

Parameter	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Total
N_{DSSD}/module	2	2	2	2	2	
$N_{modules}$/ladder	2	4	4	6	6	
$N_{ladders}$/layer	6	10	14	19	23	72
N_{DSSD}/layer	24	80	112	228	276	720
N_{chip}/module	10	10	10	10	10	
N_{chip}/layer	120	400	560	1140	1380	3600
$N_{channel}$/layer	15360	51200	71680	145920	176640	460800

4.2 Double-sided silicon detectors

Concept of Barrel DSSD module shown in Fig. 4.8. The module consists of two silicon detectors wire bonded strip to strip for p+ side (to reduce read-out channels), glued to the plastic frame and connected

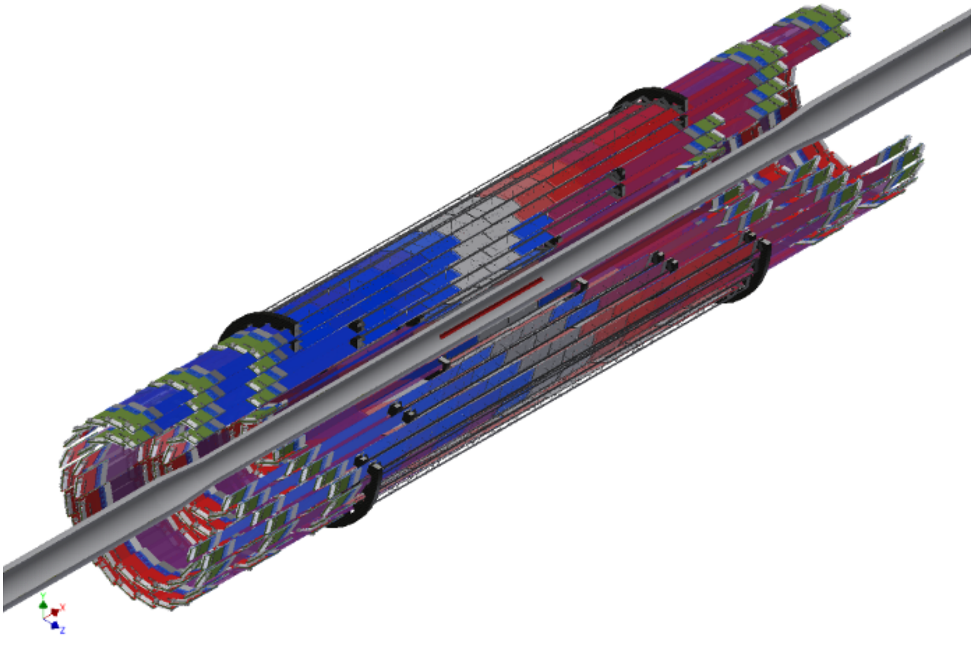
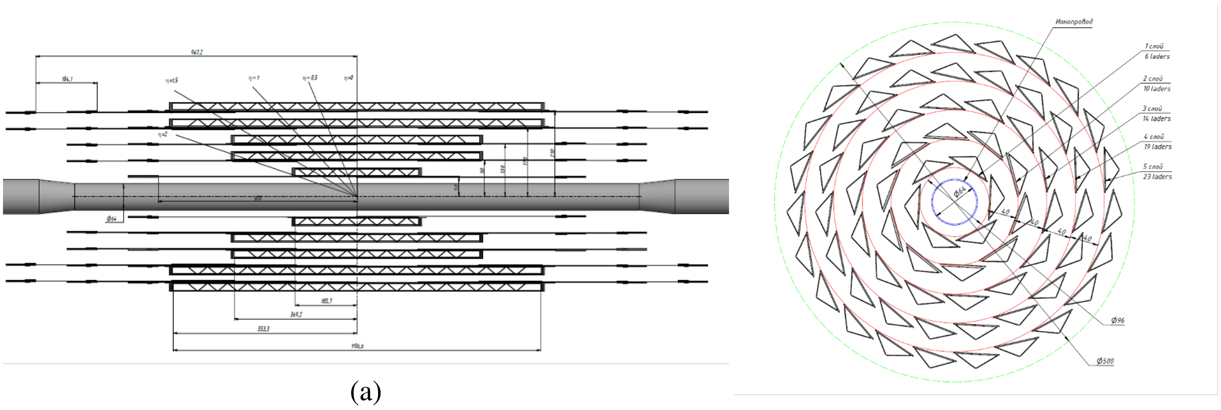


Figure 4.6: General layout of the SPD Vertex Detector.



(a)

(b)

Figure 4.7: Longitudinal (a) and transversal (b) cross-sections of the barrel part of the Vertex Detector.

with two front-end electronic boards via low-mass polyamide cable.

The Silicon Detector made with planar double side technology based on n-type conductivity 6-inch float-zone Silicon wafers (produced by ZNTC, Zelenograd, Russia). It has 63x93 mm^2 size and 300 μm thickness. Pitch for $p+$ side is 95 μm, for $n+$ side 281.5 μm. Number of strips is 640 and 320 for the $n+$ and $p+$ side, respectively. Stereo angle between strips 90 is degrees. Excepted spatial resolution for such detector topology is $pitch_{p(n)+}/\sqrt{12} = 27.4$ (81.26) μm, respectively for $r-\phi$ and $r-z$ projections. As mentioned before Barrel DSSD module contains two DSSDs (p+ strips wire bonded strip to strip) and has 640 at each side.

To bring the front-end electronics out of the tracker volume, will be used thin two polyimide cables with aluminum traces (for each side of module). Cable consists of few layers: signal layer, perforated or solid dielectric (polyimide) and shielding layer. Cable pins designed for TAB bonding with detector and pitch adapter sides. Maximum cable length is 60 cm total thickness of all cable layers less than 0.15% X0.

Since DSSDs has DC topology it's necessary to supply bias voltage to detector and electrically decouple DC current from ASICs electronics inputs. For this purpose, integrated RC circuit (sapphire plates with Si-epitaxial layer Silicon On Insulator (SOI)) Pitch Adapter (PA) will be used for each side of module (produced by ZNTC, Zelenograd) designed with different topologies for each side. After pitch adapter detector's signal goes to ASIC. Table 1 shown possible ASIC read-out solution. Optimal choice should be done after ongoing R&D.

Table 4.4: default

ASIC	APV25	VATAGP7.3	n-XYTER	TIGER
Number of channels	128	128	128	64 (128?)
Dynamic range	-40fC – 40fC	-30fC – 30fC	Input current 10nA, polarity + and −	1–50fC
Gain	25mV/fC	20μA/fC		10.35mV/fc
Noise	246 e$^-$+36 e$^-$/pF	70e$^-$+12 e$^-$/pF	900 e$^-$ at 30pF	2000 e$^-$ at 100pF
Peaking time	50ns	50ns/500ns	30ns/280ns	60ns/170ns
Power consumption	1.15mW/ch.	2.18mW/ch.	10mW/ch.	12mW/ch.
ADC	No	No	16fC, 5 bit	10-bit Wilkinson ADC
TDC	No	No		10-bit Wilkinson ADC

4.3 Mechanical layout

Concept of barrel DSSD ladder shown in Fig. 4.9. Silicon modules are laying on carbon fiber support from center to edge. Detectors connect with FFE via thin low-mass cables. Front-end electronics are located at the edges of ladder and placed to conical caves as shown in Fig. 4.10 to provide connection to voltage supply, DAQ and cooling ASIC chips subsystems.

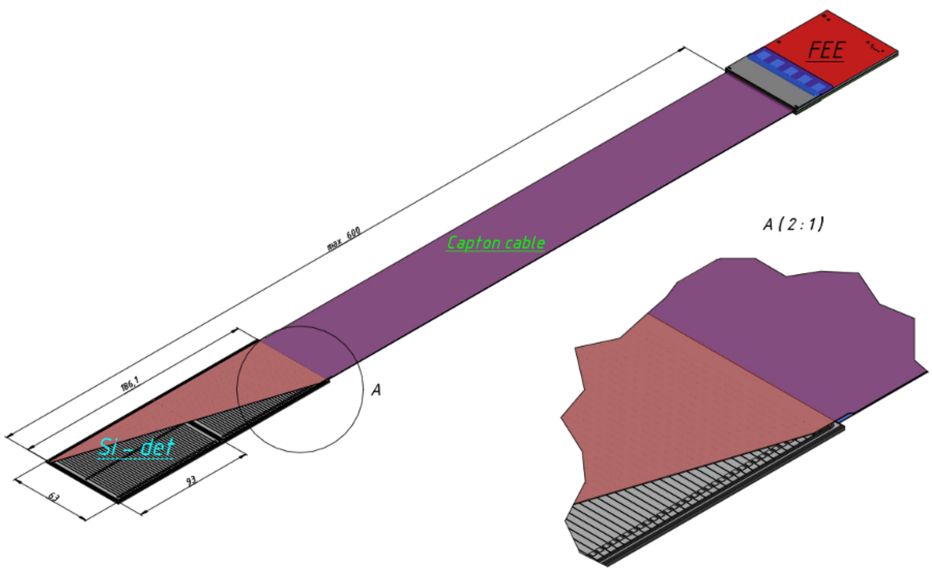


Figure 4.8: Concept of the barrel DSSD module.

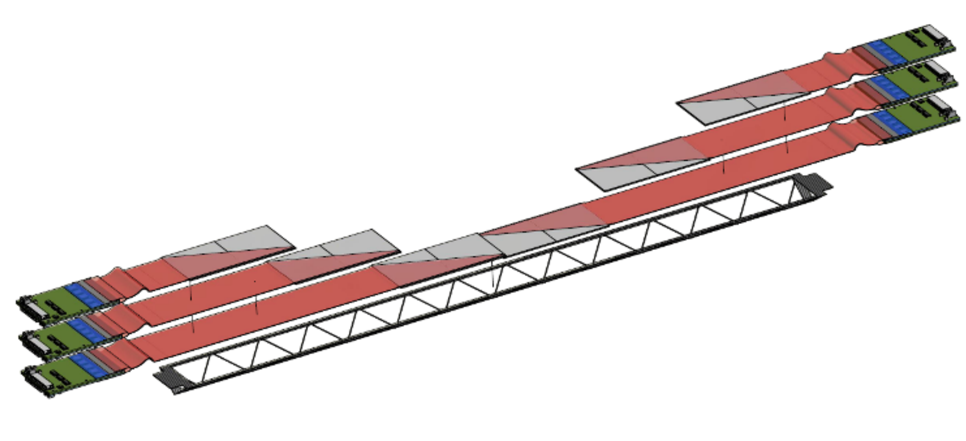


Figure 4.9: Conceptual layout of the barrel ladder.

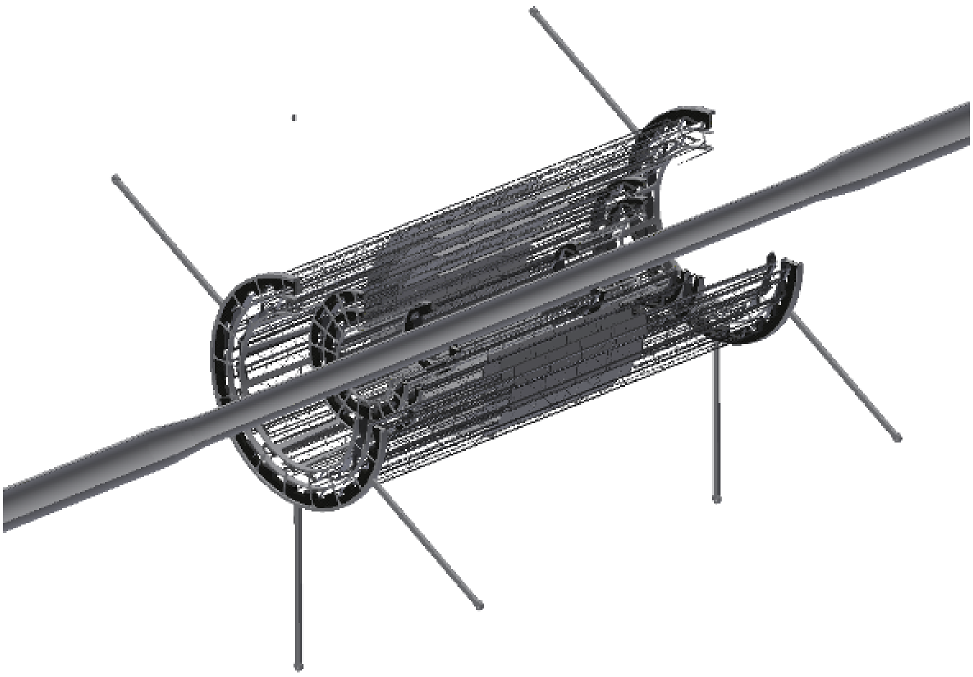


Figure 4.10: Concept of the VD mechanical support structure with conical caves for FEE.

5 Tracking system [T. Enik]

The Straw Tracker (ST) based on the gas-filled drift tubes in the main detector for determination of the particle momentum at SPD. It has to provide spatial resolution below 150 μm in the magnetic field up to 1 T in order to reconstruct the charged particle tracks and event topology with good confidence. It has to be a low-material budget detector to minimize the multiple scattering effect and does not affect physics with photons. The core technologies required to build the Straw tracker are well established. The concept of the SPD ST s similar to the ATLAS TRT [2, 3, 5] and COMPASS [28, 71] straw trackers. Low mass straws have been successfully developed for various modern projects including NA62 [76], COMET [69], SHiP [19], Mu2e [59], and PANDA [48].

5.1 Detector layout

Thin-wall gas-filled drift tubes are used as a basic detecting element. Each tube (straw) is fabricating using polyethylene terephthalate film 36 μm thick by ultrasonic welding. Each tube has a diameter of 10 mm and consists of a single anode wire in the centre that is made of 30 μm gold plated tungsten. The joint breaking strength of a tube is 31.9 kg/mm^2. A gas mixture used in the detector, Ar + CO_2, provides gas gain not greater than 10^5 that warrants a long-lasting stable detector operation. Gas leakage from a tube volume of 188.6 cm^3 under a pressure gradient of 1.0 atmosphere does not exceed 0.3×10^3 cm^3/min. The high strength, the low tensile creep due to the absence of glued layers, negligible gas leakage and reliability in long-term operation make these tubes an excellent candidate for the detector elements of the main tracker.

The SPD Straw tracker consists of three main parts: a barrel part (BST) and two end-caps. The BST has a cylindrical shape with an inner radius of 800 mm, an outer radius of 1700 mm and a length of 2360 mm. It consists of 8 stations. Each station has 40 intersecting perpendicular layers of straw and looks like a wedge. Stations of three modules with eight layers of straws. These are 4 double layers of straws along the X,Y,U and V axes. the external dimensions of the station are D=1700 mm, and the thickness is

5.2 Mechanics

5.3 Electronics

6 Electromagnetic calorimeter [O. Gavrischuk] [OUT OF DATE]

6.1 Calorimeter design

The electromagnetic calorimeter (ECAL) of the SPD setup should be placed inside the Range System and will consist of three parts: the barrel part and two end-caps. The ECAL should meet the following requirements coming from the physics tasks:

- energy range from 50 MeV to 10 GeV;
- energy resolution of about $5\%/\sqrt{E\ [GeV]}$;
- granularity $\sim$5 cm;
- time resolution $\sim$ 0.5 ns;
- operation in the magnetic field;
- long time stability of the basic parameters $\pm$5%.

The proposed calorimeter is based on the experience of the KOPIO sampling calorimeter [224] consisted of alternating layers of lead and scintillator with fine granularity. A four-tower block of the KOPIO calorimeter is shown in Fig.4.11. The SPD calorimeter should consist of 220 layers of scintillator (1.5 mm) and lead (0.3 mm) plates. The scintillator tiles and the lead plates within the four-tower block should have transverse size 5.5$\times$5.5 cm^2 and 5.5$\times$5.5 cm^2, respectively. They are fixed on the common plate with the help of 4 stainless rods. The wave length shifting fibers pulled inside the block should collect light to four avalanche multipixel diodes. The length of the active part of the module will not exceed 450 mm. Together with the readout electronics it should be fitted into 600 mm. The schematic layout of the SPD ECAL is shown in Fig. 4.12.

The barrel part of the ECAL is designed as 3 rings (one middle and two side) with 8 azimuthal sectors. Side rings will consist of 2080 towers while the central one of 2288 towers (6448 towers in total). The

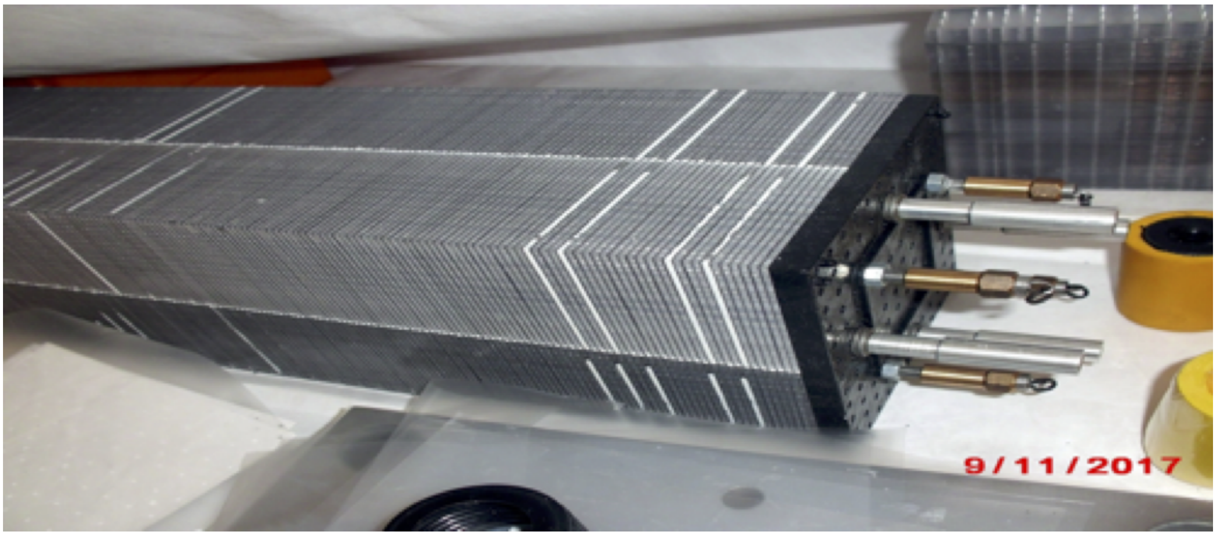


Figure 4.11: Two by two modules of the KOPIO sampling calorimeter assembled in the single block with 320 layers of lead and scintillator of 0.3 mm and 1.5 mm thick, respectively.

end-cap part is planned as two discs with the diameter of about 3.6 m and the beam hole of about 20 cm. It will consists of the modules of the same type as the barrel part. The total amount of towers in the each end-cap disc is planned to be 850. The expected weight of the barrel part and the end-cap part is 81 tons and 11+11 tons, respectively. Assuming that the weight of the supporting structures is about 15%, the total weight of the SPD ECAL could be estimated as 118.5 tons.

The prototype of the SPD ECAL module could be produced using the existing matrix form and moulding machine (shown in Fig. 4.13.

The best possible resolution of the proposed sampling calorimeter is

$$\sigma_E/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)\%/\sqrt{E}. \tag{4.1}$$

Photostatistics and nonuniformity of the light collectors add to the total energy resolution the additional terms $2.1\%/\sqrt{E}$ and $1.8\%/\sqrt{E}$, respectively.

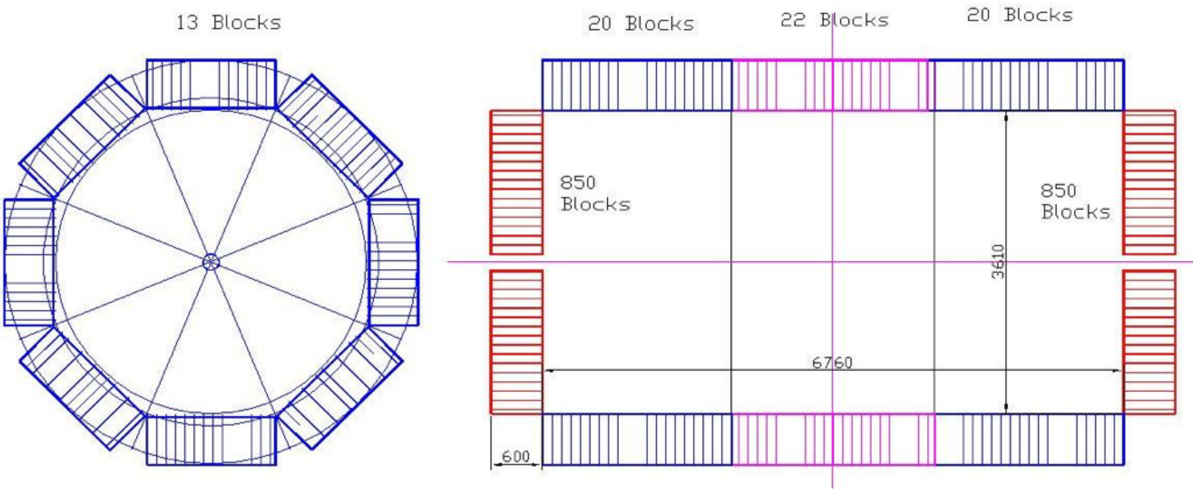


Figure 4.12: Schematic layout of the SPD electromagnetic calorimeter.

Figure 4.13: The scintillator production facility: moulding machine.

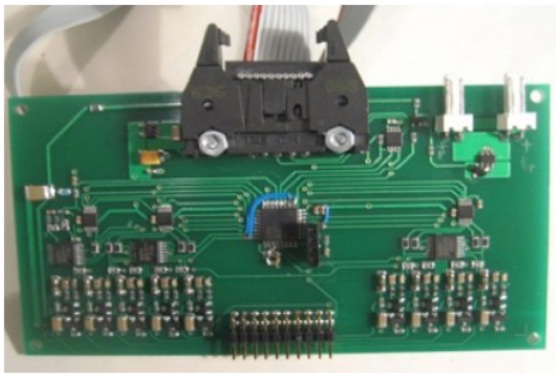
6.2 Front-end electronics

ECAL totally has 32592 channels and 510 64-channel front-end boards is needed to readout organization. It is planed to use the board ADC64s [225] that is a 64-channel 12-bit 50MS/s ADC device with signal processing core and Ethernet interface. It has dedicated serial links for clock synchronization and data readout that allows system scalability to arbitrary number of channels. The power consumption is +12V and 1.5A with proper air cooling. The board size is 145x106 mm, Fig.4.14 (a). It digitize the analogue input signal and samples it at fixed time intervals. Zero suppression logic is based on baseline estimation and threshold value. Signal shaping is performed in digital form with FIR filters. It allows to reduce the number of waveform points required for digital signal representation with minimum loss of accuracy. The ring type memory allows the read back of last 30 μs of waveforms. The ADC64s board is used successfully at NICA BM@N.

The High Voltage (HV) control for SIPM will be based on equipment designed by the HVSYS company [226]. Such modules are used successfully at NICA BM@N and COMPASS (CERN). Multichannel HV system consists of the Control Box (Fig.11, left) which is able to control and supply power for 127 cells with SIPM diodes. It has a remote Ethernet control and optionally USB-2 or RS-232 interface. The patch way (10 pair flat cable) distributes the necessary signals for powering of 127 diodes and provides feedback for taken their temperature stability. The thermo sensor is installed nearly from SIMP for these purposes. HV board for supplying of 8 channels is shown in Fig. 4.14 (b).

The slow control system is considered to be based on the LED control. For this purpose the light pulse will be distribute by via the transparent fibers from the LED driver to all SIPMs. The LED driver developed by the HVSYS company is assumed to be used.

(a)



(b)

Figure 4.14: (a) ADC64s board and (b) HV board.

7 Range (muon) system [G. Alexeev]

7.1 General description

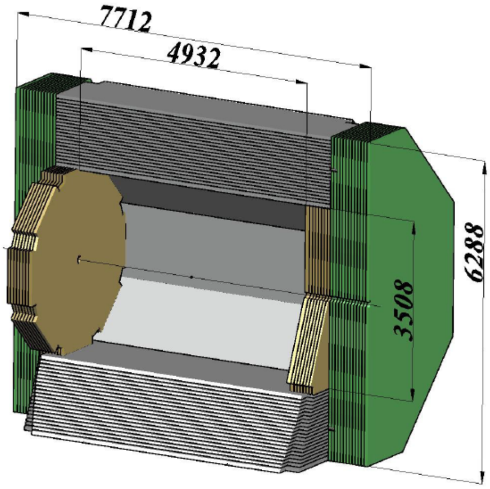
The Range System of the SPD detector serves for the following purposes: (i) identification of muons in presence of a remarkable hadronic background and (ii) estimation of hadronic energy (coarse hadron calorimetry). It is important to stress that the system is the only device in the SPD setup, which can identify neutrons (by combining its signals with the electromagnetic calorimeter and the inner trackers). Muon identification (PID) is performed via muonic pattern recognition and further matching of the track segments to the tracks inside the magnets. The precise muon momentum definition is performed by the inner trackers in the magnetic field. The Mini Drift Tubes [227, 228] are used in the Range System as tracking detectors providing two-coordinate readout (wires and strips running perpendicularly). Such readout is mostly needed for the events with high track multiplicity and also for the reconstruction of the neutron space angle.

As for the design and construction of the present system, we assume to capitalize on the experience gained by the JINR group in the development of the PANDA (FAIR, Darmstadt) Muon System [**?**]. These two systems (PANDA and SPD), dealing with muons of comparable momentum ranges and solving the same PID tasks, should look very similar in their design and instrumentation.

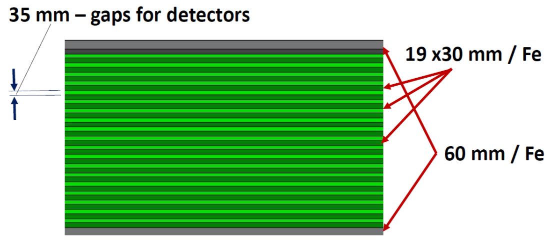
7.2 System layout

The Range System serves as an absorber for hadrons and a 'filter' for muons. It also forms the magnet yoke. It consists of a Barrel and two End Caps. Each End Cap, in its turn, consists of an End Cap Disk and a Plug. The schematic 3D view of the system and its main sizes are shown in Fig.4.15 (a). The absorber structure is shown in Fig.4.15 (b). The outer 60-mm Fe layers are used for bolting the modules together. The interlayer gaps of 35 mm are taken for reliable mounting of the detecting layers comprising the MDTs proper, the strip boards and the front-end electronic boards on them. The 30-mm thickness of the main absorber plates is selected as comparable with muon straggling in steel, thus giving the best possible muon-to-pion separation, and also providing rather good sampling for hadron calorimetry.

The Barrel consists of eight modules, and each End Cap Disk consists of two halves divided vertically. Such subdivision of the system (14 pieces in total) is chosen to optimize its further assembly and to satisfy the constructional requirements of the SPD experimental hall (cranes capability and floor load). The total weight of the system is about 810 tons, including 30 tons of detectors. The total number of MDT detectors is about 8000 units. The MDTs are deployed in the following way: along the beam direction in the Barrel, and perpendicular to the beam (horizontally) in the End Caps.



(a)



(b)

Figure 4.15: 3D view (half cut) of the Range (muon) system: (a) Barrel is shown in grey, End Cap Disks – in green, and End Cap Plugs – in yellow; (b) absorber structure.

The absorption thicknesses of Barrel and End Caps are selected to be equal - to 4 nuclear interaction lengths (λ_I) each. It provides uniform muon filtering in all directions. Together with the thickness of the electromagnetic calorimeter ($\sim 0.5\ \lambda_I$) the total thickness of the SPD setup is about 4.5 λ_I.

7.3 Mini drift tubes detector

The Mini Drift Tubes (MDT) detector was initially developed and produced at JINR for the Muon System of the D0 experiment at FNAL [229]. Later on, an MDT-based muon system was also produced for the COMPASS experiment at CERN [230]. Developed two-coordinate readout modification of the MDT with open cathode geometry and external pickup electrodes was proposed to and accepted by the PANDA collaboration at FAIR for the muon system of their experimental setup. This new version of the MDT is proposed for the SPD project, as it has all the necessary features – radiation hardness, coordinate resolution and accuracy, time resolution, robustness, as well as advanced level of already conducted R&D within the PANDA project.

The cross-section and layout of the MDT with open cathode geometry are shown in Fig.4.16. The detector consists of a metallic cathode (aluminum extruded comb-like 8-cell profile), anode wires with plastic supports, and a Noryl envelope for gas tightness. The comb-like profile of the cathode provides each wire with an opening left uncovered to induce wire signals on the external electrodes (strips) perpendicular to the wires. The strips are applied to obtain the second coordinate readout. The shape of the induced signal repeats the initial one, having the opposite polarity, but the amplitude is about 15% of the wire signal (see Fig.4.17). Thus, the strip signal readout requires higher signal amplification and proper electromagnetic shielding.

