2021

JOINT INSTITUTE FOR NUCLEAR RESEARCH

JINR

DUBNA

VEKSLER AND BALDIN LABORATORY OF HIGH ENERGY PHYSICS

In 2021, the activity of the Veksler and Baldin Laboratory of High Energy Physics was aimed at construction, development and commissioning of various units of the accelerator complex "Nuclotron–NICA" and MPD, BM@N and SPD experimental facilities. Experiments were also continued at external accelerators.

MOST IMPORTANT RESULTS IN THE DEVELOPMENT OF THE NICA COMPLEX

Nuclotron/NICA Project

Booster and Beam Transport Channels. The systems of the Booster synchrotron — one of the key units of the heavy-ion accelerator complex NICA — were brought to the design parameters in September 2021. During the run, for the first time the iron ion beam in the Booster ring was accelerated to the design energy of 578 MeV/nucleon (Fig. 1) [1]. The equipment of the Booster electron cooling system was fully launched and, for the first time in Russia, the electron cooling of the heavy-ion beam was obtained. The beam cooling experiment was performed with $^{56}Fe^{14+}$ ions circulating at the injection energy of 3.2 MeV/nucleon.

The significant outcome of the run was the successful completion of joint work between specialists from JINR and the INR SB RAS on constructing the systems of extracting the beam from the Booster and the beam transport channel to the Nuclotron. The tuning of the channel magnet system and the testing of the equipment control system were finished. After that, a unique pulsed magnetic kicker for extracting the beam from the Booster with a record level of the magnetic field of 2 kG was commissioned. A group of specialists launched a "bump" system, i.e., a system of local displacement of the closed orbit, which was also required to ensure the fast extraction of the beam from the Booster. The extraction of two types

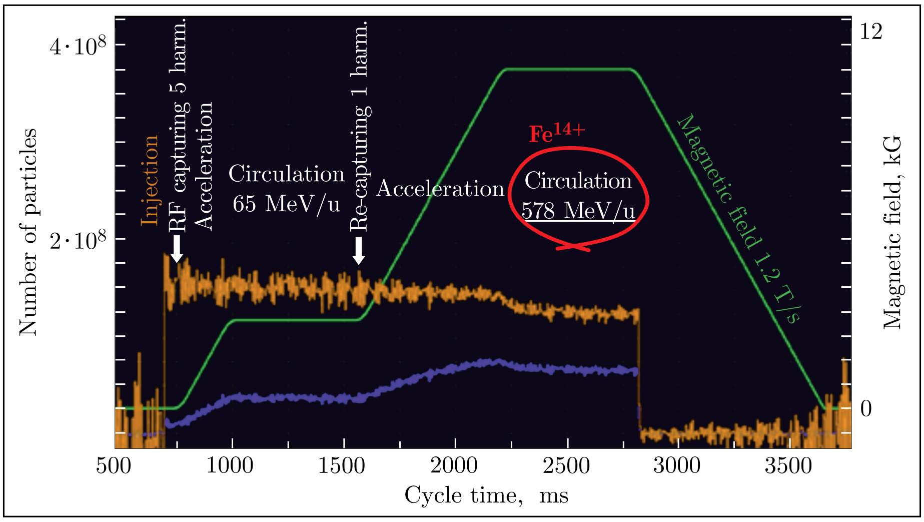

Fig. 1. A signal from the beam current sensor in the Booster

of ions, helium and iron, was obtained at an energy of 240 MeV/nucleon with their further transportation through the channel. At the final section of the channel, beam current and position sensors detected the beams, and the screenshots of the beam profiles from the phosphor screen were obtained (Fig. 2).