Application of an open cathode leads to the loss of the electric field symmetry in each of the 8 detector cells, resulting in lower gas gain for the applied voltage comparing to the standard MDT (cathode openings closed with stainless steel lid). The conducted R&D proved that the MDT with open cathode geometry easily achieves the parameters of the one with a closed cathode at higher voltages. The comparative plots of the counting rate, efficiency, and gas gain for both detector types (see Fig.4.18) show that the MDT with open cathode geometry repeats the standard MDT performance at a high voltage shift of + 100V. The drift time and the amplitude spectra of both detector variants also match, if we set this voltage shift between their operating points.

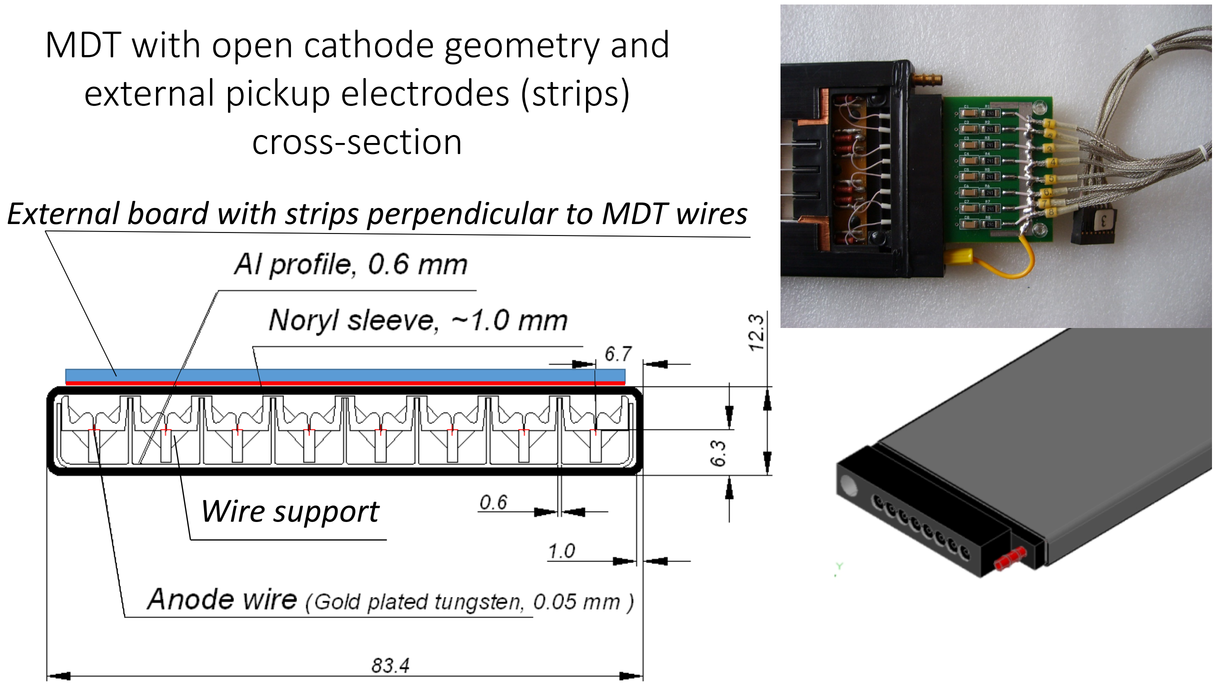


Figure 4.16: Mini Drift Tube with open cathode geometry cross-section (left) and layout (right).

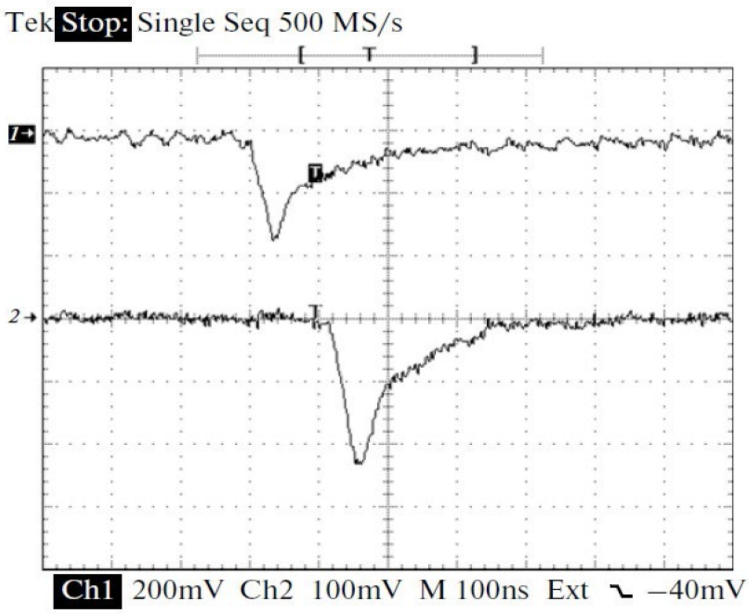


Figure 4.17: Oscillograms of single signals: from the anode wire (1) and the strip (2, inverted); the conversion factors are 60 and 480 mV/μA, respectively.

According to the results of the MDT (open cathode geometry) ageing tests, accumulation of a 1 C/cm total charge does not produce any significant effect on the detector performance. To monitor the ageing effects, measurements of the counting rate curves (Co-60 source) together with oscilloscopic observations of the MDT average signals (256 events) for Co-60 and X-rays were made twice a week over the whole period of intense irradiation (see Fig.4.19). Later on, this measurement (with X-rays) was conducted up to 3.5 C/cm of irradiation without any visible degradation of the MDT performance. It should ensure stable MDTs performance for the lifetime of the SPD project.

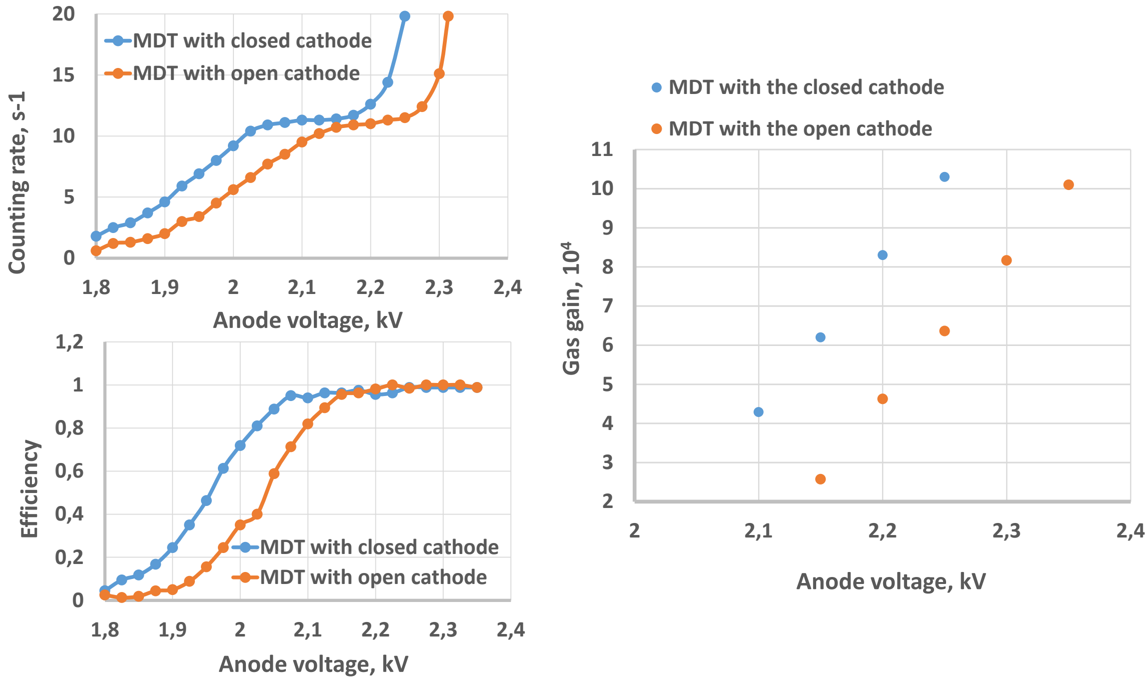


Figure 4.18: Comparative plots of the counting rate, efficiency, and gas gain versus the supply voltage for the MDT with closed and open cathode geometry.

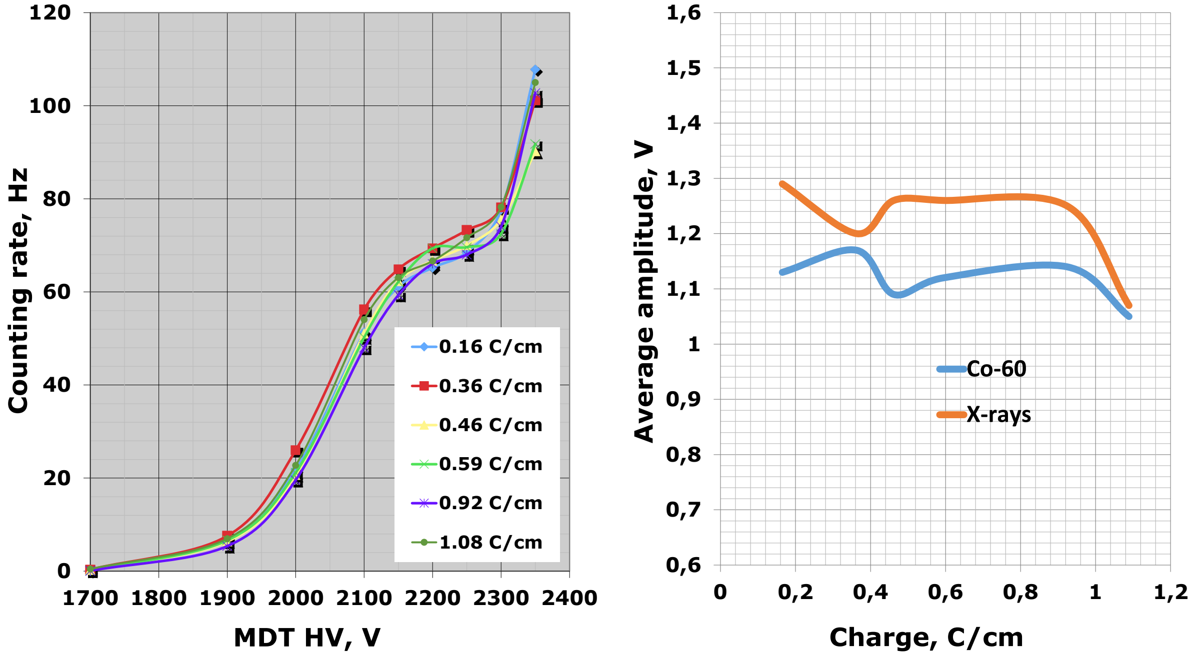


Figure 4.19: Counting rate curves for different accumulated charges (0.16÷1.08 C/cm) (left); average wire signal amplitudes vs accumulated charge for Co-60 and X-ray sources (right).

All R&D studies were made with a gas mixture of 70% Ar + 30% CO2 at atmospheric pressure, the one to be used in the proposed SPD Muon System. It is inflammable, radiation hard and fast enough (150-200 ns drift time). The wire pitch in the present design equals 1 cm, and a 3-cm strip width is selected for the second coordinate. These spatial parameters provide the Range System with coordinate accuracy well enough for identification of muons and give the system the features of a digital hadron calorimeter.

7.4 Front-end electronics

We plan to use the analog front-end electronics (with probable minor modifications) developed for the D0/FNAL and COMPASS/CERN experiments and also accepted by PANDA/FAIR. It is based on two ASIC chips: 8-channel amplifier Ampl-8.3 [231] and 8-channel comparator/discriminator Disc-8.3 [232].

The HVS/A-8 card serves for two purposes - as an MDT high voltage distributor and a signal amplifier designed to be the first stage of the Barrel and the End Cap Plugs wire signal readout. It is followed by Disc-8.3 based discriminating electronics (design in process) to fulfill the readout.

The ADB-32 card (initially designed for D0/FNAL) [233] is used for the End Cap Disks wire readout. It amplifies and discriminates the MDT signal, shaping it to the LVDS standard for further treatment by the digital front-end electronics.

An A-32 preamplifier card is used to start the strip signal readout in the whole system. It should be terminated (similarly to wire readout) by Disc-8.3-based discriminating electronics. In case of the End Cap Disks an ADB-32 card will be used for this purpose. The view of the basic FEE cards is shown in Fig.4.20.

Totally, the Range System has 106000 readout channels (65000 of which are wires and 41000 strips).

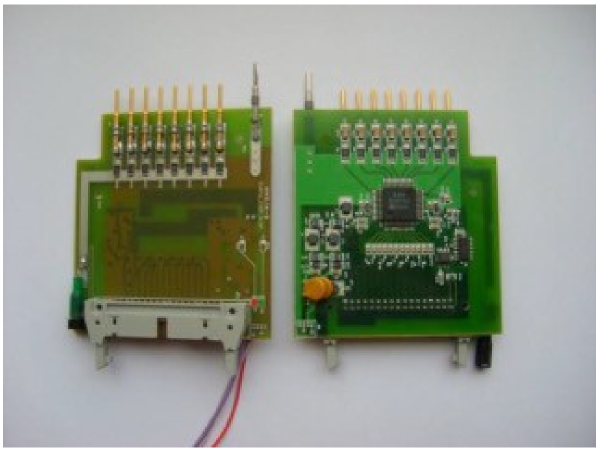
After having been shaped to the LVDS standard, the signals from the analog electronics go to the digital front-end electronics for further treatment.

The digital electronics being created for the Muon System is based on the use of FPGA chips. The prototype of the digital 192-channel MFDM module (Muon FPGA Digital Module) that we have developed includes a XC7A200T chip of the Xilinx Artix 7 family. This unit is functionally, mechanically, in data format and DAQ interface, compatible with the previously developed MWDB (Muon Wall Digital Board) unit [**?**] made on the basis of TDC F1 (ASIC) and successfully used for data readout from the Muon System of the COMPASS experiment (CERN). This approach allows both types of units to be used in the same readout system, thus making it possible for the new MFDBs cards to be tested under actual operating conditions.

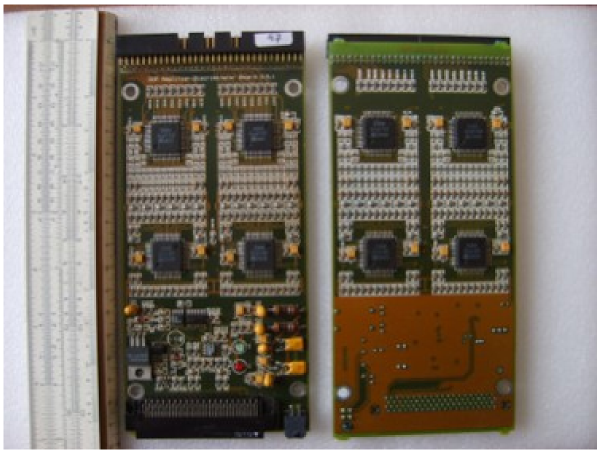
The unit includes three electronic boards (Fig.4.21): motherboard, mezzanine card, and interface card. The motherboard accepts 96 LVDS signals from the analog electronics through 3 high-density connectors, converts them to LVTTL levels and writes to the FPGA, and also communicates with two other boards. The mezzanine card also accepts 96 LVDS signals through 3 connectors, converts them to LVTTL levels and transmits through the 120-pin board-to-board connector to the motherboard. The interface card is designed to connect the MFDM module with the DAQ via the HotLink interface (RJ45 connector), to download the firmware to the FPGA from a local computer, as well as to download the firmware via the RS-485 interface (RJ45 connector) from a remote computer.

Tests performed at CERN with the Muon System prototype on cosmic muons gave encouraging results. The further tests will be conducted with a prototype of the SPD range system ($\sim$ 1200 channels of wire and strip readout) at the Nuclotron test beam area.

In the future, after the final tuning of the unit, we are planning to replace the HotLink interface in the MFDM module with the S-Link interface for direct connection of the Muon System digital electronics to the FPGA-based SPD DAQ. A general view of the data flow structure for the Muon System is shown in Fig.4.22.



(a)



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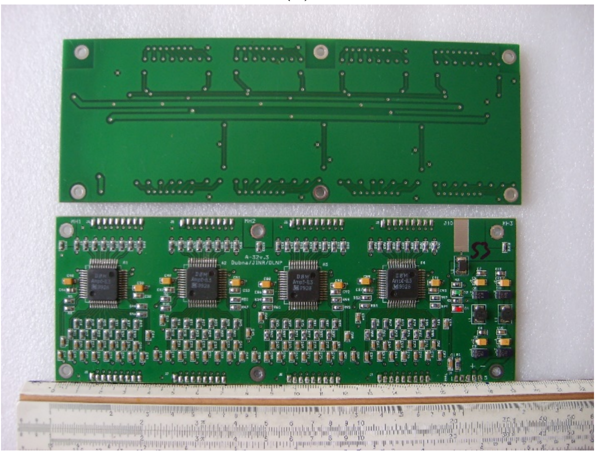
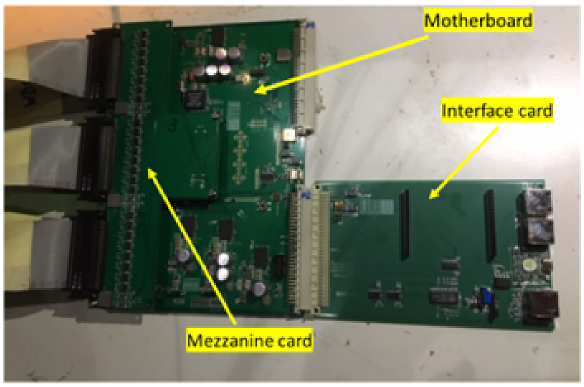
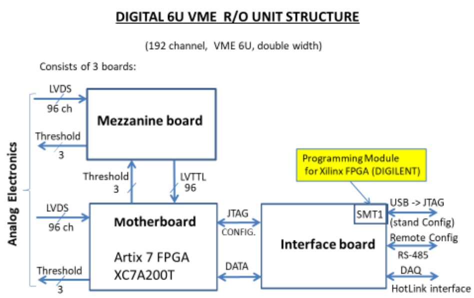


(c)

Figure 4.20: Front-end analog electronics cards: HVS/A-8 (a), ADB-32 (b) and A-32 (c).



(a)



(b)

Figure 4.21: Digital 192-channel MFDM module (a) and its block-diagram (b).

7.5 Performance figures

The evaluation of the main parameters of the proposed Range System is being performed with big prototype installed at CERN within the PANDA program. The prototype (Fig.4.23) has a total weight of

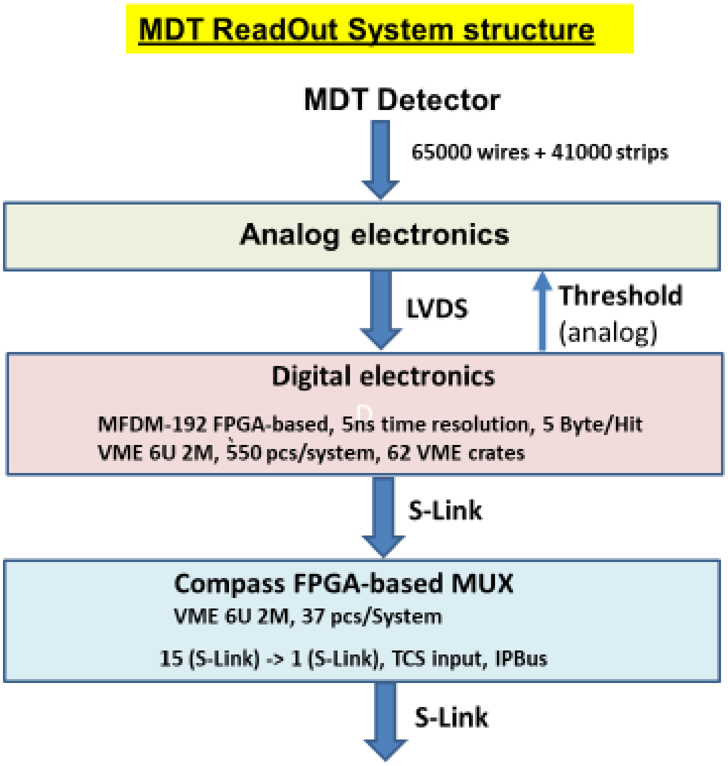


Figure 4.22: Data flow diagram – from detector to DAQ.

about 10 tons (steel absorber and detectors with electronics) and comprises 250 MDT detectors with 4000 readout channels (2000 for the wires and 2000 for the strips, 1 cm wide). It has both samplings (3 cm and 6 cm) present in the system (Barrel and End Caps), thus providing an opportunity for direct calibration of the response to muons, pions, protons, and neutrons.

Fig.4.24 gives the examples of the prototype response to different particles. The patterns demonstrate excellent PID abilities of the Range System. The data were taken during the May and August runs of 2018 at the T9/PS/CERN test beam. The beam particles hit the prototype from the top of the picture. The beam momentum for all the particles is 5.0 GeV/c. Neutrons were generated by a proton beam on a carbon target placed in the very vicinity of the first detecting layer. The points on the pictures represent hit wires, thus giving the impression of a typical device response with an accuracy $\sim$ 1 cm.

8 Time of flight system [OUT OF DATE]

8.1 SPD-ToF system

Newest SPD detector should allow identifying different particles with good resolution. In this case it has to have good time-of-flight (TOF) system. Estimate time resolution of such TOF system should not be worse than (60?) ps. The efficiency of particle registration at high rate (few kHz/cm^2) must be above 98%. Based on the experience of built similar systems in experiments as ALICE [1], HARP [2], STAR [3], PHENIX [4] and BM@N the glass multigap Timing Resistive Plate Chamber (mRPC) could be proposed as base time detector. For example, ToF-700 wall in BM@N experiment provides us with

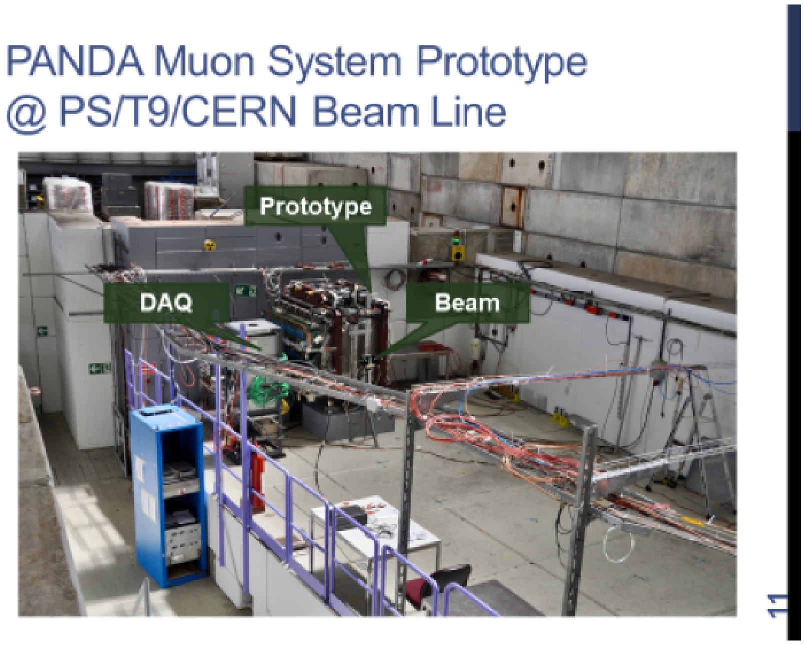
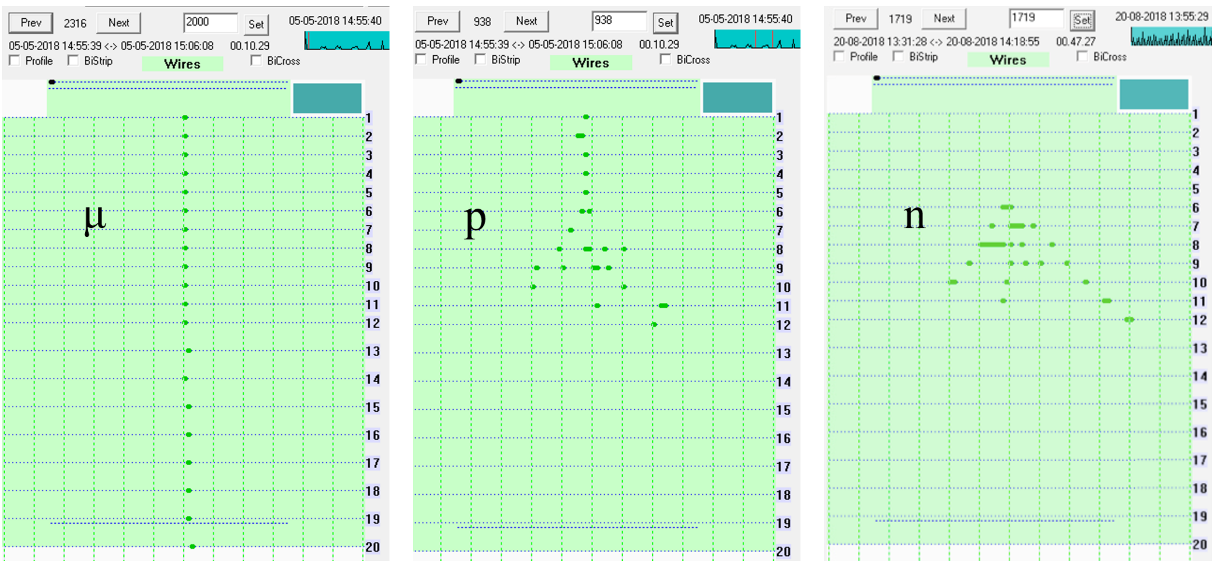


Figure 4.23: Range System prototype (10 ton, 4000 readout channels) at CERN.



(a) (b) (c)

Figure 4.24: Demonstration of PID abilities: patterns for - (a) muon, (b) proton and (c) neutron.

the pion/kaon separation up to 3 GeV/c and proton/kaon separation up to 5 GeV/c. In an assumption that time resolution of start timing detector will be <40 ps.

Design of the BM@N ToF-700 wall was based on experimental results obtained during multiple tests of various modifications of glass mRPC exposed in charge particles beam [38, in preparation]. The counting rate for standard glass mRPC is limited to several hundreds Hz/cm^2 due to the use of conventional float glass plates with a bulk resistivity in the range $10^{12} - 10^{13}$ Ω· cm. Therefore, the extension of the counting rate capabilities of mRPC has become an important issue.

One of the way to increase the mRPCs performance at high rates is to use the low resistivity glass (less than $10^{10} - 10^{11}$ Ω· cm) [24, 25, 26, 27] or ceramics [28] as the electrode materials. For instance,

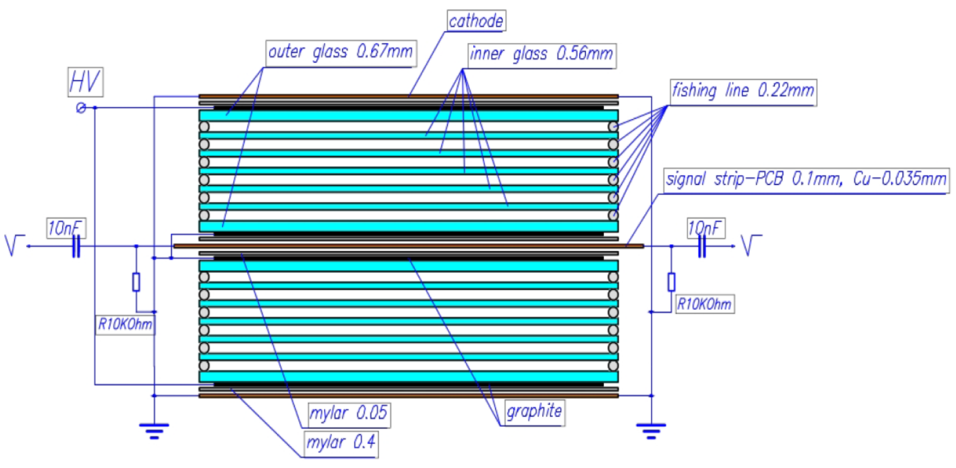


Figure 4.25: Schematic cross-section of the twelve gap MRPC.

time resolutions below 90 ps and efficiencies larger than 90% were obtained for particle fluxes up to 25 kHz/cm^2 for the 10-gap mRPC [26]. An alternative method is to reduce the glass stack resistance by minimizing of the used electrodes thickness and to increasing a temperature of the glass [29, 30]. It was shown that such method can provide high time resolution at continuous rate up to 20 kHz/cm^2 [31].