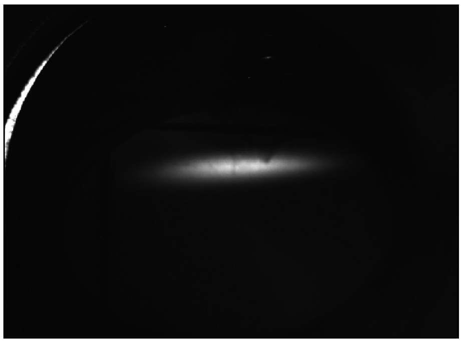

Fig. 2. A beam of $^{56}Fe^{14+}$ ions on the phosphor screen at the end section of the Booster–Nuclotron transport channel

The installation of a new system of injection of a beam into the Nuclotron has been completed, as well as the construction of a chain of magnets for the acceleration of heavy ions, which will be the basis for operating the NICA collider and the BM@N facility. The first run at the NICA complex with a full acceleration cycle is planned for January 2022.

The infrastructure for conducting applied and radiobiological studies within the framework of the ARIADNA (Applied Research Infrastructure for Advance Development at NICA fAcility) collaboration is being actively developed. The ion beam transport channel from HILac to the Station Of CHip Irradiation (SOCHI), which is designed for irradiating microchips, has already been constructed. In December 2021, the first cycle of commissioning to tune the channel magnetic system was carried out. The beam was transported to the SOCHI station, where it was registered by several detectors. The plan is to complete the installation of equipment of three stations for applied research and their testing in 2022.

Collider. The NICA collider is located in building 17. The readiness of the building by the end of 2021 is as follows: 100% of works on piles, concrete structures, load-bearing floors, metal structure installation, earth works and temporary roads, brick and foam block partition walls, the wall drainage system, and the displacement of water supply networks are completed; the works on the roofs (93%), facades installation (94%), finishing works (84%), engineering systems (28%), installation of household and storm sewer (92%), installation of individual heating units (75%), inside doors (40%) and landscaping (82%) are in their final stage.

The change of deadlines for completing the civil works is primarily due to a significant (50%) increase in construction volume at the stage of the project implementation. The coronavirus pandemic has also affected meeting the contract deadlines.

In 2021, the production and testing of equipment for the collider subsystems continued. 100% of the collider's dipole and 65% of the quadrupole magnets have already been produced and tested on the high-technology line for assembling and testing superconducting magnets.

Work on the reconstruction of power lines continued. A permit was obtained to operate eleven 6 kV upgraded substations with a total power of up to 33.6 MW.

Cryogenic Complex. New cryogenic equipment was installed at the central compressor station in building 1B: a helium liquefier with a capacity of more than 1000 l/h, a helium refrigerator for cooling the Booster at 2000 W at a temperature of 4.5 K, four purification units of compressed helium, a 1300 kg/h nitrogen liquefier and a recondenser of nitrogen vapors from the Booster shield with a capacity of 500 kg/h.

Large-scale cryogenic equipment, which is located outside the buildings, is completely ready for operation: a 40 m^3 tank container for liquid helium, 1000 m^3 gasholder tanks for gaseous helium and nitrogen.

In general, the volume of work performed to construct the design configuration of the Nuclotron–NICA complex is about 85% by the end of 2021.

MPD Project

The formation of the MPD collaboration was completed in 2020. Now, the collaboration numbers 42 institutes from 12 countries and more than 500 members. Eight collaboration meetings were held, at which the implementation of the project was discussed and coordinated. The installation of incoming equipment and engineering systems was started in a special hall of the main building 17 of the NICA complex, where the MPD detector will be located.

MPD Superconducting Solenoid. At the end of December 2020, the magnetic circuit was fully assembled in the MPD hall. The control measurements showed a high-quality, accurate assembly, which is necessary for obtaining a uniform magnetic field in the detector. The deviations of most of the measured geometric dimensions and parameters were within 0–200 μm with a magnetic circuit length of 8970 mm and a diameter of 6670 mm. The solenoid was installed into the yoke in July 2021. Measurements of the position of the yoke and the solenoid after the installation showed that the axis displacements did not exceed the expected 2 mm.

The simulation of the magnetic field by ASG specialists based on the actual position of the magnet demonstrated satisfactory performance without the need for further adjustment of the solenoid relative to the yoke. Now, the magnetic circuit is assembled to 13 plates. Further assembly of the yoke involves the installation of support rings and assembly up to the last 28th plate.