8.2 Warm mRPC for BM@N

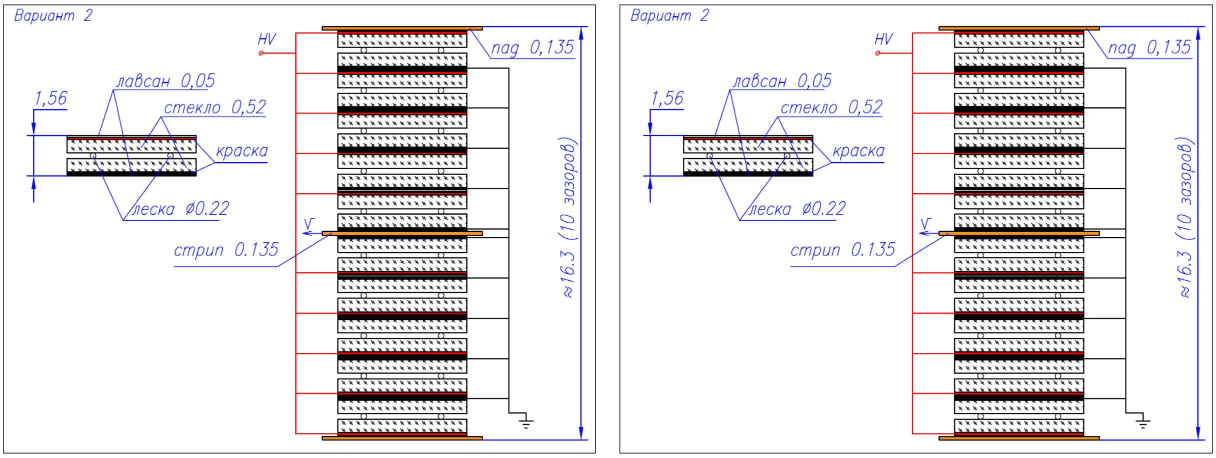
Schematic cross section of mRPC is shown in Fig. 4.25. It consists of two identical 6-gap stacks with anode strip readout plate in between. The size of mRPC is 473$\times$279$\times$17 mm^3 with the working area of 351x160 mm^2. Each mRPC has 32 10x160 mm^2 readout strips with 1 mm gaps between them.

Each stack is formed by seven glass plates with the 2×10^{12} Ω·cm bulk resistivity. The gap between the glasses 0.22 mm is fixed by spacers – usual fishing-lines, which ran directly through the RPC working area. Graphite conductive coating with surface resistivity of $\sim$1 MΩ is painted to outer surfaces of external glass plates of each stack to distribute both the high voltage and its separate ground and thus to form the uniform electrical field in the stack sensitive area. The anode readout strips plate is a one-sided printed PCB with the thickness of 100 mm, the thickness of the copper is 35 microns. Signals are taken from the both ends of anode strips. The entire mRPC assembly is put into a gas-tight box. Bottom of box is made of a double side PCB (motherboard) with a thickness of 2.5 mm, side frame of the box is made of aluminum profile, the top of box is closed by aluminum cover having thickness of 1.5 mm. Paper [38] presents the performance of 12-gap mRPC in the range of the counting rate from 0.45 kHz/cm^2 up to 10 kHz/cm^2 obtained using secondary muon beam from U70 at Protvino. The measurements at different rates were performed in the mRPCs temperature range 25-45 ^{o}C with the step of 5 ^{o}C. The time resolution is reached up to 50-60 ps with good and stable efficiency under temperature of 40-45 ^{o}C.

8.3 Chamber for SPD

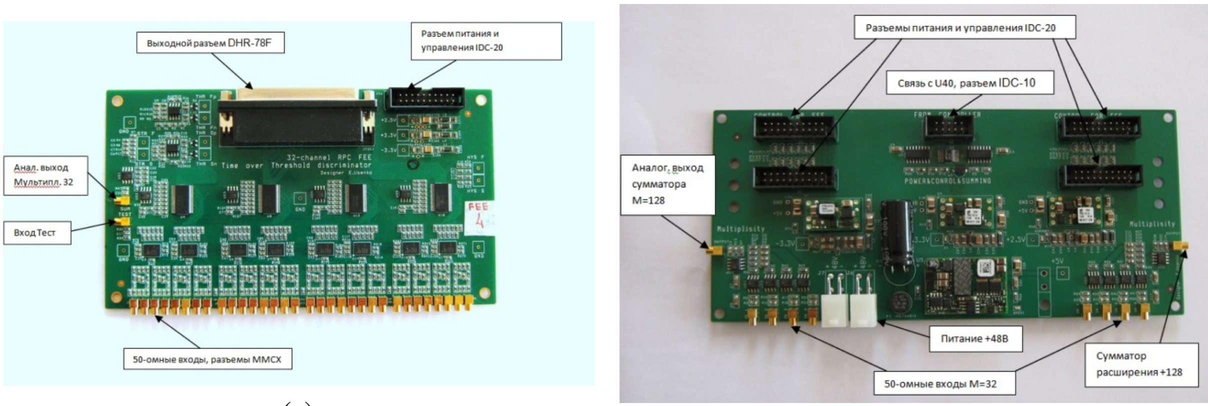
Particle flux in SPD experiment is expected up to 10 and more kHz/cm2 (??). Therefore the high-speed performance of TOF system is important parameter. In order to increase the high-speed performance of mRPC now is decided to make new chamber using of glass plate with less thickness and cover each plate by graphite (Fig. 4.26). It should decrease the time dissipation of charge inside glass.

Using such structures we expect to increase high-speed performance twice with time resolution better than 50 ps



(a) (b)

Figure 4.26: Schematic cross-section of the new MRPC.



(a) (b)

Figure 4.27: The 32RPC (a) and PWR&CTRL (b) modules.

8.4 FEE of mRPC

The 32-channels FEE module (32RPC board) designed for our mRPCs bases on NINO chip. The output signal of NINO amplifier-discriminator is the time-over-threshold pulse whose leading edge provides with the time of the hit while its pulse width is proportional to the input signal charge [9]. The signals from mRPC to the module 32RPC are coming by 50Ω coaxial cables with use MMCX connectors. Output LVDS signals are transmitting to the module of digitization with use of DHR-78F sockets. At present a 64-channel VME time-to-digital converter TDC64VHLE based on the HPTDC chip is used for digitization [10]. Power supply, threshold settings, stretch time settings and hysteresis settings of the four 32RPC boards are made by a special designed module power and control (PWR&CTRL). PWR&CTRL module is controlled by the U-40 VME module [11] via digital SPI interface.

8.5 SPD time resolution requirements

- Diameter = 2 m
- Time of flight = ∼10 ns
- Required time resolution = 20 ps (??)

9 Beam-beam counter [V. Ladygin]

Two Beam-Beam Counters are located just in front of the PID system endcups. The main goal of the Beam-Beam Counter is the local polarimetry at SPD using the measurements of the azimuthal asymmetry in inclusive production of charged particles in collision of transverse polarized proton beams.

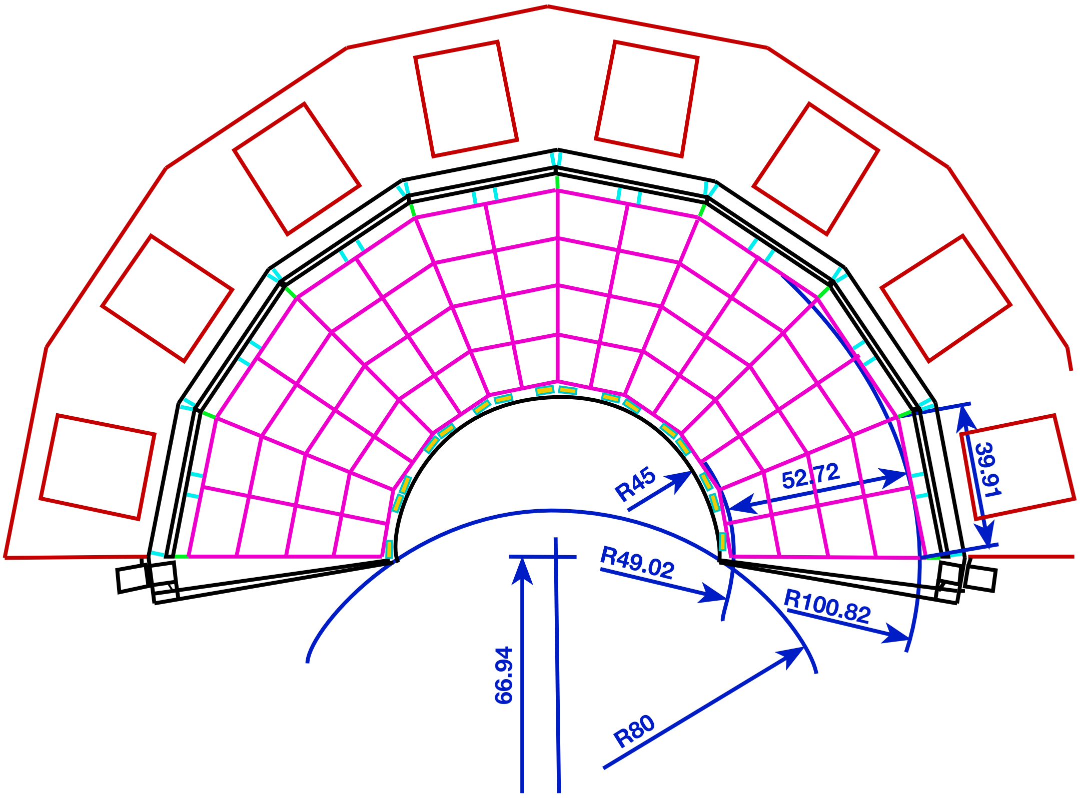


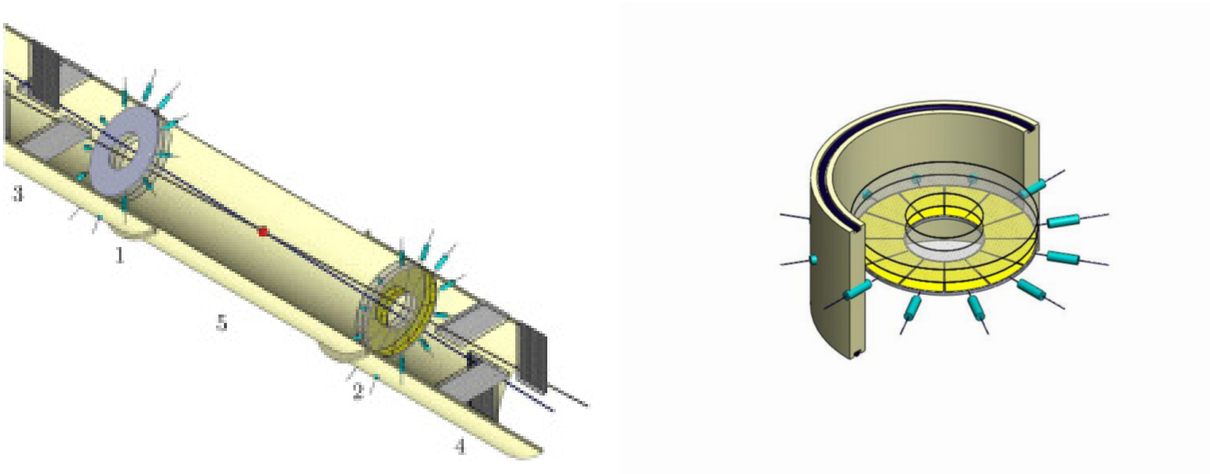
Figure 4.28: Beam-beam counter azhimuthal and polar angle segmentation.

Another goal of BBC is the fast selection of the different types of events. The simulation performed at $\sqrt{s}$=27 GeV/c^2 for minbias pp- collisions gives that at least one BBC will have a signal for 72% events (only 41% in both BBCs). However, in the case of hard processes at least one BBC will hit in 96.5% of events, while both BBCs will have signals in 67% cases. Therefore, the requirement of the BBC signals allows to select hard processes.

The concept of the BBC is shown in Fig.4.28. It consists of two major part: inner and outer, which are based on different technologies. BBC inner part will be based on fast segmented Micro Channel Plate (MCP) detectors, while BBC outer part will be produced from fast plastic scintillator tiles. The inner part covers 30-60 mrad and and should be separated on to 4 layers consisting of 32 azimuthal sectors. The outer part covers 60-500 mrad divided on 5-6 layers on the polar angle each of them has 16 azimuthal sectors. Final segmtntation will be obataied from the ptimization of the polar angle granularity for the whole energy range of NICA.

9.1 Inner part of BBC: MPC

Two compact detector systems are proposed to meet the challenges of the fast beam-beam collisions monitoring, event selection and the precise timing determination in proton-proton and nucleus-nucleus collisions at NICA. Beam Position Monitor (BPM) and Fast Beam-Beam Collision (FBBC) monitor are capable to provide the information for each bunch crossing both on the beams location and on the intensity of collisions, as well as on the azimuthal distribution of the particles in the event. The systems use fast Micro Channel Plate detectors (MCPs). The ultra-high vacuum (UHV) compatibility and low-mass compact design of the BPM and FBBC components allow one to consider their application inside the vacuum beam line of NICA collider. The BPM is based on the effect of the residual gas ionization and provides high accuracy, fast, bunch-by-bunch measurements of the beam position. FBBC uses the concept of the fast isochronous timing for the multi-pad readout of short ($\sim$ 1ns) MCP signals, produced by the particles in the collisions of the beams. Studies of the polarization phenomena in light- and heavy-ion interactions at SPD NICA is another goal of research at NICA, and the FBBC is also considered for the local polarimetry at SPD.



(a) (b)

Figure 4.29: (a) General layout: the Fast Beam-Beam Collision (FBBC) monitor composed of MCP discs (1 and 2) in combination with the Beam Position devices (BPM) (3 and 4) are situated symmetrically to the Interaction Point (5) inside the vacuum beam-pipe of NICA collider. (b) Compact module of the Fast Beam-Beam Collision Monitor (FBBC) based on the circular MCPs. Sector cathode readout pads and two MCP set-ups are embedded into a separate flange with hermetic 50 Ohm signal and HV feedthroughs (the last ones are not shown).

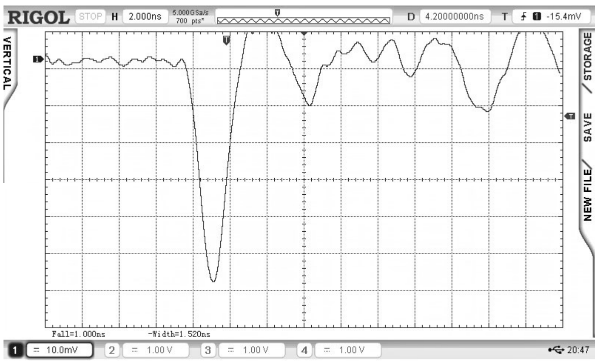


Figure 4.30: Compact module of the Fast Beam-Beam Collision Monitor (FBBC) based on the circular MCPs. Sector cathode readout pads and two MCP set-ups are embedded into a separate flange with hermetic 50 Ohm signal and HV feedthroughs (the last ones are not shown).

One of the promising directions of beam diagnostics is the registration of residual gas ionization products by the fast MCP based detector. Such detectors work in high vacuum conditions and are used for registration of circulating beam profile at many accelerators, including Nuclotron (JINR), and heavy ion colliders.

To meet the challenges of fast monitoring of beam-beam collisions for high intensity NICA beams, the MCP-based Fast Beam-Beam Collisions (FBBC) detector with high timing properties is proposed in combination with the Beam Position Monitor (BPM). This will provide monitoring of bunch-by-bunch crossing, the beams location and their profiles, the collision intensity, and the azimuthal distribution of produced particles.

Two compact systems based on the application of Micro Channel Plates (MCPs) are proposed to meet the challenges of the fast beam-beam collisions monitoring, event selection and determination of the precise timing signal (T0) of the collisions, see Fig.4.29. These systems of monitor detectors consist of 2D position-sensitive beam imaging detectors (BPM) and two ring beam-beam collision detectors (FBBC-left and FBBC-right) that are situated inside the vacuum beam line. The ultra-high vacuum (UHV) compatibility and low-mass compact design of the Fast Beam-Beam Collisions (FBBC) monitor in combination with the Beam Position device (BPM)[10], allow their application inside the vacuum beam line of NICA collider. FBBC uses the concept of the isochronous multi-pad fast readout and the precise timing determination of short ($\sim$1ns) MCP signals. New MCPs with the improved characteristics, such as small diameter (8μm) channels, low resistivity (100-500 MOhm), high gain ($\sim 10^7$), short fast rise-time ($\sim$0.8ns) signals, will be used.

Fig.4.30 shows a typical MCP signal from the testing of the prototype detector. The colliding beams pass through the central opening of the MCP, and the outer edges of the MCP capture secondary particles flying some definite distance from the interaction point (IP). Signals are recorded at 12 sector cathode and their arrival times are digitized along with the multiplicity information.

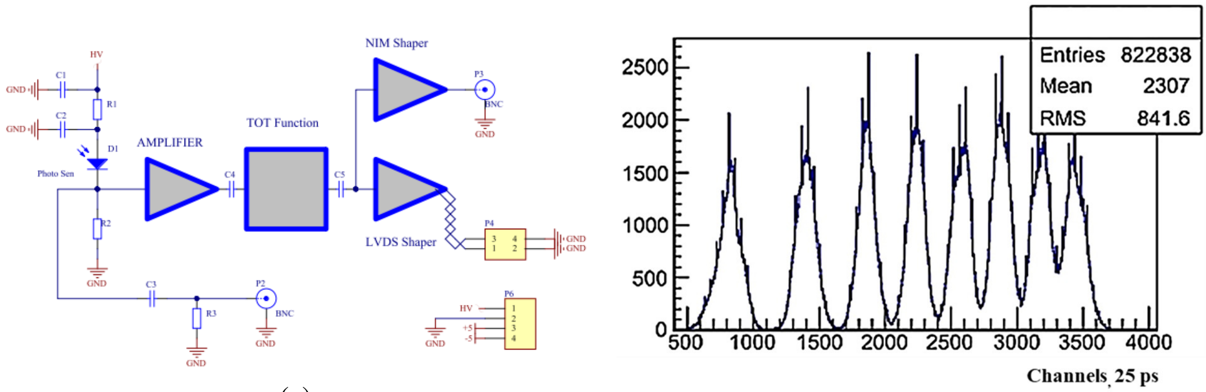
The main feature of the new MCP is a high secondary emission coefficient and fast fronts of the output signal. The new MCPs have a fast leading edge and high gain.

A compact set-up of two detectors with high timing capabilities based on the MCP applications – the Fast Beam-Beam Collision counters (FBBC) and the Beam Position Monitor (BPM), is proposed to meet the wide set of requirements including those of the future physics program with the polarized beams at SPD NICA . The feasibility of the event-by-event monitoring of the beam-beam interactions at NICA is confirmed both by the previous developments of the UHF-UHV technology and by the beam tests at JINR and CERN of the prototype detectors and electronics, as well as by the in-lab tests of new 8-channels MCPs with the improved characteristics.

9.2 Outer part of BBC: scintillation tiles

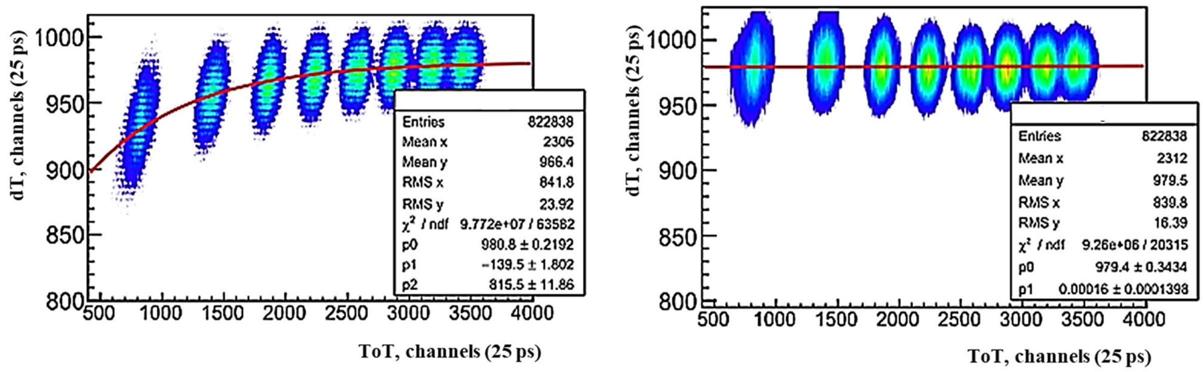
The scintillation part of BBC will consist of tiles viewed by SiPMs. The measurement of the signal amplitude is required for time-walk correction to improve the time resolution.

At single-channel prototype of detector we have the ability to measure the amplitude using developed FEE based on the ToT technique. This technique is a well-known method that allows us to measure the energy deposited in the material by reconstructing a given property of the output current pulse – the total charge collected, the pulse amplitude, etc. The ToT method converts the signal pulse height into a digital value in the early stage of the FEE, which greatly simplifies the system in comparison to analog detectors with serial readout through ADCs. The measurement of the ToT is composed of two measurements of time for the signal going above (leading) and returning below (trailing) a given threshold. The first version of the prototype includes a power supply and the electronics (Fig.4.31 a)) made on a separate PCB. This PCB used for each cell of the SiPM. Power supply for SiPM with the total (65 V) and individual (range of 0 to +10 V) voltage, built-in voltmeter, and manual interface for voltage supply. It is possible to connect eight cells simultaneously. The amplifiers are used that do not



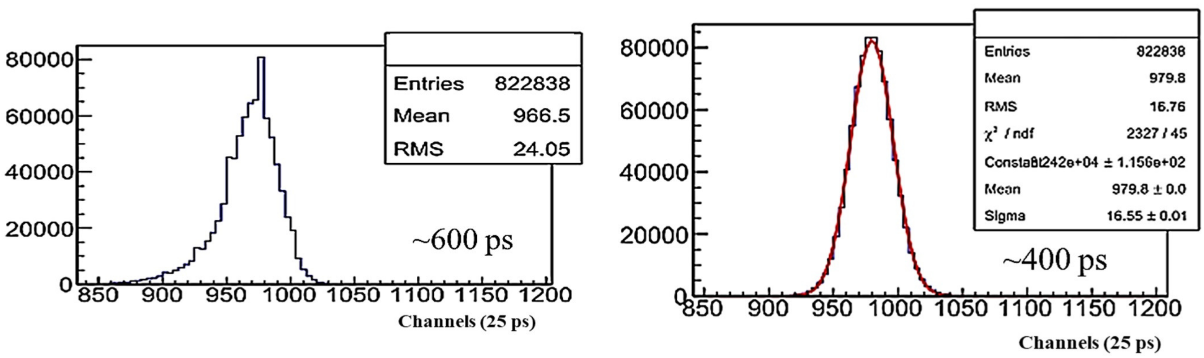
(a) (b)

Figure 4.31: (a) The schematic view of the front-end electronics with a ToT function, **b**) The distribution of the ToT for LED signal.



(a) (b)

Figure 4.32: The dT (T_{SiPM1} - T_{SiPM2}) correlation on the ToT. (**b**) The result after the time-walk correction for the dT (T_{SiPM1} - T_{SiPM2}) correlation on the ToT.



(a) (b)

Figure 4.33: (**a**)The dT (T_{SiPM1} - T_{SiPM2}). (**b**) The result after the time-walk correction for the dT (T_{SiPM1} - T_{SiPM2}).

change the leading edge of the signal. This allows to get the time stamp of the event. Then the signal is integrated and transmitted to the comparator.

The response of Hamamatsu S12572-010P SiPM [234] with FEE to the LED have been studied. The electrical signal from a lemo output of the LED was used as a trigger. The illumination was performed by uniform light in light isolated box. In addition to the ToT information (Fig.4.31 b)) the time stamp of the event for each SiPM cell was investigated. The distribution (Fig.5.1 a)) shows the correlation of these values and that the signal in the region of small amplitudes comes later in time. This is due to signal latency (so called time-walking effect). This delay occurs due to the difference between the time when a photon or charged particle passes through the detecting element and the time when the electronics register this signal. This leads to a deterioration in the time resolution. After performing the correction (see Fig.5.1 b)), the time-walking effect is removed [235].

The time resolution was defined as the RMS and was approximately 600ps. Taking into account the non-Gaussian waveform (Fig.5.3 a)) and the fact that the time resolution is not the maximum allowed for this type of detector, the time-walk correction has been applied. The main and important result of the correction was a time resolution of approximately 400 ps (Fig.5.3 b)), which is 1.5 times better before the correction.

The first version of the prototype using developed front-end electronics based on the Time-over-Threshold method was tested. After the time-walk correction, the time resolution improved to 400 ps. Taking into account the SiPM suboptimal for precise time measurements the result is promising. Further development of the FEE with a ToT function allows to use standard TDCs for timing measurements.

Chapter 5

Local polarimetry [V. Ladygin]

The main goal of the local polarimetry at SPD is the permanent monitoring of the beam polarization during data taking to reduce the systematic error coming from the beam polarization variation. Another task is beam polarization monitoring independent on the major polarimeters (CNI and the absolute one), as well as possible usage of this tool to tune the beam polarization axis. Since the SPD energy range is relatively new for spin physics, there is a lack of precise polarization data allowing one to find the explicit solution for the local polarimetry.

1 Asymmetry in inclusive production of charged particles

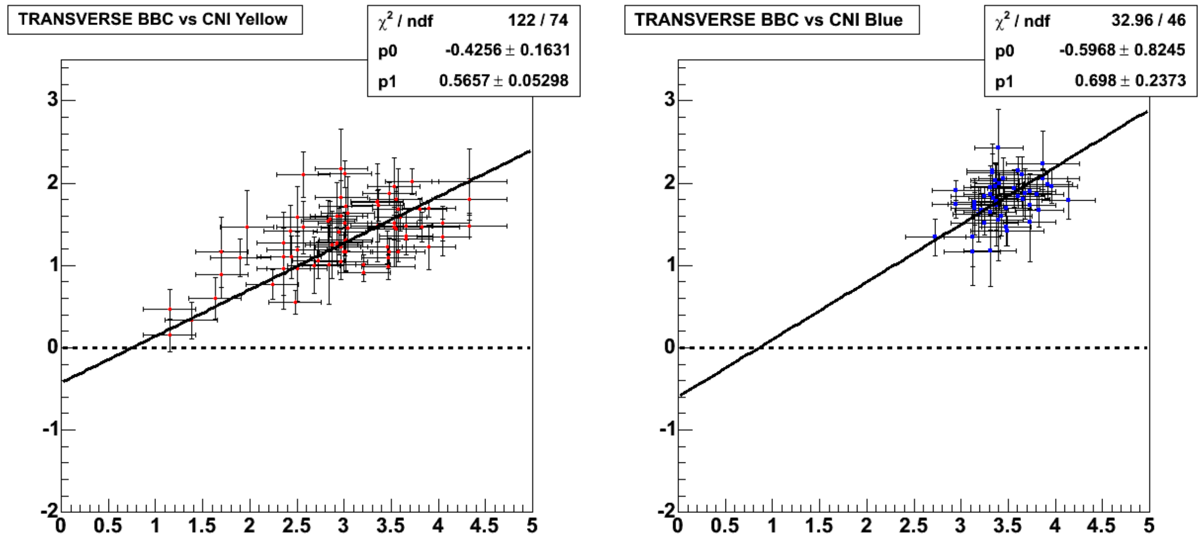
One of the tools to control the proton beam polarization is measurements of the azimuthal asymmetry in inclusive production of charged particles in collisions of transverse polarized proton beams. Such a method is well adopted at the STAR detector. Two Beam-Beam Counters (BBCs) are used for this purpose. Each BBC consists of two zones corresponding to different rapidity range. The inner and outer zones cover $3.3< |\eta| < 5.0$ and $2.1< |\eta| <3.3$, respectively. The BBCs detect all the charged particles produced in the forward direction within their acceptance.

The correlation of the beam asymmetries measured by the RHIC *pC* CNI polarimeter [236, 237] and the STAR BBCs is demonstrated in Fig.5.1. One can see that the measurements by BBCs are sensitive to the transverse polarization of the colliding beams. The value of the effective analyzing power A_N for inclusive production of charged particles at $\sqrt{s}$= 200 GeV is about $(6 \div 7)\times 10^{-3}$. At NICA energies it will have, in principle, the same magnitude, or even a larger one due to a larger analyzing power for the *pp* elastic scattering. Therefore, the BBCs can be used for the local polarimetry at SPD. The design of the SPD BBCs is described in Sec. **??**.