The first cycle of leakage tests of the solenoid was successfully carried out in September 2021. Due to this, it was concluded that there was no leakage at a pressure of 10 bar for nitrogen and 25 bar for helium. At present, the solenoid is ready for vacuum tests. Most of the MPD cryogenic infrastructure equipment has already been ordered.

Time Projection Chamber (TPC). TPC is the main tracking detector of the MPD experiment for reconstructing the tracks of charged particles and their identifying by dE/dx for high-multiplicity events. It consists of four cylinders (C1–C4) produced by the Russian industry from composite materials. This ensures sufficient longitudinal strength of the cylinders (deflection at the centre is less than 100 μm) and a small amount of material budget on the beam line — 0.4 g/cm^2. All four cylinders are interconnected by two aluminum flanges.

Readout Chambers (ROC) for the initial version of MPD are based on MWPC with pad readout. The total number of readout pads for TPC is 95 232. All of 24 serial ROC chambers are produced and tested.

Gas System was developed based on the experience of constructing the STAR and PHENIX gas systems at BNL, USA. The system consists of two circulation loops, outer and inner, and operates as a closed-loop system with recirculation of the working gas mixture through the TPC through an inner loop containing a purification system.

Cooling System is used for stabilization of the gas temperature inside the TPC volume within 0.5°C. The system uses 180 Pt1000 sensors placed on the detector surface and providing temperature measurement with an accuracy of 0.1°C. Thermal screens for the TPC thermal stabilization system were supplied to JINR. The electronics for the TPC cooling system are produced and being tested.

Front-End Electronics (FEE) and TPC Data Readout System are based on specialized ASIC, FPGA and chips for high-speed datalink. Each of the 62 cards (FEC) has 64 registration channels and a separate bidirectional communication interface with its controller (2.5 Gbit/s). FECs work in parallel, providing a full bandwidth of up to 100 Gbit/s. Each FEC has two specialized ASIC SAMPA chips (1488 in total), developed by the USP Brazil group of electronic engineers together with CERN to upgrade the ALICE experiment and made using radiation-resistant technology (TID $\sim$ 100 krad). The use of SAMPA chips on FEC cards made it possible to significantly reduce their geometric size and radiation length ($X/X_0 \sim 3\%$). FPGA Altera Cyclon-5, used to read out data from two SAMPA chips, is a commercial chip. Taking into account the radiation vulnerability of FPGA of this class to SEE (Single Event Error), MEPhI is developing a radiation-resistant ASIC (65 nm CMOS process) to replace it in the future. The total ionization dose stated by the developer will be $\sim$ 100 Mrad. The FPGA prototype was put into production (Europractice) in November 2020.

TPC Assembly and Infrastructure. At the beginning of 2022, it is planned to complete the series production of readout electronics, install ROC cameras into TPC and test TPC with cosmic rays. In March 2022, TPC will be transported to the MPD experimental hall. After that, it will be installed into MPD and adjusted. The MPD facility is planned to be tested with cosmic rays, starting in August 2022.

Time-of-Flight System (TOF). TOF is the basic identification system for charged hadrons in MPD. In the initial configuration, TOF will be presented as a cylinder about 6 m long and 3 m in diameter, assembled from 28 modules. In addition to these modules, each having 10 subdetectors based on Multi-gap Resistive Plate Chambers (MRPC), TOF also includes service subsystems. The TOF system should be put into operation at the beginning of 2022.

Multi-Gap Resistive Plate Chambers (MRPC). Each TOF module consists of 10 identical MRPCs with 24 readout channels. The final version of the MRPC is made of commercial float glass, 280 μm thick. It has 15 gas gaps 200 μm wide and provides a time resolution of 50 ps. The production of 280 MRPCs will be completed in June, and 28 TOF modules will be ready by December 2022. TOF modules have been tested since the beginning of 2020 at a special cosmic stand.

Readout and DAQ System for MPD TOF and FFD systems is developed on the basis of the time-to-digital converter VME64x VXS TDC72VHLv4 with an HPTDC chip. It is used to digitize LVDS signals with a sampling time of 24.4 ps. TDC72VHLv4 provides the possibility of accurate time synchronization with other devices using White Rabbit technology. The total number of TDC required for MPD TOF is 196 (14 modules for each of 14 VME crates). All VME crates were purchased and delivered to JINR. The required number of TDC72VHLv4 modules was produced, and testing and calibration of the readout electronics was performed.

Electromagnetic Calorimeter (ECal). ECal is designed to identify particles, measure the flow of photons and reconstruct some decays involving photons. A large-sized (6 m long and 4.5 m in diameter) cylindrical electromagnetic calorimeter covers the central region of the pseudorapidity $|\eta| < 1.2$ and has a projective geometry in which the axis of each tower is directed to the beam intersection point. The layout of the towers in such a calorimeter is shown in Fig. 3.

At present, the companies OOO Polipak in Dubna and OOO Uniplast in Vladimir produced 10 million scintillation plates, which is 100% of the total ECal. The production of calorimeter modules was established at PAO TENZOR in Dubna and IHEP in Protvino. The first order, amounting to 40% of the

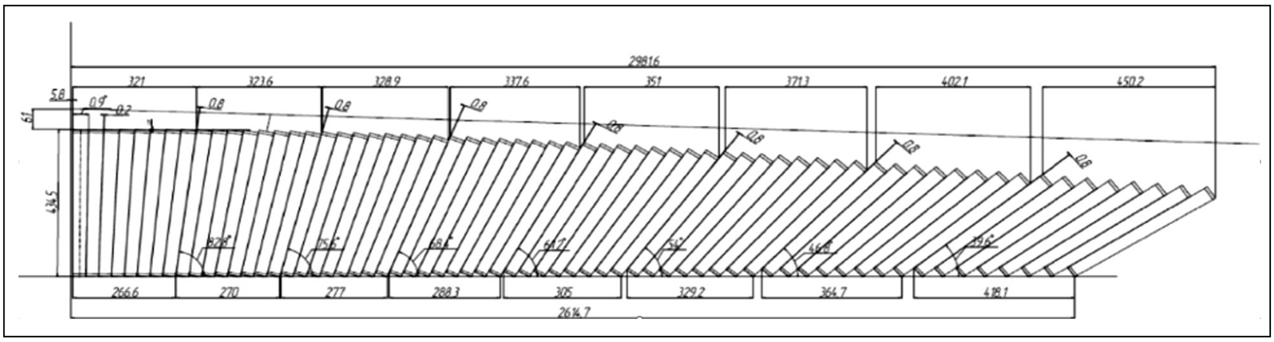

Fig. 3. Layout of the towers in the half-sector of the electromagnetic calorimeter with a projective geometry

JINR quota and 15% of the total number of calorimeter modules, was placed in 2020 at these enterprises. The second part of the order is being produced. A total of 800 modules will be produced until the end of 2022. This will make it possible to assemble 8 (out of 25) complete sectors of the calorimeter.

The production of modules for 8 more sectors was started in China. The most essential part of the materials is supplied from JINR. The assembly is being performed in four institutes. The first prototypes of the calorimeter modules were produced, and their testing is underway. By the last quarter of 2022, the production of 800 modules in China is expected to be completed.

In geometrical terms, ECal consists of 25 sectors or 50 half-sectors. Each half-sector (Fig. 4) has 48 modules of 8 different types, which are glued into a fiberglass container (basket), as well as the corresponding readout and control electronics, and it weighs about 1.5 t. Calculations show that the deformation of the half-sector under its own weight will not exceed 0.5 mm for all possible spatial orientation. According to the signed contract, all 52 baskets are planned to be received by June 2022.

The readout and control electronics were developed at JINR. Their mass production was completed in November 2021. Now, the ECal group is making every effort to develop an innovative system for installing and replacing the calorimeter electronics without dismantling the calorimeter itself.

To control the quality of the modules produced and perform the initial calibration of the detectors, a special stand was developed that allows simultaneous testing of 12 ECal modules with cosmic muons. Eight such stands were put into operation (for 8 different types of modules) with a total capacity of 96 modules (or 2 half-sectors) for every 2 weeks. This will allow testing all ECal modules within a year.