2 Inclusive π^0 production

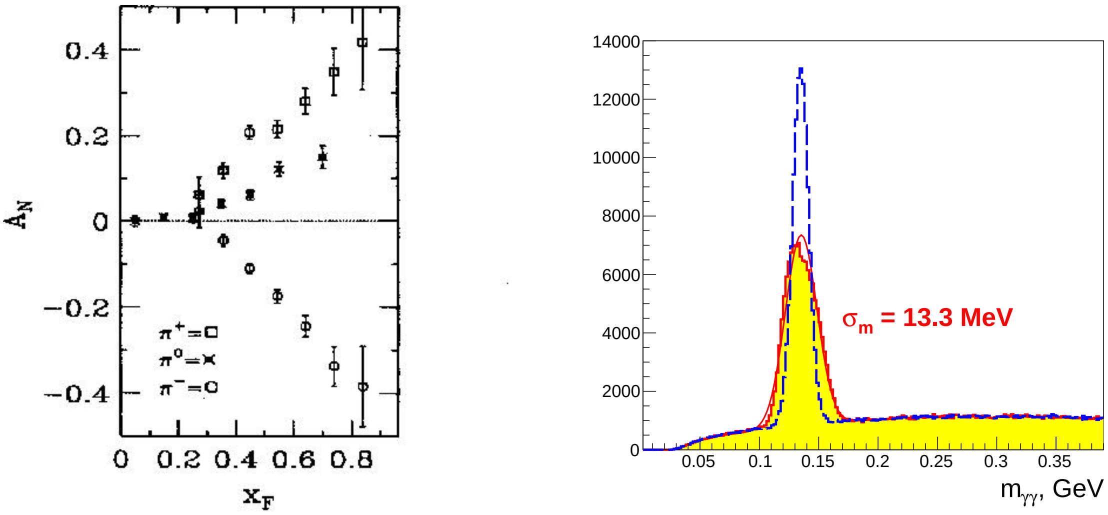
One of the reactions to measure and to monitor the vertical component of the polarized proton beam is the inclusive $pp \to \pi^{\pm,0}X$ reaction. Fig.5.1 demonstrates the single transverse spin asymmetries A_N obtained in the *p-p* collision for π^+, π^0 and π^- inclusive production at 200 GeV ($\sqrt{s}$ ∼20 GeV)[238, 239]. The data demonstrate large values of the single transverse spin asymmetries with their signs following to the polarization of the valence quarks in the pions. This regime occurs already at 22 GeV [240] corresponding to $\sqrt{s_{NN}}$ ∼7 GeV for the collider option. Therefore, the inclusive neutral pion production can be used for the polarimetry over the full energy range of the SPD experiment.

The value of the single transverse spin asymmetry in the $pp \to \pi^0 X$ reaction is almost twice smaller than



(a) (b)

Figure 5.1: Correlation of the beam asymmetries measured by the RHIC *pC* CNI polarimeter [236, 237] and left (a) and right (b) STAR BBCs.



(a) (b)

Figure 5.2: (a) Single transverse spin asymmetry A_N for inclusive pion production in *p*-*p* collisions at 200 GeV [238, 239].. (b) The π^0 reconstruction in the SPD ECAL end-cup with (red) and without (blue) vertex position information.

for the charged pions production. However, the π^0 selection can be done more easily, since it does not require track reconstruction.

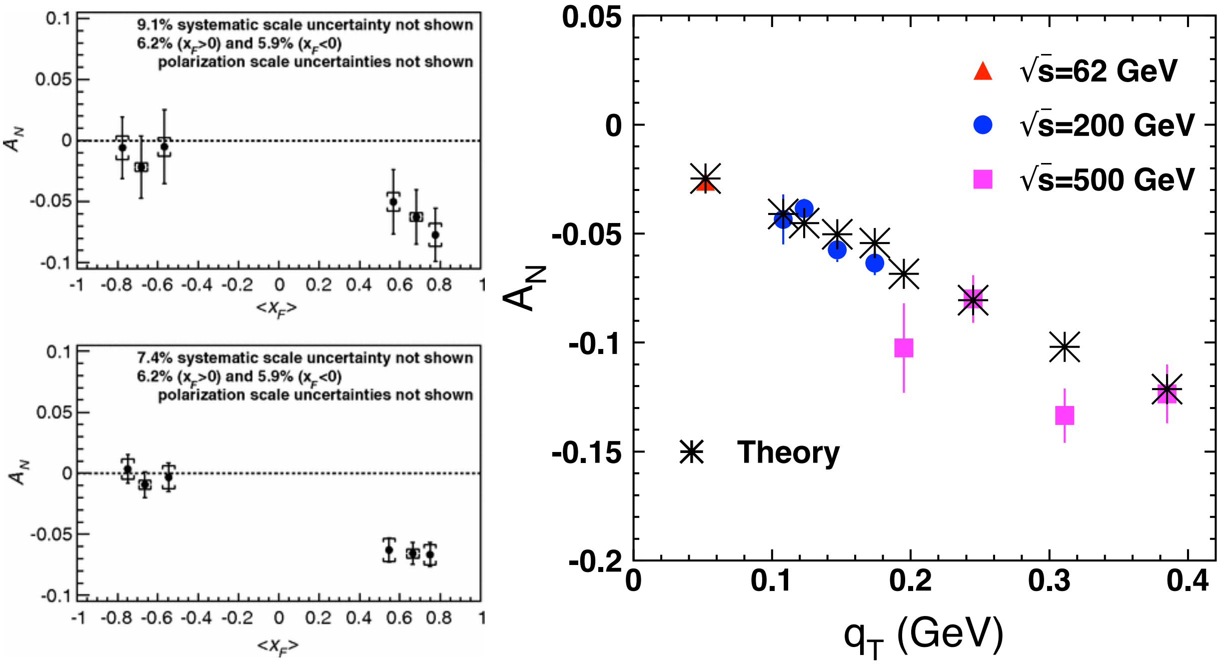
For online local polarimetry one can use the parts of the ECAL end-cups placed around the beam pipe. Fast π^0 reconstruction algorithms will not include the information on the vertex position along the beam axis, therefore, the width of the π^0 peak will increase. The Monte-Carlo results obtained for $\sqrt{s_{NN}} \sim$27 GeV and presented in Fig.5.3 demonstrate such enlargement. However, one can see that the selection of π^0 is good enough for the local polarimetry purposes. An effective analyzing power $< A_N >$ for the kinematic range of produced π^0 $p_T > 0.5$ GeV/c and $x_F > 0.5$ is about 0.1. The rate of π^0 decays reconstructed in the end-caps of the calorimeter provides statistical accuracy of the beam polarization estimation at a few-percent level after 10 minutes of data taking at 10 GeV$< \sqrt{s} \leq 27$ GeV. The corresponding accuracy of the spin direction reconstruction is about a few degrees.

3 Single transverse spin asymmetry for very forward neutron production

The energy dependence of the single transverse spin asymmetry, A_N, for neutron production at very forward angles was measured in the PHENIX experiment at RHIC for the polarized p-p collisions at $\sqrt{s}$=200 GeV [241]. The neutrons were observed in the forward detectors covering an angular range of up to 2.2 mrad. The observed forward neutron asymmetries are large, reaching A_N=-0.08 ± 0.02 for x_F=0.8; the measured backward asymmetries, for negative x_F, are consistent with zero. The results of x_F dependence of A_N for neutron production in the (upper) ZDC trigger sample and for the (lower) ZDC$\otimes$BBC trigger sample are shown in Fig.5.2(a). The error bars show statistical uncertainties, and the brackets show the p_T-correlated systematic uncertainties. The data were obtained for 2 types of triggers: the first one is the ZDC trigger for neutron inclusive measurements, requiring an energy deposit in the ZDC to be greater than 5 GeV. The other one was a ZDC$\otimes$BBC trigger, a coincidence trigger of the ZDC trigger with the BBC hits defined as one or more charged particles in both of the BBC detectors.

The observed large asymmetry for forward neutron production was discussed within the pion exchange framework, with interference between the spin-flip amplitude due to the pion exchange and the non-flip amplitudes from all Reggeon exchanges. The numerical results of the parameter-free calculation of A_N are in excellent agreement with the PHENIX data (see Fig.5.2(b)). One can see that A_N is increasing almost linearly as a function of neutron transverse momentum q_T. One can expect the A_N value of $\sim$-0.02 at $\sqrt{s}$=27 GeV. Therefore, the $pp \to nX$ reaction with the neutron emission at very forward angles can be used at SPD at least at a higher energy.

Very forward neutrons are detected by two zero-degree calorimeters (ZDCs) [243] placed in the gaps between the ion tubes of the colliding beams on the left and right from the center of the detector. Two ZDCs will be also placed at SPD. These ZDCs can be considered as an additional tool for the local polarimetry for pp-collisions at the highest NICA energy.



(a)

(b)

Figure 5.3: (a) x_F dependence of A_N for neutron production in the (upper) ZDC trigger sample and for the (lower) ZDC⊗BBC trigger sample. (b) Single transverse spin asymmetry A_N in the reaction $pp \to nX$ measured at $\sqrt{s}$= 62, 200, 500 GeV at PHENIX. The asterisks show the result of the theoretical calculations [242].

Chapter 6

Detector control system [A. S. Chepurnov]

SPD detector control system (DCS) is designed to control the main operating modes of the detector parts and the entire detector as a whole, for continuous monitoring of slowly changing parameters of the detector, engineering means which ensure the operation of the detector and the environment. DCS is synchronized with the main operating modes of the NICA accelerating complex through a synchronization subsystem common to DCS and DAQ. DCS provides parameterization of the control object (SPD detector), implements algorithms for normalization, measurement of parameters and control based on these parameters and provides the formation of the necessary sets of abstractions and options for representing these abstractions to the operator in an intuitive way.

When critical values of parameters go beyond the predefined boundaries in predetermined situations emergency events are caused and initiate procedures for handling such events, including the procedure for automatically detector stopping in order to prevent its damage. Parameter values are archived in a database to implement the procedure for long-term monitoring of the detector's operation and identify possible failures in the operation of the equipment and emergency situations. The configurations of the detector parameters saved in the database make it possible to start the detector promptly and use it with various preset parameters and in various operating modes in accordance with the current requirements of a physical experiment

DCS allows the autonomous operation of each detector subsystem at the stage of initial start-up, periodic maintenance, calibration and planned upgrades. The number of parameters in the system is expected to be significant, so it is assumed that the system should be extendable and flexibly configurable. When building general DCS and control systems of each part of the detector, the preference should be given to architectural and software solutions based on the event-oriented model and client-server and producer-consumer interaction models should be implemented for communication. Centralized systems operating in the master-slave polling mode should be avoided.

1 DCS concept

Almost all detectors used in high-energy physics include parts consisting of similar systems consists from devices, sensors and actuators with similar or identical functionality that determine the parameterization of the entire detector as a control object. Such systems include:

1. HV power supply system for powering gas detectors and light (photon) sensors (PMT and SiPM);

2. LV power supplies for powering of magnets, digital and analog electronics;

3. cryogenic systems;
4. gas supply and mixing systems;
5. vacuum systems;
6. front-end electronic LW powering control and temperature monitoring;
7. various cooling and temperature control systems;
8. DAQ system;
9. accelerator interface and sync.;
10. deneral external electricity, water cooling, etc.

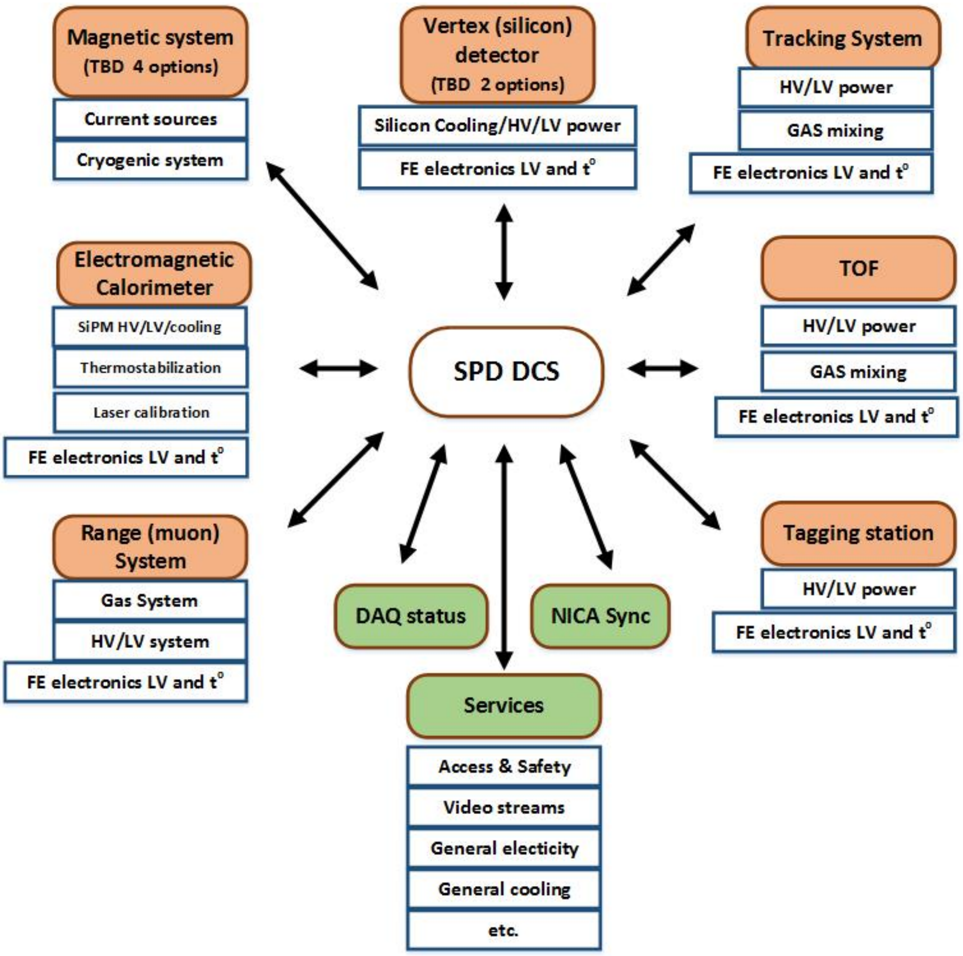


Figure 6.1: SPD detector control system layout.

The SPD detector is no exception and includes almost all of these systems included in separate parts of the detector as shown in the layout diagram Fig. 6.1. Each part of the detector contains one or more subsystems. The composition of the systems will be refined as the individual parts of the detector are developed.

All of these systems can be similarly parameterized and shown to the operator in an intuitive representation in order to simplify the operator's decision-making algorithm. However, the physical implementation at the hardware level of these elements may differ significantly in different parts of the SPD, which is due to the fact that - these parts inherit the experience of their developers gained in previous experiments, - hardware and software components are selected based on their cost and availability, - parts of the detector are manufactured at different times.

Nevertheless, in order to optimize the cost of financial and human resources for the creation of the entire detector and DCS, in particular, it is necessary to recommend the developers of the detector parts to strive for standardization of the used hardware and embedded software. This will significantly reduce the effort in developing, setting up and operating the detector and will result in significant cost savings. To achieve these goals, it is advisable to work out at the stage of prototyping detector systems not only the detector itself, front-end electronics and DAQ, but also slow control systems. This work can be carried out in the BeamTest Zone, for which the BTZ slow control system must be made as similar as possible to the final DCS version.

2 DCS architecture

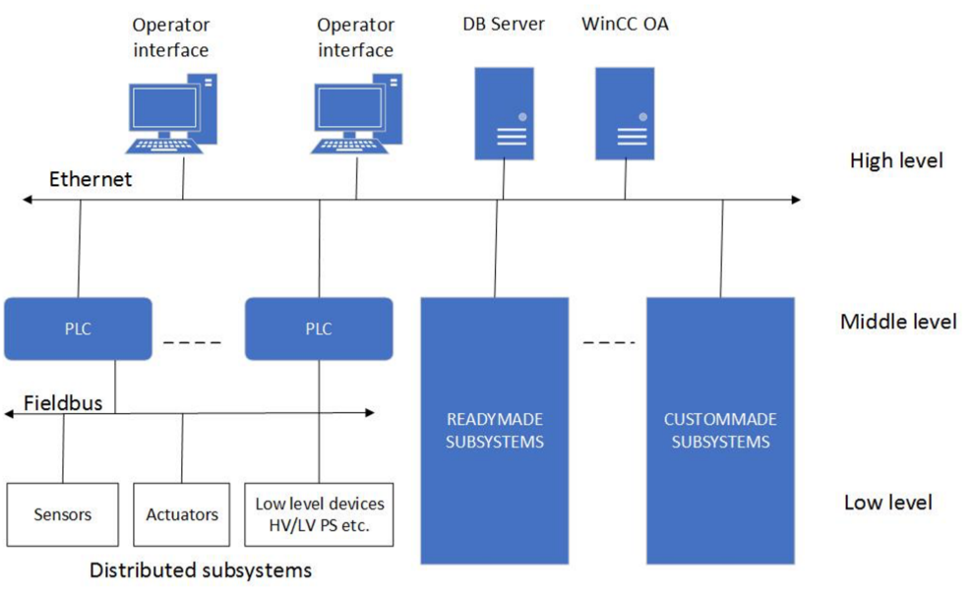


Figure 6.2: SPD detector control system architecture.

The detector control system is divided into three logical levels as it is shown in Fig. 6.2. The lower layer includes measurement channels built into the Front End Electronics (FEE) and Data Acquisition (DAQ) of the detector parts, various stand-alone sensors, I/O devices, and low and high voltage power supplies. The middle level is represented by programmable logic controllers and integrated ready-made and custom made subsystems (vacuum posts, gas consoles, multichannel ready-made power subsystems etc.). Interfaces to the Front End Electronics (FEE) and Data Acquisition (DAQ) subsystems that provide data for the benefit of the detector control system are also at this level. The upper level is designed to provide a human-machine interface for operators, implement a database of detector parameters and configurations, communicate with the outside world (accelerator, engineering support systems, access system, etc.) and implement macro-control algorithms common for the entire detector. All these levels are connected in a hierarchical network using fieldbuses between the first and second level, for example CAN-bus with CANopen protocol. Ethernet LAN is used between the middle and upper levels. At the top level, special software such as SCADA (Supervisory Control And Data Acquisition) is used, which provides control, collection and storage of data in real time. It is proposed to use the WinCC OA system widely used in CERN as a SCADA system. We understand that for smooth and reliable communication with NUCLOTORN's control system, a gateway to the Tango Controls system should be developed and built in.

3 SCADA for DCS

WinCC OA is a commercial SCADA system. It is a software component constructor that allows to use both preinstalled prototypes and templates, and software modules and system components developed of its own in C. This system is actively used in many experiments at CERN and has support and safety certificates in the Russian Federation. The following properties make WinCC OA an attractive solution for use in DCS SPDs:

- object-oriented approach built into the system ensures an efficient development process and the ability to flexibly expand the system;
- capability to create distributed systems - up to 2048 WinCC OA servers;
- scalability from a simple single-user system to a distributed redundant network system with¿ 10 million tags (physical and synthetic parameters);
- platform independent system is available for Windows, Linux;
- event-driven system;
- hot standby and 2x2 redundancy (DRSystem), the required level of availability and reliability;
- wide range of drivers and options for communication OPC, OPC UA, S7, Modbus, IEC 60870-5-101/104,DNP3, XML, JSON, SOAP...;
- support by major manufacturers of electronic devices for building automation systems in high energy physics.

A functional unit of the system that is programmatically implemented as a separate process is called a manager. A set of managers forms a system. Data exchange and communications between managers are realized via TCP. There exists a possibility to exchange data via events. The system allows to parallelize processes (managers) by running them on different computers with different OC, which are connected via TCP (each of these processes is called a manager). The system provides a capability of scalability and load balancing on managing computers. The required managers are started only by necessity, and they can also be run several times in parallel. Managers can be distributed across multiple computers / servers. The WinCC OA block diagram is shown in figure 6.3. The main process is the Event Manager, it contains and manages the process image (current values of all process variables), receives and qualifies data (central message manager), distributes data across other managers, acts as a data server for others, manages users authorization, manages the generation and status of alarm messages.

The Database Manager receives data from the Event Manager and manages them based on the embedded program. In the capacity of a historical database it can be used both as an own database (HDB) and as an Oracle DBMS (the Oracle Real Application Clusters configuration is also supported). Parallel archiving in Oracle and HDB databases is possible. It is also possible to record user-defined data and log system events and messages in an external relational database (MS SQL, MySQL, Oracle, etc).

The WinCC OA Report Manager supports different ways of generating reports:

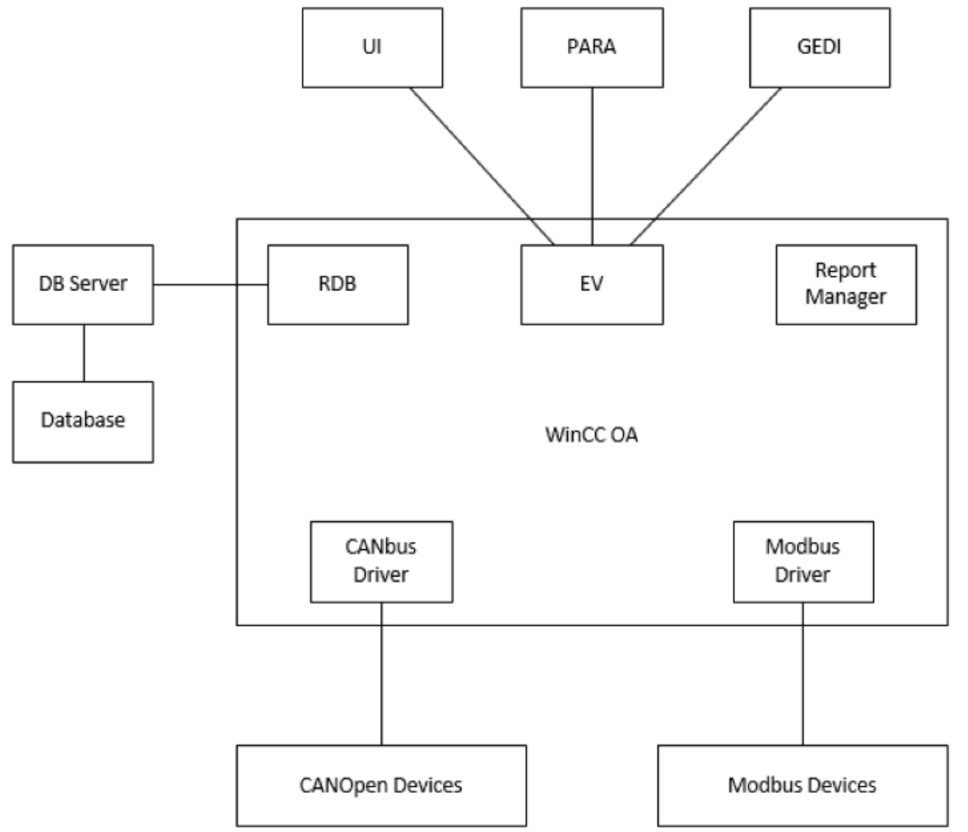


Figure 6.3: SCADA structural scheme of WinCC OA software.

– in Microsoft Excel format;

– in xml format with the ability to display in any external tool for working with reports (Eclipse BIRT, Crystal Reports, SYMATIC Information Server etc.), SOAP protocol is also supported (Simple Object Access Protocol).

The development of projects in the WinCC OA system is based on an object-oriented approach. In the WinCC OA data model, objects are represented as data points that characterize the image of a specific physical device or process. For each data point (tag) element, properties and actions can be defined in relation to it, such as signal processing (smoothing, setting ranges, etc.), communication with external systems, archiving, generation of alarm messages (alarms), etc. Typing and inheritance are supported, due to which arbitrary hierarchical data structures can be created. Similarly, the principles of inheritance and reusability are implemented for graphical objects. The WinCC OA IDE includes the PARA configuration editor and the GEDI graphical editor of User Interface Manager (UI) (includes a data model editor, mass configuration tools, administration tools, an interface to version control systems, a debugger, etc.).

Changes to data structures and graphics are applied without restarting the project. Writing custom scripts is carried out in CONTROL++ (syntax is similar to C / C ++). Such scripts can be both event handlers associated with elements of the graphical interface, and data processing procedures.

The system has a library of standard graphical objects; it can be scaled via developing its own objects or using the Qt Toolkit widgets. It is also possible to use the JavaScript libraries available on the market or JavaScript scripts of its own. Thanks to the open API (C++ / C# API), it is possible to create managers, drivers, widgets and CONTROL++ extensions of its own. It is available a new set of tools for implementing the concept of High Speed Programming, which supports the formation of documentation from the source code, unit testing and autocompletion of program structures.

TANGA.

Chapter 7

Data acquisition system [L. Afanasyev]

1 Introduction

The data acquisition system of the SPD should provide continuous data taking, including data readout from front-end electronics, data consistency check, event building and writing events to a storage. The system should have no dead time or minimal dead time. *These features will be realized with the DAQ operating in a free-running (trigger-less) mode.*

Other important tasks of DAQ are:

– initialization of hardware;

– control and monitoring of the data taking process: control of the status of all hardware devices including front-end electronics, status of software, quality of collected data;

– monitoring of the parameters characterizing the detector performance (accumulation of time, amplitude and hit distribution histograms, detector rates, etc.);

– logging of information and errors;

– distribution of the data over the computing nodes for following on-line analysis;

– etc.

The data acquisition system of SPD should withstand the data flux from p-p, p-d or d-d interactions at the extreme conditions of high luminosity. At the highest NICA energy and luminosity, $\sqrt{s} = 27$ GeV and $L = 10^{32}$ cm^{-2}s^{-1}, the interaction rate within the SPD aperture will be 4 MHz, and the average multiplicity about 20 ????. This drastically differs from conditions of another NICA experiment, MPD, where the collision rate of heavy ions is orders of magnitude less but multiplicity is much higher.

The structure of DAQ will be similar to recently modernized DAQ of the COMPASS experiment at CERN [244–246]. The COMPASS DAQ extensively uses the logical programmable integrated circuits FPGA at different levels of the system. This allows one to handle large data streams with minimal latency and provides very good flexibility. Unlike the COMPASS experiment, which uses the beam of the CERN SPS with a spill time structure, the SPD DAQ will deal with continuous beam.

The DAQ of SPD will operate in a free-running mode, when readout is not controlled by a trigger system, but occurs with a fixed frequency. It requires all front-end electronics running in a self-triggered mode, and readout happens synchronously with a common clock distributed by precise timing system. All the data, received between the acts of readout, are accumulated in memories implemented in the front-end electronics modules and are preserved there until the next readout. The readout frequency value will be chosen depending on detector rates and memory depths available in the front-end cards. The width of the time slice between the successive readouts should be much larger than the response time of the sub-detectors in order to minimize the probability of separating an event into two slices.

Digitization of data and zero suppression occur in front-end electronics. It is expected that so-called "feature extraction algorithm" will be implemented in front-end electronics of the Vertex detector and the Calorimeter. This algorithm, which is under development in several collaborations (in particular, PANDA [247], COMPASS [248–250]), allows transferring only the extracted time and amplitude, instead of many samples of a digitizer, thus greatly decreasing the amount of data to be transferred.

The expected data flux in the hardest conditions of the experiment (maximum energy and luminosity) has been estimated without detailed simulations yet, but using the current knowledge of the sub-detector structure, particle multiplicity per event, hit multiplicity in different detectors, expectations about the front-end electronics parameters and, where relevant, some results of the beam tests of other experiments (MPD, PANDA). A total number of channels to be readout is about 700 thousand, with the major part coming from the Vertex Detector ($\sim$ 460 thousand for the VD strip option). Preliminary estimation for the data flow is about 20 GB/s (including 7 GB/s added for safety).

2 DAQ structure

The scheme of DAQ is presented in Fig. 7.1. The data from front-end electronics cards come to detector interface cards (FE concentrators). The Data-Handler multiplexers (DHMux) are configured on the base of FPGA. They verify consistency of data and store them until receiving the readout signal. The existing version of the multiplexer [246] is equipped with memory of 4 GB and has a bandwidth of 2 GB/s. The FE concentrators and Data-Handler multiplexers are implemented on the same electronics cards by means of different firmware.

The two Data-Handler Switches (DHSw) function as 10×10 switch and perform event building with a maximum throughput rate of 10 GBytes/second. DHSw's perform the final level of event building and distribute the assembled events to 20 readout computers. Each readout computer is equipped with a dedicated PCIe buffer card for data collection. These cards are built on a FPGA chip and are commercially available. The current version of the card used in COMPASS has the bandwidth close to 1 GB/s [251–254]. Finally, the continuous sequence of slices is formed below the Network Switch in each of on-line computers to be used for on-line filtering and event monitoring.

A slow control software accesses front-end electronics via the FE concentrators using UDP-based IPBus protocol [255]. The interface cards retransmit control and clock signals provided by a time distribution system to corresponding front-end electronics, and convert the detector information from detector specific interfaces to a common high speed serial interface running over an optical fiber. It is foreseen to use UCF [256] as a standard high speed link protocol within the DAQ.

The White Rabbit system [257, 258] is planned to be used in NICA for time synchronization. It provides synchronization for large distributed systems with time-stamping of 125 MHz, sub-nanosecond accuracy and $\sim$10 ps precision. Signals from the White Rabbit system will be used as an input for the Time Control System (TCS) [259] which will distribute clock signals through the whole electronic system.