BM@N Experiment

The BM@N collaboration includes 230 physicists and engineers from 19 institutes and 10 countries. The experiment is aimed at studying the dynamics of reactions and the properties of hadrons in dense nuclear matter in the interactions of extracted Nuclotron beams with fixed targets [2, 3]. Within the framework of the project, the structure of nuclei at small inter-nucleon distances is also studied [4]. The development and production of detectors for the full configuration of BM@N are underway [5] (Fig. 5). The status of the construction of the main components for the heavy-ion programme is as follows:

• Silicon Beam Tracker detectors and beam profile meters were constructed; their installation and commissioning is scheduled for the spring of 2022;

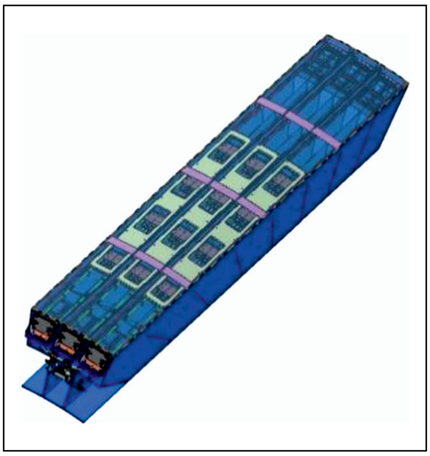

Fig. 4. ECal basket with electronics

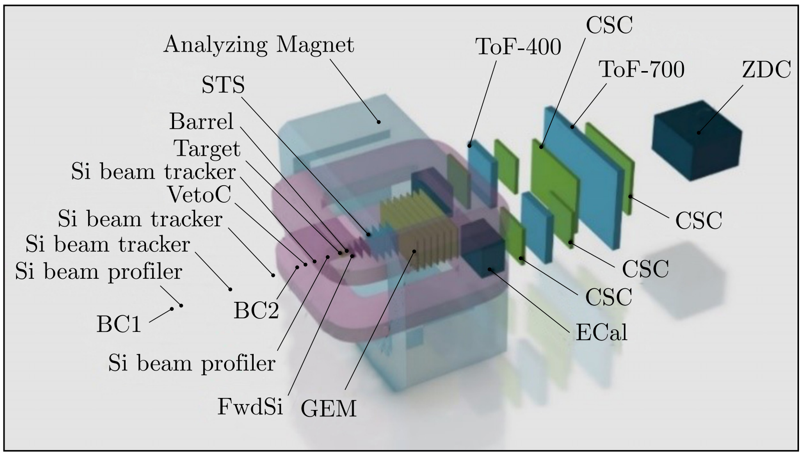

Fig. 5. Complete configuration of the BM@N detectors for studying heavy nucleus interactions

• Forward Silicon detectors (FwdSi) for the Central Tracker were constructed; the detectors have already been operated in the C, Ar, Kr runs. Their installation and commissioning is scheduled for the spring of 2022;

• Large-aperture Silicon Tracking System (STS) for the Central Tracker is being jointly developed by Russia (JINR, MSU) and Germany (GSI/FAIR, Tübingen). Two STS pilot stations (out of four) are planned to be developed and installed for the BM@N physics run in 2023;

• Full STS configuration is planned to be commissioned after 2023.

• GEM detectors for the Central Tracker, produced in CERN together with the BM@N specialists, were tested. Their installation and commissioning is scheduled for the spring of 2022. A contract for fast FEE (VMM3a chips) production (contribution from Germany) is being fulfilled;

• Trigger and T0 detectors will be ready by the spring of 2022 — by the start of installation and commissioning;

• CSC chambers for track matching with ToF-400 are ready; one big CSC chamber for track matching with ToF-700 is planned to be constructed in the spring of 2022, and another one — at the end of 2022;

• Carbon fibre beam pipe inside BM@N and the target station will be constructed and tested by the spring of 2022;

• Beam pipe in front of the target and the detector boxes are ready;

• New forward hadron calorimeter (ZDC) was installed into BM@N; the hodoscope in front of the calorimeter is planned to be installed in the spring of 2022.