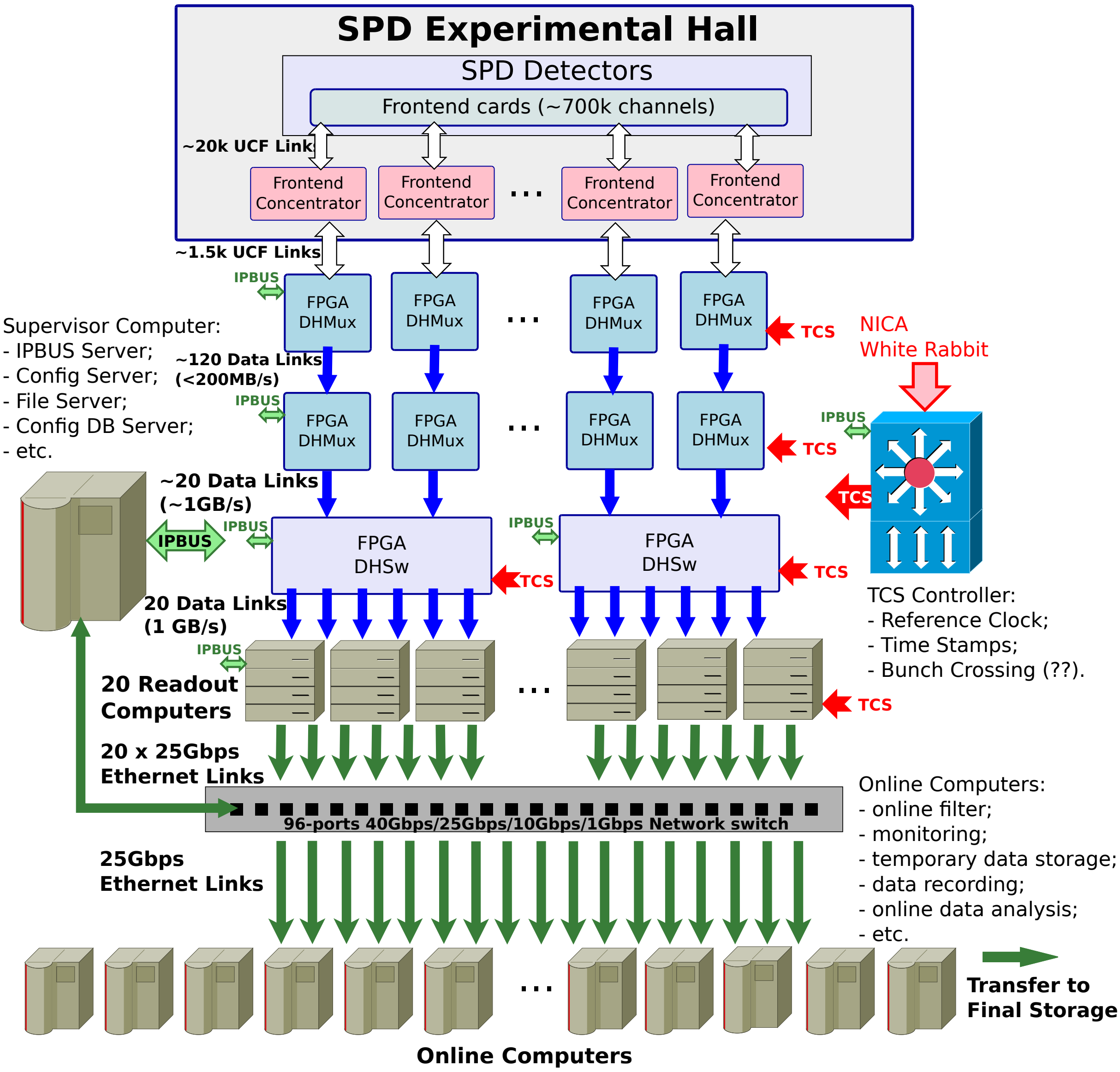


Figure 7.1: General structure of DAQ-SPD.

3 Data Format

The time structure of the expected data flow during a run is shown in Fig. 7.2. All processes are synchronized with 125 MHz clock coming from the White Rabbit system. A Run is started after the reset procedure which includes all initialization processes. Then, the continuous date flow is divided into a sequence of time slices. The proposed time slice duration can be selected in the range from 1 µs to 8.3 ms and will be chosen according to the data flux and capacity of the whole chain of data collection. The longer slices are preferable because the longer slice, the less probability of falling an event into two adjacent slices. The slices have a continuous numbering within a frame, a wider time interval, which can extend from 65 ms to 549.7 s. The slice numbering is reset every Frame by the Start of Frame signal.

The proposed format of the collected data is shown in Figs. 7.3 and 7.4. The data are formatted at all stages of transfer from Front-End Concentrators to Data-Handler Switches. The required headers and checksums are added at all stages.

In Fig.7.3 the structure of a Run and of a Frame is shown. The Run consists of a sequence of Frames which are numbered from 0 to N, where N, the maximum number of frames in the Run, is assigned by the TCS controller. The Frame consists of a sequence of slices numbered from 0 to K, the maximum number of slices in the Frame, which is also assigned by the TCS controller.

Fig.7.4 shows the structure of the Slice and of the Data Blocks. The Slice contains a sequence of Data Blocks from the Data Concentrators. Finally, the lowest unit in the Data Format chain is the Data Block of FE Concentrators which contains Physical Data from several ports whose amount depends on the FE Data Concentrator type.

The proposed format provides a unique connection of the physical information to the detectors geometry and event time.

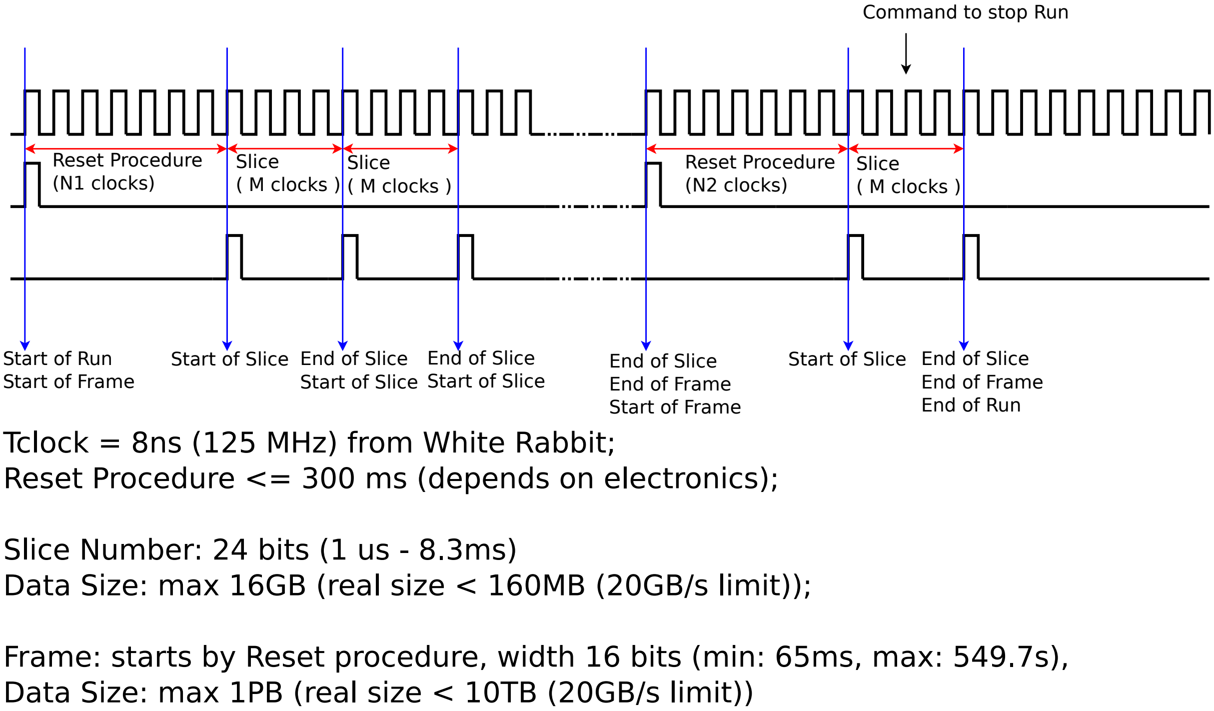


Figure 7.2: Time diagram of a sequence of clocks, Slices and Frames within the Run.

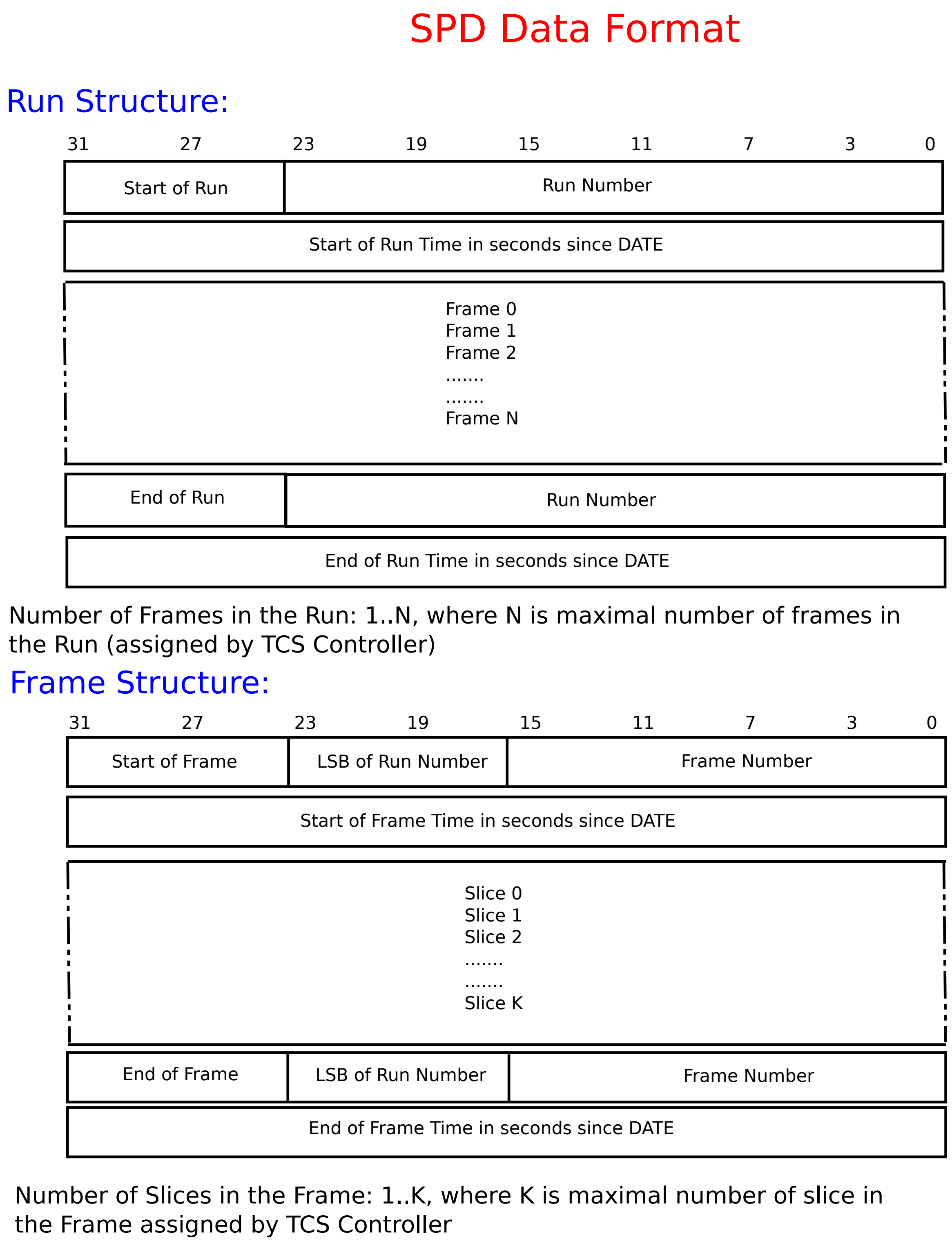
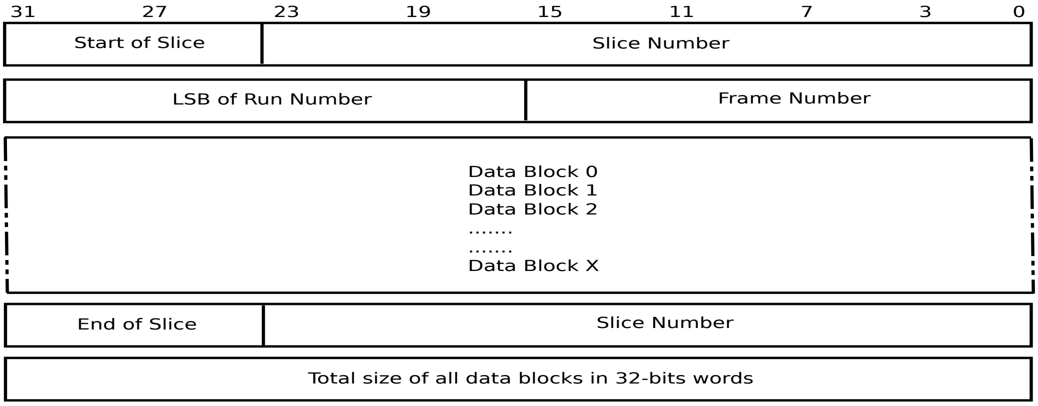


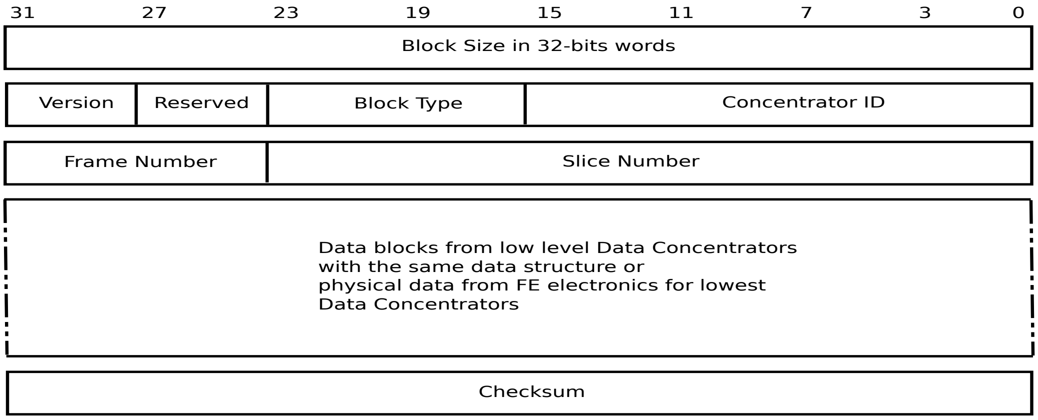
Figure 7.3: Data Format: Run and Frame structure.

Slice Structure:

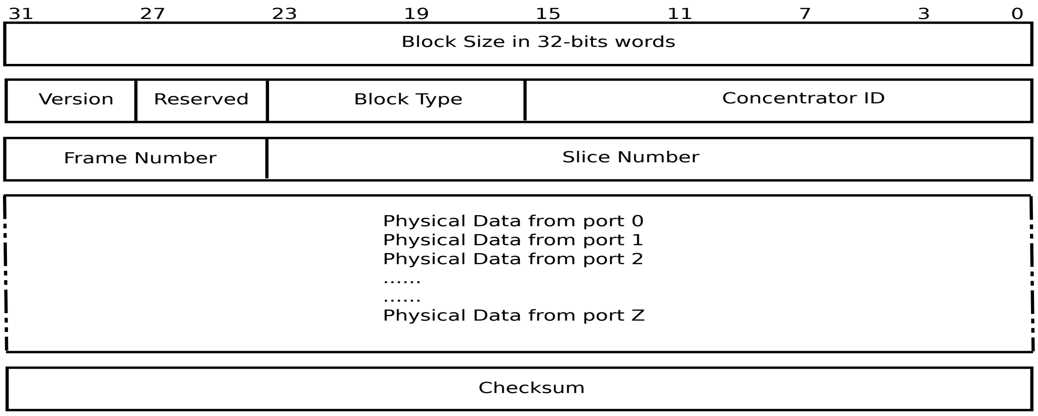


Number of Blocks in the Slice depends on DAQ configuration and data flux.

Data Block Structure of High Level Data Concentrators (Switches, Multiplexers etc.):



Data Block Structure of Lowest Level Data Concentrators (FE Concentrators):



Number of ports depends on FE Data Concentrator Type.
For instance, Igor Konorov if TDC Multiplexer has 15 input ports.

Figure 7.4: Data Format: Slice structure and structure of Data Blocks of High Level and Low Level Data Concentrators.

Chapter 8

Computing and offline software [A. Zhemchugov]

1 SPD computing model

Expected event rate of the SPD experiment is about 3 MHz (pp collisions at $\sqrt{s}$ = 27 GeV and 10^{32} $cm^{-2}s^{-1}$ design luminosity). This is equivalent to the raw data rate of 20 GB/s or 200 PB/yr, assuming the detector duty cycle is 0.3, while the signal-to-background ratio is expected to be in order of 10^{-5}. Taking into account the bunch crossing rate of 12.5 MHz, one may conclude that pile-up probability will be sufficiently high.

The key challenge of the SPD Computing Model is the fact, that no simple selection of physics events is possible at the hardware level, because the trigger decision would depend on measurement of momentum and vertex position, which requires tracking. Moreover, the free-running DAQ provides a continuous data stream, which requires a sophisticated unscrambling prior building individual events. That is the reason why any reliable hardware-based trigger system turns out to be overcomplicated and the computing system will have to cope with the full amount of data supplied by the DAQ system. This makes a medium-scale setup of SPD a large scale data factory.

The continuous data reduction is a key point in the SPD computing. While simple operations like noise removal can be done yet by DAQ, it is an online filter that is aimed at fast partial reconstruction of events and data selection, thus being a kind of a software trigger. The goal of the online filter is to decrease the data rate at least by a factor of 50 so that the annual upgrowth of data including the simulated samples stays within 10 PB. Then, data are transferred to the Tier-1 facility, where full reconstruction takes place and the data is stored permanently. Two reconstruction cycles are foreseen. The first cycle includes reconstruction of some fraction of each run necessary to study the detector performance and derive calibration constants, followed by the second cycle of reconstruction of full data sample for physics analysis. The data analysis and Monte-Carlo simulation will likely run at the remote computing centers (Tier-2s). Given the large data volume, a thorough optimization of the event model and performance of reconstruction and simulation algorithms are necessary.

Taking into account recent advances in the computing hardware and software, the investment in the research and development necessary to deploy software to acquire, manage, process, and analyze the data recorded is required along with the physics program elaboration and the detector design. While the core elements of the SPD computing system and offline software now exist as prototypes, the system as a whole with capabilities such as described above is in the conceptual design stage and information will be added to SPD planning documents as it is developed.

2 Online filter

The SPD online filter facility will be a high-throughput system which will include heterogeneous computing platforms similar to many high performance computing clusters. The computing nodes will be equipped with hardware acceleration. The software framework will provide the necessary abstraction so that common code can deliver the selected functionality on different platforms.

The main goal of the online filter is a fast reconstruction of the SPD events and suppression of the background ones at least by a factor of 50. This requires fast tracking and fast clustering in the electromagnetic calorimeter, followed by reconstruction of event from a sequence of time slices and an event selection (software trigger). Several consecutive time slices shall be considered, tracker data unpacked and given for a fast tracking. The result of the fast track reconstruction is the number of tracks, an estimate of their momentum and an estimate of primary vertex (to distinguish between tracks belonging to different collisions). Using this outcome, the online filter should combine information from the time slices into events and add a trigger mark. The events shall be separated in several data streams using the trigger mark and an individual prescale factor for each stream is applied.

One of the most important aspects of this chain is the recognition of particle tracks. Traditional tracking algorithms, such as the combinatorial Kalman filter, are inherently sequential, which makes them rather slow and hard to parallelized on modern high-performance architectures (graphics processors). As a result, they do not scale well with the expected increase in the detector occupancy during the SPD data taking. This is especially important for the online event filter, which should be able to cope with the extremely high data rates and to fulfill the significant data reduction based on partial event reconstruction 'on the fly'. The parallel resources like multicore CPU and GPU farms will likely be used as a computing platform, which requires the algorithms, capable of the effective parallelization, to be developed, as well as the overall cluster simulation and optimization.

Machine learning algorithms are well suited for multi-track recognition problems because of their ability to reveal effective representations of multidimensional data through learning and to model complex dynamics through computationally regular transformations, that scale linearly with the size of input data and are easily distributed across computing nodes. Moreover, these algorithms are based on the linear algebra operations and can be parallelized well using standard packages like Tensorflow or Torch. This approach was already been applied successfully to recognize tracks in the BM@N experiment at JINR and in the BESIII experiment in IHEP CAS in China [260, 261]. In the course of the project an algorithm, based on recurrent neural networks of deep learning, will be developed to search for and reconstruct tracks of elementary particles in SPD data from the silicon vertex detector and the straw tube-based main tracker. The same approach will be applied to the EMC clustering. The caution is necessary, though, to avoid possible bias due to an inadequacy of the training data to the real ones, including possible machine background and the detector noise. The continuous monitoring of the neural networks used in the online filter is necessary and needs to be elaborated.

Besides the high-level event filtering and corresponding data reduction, the online filter will provide input for the run monitoring by the shift team and the data quality assessment, as well as local polarimetry.

3 Computing system

The projected rate and amount of data produced by SPD prescribe to use High Throughput Computing (HTC) solutions for the processing of collected data. It is the experience of a decade of the LHC computing that already developed a set of technologies mature enough for the building of distributed high-throughput computing systems for HEP.

3.1 The computing model

The ’online’ part of computing systems for the SPD experiment, namely the online filter described above, is an integral part of experimental facilities, connected with the ’offline’ part using a high throughput backbone network. The entry point to ’offline’ facilities is a high capacity storage system, connected with ’online facility’ through a multilink high-speed network. Data from high capacity storage at the Laboratory of Information Technologies will be copied to the tape-based mass storage system for long term storage. At the same time, data from high capacity storage will be processed on different computing facilities as in JINR as in other collaborative institutions.

The hierarchy of offline processing facilities can be introduced:

- Tier 1 level facilities should provide high capacity long term storage which will have enough capacity to store a full copy of primary data and a significant amount of important derived data.
- Tier 2 level facility should provide (transient) storage with capacity that will be enough for storing of data associated with a period of data taking.
- Optional Tier 3 level are opportunistic resources, that can be used to cope with a pile-up of processing during some period of time or for special analysis.

Offline data processing resources are heterogeneous as on hardware architecture level so by technologies and even in JINR includes batch processing computing farms, high performance (supercomputer) facilities, and cloud resources. A set of middleware services will be required to have unified access to different resources.

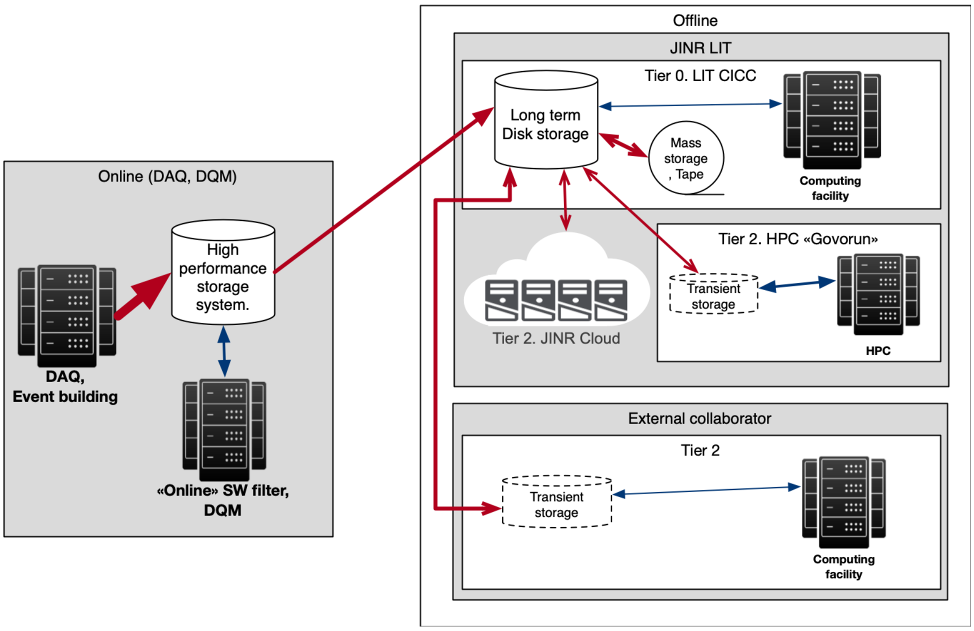


Figure 8.1: Scheme of the SPD computing system

3.2 Computing services

Computing systems for NICA in JINR are naturally distributed. Experimental facilities and main data processing facilities placed across two JINR sites and, sometimes, managed by different teams. That causes some heterogeneity not only on hardware systems but also on the level of basic software: different OSs, different batch systems etc.

Taking into account the distributed nature and heterogeneity of the existing infrastructure, and expected data volumes, the experimental data processing management system must be based on services that have proven reliability and performance.

It is necessary to develop a high-level orchestrating system that will manage the low-level services. The main task of that system will be to provide efficient, highly automated multi-step data processing following the experimental data processing processes.

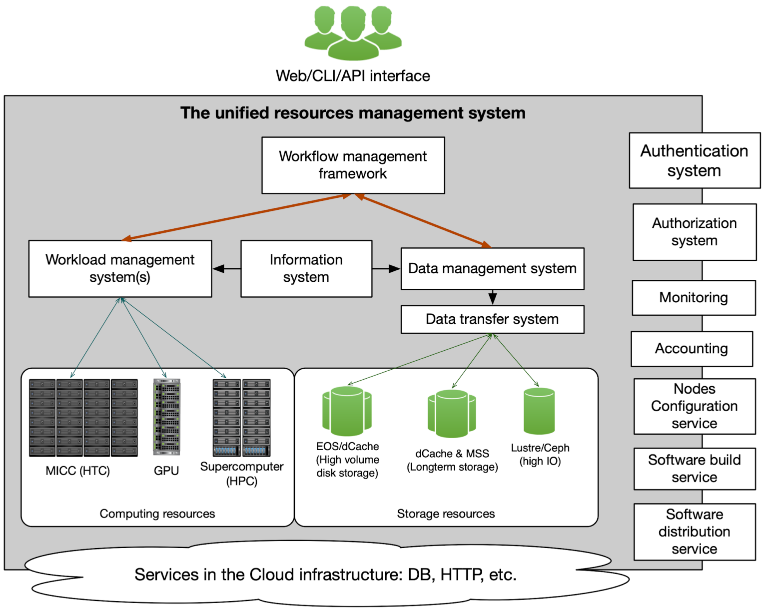


Figure 8.2: Distributed SPD computing services

The Unified Resource Management System is a IT ecosystem composed from the set of subsystem and services which should:

- Unify of access to the data and compute resources in a heterogeneous distributed environment
- Automate most of the operations related to massive data processing
- Avoid duplication of basic functionality, through sharing of systems across different users (if it possible)
- As a result - reduce operational cost, increase the efficiency of usage of resources,
- Transparent accounting of usage of resources

Many distributed computing tools have already been developed for the LHC experiments and can be re-used in SPD. For the task management one can use PANDA [262] or DIRAC [263] frameworks. For the distributed data management RUCIO [264] package has been developed. For the massive data transfer FTS [265] can be used. Evaluation of these tools for the SPD experiment and their implementation within the SPD Unified Resource Management System is planned in scope of the TDR preparation.

4 Offline software

Offline software is a toolkit for event reconstruction, Monte-Carlo simulation and data analysis. Linux is chosen as a base operating system.

Currently, the offline software of the SPD experiment – SpdRoot – is derived from the FairRoot software [266] and it is capable of Monte Carlo simulation, event reconstruction, and data analysis and visualization. The SPD detector description is flexible and based on the ROOT geometry package. Proton-proton collisions are simulated using a multipurpose generator Pythia8 [267]. Deuteron-deuteron collisions are simulated using a modern implementation of the FRITIOF model [268, 269], while UrQMD [270, 271] generator is used to simulate nucleus-nucleus interactions. Transportation of secondary particles through the material of the SPD setup and the simulation of detector response is provided by Geant4 toolkit [272–274]. Track reconstruction uses GenFit toolkit [275] and KFparticle package [276] is used to reconstruct primary and secondary vertices. The central database is going to be established to keep and distribute run information, slow control data and calibration constants.

Recent developments in computing hardware resulted in the rapid increase in potential processing capacity from increases in the core count of CPUs and wide CPU registers. Alternative processing architectures have become more commonplace. These range from the many-core architecture based on standard x86_64 cores to numerous alternatives such as GPUs. For GPUs, the processing model is very different, allowing a much greater fraction of the die to be dedicated to arithmetic calculations, but at a price in programming difficulty and memory handling for the developer that tends to be specific to each processor generation. Further developments may even see the use of FPGAs for more general-purpose tasks.

The effective use of these computing resources may provide a significant improvement in offline data processing. However, the offline software should be capable to do it by taking advantage of concurrent programming techniques, such as vectorization and thread-based programming. Currently, the SPD software framework, SpdRoot, cannot use these techniques effectively. The studies of the concurrent-capable software frameworks (e.g. ALFA [277], Key4Hep [278]) are needed to provide input for the proper choice of the offline software for Day-1 of the SPD detector operation.

A git-based infrastructure for the SPD software development already established at JINR [279].

5 Resource estimate

For the online filter we assume the CPU consumption of 1000 SPD events/core/second. This requires 3000 cores simultaneously for the fast tracking. Taking into account additional expenditures to the event unscrambling and data packing and including a real efficiency of CPU which will be lower than 100%, one derives the CPU resources for the online filter as 6000 CPU cores. This number sets the upper limit and the required computing power may decrease substantially if an efficient way to use GPU cores are implemented for the event filtration. As for the data storage, a high performance disk buffer of 2 PB capable to keep data of about one day of data taking is needed.

For the offline computing, the data storage is determined by the data rate after the online filter? or 4 PB/year of raw data. Besides that, we may expect the comparable amount of simulated data and estimate the long term storage as 10 PB/year, assuming two cycles of data processing and possible optimization of the data format and data objects to be stored permanently. We assume that a half of the annual data sample ($\sim$5 PB) is kept on disk storage, and the rest is stored on tape. The CPU power necessary to process the amount of data like this and to run Monte-Carlo simulation is estimated as many as 30000 CPU cores. The summary of computing resources is given in Table. **??**. The cost estimate is conservative and will be defined more exactly in the TDR, when detailed hardware solutions and their actual price in the market will be considered.

Table 8.1: Required SPD computing resources

	CPU [cores]	Disk [PB]	Tape [PB]
Online filter	6000	2	none
Offline computing	30000	5	9 per year
Cost estimate [kUSD]	4000	8000	4500 per year

The burden of the SPD computing system operation is a subject of sharing between the computing centers of the participating institutes.

Chapter 9

Beam test facility [A. Baldin] [OUT OF DATE]

In order to create the conditions for testing and certification of detectors and data acquisition and analysis systems at SPD close to those anticipated at the collider NICA, it is proposed to reconstruct the existing installation MARUSYA [280–283] situated in building 205 of LHEP JINR and build the additional high momentum channel (HMC) for 1–10 GeV/c beams. Both channels spectrometers are situated in the region of focus F4 of extracted beams of Nuclotron.

It should be noted that it is not planned to change the biological shielding in the considered zone. Instead, the existing channel of the spectrometer MARUSYA will be upgraded and developed to provide testing of prototypes and detector elements, as well as the electronics of the data acquisition system of SPD at secondary beams of pions, kaons, protons, neutrons, muons, electrons, and light nuclear fragments in a momentum range of 0.4 – 1.2 GeV/c. It is advantageous that there exists positive experience in working with extracted polarized beams at MARUSYA [284].

This would ensure physical measurements at extracted beams using the existing experimental installation and infrastructure. The installation MARUSYA is well suitable for applied studies with secondary beams at maximum possible intensity of the beam extracted to building 205 (up to 10^{11} protons per acceleration cycle). The development of HMC requires two new magnetic elements; therefore, it is considered as an independent installation to be put in operation at the second stage of upgrade in accordance with the existing regulations for commissioning of experimental facilities.

The power supply and water cooling with the parameters sufficient for the required operation modes of all six magnetic elements are available, the approval by the LHEP engineer in chief has been received.

Each channel-spectrometer provides spatial registration, identification, and tagging of each particle hitting the detector under the condition of matching of the electronic registration system (DAC) of the installation and the tested detector or data acquisition system element.

Figure 9.1 shows the drawing of the considered magnetic elements.

It is planned to use SP12 magnet of VP1 extraction channel situated directly in front of F4 focus in order to turn the primary extracted beam toward HMC. Calculations show that the primary beam can be turned to the required angle in a proton momentum range of 1–7 GeV/c. For higher-energy particles, it is necessary to use a target in F4 focus. In this operation mode, secondary beams are formed at the installation MARUSYA and HMC simultaneously.

Note that this operation mode is possible with simultaneous (parallel) operation of other installations at

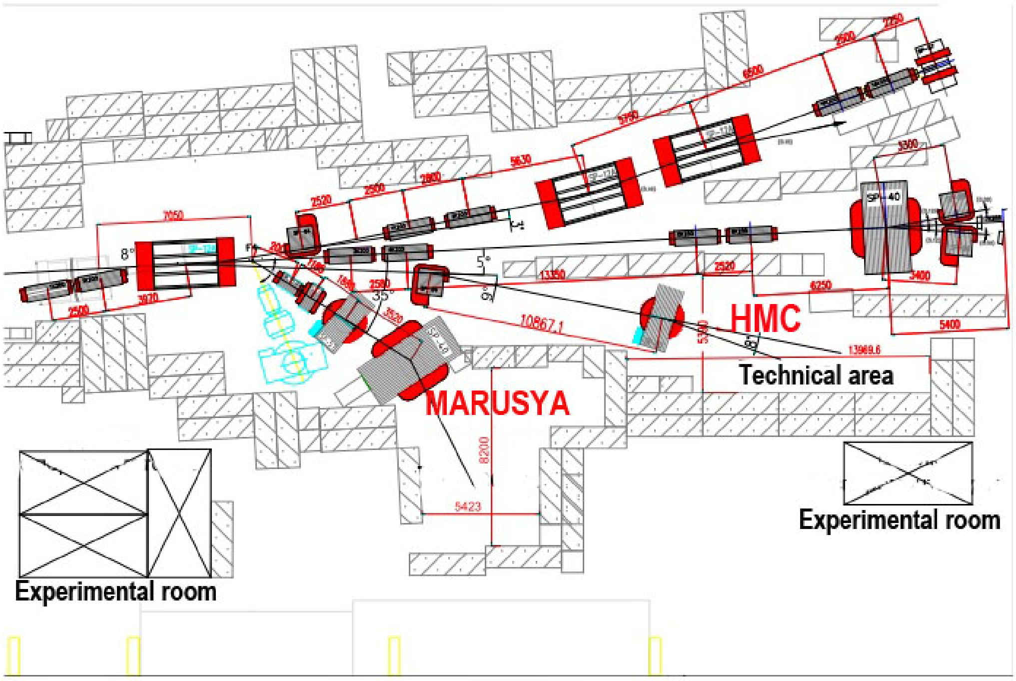


Figure 9.1: Magnetic elements of the test zone.

VP1 extraction channel (in particular, the installation BM&N).

Figure 9.2 shows the schematic diagram of the magnetooptical part of the installation MARUSYA and the detector stations:

- M1–M3 scintillation monitors for the extracted beam (and polarization monitoring);
- K100, ML17 magnetic lenses;
- SP57, SP40 dipole magnets;
- G time of flight scintillation hodoscopes;
- PC proportional chambers;
- acceptance 50 - 80 msr$\times$ %;
- momentum resolution $\Delta P/P \sim$0.5%;
- particle registration angles 20-90^o;
- particle momenta 0.3 –1.5 GeV/c.

It is planned to place tested detectors behind SP40 magnet; there, a concrete-shielded region with a size of 5$\times$7 m^2 without an upper plate is planned.

This region is available for personnel during the accelerator operation and beam extraction along VP1 channel if the target is in F4 focus.

At present, the remote-controlled target station is used; it provides the target movement in three directions (horizontal, vertical, and along the beam axis); the target can be automatically removed out of the beam if a personnel member enters behind the shielding to attend to detectors behind the SP40 magnet.

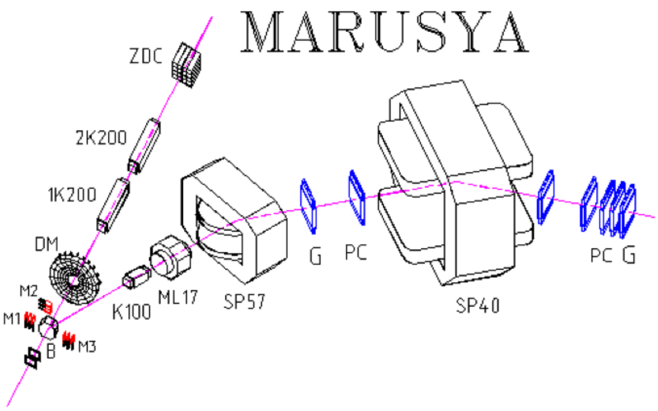
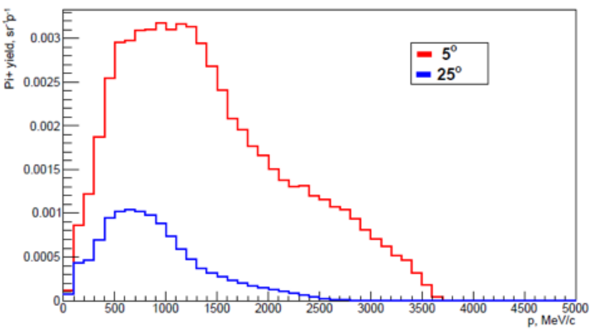
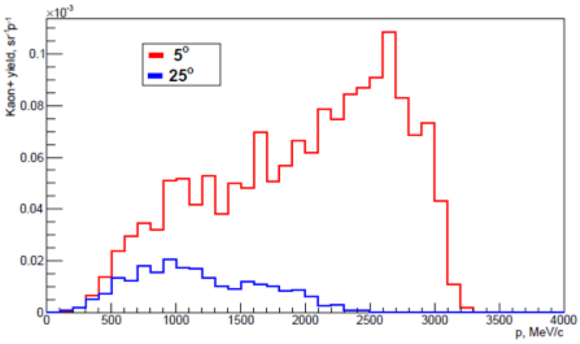


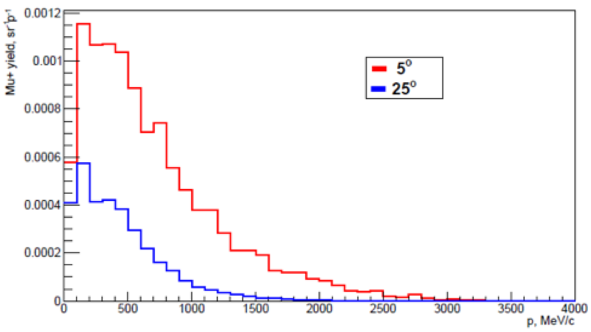
Figure 9.2: MARUSYA installation and the detector stations.



(a)



(b)



(c)

Figure 9.3: GEANT4 Monte Carlo simulation of yield of (a) π^+, (b) K^+, and (c) μ^+ per one incoming proton for production angles of 5^o and 25^o in the reaction 4 GeV p + C.

Taking into account the requirement of creation of VP1 vacuum extraction channel, it is planned to develop, approve with the beams division staff, and manufacture a new target station in the vacuum box of F4 focus.

Simulation using the software TRANSPORT and GEANT4, as well as experimental measurements at deuteron, carbon, magnesium, lithium, etc. beams showed that the channel-spectrometer MARUSYA provides the following parameters: for an extracted 2-4 GeV/nucleon deuteron beam with an intensity of 10^10 and carbon and copper targets with a thickness of 1 g/cm^2, secondary pion beams with an intensity of 10^4 can be obtained. The size of the secondary beam at a studied detector behind SP40 is 100×150 mm. The prototype time of flight system based on scintillation hodoscopes demonstrated reliable identification of protons, pions, kaons in a momentum range of 600-1200 MeV/c.

For 5 GeV/nucleon deuteron beams extracted to building 205 and carbon targets with a thickness from 0.005 to 5 g/cm^2, the beam parameters feasible at the channel-spectrometer MARUSYA are given in rows 1–3 of Table 9.1, and the parameters for the high-momentum channel, in rows 4–5 of Table 9.1.

Table 9.1: Beam parameters feasible at the channel of the spectrometer MARUSYA and the high-momentum channel.

P, MeV/c	d	p,n	$\pi^{\pm}$	K^{+}	K^{-}	$\mu^{\pm}$	$e^{\pm}$
400	10^3	10^5	10^5	10^3	10^2	10^3	10^3
800	10^3	10^4	10^4	10^3	10^2	10^3	10^3
1500	10^2	10^4	10^4	10^3	10^2	10^2	10^2
2000	10^4	10^5	10^4	10^3	10^2	10^2	10^2
7000	10^4	10^6	10^3	10^3	10^2	10^2	10^2

The region between magnets SP57 and SP40 is preferable for measurement of momenta below 600 MeV.

In order to achieve a momentum resolution o f 0.2%, it is necessary to equip the magnetooptical spectrometer MARUSYA with four sets of chambers with a spatial resolution of at least 150 μm in the vertical and horizontal directions. Two chambers will be situated between the dipole magnets and two chambers behind SP40.

For muon and electron registration and identification, it is planned to use the electromagnetic calorimeter with a size of 100×150 mm^2 based on BGO crystals.

It It is planned to use the gas Cherenkov counter for testing of the electromagnetic calorimeter at secondary muon and pion beams; this Cherenkov counter will be provided by the SPD collaboration.

The new electronics of the data acquisition system TQDC based on VME standard (developed at LHEP) was tested during the accelerator run in 2018. The testing was successful; it demonstrated that the experiment SPD should use this new VME-based electronics or improved data acquisition systems.

The structural diagram of the data acquisition, analysis and storage system is shown in Fig. 9.4.

The upgrade of the SPD test zone consists of the following stages.

1. Cleaning of the zone, removal of unnecessary elements (magnets, lenses, detectors, etc.). Refurbishment of biological shielding and walls.

2. Renovation and repair of experimental rooms, installation of electric communications. Reconstruction of electrical control units for power supply of detectors and auxiliary equipment.

3. Manufacture and installation of gas consoles.

4. Manufacture of scintillation beam detectors and electronics of the data acquisition system. Manufacture of small-size track detectors based on straw, RPS, Si, etc. in the framework of prototyping and production of main detectors of SPD.

5. Purchase and commissioning of computer equipment for the data acquisition, communication, and processing system.

6. Mounting of two magnets of the new high momentum channel. Geodesy and measurement of magnetic field maps.

7. Manufacture of scintillation time of flight HMC system.

8. Development and production of the channel slow control systems.

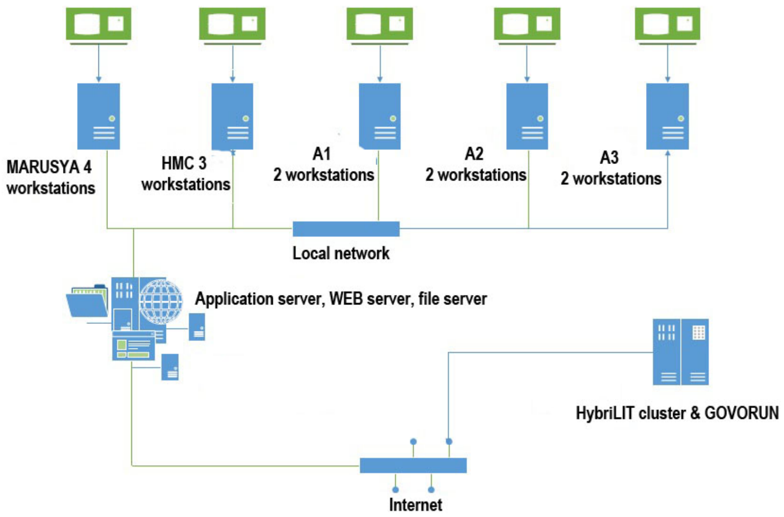


Figure 9.4: Computers and servers for MARUSYA and HMC.

Chapter 10

Integration and services [OUT OF DATE]

According NICA TDR [285] the SPD is allocated in southern point of beams collision. The NICA SPD location is shown in Figure 10.1.

Figure 10.1: NICA layout with SPD.

The experimental hall is designed very close to MPD hall [286].

1 Hall facilities and services

The hall solid concrete floor is considered to have the bearing capacity to be able to perform the operation and assembly of the SPD. It would be quite enough:

1. to bear the weight of the assembled detector with needed services,
2. to keep the integrity of the detector in the process of its transportation on the rail guided carriage and its assembling,
3. to provide a stable detector position during operation cycles with high accuracy .

A helium refrigerators has to be mounted in close to the detector to provide cryogenic fluids and gases for toroidal and solenoidal magnets operation (see chapter 3.2). The crates of the data acquisition systems and power supplies has to be placed in close the detector on special electronic platforms.

2 SPD integration

The SPD hall shown in Figures 10.2, 10.3, consists of the Production area and Experimental hall. The experimental area is located on the right side of the Figure 10.2, below the level of the production area. The production area will be used for the preparation and testing of the SPD detectors system and for the installation and the final assembly for the data taking. Also, the Production area will be used for technical work and maintenance of the set-up. It is assumed that the maximum for the power supply of the SPD hall will be about 1.2 MWatts.

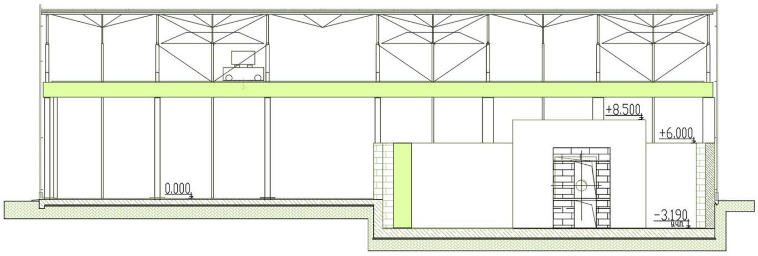


Figure 10.2: SPD experimental hall.

The sizes of the SPD hall is as follows: the total area is more than 2000 m^2, the main gate for trucks - 4000 *mm* x 4000 *mm*, the dismantle part of wall for widest equipment - 8000 *mm* x 8000 *mm*.

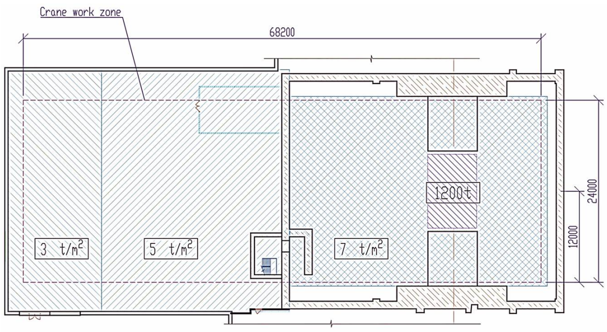


Figure 10.3: The view from the top of the SPD experimental hall.

To provide access to the electronic racks and to sections of the detector, between the detector and the electronics platform especial radiation shielding can be installed.

The Figure 10.4 shows transportation system to operate with set-up. The mark 1 is beam line, 2 - interaction point, 3- rails, 4- collider systems, 5,6 - walls of the hall.

The integration of the SPD within the accelerator rings is given in Figure 10.5.

3 Detector assembly

The assembly of the SPD is a very critical point because of their essential weights, modularity (see chapter 3) and three different magnet systems.

The Figure 10.6 shows possible procedure of the operating with SPD, one includes the transportation of the whole detector to (C) or out (A,B) beam position. Also the detector can be dismounted into three parts (two endcaps an barrel parts) at B position.

The preliminary view of assembled SPD is shown in Figure 10.7.

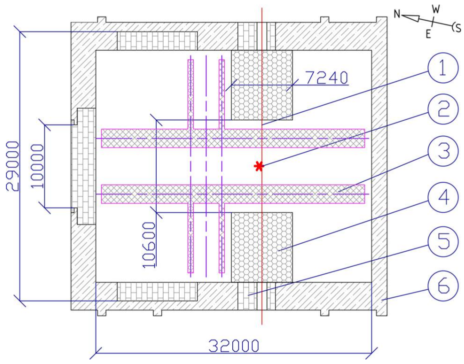


Figure 10.4: The view from the top of the SPD hall with elements of detector transportation. Descriptions given in the text.

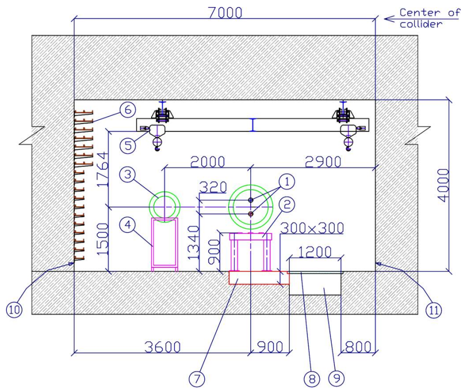


Figure 10.5: The view of the hall in section with collider beam lines (1,2) with sizes and technical cable supports (5,10), cranes (5) and garage position of collider magnets (3,4).

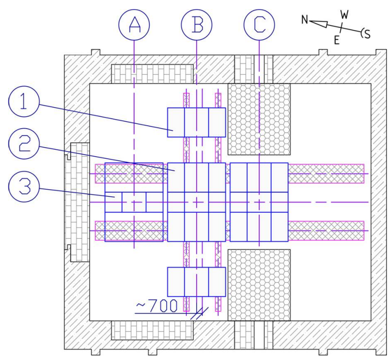


Figure 10.6: The SPD position in experimental hall. Details are given in the text.

4 Technical requirements

Technical requirements of SPD includes subdetectors having their subsystems as follows:

1. Magnet:Current source, Cryogenic system
2. Vertex Detector: HV power supply system, LV power supplies for powering of digital and analog electronics, Cooling system to provide silicon detector stable working temperature, FE temperature

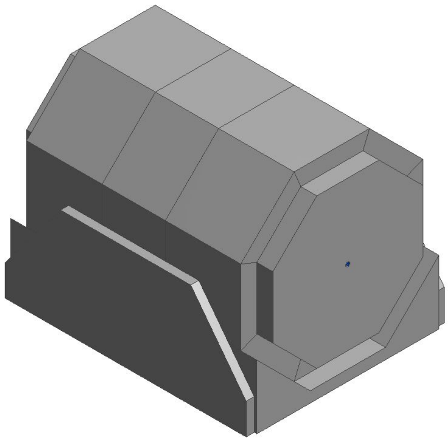


Figure 10.7: View of assembled SPD detector.

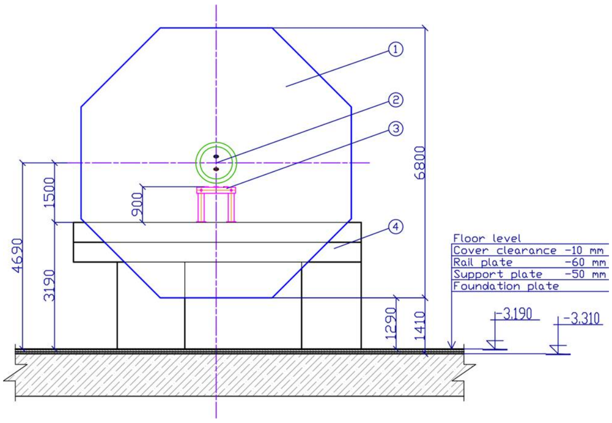


Figure 10.8: The view of the SPD with collider magnet and beam lines.

monitoring system, FE control

3. Tracking System: HV power supply system, LV power supply system, Gas mixing system, FE control

4. TOF: HV power supply system,LV power supply system,Gas mixing system, FE control

5. ECAL: HV power supply system, LV power supply system,Cooling, Thermo-stabilization, FE control, laser calibration/monitoring system

6. Muon system(Range system): HV power supply system, LV power supply system, Gas mixing system, FE control

7. Tagging station:HV, LV, FE control

8. Local polarimetry: HV, LV, Cooling, FE control, monitoring system.

Chapter 11

MC simulation and physics performance

1 General performance of the SPD setup

1.1 Rates and spectra for minimum bias events [A. Guskov]

The beam particles collision in the interaction point is the source of numerous secondary charged and neutral particles in the SPD setup. Table 11.1 shows the total cross-section of the *p*-*p* collisions, the multiplicity of charged and neutral secondary particles for the different collision energy $\sqrt{s}$. The angular and momentum distributions for different particles produced in the primary vertex in the *p*-*p* interactions at $\sqrt{s} = 26$ GeV/*c* are presented in Fig. 11.1.

Table 11.1: The total cross-section and the average multiplicity for the charged and neutral particles produced in the *p*-*p* collisions as a function of $\sqrt{s}$.

$\sqrt{s}$, GeV	σ_{tot}, mb	Charged multiplicity	Neutral (γ) multiplicity
13	38.4	5.9	4.6 (3.8)
20	38.9	7.2	6.0 (5.0)
26	39.7	7.8	6.5 (5.5)

Secondary particles are produced in the interaction of primary particles with elements of the setup. The material budget between the interaction point and the closest internal surface of the ECAL is $\sim 0.15X_0$ or $\sim 0.03\lambda_I$. The flux of charged particles and photons with an energy above 0.1 GeV at the internal surface of the ECAL for the Barrel and one End-cap for the *p*-*p* collisions at $\sqrt{s} = 26$ GeV/*c*. is shown in 11.2.

Energy deposit in the ECAL per one minimum bias event for the Barrel and the End-cap is shown in Fig. 11.3. Average energy deposit in the ECAL is 2.0 GeV per event (1.2 GeV from charged particles and 0.8 GeV for photons) in the barrel and 5.0 GeV per event (3.7 GeV from charged particles and 1.3 GeV for photons) in each End-cap for *p*-*p* collision at $\sqrt{s} = 26$ GeV/*c*.