Implementation of the BM@N physics programme in heavy-ion beams is foreseen to start in the spring of 2022 (April–May 2022) with the Xe ion beam of up to 3.9A GeV kinetic energy. Statistics of around $2 \cdot 10^9$ interactions with the CsI target for the period of 800 h are planned to be collected. In the spring of 2023, the implementation of the physics programme with heavier ions will be continued to collect statistics up to $2 \cdot 10^9$ interactions (Au + Au or Bi + Bi).

SPD Project

The Conceptual Design Report (CDR) of the SPD experiment was presented at the meeting of the PAC for Particle Physics in January 2021. Later, SPD Detector Advisory Committee was formed, which conducted a thorough review of the project to develop the SPD TDR (Technical Design Report). A considerable progress was achieved in forming the international collaboration. More than 300 scientists from 32 institutes became interested in joining it. Such collaboration bodies as the Executive Board, Technical Board, etc., were formed and started their work. The SPD Collaboration Board adopted the Constitution of the Collaboration. Memoranda of Understanding are being prepared. Two collaboration meetings were held. The physics programme of the future experiment is being actively developed [6–9].

The first version of the technical design of the detector was prepared (Fig. 6), in which two options of the SPD solenoid magnetic system were considered based on technologies developed at JINR VBLHEP and INP (Novosibirsk).

A prototype of the muon system for Nuclotron test beams is being developed: about 100 MDT detectors were produced, analog electronics were prepared, and new digital electronics were developed and produced. The total number of electronic channels in a fully equipped prototype is 1300.

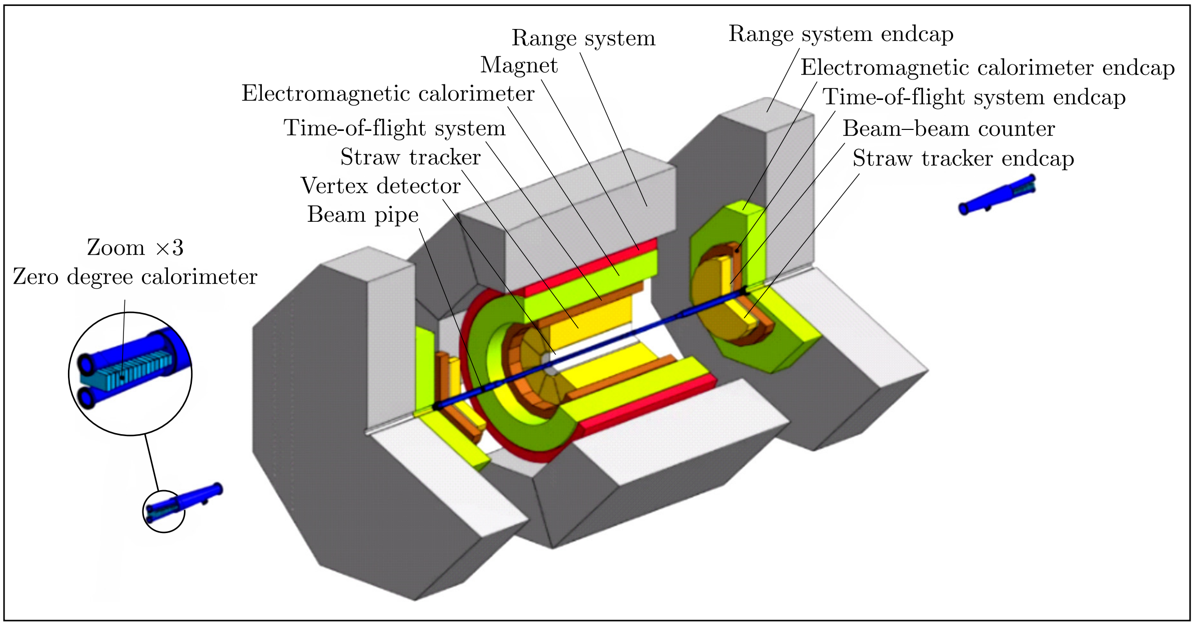

Fig. 6. Upgraded configuration of the SPD detector

The design of the electromagnetic calorimeter was finalized taking into account changes in the SPD magnetic system. A new prototype of the calorimeter module was constructed and tested at the cosmic ray test bench. A prototype of the DSSD sensor was produced for a vertex detector using 6″ FZ-Si wafers with a sensitive area of 93×63 mm. It is planned to conduct a series of tests using it.