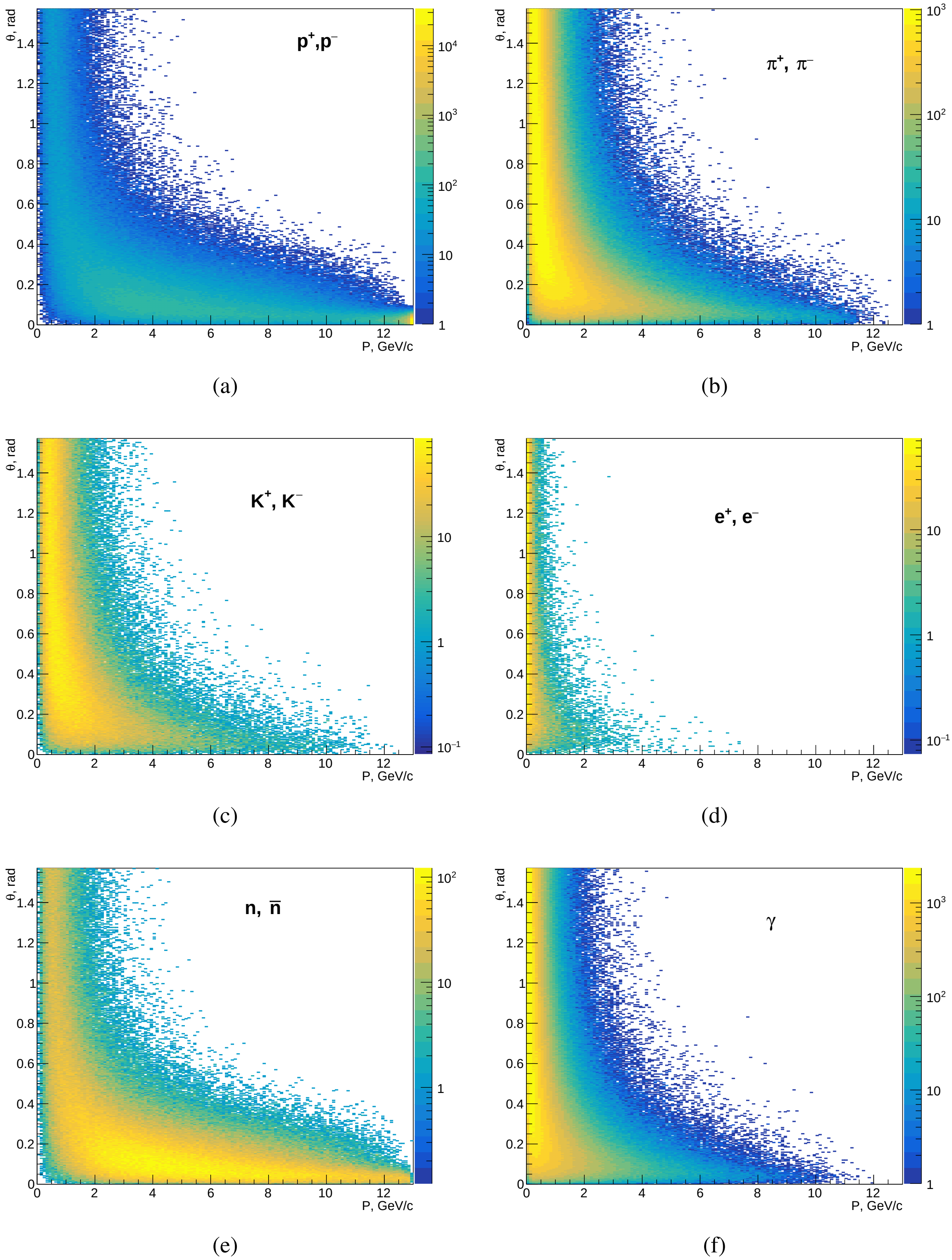
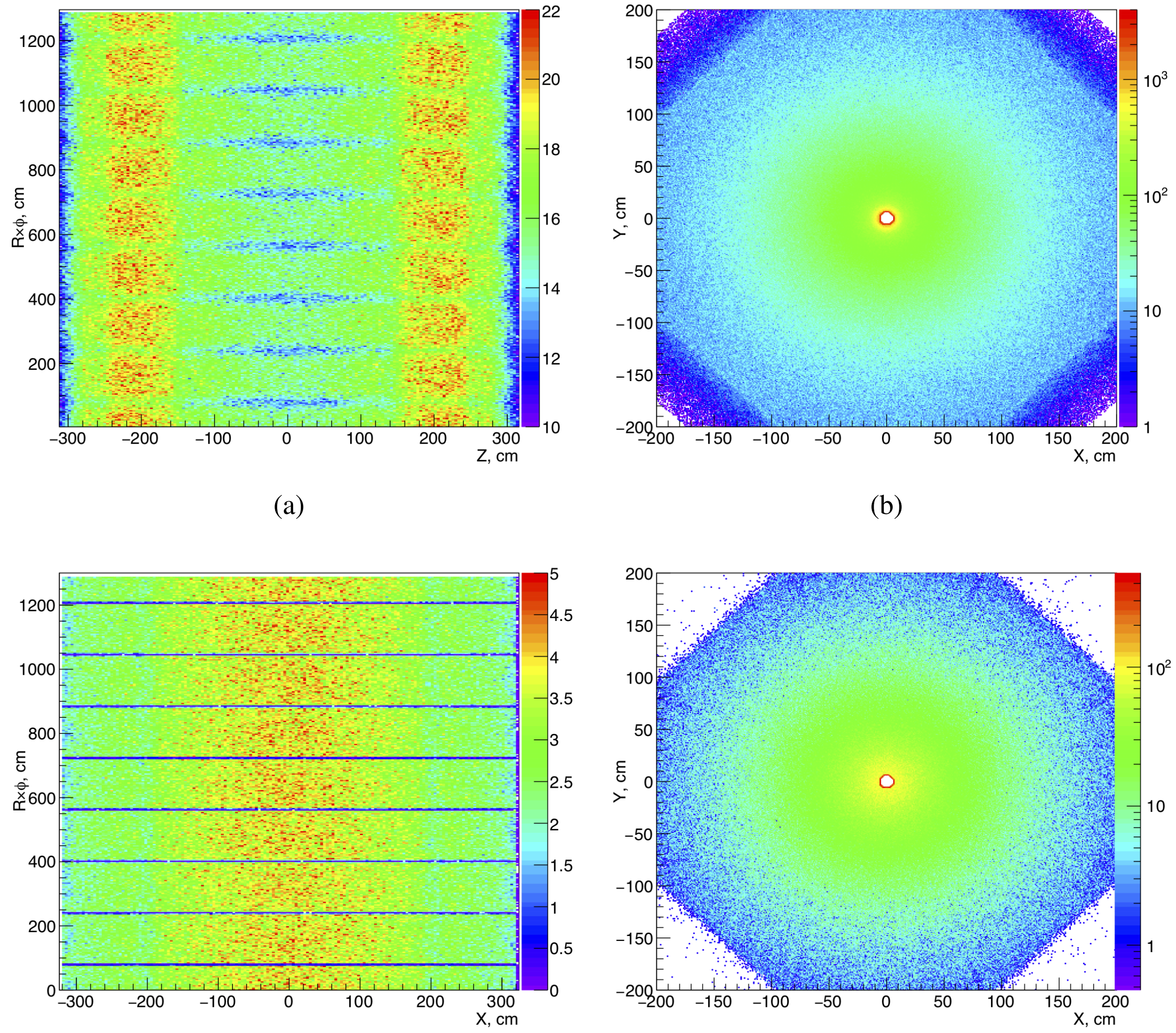
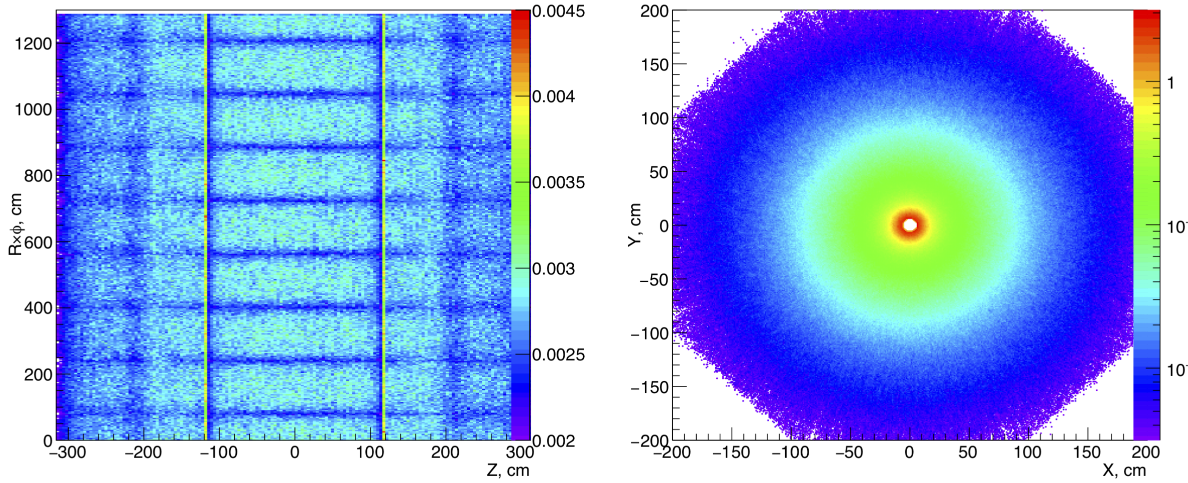


Figure 11.1: Momentum and angular distributions for particles produced in the primary vertex of p-p interactions at $\sqrt{s} = 26$ GeV/c: $p^{\pm}$ (a), $\pi^{\pm}$ (b), $K^{\pm}$ (c), $e^{\pm}$ (d), n and $\bar{n}$ (e) and γ (f) per 10^6 minimum bias events.



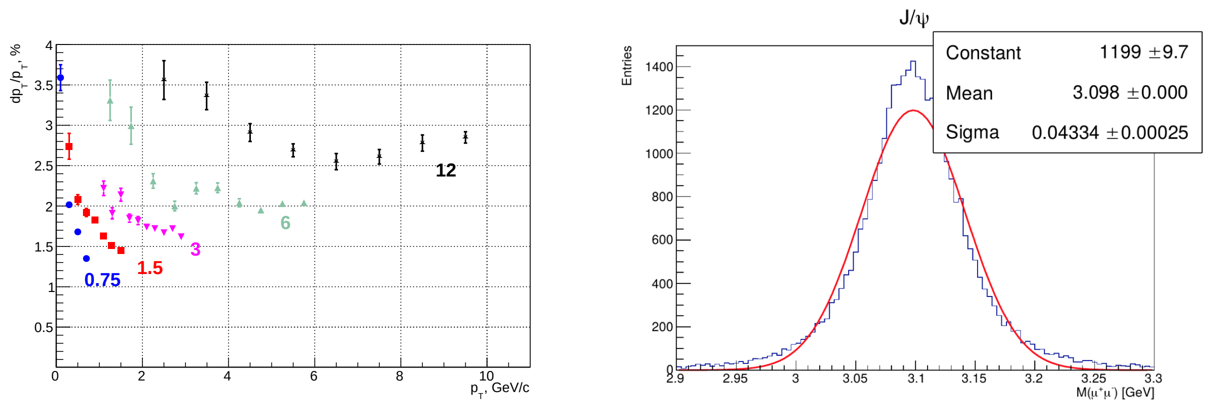
(a) (b) (c) (d)

Figure 11.2: Flux of charged particles and photons with energy above 0.1 GeV at the internal surface of the ECAL for the Barrel (a, c) and one of the End-caps (b, d) in particles per 1 cm^2 per 10^6 interactions.



(a) (b)

Figure 11.3: Energy deposit in the ECAL in the Barrel (a) and one End-cap (b) in MeV/cm^2 per one minimum bias event.



(a) (b)

Figure 11.4

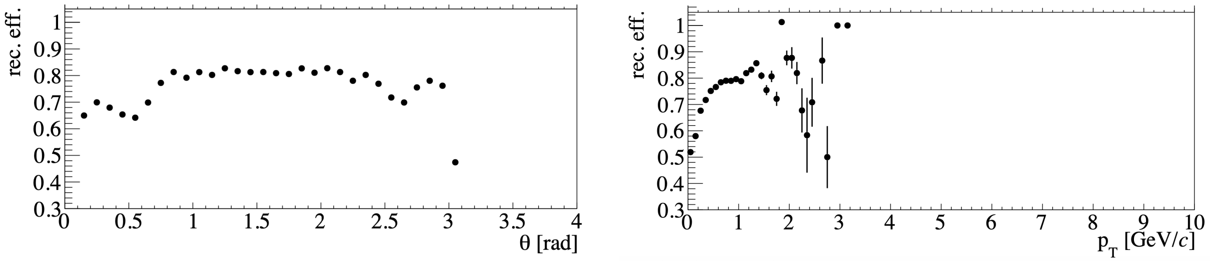
1.2 Tracking [A. Guskov]

1.3 Vertex reconstruction [A. Guskov]

1.4 Calorimetry [A. Guskov]

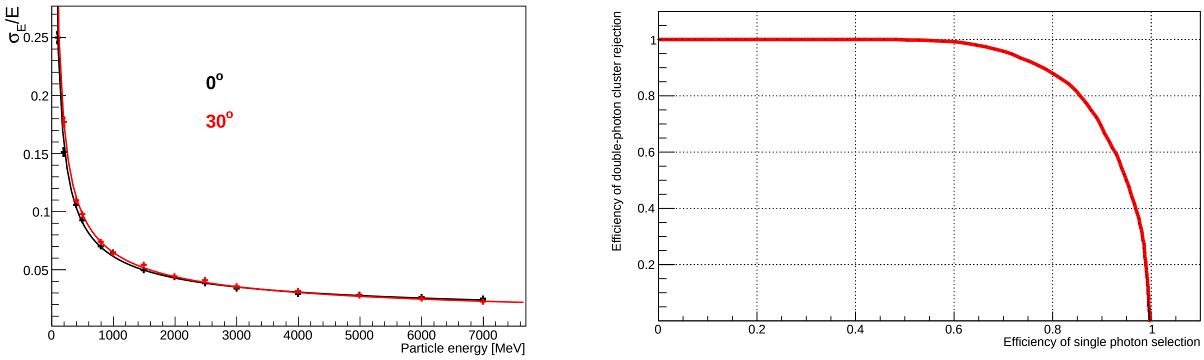
The electromagnetic calorimeter is one of the main detectors for the SPD gluon program. Its function is: (i) to measure the energy and position of hard prompt photons, and photons from the radiative decays of π^0 and η mesons; (ii) to reconstruct soft photons from the decays $\chi_{c1,2} \to J/\psi\gamma$; (iii) to provide identification of electrons and positrons via comparison of an energy deposit in the ECAL and a momentum measured in the tracking system. End-cup part of the ECAL participates also in online polarimetry with inclusive π^0 production at high x_F (see Sec. 2).

Transparency of the SPD setup allows to detect photons produced in the interaction point in a wide kinematic range. Efficiency of photon detection as a function of a production angle θ in respect to the beam direction and as a function of a transverse momentum p_T is shown in Fig. 11.5(a) and (b), respectively. Expected energy resolution of the ECAL obtained from the Geant4-based Monte Carlo



(a) (b)

Figure 11.5: Efficiency of photon detection as a function of (a)θ and (b) p_T. **[Dummy now!]**



(a) (b)

Figure 11.6: (a) Energy resolution of the ECAL for the normal incidence of photons and for an angle of 30°. (b) Purity of double-photon rejection vs. the efficiency of single photon reconstruction for 6 GeV photons and two 3 GeV photons separated by 4 cm of distance basing on the cluster shape analysis.

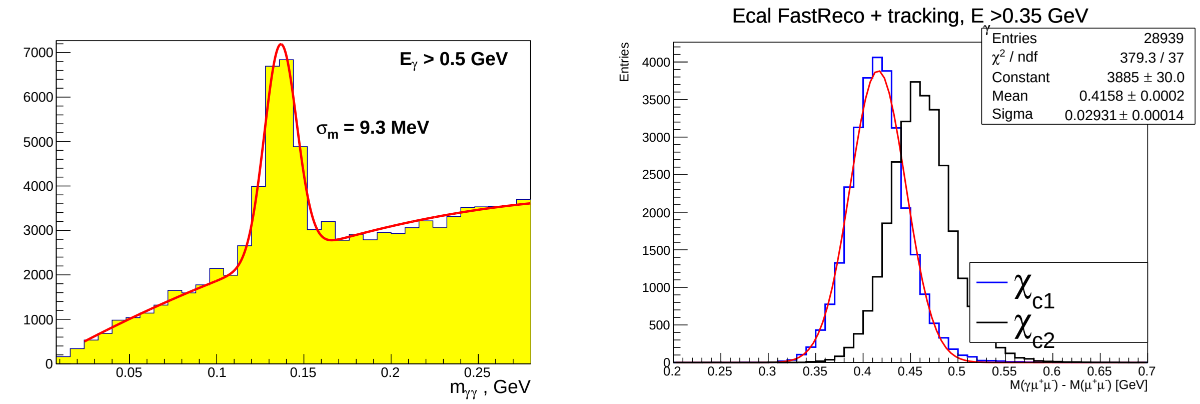
simulation for the normal incidence of photons and for an angle of 30° in respect to the normal line is shown in Fig. 11.6(a). Such effects as individual cell energy threshold on the level of 50 MeV, light absorption in optic fibers and fluctuation of the number of photons are taken into account. The fitted curve has a shape:

$$\sigma_E/E = A \oplus \frac{B}{\sqrt{E/GeV}} \oplus \frac{C}{E/GeV}, \tag{11.1}$$

were the sets of parameters A, B and C are 0.9%, 5.9%, 1.7% and 0.0%, 6.0%, 2.2%, respectively, for 0° and 30° of incidence angle. The superconducting coils of the magnetic system (0.? X_0 of material) placed in front of the calorimeter do not reduce its acceptance and do not produce any sizable impart to the energy resolution. For instance, the average resolution for 1-GeV photons passed through the coil changes from 6.1% to 6.3%.

As soon as the internal longitudinal and transverse size of the ECAL is quite small, for photons from the high-energy pions decay ($E_{\pi^0} \gtrsim 6$ GeV) there is a probability to produce a single cluster and be misidentified as a single high-energy photon. That is especially important fo the prompt-photon part of the physics program. But it is possible to identify such clusters with a certain precision performing the cluster shape analysis. Cluster shape can be characterised using variables such as dispersion, or second-order moment (in one or two dimensions), fourth-order moment, ratio of major and minor semiaxes of the ellipse corresponding to deposited energy, etc. The machine learning classification techniques are planned to be applied (multilayer perceptron, k-nearest neighbors, etc.) using these variables as an input to classify between singe and double-photon clusters. Figure 11.6 illustrates the purity of double-photon rejection vs. the efficiency of single photon reconstruction for 6 GeV photons and two 3 GeV photons separated by 4 cm of distance (exactly the ECAL cell size) basing on the cluster shape analysis.

Impact of the ECAL energy resolution to the reconstruction of such states as π^0 and $\chi_{c,1,2}$ via their radiative decays is presented in Fig. 11.7. For the latter case the χ_{c1} and χ_{c2} cannot be fully resolved ($\Delta M/\sigma_M \approx 1.5$) but nevertheless a relative contribution of these states could be estimated basing on the detailed peak shape analysis.



(a) (b)

Figure 11.7: (a) π^0 peak in the $\gamma\gamma$ mass spectrum. (b) Mass resolution for $\chi_{c1,2}$ reconstructed via their decay into $J/\psi\gamma$ final state.

1.5 Particle identification [A. Guskov]

The particle identification with the TOF detector is based on the comparison between the time of flight of the particle from the primary vertex to the TOF detector and the expected time under a given mass hypothesis. Presence of only one plane of the TOF detector requires for particle identification the precision knowledge of the event collision time t_0. It can be estimated by the TOF detector on an event-by-event basis using χ^2 minimization procedure for events with two and more reconstructed tracks. Having in the event N tracks matched to a corresponding hits on the TOF plane it is possible to define certain combinations of masses $\vec{m}_i$ assigning independently for each track the π, K or p mass. The index i indicates one of the possible combination $(m_1, m_2, \ldots, m_{N\ tracks})$ among the 3N tracks ones [287].

For each track the following weight is attributed

$$W_i = \frac{1}{\sigma_{TOF}^2 + \sigma_{t_{exp.\ i}}^2}. \tag{11.2}$$

Here σ_{TOF} and $\sigma_{t_{exp.\ i}}$ are the time resolution of the TOF detector and uncertainty of the expected time of flight under a given mass hypothesis $t_{exp.\ i}$, respectively. The latter is defined by uncertainty of the momentum and track length measurements.

The following χ^2 function has to be minimized

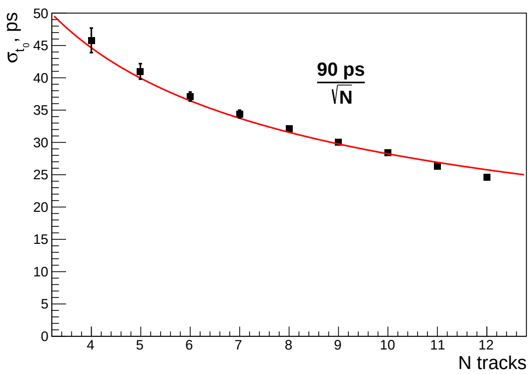
$$\chi^2(\vec{m}_i) = \sum_N W_i((t_{TOF} - t_0(\vec{m}_i)) - t_{exp.\ i})^2. \tag{11.3}$$

Here

$$t_0(\vec{m}_i) = \frac{\sum_N (t_{TOF} - t_{exp.\ i})}{\sum_N W_i}. \tag{11.4}$$

The mass vector $\vec{m}_i$ that minimizes χ^2 in Eq. 11.3 can be used in Eq. 11.4 for determination of the event collision time t_0. For unbiased particle mass determination, each track has to be subsequently excluded from the t_0 calculation procedure.

Figure 11.8(a) illustrates an accuracy of t_0 reconstruction as a function of the number of tracks for $\sigma_{TOF} =$ 70 ps. One can see that σ_{t_0} is proportional to $1/\sqrt{N}$ and for the track multiplicity 10 (typical for hard interaction events) is about 30 ps. Pion, kaon and proton separation with the TOF detector is shown in Fig. 11.9. π/K and K/p separation power as a function of particle momenta and emission angle in the primary vertex is presented in Fig. 11.10 (a) and (b), respectively, for the time of flight ($t_{TOF} - t_0$) resolution 80 ps. It is mostly defined by the time measurements while the accuracy of momentum reconstruction becomes sizable only for $\theta < 10^o$.



(a)

Figure 11.8: Accuracy of t_0 reconstruction as a function of the number of tracks in the primary vertex.

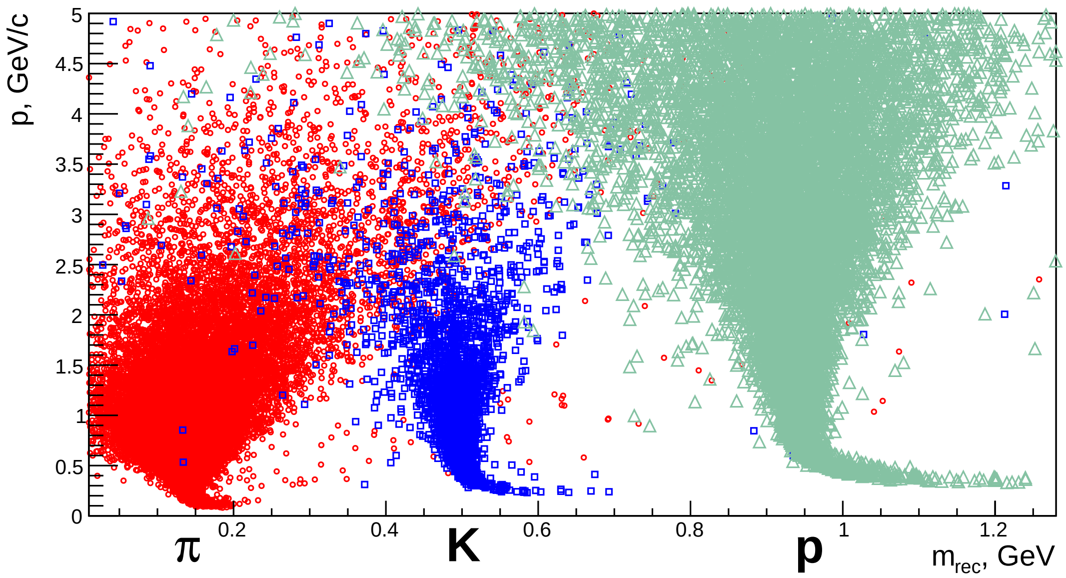
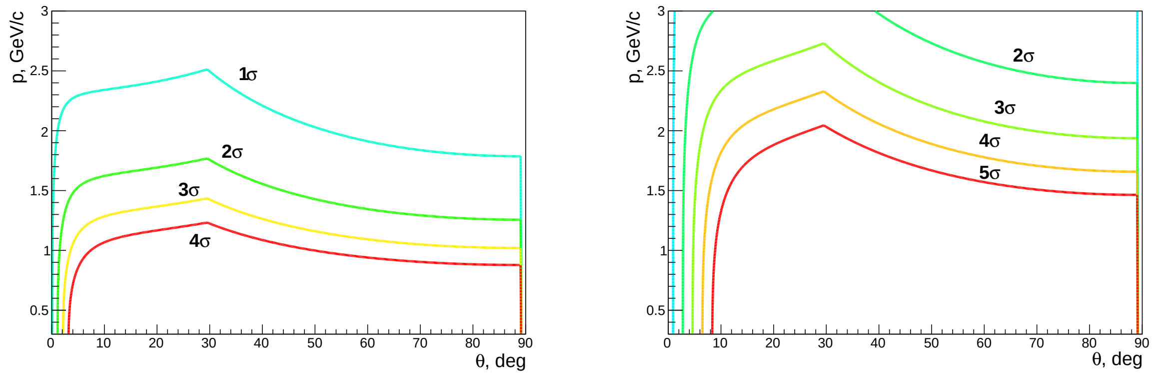


Figure 11.9: Reconstructed mass vs. particle momentum for pions, kaons and protons.



(a) (b)

Figure 11.10: π/K (a) and K/p (b) separation power of the TOF system as a function of particle momenta and emission angle.

2 Accuracies of asymmetries measurement

2.1 Charmonia production [I. Denisenko]

According to the modern theoretical approaches, the charmonia production at the SPD energies (10 GeV $\leq \sqrt{s} \leq$ 27 GeV) is dominated by gluon-gluon fusion process. The inclusive J/ψ production has a large cross-section (200 – 250 nb at the maximum energy) and clear experimental signature in the dimuon decay mode, and thus is a powerful probe of internal structure of proton [and deuteron]. The distinct J/ψ signal allows us to also reconstruct excited charmonia states in the decays $\chi_{c1,2} \to \gamma J/\psi$ and $\psi(2S) \to \pi^+\pi^- J/\psi$. The feasibility of physics with η_c (e.g. decaying to $p\bar{p}$) is questionable. There is also a possibility to reconstruct J/ψ from e^+e^- final state, but it look less promising due larger background, a larger observed J/ψ width and more complicated shape of the peak, which will significantly affect both statistical and systematic errors.

Muons are identified in the RS. The system is expected to separate showers from strongly interacted pions and muon tracks (using standard or machine learning techniques.) The main background are muons from pion decays and pions that passed large distance in the RS. The pion decays result in a small kink of charged track (about 2°), and the decay muon retains from 60% to almost 100% of the initial pion energy. There is a possibility that a fraction of decay muons can be suppressed by search of a kink in the tracker or by considering correlation between particle momentum and amount of material it crossed. But the results in this section are based on a simplified model (gives a lower performance boundary). A particle is identified as a muon based on the amount of material it passes in the active part of the RS, this amount is given as a number of proton nuclear lengths (n_λ). Two possibilities are considered: a particle from the initial interaction and a muon from a pion decay (the pion must be from the initial interaction). In the latter case, if pion decays in the RS, the amount of material is added for pion and muon.

It clear that higher running energies are preferable for physics with charmonia due to higher production cross-section, stronger boost for pions and more energetic muons. All estimates in this section assume a pp collision energy of 27 GeV, 10^7 s time of data taking (one year) with the maximum luminosity and a polarization P of 0.7. At these conditions one expects about 12 million $J/\psi \to \mu^+\mu^-$ decays in the SPD detector.

The J/ψ events are simulated using Pythia8 and their number normalized to the cross-section of 200 nb. For background minimum bias events generated with Pythia6 and Pythia8 are considered (giving almost the same predictions around J/ψ peak). Approximately half of background events are produced in hard interaction, but sizable fraction comes also from diffraction processes. It appears that significant amount of background events can be suppressed by a requirement on polar angle of a muon candidate. The $\mu^+\mu^-$ invariant mass spectrum for muon candidates with $n_\lambda > 3$ and satisfying $|\cos\theta| < 0.9$ is shown in Fig 11.11. The selection efficiency can be estimated to be around 35 – 45% depending on the cut on θ, resulting in 4 – 5 million selected events. The statistical errors for observables can be estimated using a linear LSM fit []. As an example, the estimated statistical precision for polarization is shown in Fig. 11.11.

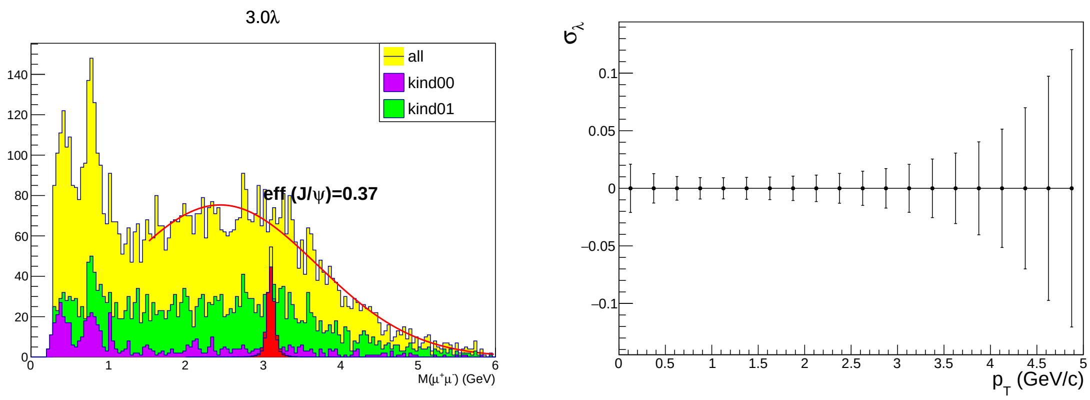


Figure 11.11: (left) The dimuon candidate spectrum and the J/ψ peak. (right) Expected statistical precision for polarization as a function of J/ψ transverse momentum [plot on predictions?]. (λ is the polarization in the helicity frame, $d\sigma/d\cos\theta \propto 1+\lambda\cos^2\theta$). The estimate is made assuming $\lambda \ll 1$.

The transverse single spin asymmetry A_N in J/ψ production probes the Sivers function. It is observed as modulation of the cross-section with respect to azimuth angle ϕ: $d\sigma/d\phi \propto 1 + PA_N\cos(\phi-\phi_0)$, where P and ϕ_0 are the beam polarization and its direction, respectively. At $\sqrt{s} = 200$ GeV it was measured the PHENIX Collaboration and found consistent with zero [17, 18]. To estimate our statistical precision 8 bins in ϕ are considered. The same linear fit is used to firstly estimate error in bins based on expected J/ψ number and secondly to extract A_N. The projected statistical uncertainties for A_N as a function of x_F are compared to the GPM model predictions from Ref. [**?**] in Fig 11.12. Compared to the PHENIX measurement, we expect much better precision and much wider kinematic range in x_F. Our rapidity range is approximately $|y| < 2$.

The longitudinal double spin asymmetry A_{LL} is sensitive to the polarized gluon distribution. It is defined as

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}},$$

where σ^{++} and σ^{+-} are cross-sections for protons with the same and the opposite helicities, respectively. In terms of J/ψ yields N^{++} and N^{+-} it reads

$$A_{LL} = \frac{1}{P_1 P_2}\frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}},$$

where R is the ratio of luminosities and P_1 and P_2 are polarizations of beams. The asymmetry is expected to be small. Taking $R = 1$ (and neglecting its uncertainty), approximating for N^{++} and N^{+-} by the same distribution (N) and assuming $P_1 = P_2 = P$, the statistical error of A_{LL} can be approximated as $\sigma_{A_{LL}} \approx \frac{1}{P^2}\frac{\sigma_N}{N}$. They projection of statistical uncertainties as functions of p_T and $|y|$ are shown in Fig 11.13. Compared to previous results obtained by the PHENIX Collaboration at $\sqrt{s} = 510$ GeV [114], we have much better precision and probe wider kinematic range.