As part of R&D for developing a track system, coordinate straw detectors, as well as electronics, were prepared and tested in the SPD test zone. Negotiations are underway with a group from Saclay (France) on their participation in the construction of Micromegas chambers, which are designed for the vertex detector for the second stage of the experiment.

In 2021, together with ITEP, prototypes of scintillating detectors for SPD BBC (beam–beam counter) with two types of electronics were tested: one with the TOT function and one developed for the DANSS experiment.

While constructing the SPD test zone, two target stations were developed and produced to place targets and detectors in the common vacuum volume of the extracted beam channel. Two control rooms were constructed. Work is underway to construct detecting and metrological equipment for low-energy and high-energy channels.

A new concept of triggerless/streaming DAQ is being developed. The possibility of developing dedicated electronics based on FPGA/ASIC and implementing commercially available industrial network solutions is under consideration.

The development of online filtering of events, algorithms for fast online event reconstruction, simulation and offline data processing was carried out in 2021 — both at the design stage of the facility and during the experiment.

Study of Polarization Phenomena and Spin Effects at JINR Nuclotron-M

As part of the work on the development of the infrastructure for spin physics studies at the Nuclotron and other complexes, a contract with STL Zaryad (Novosibirsk) was signed and fulfilled on the development of a proton polarization control system for the NICA collider, operating in two configurations of the spin transparency mode. An agreement with MIPT (Dolgoprudny) was also signed on performing an experiment to search for the electric dipole moment (EDM) of protons at the NICA collider in the spin transparency mode. The magnetic structure of the solenoids and the collider was coordinated, the resonator power was calculated, a proton polarization control system [10] and error compensation was developed, and the spin dynamics of protons was numerically simulated.

The concept of a superconducting solenoid with a static magnetic field of up to 6 T and a length of 1 m continues to be developed. It will allow the collider to operate with a polarized proton beam with an energy of up to 1.6 GeV. In 2022, together with STL Zaryad and MIPT, it is planned to develop a spin navigator to control the polarization of protons in the entire energy range of the collider at integer spin resonances, taking into account the synchrotron energy simulation [11]. Work will be carried out to optimize the parameters of the optics of the NICA collider for maximum amplification of the EDM signal, and the development of a 3D navigator based on existing correcting magnetic elements of the collider will start.

In the **ALPOM-2** project, the data previously collected on a polarized neutron beam were analyzed on the charge exchange reaction $dp \to (pp)n$ at $1.75A\,\mathrm{GeV}/c$ at the spectrometer STRELA [12]. The group's plan to continue the experiment was supported by the PAC for Particle Physics. It will ensure the leadership of JINR in the field of polarimetric equipment and research. Work is being completed to equip the ALPOM-2 setup with new drift chambers and a wide-aperture hadron calorimeter.

A proposal was prepared for a new project "Search for Polarized Phenomena at Nuclotron (**SPPN**)", based on the previously obtained results on the search for high-momentum asymptotic of spin observables of a bound np pair and the results of studying a free L-polarized np pair in the measurements of $\Delta\sigma_{L,T}(np)$. This programme also offers new up-to-date studies of the spin structure of np interactions. The implementation of the SPPN project will require equipping a polarized proton target with a cryostat and HTSP magnets to rotate the proton spins of the target from a horizontal state (L) to a vertical state (T), and constructing a vertex detector.

In the framework of the **DSS** project, the data were obtained [7, 13] on the angular dependences of the deuteron analyzing powers A_y, A_{yy} and A_{xx} of elastic deuteron–proton scattering at deuteron energies of 400–1300 MeV at the internal target. The experimental data on the angular dependences of the analyzing power A_y of the quasi-elastic proton–proton scattering reaction at energies of 200–650 MeV/nucleon were also collected.