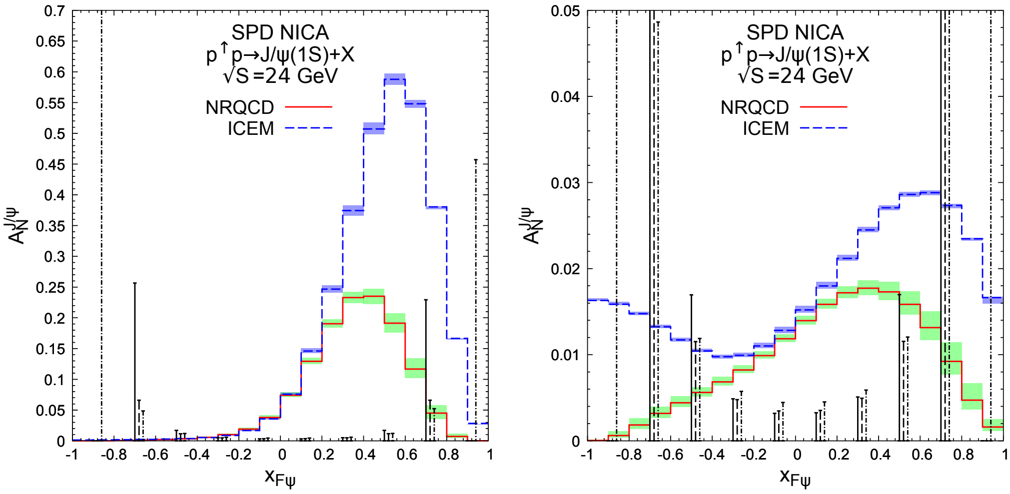


Figure 11.12: Projection of the estimated statistical uncertainties for A_N compared to GPM predictions from Ref. [?] for SIDIS1 (left) and D'Alesio PDF parameterizations (right).

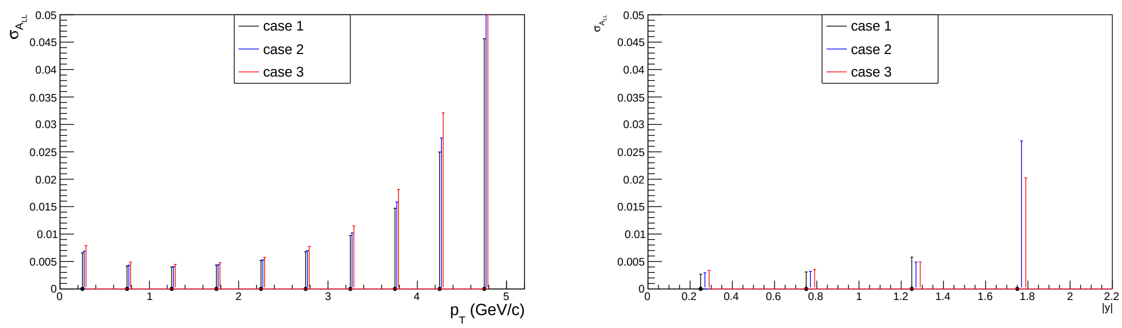


Figure 11.13: Estimated statistical precision of A_{LL} as a function of p_T (left) and x_F (right).

The study of associated J/ψ production will likely strongly restricted by the small expected statistics. The double J/ψ production cross-section was measured by the NA3 Collaboration [?] and was found to be 27 ± 10 pb in proton nucleus interaction at $\sqrt{s} \approx 27$ GeV. Optimistically, such cross-section would result in 50-100 reconstructed events if both e^+e^- and $\mu^+\mu^-$ modes are used to reconstruct J/ψ. It may be enough to determine low-p_T cross-section dependence, but a study of any angular modulation will not be possible. The $\gamma J/\psi$ [cs??] will be challenging experimentally due to both lack of statistics and high expected background. The reasonable statistics might be expected for $J/\psi D$ production.

The $\psi(2S) \to \mu^+\mu^-$ decay is suppressed as compared to $J/\psi \to \mu^+\mu^-$ by approximately a factor of 60 and and its reliable extraction may not be feasible. At the same time the decay $\psi(2S) \to \pi^+\pi^- J/\psi$ can be reliably identified as a narrow (about 10 MeV/c^2 wide) peak in the $M_{\pi^+\pi^-\mu^+\mu^-} - M_{\mu^+\mu^-}$ distribution [Show?]. The expected statistics is about 200×10^3 selected events.

The χ_{c1} and χ_{c2} states have a large partial of decay to $J/\psi\gamma$ and can be reconstructed using it. The production properties of these states at low energies are poorly known (e.g. see Ref). At SPD identification of these decays relies on the ECAL performance. The result of MC simulation for $M_{\gamma\mu^+\mu^-} - M_{\mu^+\mu^-}$ is shown in Fig. 11.7(b). The states χ_{c1} from χ_{c2}, but their relative fractions should be well measurable for the expected statistics of approximately 0.5 million reconstructed decays (for both states together) per year.

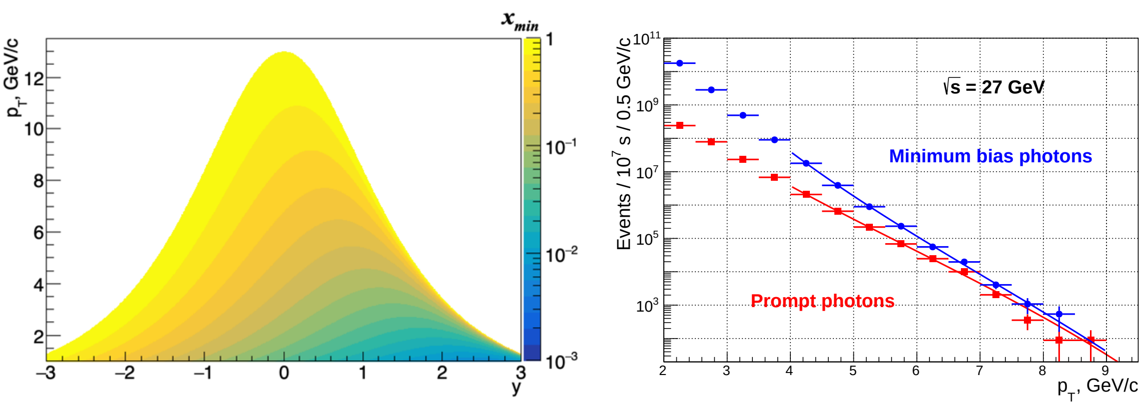
2.2 Prompt photon production

As it was already mentioned in the Sec. , the two hard processes determine the production of prompt photons in p-p collisions in the leading order: gluon Compton scattering $gq(\bar{q}) \to \gamma q(\bar{q})$ and quark-antiquark annihilation: $q\bar{q} \to g\gamma$. Contribution of the latter process to the total cross section does not exceed 20% at the discussed energy range. That is what makes prompt photons a convenient probe for gluons inside the nucleon. In ultrarelativistic approximation the minimal value of the longitudinal momentum fraction of struck parton x_{min} accessible by detection of prompt photon with normalized transverse momentum $x_T = 2p_T/\sqrt{s}$ and rapidity y could be expressed as [288]

$$x_{min} = \frac{x_T e^{-y}}{2 - x_T e^{y}}. \tag{11.5}$$

For the fixed x_T the minimal $x_{min} = x_T^2$ is reached at $y_0 = -ln(x_T)$. The value x_{min} as a function of rapidity y and p_T of photon for $\sqrt{s} = 27$ GeV is shown in color in Fig. **??**(a). One can see that possibility to access low-x region is limited by our capability to detect prompt-photon signal at low p_T and angular acceptance of the experimental apparatus. The latter is especially important for collider experiments like SPD where large values of $|y|$ correspond to a blind area near beam pipes.

Huge rate of decay photons makes rather difficult determination of the prompt photon production cross-section. Main source of decay photons id the two-body decay $\pi^0 \to \gamma\gamma$. The second most important source is the decay $\eta \to \gamma\gamma$. In the kinematic range $p_T > 3$ GeV/c at $\sqrt{s} = 27$ GeV there are 0.18 photons from the η decay per one photon from the π decay. Relative contribution of all other decay photons (ω, ρ, ϕ decays) does not exceed 0.03.

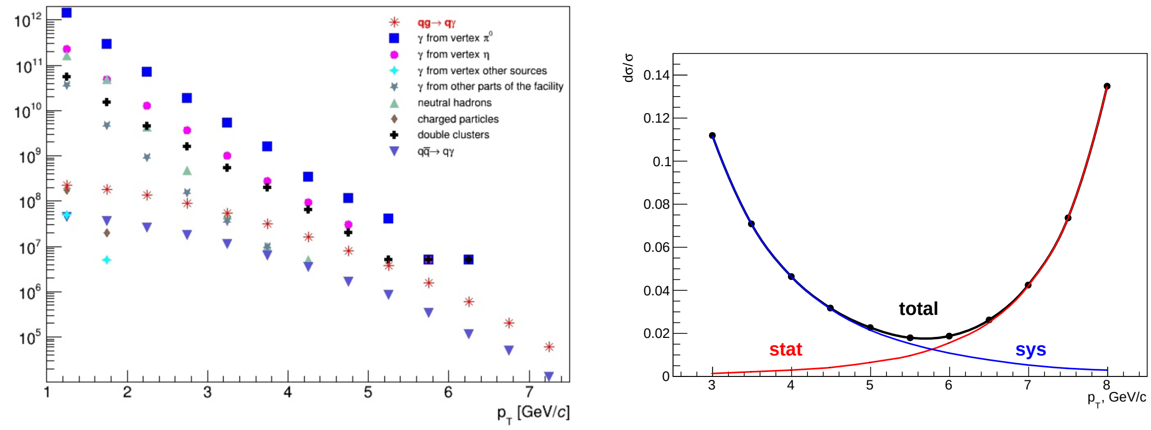


(a) (b)

Figure 11.14: (a) A minimal value of gluon x accessible via registration of prompt photon with rapidity y and transverse momentum p_T at $\sqrt{s} = 27$ GeV. (b) p_T spectra of produced prompt (red) and decay or minimum bias (blue) photons in p-p collisions at $\sqrt{s} = 27$ GeV. Distributions are scaled to one year of data taking (10^7 s).

The p_T spectra for prompt and decay photons expected at SPD after one year of running at $\sqrt{s} = 27$ GeV are presented in FIg. (b). The result was obtained using Pythia8 generator with parameters tuned to reproduce high-p_T spectra of π^0 and prompt photons measured at similar energies by WA70 ($\sqrt{s} = 22.96$ GeV) [289, 290] and UA6 ($\sqrt{s} = 24.3$ GeV) [], respectively. One can see that the p_T spectrum of decay photons goes down with grows of p_T faster that for prompt photons an their rates becomes comparable at $p_T \approx 7$ GeV/c. The fitted functions presented on the plot have shape

$$N(p_T) = A(1 - x_T)^n (p/p_0)^{-m}. \tag{11.6}$$



(a) (b)

Figure 11.15: (a) Contributions of different background components for the prompt photon production in p-p collisions at $\sqrt{s} = 27$ GeV.) (b) Expected uncertainty of the unpolarized cross section $Ed^3\sigma/dp^3$ measurement as a function of p_T.

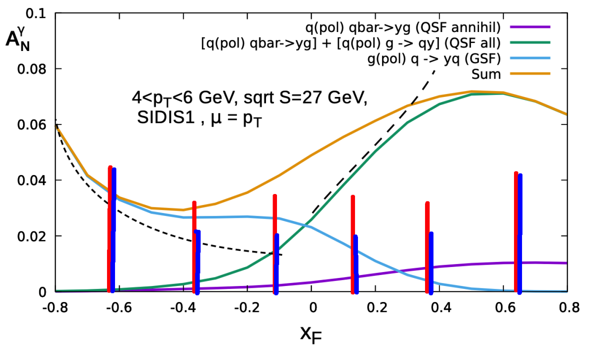
Each cluster of energy deposition in the ECAL with energy above the threshold $E_0 = 100$ MeV that is not associated with any reconstructed tracks is treated as a prompt photon candidate. The momentum of such photon is reconstructed under assumption of its production in the primary vertex. In order to reject photons from the $\pi^0 \to \gamma\gamma$ decay the invariant mass of each to photons is calculated. If the difference between the reconstructed mass and the nominal mass of π^0 is smaller than 10 MeV, both photons are removed from the list of candidates. Nevertheless this procedure removes just about 40% of false candidates. The photons from the $\pi^0 \to \gamma\gamma$ decay whose partner was not reconstructed due to conversion in the material, too low energy or acceptance issue remain in the list of candidates. Photons from radiative decays of other particles are also in the list. The list of candidates includes also photons associated with two or more overlapping clusters, first of all clusters from the decay of energetic π^0. Significant part of such false candidates could be rejected by a sophisticated analysis of the cluster shape. Clusters produced by charged particles whose tracks are lost, clusters deposited by photons originated from elements of the setup and clusters induced by neutral hadrons are also taken into account as a background. Contributions of each source of background mentioned above are presented as a function of p_T in Fig. 11.15(a).

As one can see, photons from unreconstructed decays of neutral pions are the main source of background. Fraction of such unreconstructed decays can be estimated from the Monte Carlo simulation and is about 50%. Basing on the number N_{π^0} of reconstructed $\pi^0 \to \gamma\gamma$ decays the corresponding number of remaining background photons $k \times N_{\pi^0}$ should be subtracted from the number of prompt photon candidates N_γ in order to get estimation of a true number of prompt photons:

$$N_{prompt} = N_\gamma - k \times N_{\pi^0}. \tag{11.7}$$

Here $k \approx 0.3$ is a coefficient, calculated from the MC simulation and takes into account not only an inefficiency of the $\pi^0 \to \gamma\gamma$ decay reconstruction but also overall contribution of all other background photons including photons from radiative decays of η, ω, ρ,ϕ etc. The described subtraction procedure has to be performed for each bin of p_T and x_F ranges. One should keep in mind that the background of decay photons is also spin-dependent: there is an indication of nonzero asymmetries A_{LL} and A_N in inclusive π^0 and η production [].

An expected accuracy of the unpolarized cross section $Ed^3\sigma/dp^3$ measurement after one year (10^7 s) of data taking is shown in Fig. 11.15(b). At low-p_T the main contribution to the total uncertainty is coming from the systematics of the π^0 background subtraction procedure while at high p_T statistical uncertainty



(a)

Figure 11.16: (a) Expected accuracy of the A_N measurement for prompt photons with $p_T > 4$ GeV/c at $\sqrt{s} = 27$ GeV as a function of x_F (**dummy at the moment**). Model predictions are also shown.

dominates. To estimate systematics $dk/k = 1\%$ is assumed.

An accuracy of the A_{LL} spin asymmetry measurement is estimated basing on the assumption of approximately equal statistics collected under similar conditions for same (N^{++}) and opposite (N^{+-}) spin orientations of colliding protons. So

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{P_1 P_2} \times \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}} \approx \frac{1}{P_1 P_2} \times \frac{N^{++} - N^{+-}}{N^{++} + N^{+-}}, \tag{11.8}$$

where P_1 and P_2 are the absolute values of proton beams polarizations and R is the ratio of integrated luminosities for the samples with same and opposite spin orientations.

To estimate the A_N asymmetry the function

$$f(\phi) = C + P \times A_N cos\ \phi \tag{11.9}$$

is fitted to the expected acceptance-corrected azimuthal distribution of prompt-photon events. Here ϕ is the azimuthal angle of produced photon in the lab. system in respect to the direction of the proton beam polarization. The expected accuracy of A_{LL} and A_N measurement as a function of x_F is shown in Fig. . It does not include uncertainties related with luminosity and beam polarization measurement.

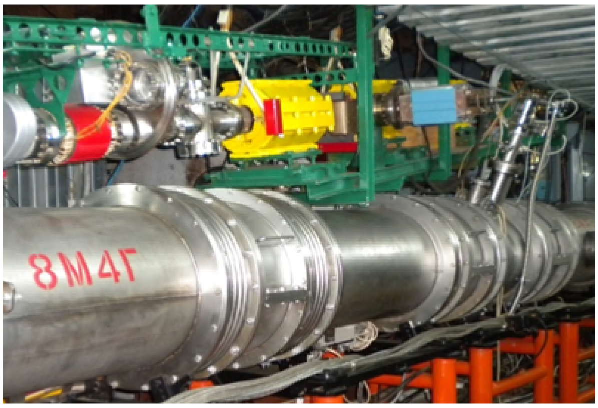
Chapter 12

Running strategy

1 Accelerator [A. Kovalenko]

We consider the strategy of SPD operation as successive chain of the experimental work with polarized proton and deuteron beam aimed at the obtaining of the ultimate polarized proton beam parameters at the collider and the use of the existing unique polarized deuteron beam for physics experiments from the early beginning of the collider putting into commissioning. Polarized deuterons d↑ was first accelerated at the old LHEP proton accelerator Synchrophasotron in 1986 and much later at the new superconducting synchrotron- Nuclotron in 2002 (see Fig. 12.1).

Polarized protons p↑ was first obtained in 2017. The first test was performed after analysis of the proton spin resonances in 2018. The first dangerous proton spin resonance in Nuclotron corresponds to the beam momentum of about 3.5 GeV/c, whereas in the deuteron case the spin resonance will be occurred at the particle kinetic energy of 5.6 GeV/nucleon. This limit is practically equal to the maximum achievable energy corresponding to the magnetic rigidity of the Nuclotron dipoles.



(a)

Figure 12.1: (a) View of the Nuclotron ring.

The existing polarized proton and deuteron ion source SPI provides up to 3 mA pulse current over t ≈ 100 mks. Thus up to 1.5×10^{11} can be injected in the Nuclotron during the injection time (8 mks). The spin modes (pz, pzz): (0,0), (0,-2), (2/3, 0) and (-1/3,+1) were adjusted. Polarization degree of 80 % was achieved.

The existing pre-accelerator of RFQ-type put limit for the achievable proton energy in the next element of the injector chain - linac LU-20. We can obtain only 5 MeV at it output instead of 20 MeV that we

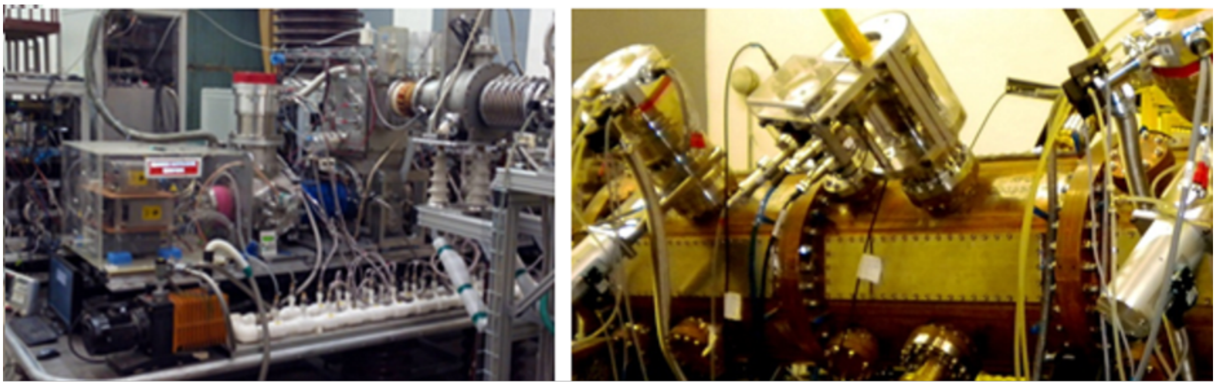


Figure 12.2: View of the SPI (left) and existing RFQ (right).

have had in the past years. The new proton and light ion linac "LILAC" is now under manufacturing. The LILAC output energy will be of 12 MeV. Commissioning is scheduled in 2015-2016. Photos of the SPI and existing RFQ are presented in Fig. 12.2.

The further tasks for the period of 2021-2025 are reasonable and necessary for the starting the SPD operation at the ultimate beam parameters:

- continuation of operation and further improvement of polarized ion source SPI, waiting beam time at Nuclotron – 2021-2022;
- upgrade of the polarimeters: linak output; coasting beam; extracted beam; new polarimeter for proton energy above 6 GeV – 2020-2023;
- manufacturing of the 6T SC-solenoid model; for the SPD test bench -2021-2022;
- design and manufacturing equipment for the SPD test bench at the collider - 2020-2023;
- LILAC manufacturing and tests – 2020-2025;
- analysis of ^{3}He (2+) polarized ion source based on the SPI upgrade.

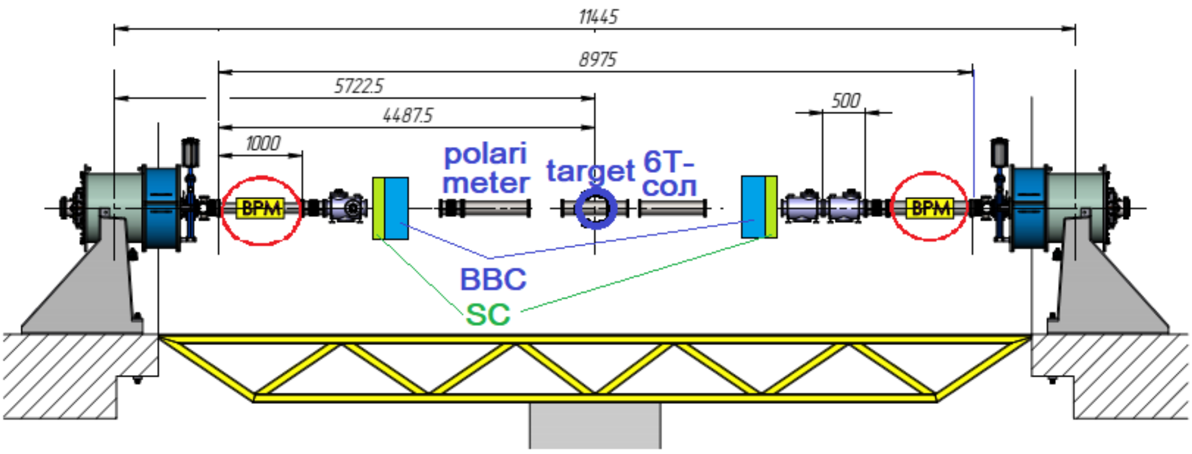


Figure 12.3: The SPD straight section equipped with the diagnostic and control units.

We suppose also, the beam test experiments and preparation to getting the luminosity of 10^{32} cm^{-2} s^{-1} at $\sqrt{s} = 27$ GeV including the proton polarization control will be demonstrated by the SPD commissioning. For that reason we propose installation of the diagnostic and control equipment at the SPD straight section (see Fig. 12.3).

2 Spin Physics Detector [A. Guskov]

Chapter 13

Cost estimate

Table 13.1: **DUMMY**

	Subsystem		Cost, M$
SPD setup	Vertex detector	detector electronics	10 5
	Straw tracker	detector electronics	1 1
	ToF system	detector electronics	2 0.5
	Electromagnetc calorimeter	detector electronics	10 5
	Range system	detector electronics	10 2
	ZDC	detector electronics	1 0.5
	Magnetic system		10
	Beam pipe		0.5
General infrastructure			5
Data acquisition system			0.5
Computing			10
TOTAL COST			74

Chapter 14

Participating institutions and author list [OUT OF DATE]

Host institute of the project is the Laboratory of High-Energy Physics of the Joint Institute for Nuclear Research. The main part of the human resources engaged with the project comes from there (61 researchers, 24.4 FTE). The Laboratory of Nuclear Problems is the other laboratory of the JINR that participates in the project with substantial number of researchers (29 researchers, 11.3 FTE). Altogether the JINR engagement in the project now evaluates to 37.7 full-time-equivalent (FTE) researchers.

Fourteen institutes from the JINR Member States and other countries have expressed by now their interest for participation in the project and indicate that they could allocate resources and manpower for the project. The list of institutes together with the names of researchers (in some cases only the leaders of the teams are listed) is given below. Received Expressions of Interest are collected under a separate cover.

Institute of Applied Physics of the National Academy of Sciences of Belarus
Shulyakovsky R.

Higher Institute of Technologies and Applied Sciences (InSTEC), Havana University, Havana, Cuba
Guzman F., Garsía Trapaga C.E.

Charles University, Prague, Czech Republic
Finger M., Finger M. (jr.), Hrusovsky J., Jandek M., Prochazka I., Slunecka M., Sluneckova V., Stepankova H., Zemko M.

Czech Technical University in Prague, Czech Republic
Jary V., Lednicky D., Marcisovsky M., Neue G., Novy J., Popule J., Virius M., Vrba V.

University of Turin and INFN Section, Turin, Italy
Denisov O.Yu., Panzieri D., Rivetti A.

Joint Institute for Nuclear Research, JINR, Dubna, Russia
Directorate

Lednický R.

Laboratory of High-Energy Physics

Anosov V.A., Akhunzyanov R.R., Azorskiy N.I., Baldin A.A., Baldina E.G., Barabanov M.Yu., Beloborodov A.N., Dunin V.B., Enik T.L., Filatov Yu.N., Gavrishchuk O.P., Galoyan A.S., Gribovsky A.S., Gromov V.A., Gurchin Yu.V., Gusakov Yu.V., Ivanov A.V., Ivanov N.Ya., Isupov A.Yu., Kekelidze G.D., Khabarov S.V., Kharusov P.R., Kovalenko A.D., Kovalev Yu.S., Kozhin M.A., Kolesnikov A.O., Kokoulina E.S., Kopylov Yu.A., Kostukov E.V., Kramarenko V.A., Khrenov A.N., Kruglov V.N., Kuzmin N., Ladygin E., Ladygin V.P., Lapshina I.V., Lysan V.M., Makankin A.M., Meshcheriakov G.V., Moshkovsky I.V., Nagaitsev A.P., Nagorniy S., Nikitin V.A., Pavlov V.V., Paraipan M., Parzhitskii S.S., Perepelkin E.E., Petukhov Yu., Peshekhonov D.V., Reznikov S.G., Rogachevsky O.V., Savenkov A.A., Sheremeteva A.I., Shimanskii S.S., Skhomenko Ya.T., Starikova S.Yu., Streletskaya E.A., Tarasov O.G., Tarasova L.N., Teryaev O.V., Tishevsky A.V., Topilin N.D., Topko B.L., Tsenov R., Usenko E.A., Vasilieva E.V., Veselova N.I., Volkov P.V., Yudin I.P., Zamyatin N.I., Zemlyanichkina E.V., Zhukov I.A., Zinin A.V., Zubarev E.V.

Laboratory of Nuclear Problems

Abazov V.M., Alexeev G.D., Afanasyev L.G., Denisenko I.I., Duginov V.N., Fedorov A.N., Frolov V.N., Golovanov G.A., Gritsay K. I., Guskov A.V., Komarov V.I., Kulikov A.V., Kutuzov S.A., Nefedov Yu.A., Piskun A.A., Prokhorov I.K., Romanov V.M., Rudenko A.I., Rymbekova A., Samartsev A.G., Semenov A.V., Skachkov N.B., Skachkova A.N., Tsirkov D.A., Tkachenko A.V., Tokmenin V.V., Uzikov Yu. N., Verkheev A.Yu., Vertogradov L.S., Zhuravlev N.F.

Laboratory of Theoretical Physics

Anikin I.V., Efremov A.V.,Goloskokov S.V., Klopot Ya., Strusik-Kotlozh D., Volchansky N.I.

Laboratory of Information Technologies

Uzhinsky V.V.

St. Petersburg Nuclear Physics Institute, Gatchina, Russia

Kim V.T.

Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

Andreev V.F., Baskov V.A., Dalkarov O.D., Gerassimov S.G., L'vov A.Yo., Negodaev M.A., Nechaeva P.Yu., Polyanskiy V.V., Soutchkov S.I., Terkulov A.R., Topchiev N.P.

Skobeltsin Institute of Nuclear Physics of the Moscow State University, Moscow, Russia

Boos E., Merkin M.

Institute for Theoretical and Experimental Physics, Moscow, Russia

Akindinov A.V., Alekseev, Golubev A., Kirin D.Yu., Luschevskaya E., Malkevich D.B., B. Morozov, Plotnikov V.V., Polozov P., Rusinov V., Stavinskiy A.V., Sultanov R.I., D. Svirida, Tarkovskyi E.I., Zhigareva N.M.

Institute for High-Energy Physics, Protvino, Russia

Vorobiev A.

Samara National Research University, Samara, Russia

A.V. Karpishkov, M.A. Nefedov, V.A. Saleev, A.V. Shipilova

St. Petersburg Polytechnic University, St. Petersburg, Russia
Berdnikov Ya.

St. Petersburg State University, St. Petersburg, Russia
Feofilov G.A., V.Kovalenko V.N., Valiev F.F., Vechernin V.V., Zherebchevsky V.Yo.

Tomsk State University, Tomsk, Russia
Burtsev V., Chumakov A., Dusaev R., Lyubovitskij V., Mamon S., Sharko K., Trifonov A., Vasilishin B., Zhevlakov A.

Chapter 15

Project timeline

We propose a five-year project for delivering of a complete technical design of the SPD facility based on the necessary simulation work, prototypes construction and test measurements.

The timeline is seen like follows:

– Approval of a formal JINR project for design of the SPD facility by the PAC for HEP in its meeting in January 2019;

– Setting up of the SPD collaboration and election of its management bodies (2019);

– Signing of MoU based on ”Regulations for the organization of experiments conducted by international collaborations using the capabilities of the JINR basic facilities” [291] (2019);

– Preparation of Conceptual Design Report and its approval by the PAC for HEP at its meeting in January 2020;

– Preparation of Technical Design Report for the first stage of the facility, including prototyping and test measurements (2020 – 2022);

– Preparation of Technical Design Report for the second stage (2023);

We hope to be able to start construction of the first stage of the detector in 2022 and perform first measurements somewhere in 2025.

Chapter 16

Conclusion

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