The upgrade and adjustment of the **HyperNIS** spectrometer for searching for hypernuclei ($^{6}_{\Lambda}$H) is being completed. Work is advancing towards the development of a more efficient software programme for tracking and determining the momentum of particles. In a joint project with the Short Range Correlations (SRC) experiment, calculations and the search for optimal technical solutions for the placement of appropriate detectors are being performed.

Experiments at the Large Hadron Collider

ALICE. The main efforts of the JINR group in the data analysis and the physics simulation were focused on the study of femtoscopic correlations and the production of light vector mesons in Pb–Pb ultra-peripheral collisions (UPC) [14, 15]. In addition, the JINR group continued to participate in the maintenance and development of the GRID–ALICE analysis at JINR.

During the 1D and 3D femtoscopic correlation analyses of identical charged kaons for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, the source radii versus particle multiplicity and transverse pair momentum were studied. It is shown for the first time (Fig. 7) that kaon emission time decreases three-fold in the peripheral interactions compared to the central ones.

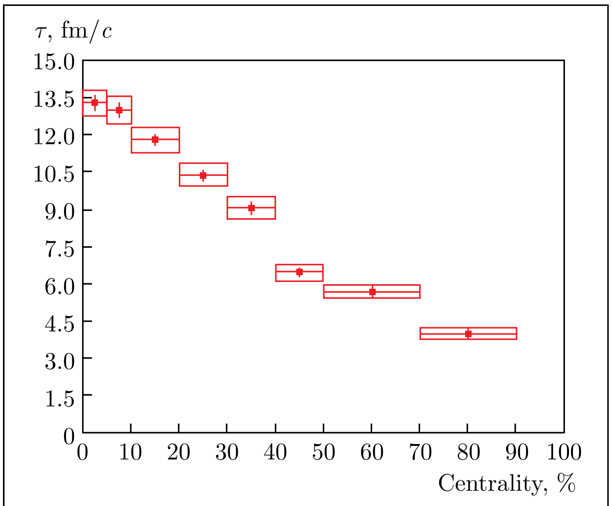

Fig. 7. Kaon emission time at different centrality

The analysis of only four pions ($\pi^+\pi^+\pi^-\pi^-$) coherent photo-production in the Pb–Pb UPC at an energy of 5.02 TeV continued. The preliminary results show that the best description of the four-pion invariant mass distribution has been obtained using two Breit–Wigner functions and interference between them. At the same time, the resonance states have masses close to the tabular ones — $\rho(1450)$ and $\rho(1700)$.

The results were published for the description by the three-component model of the transverse momentum spectra and the ratios of the hadrons produced in pp and Pb–Pb collisions at the LHC energies [16].

ATLAS. After completing the analysis of the full Run-2 dataset to search for and measure the properties of the Higgs boson decaying into a pair of b quarks and produced in association with an electroweak vector boson V (W or Z), a combined analysis was started. It integrates the $VH(\to bb)$ process, when the Higgs decay products are reconstructed as two distinct jets or as one large-radius jet, and the $VH(\to cc)$ process with the Higgs boson decaying into a pair of c quarks.

The parameters of the Monte Carlo event generator MadGraph were adjusted for $t\bar{t}$ samples with $0, 1, 2$ jets at next-to-leading order precision in QCD using the MadGraph5_aMC@NLO + Pythia8 generators and the FxFx merging scheme for $\sqrt{s} = 13$ TeV: merging scale μ_Q, strong coupling constant α_S. In addition, for parton shower setups, the effect from varying some parameters of the default A14 tune was estimated. The results obtained are consistent with the unfolded ATLAS and CMS data and the Powheg + Pythia8 generator.

CMS. Based on the full Run-2 LHC statistics in 140 fb^{-1}, the JINR group searched for the signatures beyond the Standard Model (SM) and tested its predictions [17–21]. As a result, the most stringent lower limits to date were obtained on the masses and other parameters for scenario beyond the Standard Model. Thus, upper limits are set on the ratio of the production cross section in a dilepton channel of a various spin-1 and spin-2 new resonance to that of the SM Z^0 boson at 95% confidence level. The limits are interpreted in the context of a sequential SM (SSM) and a superstring-inspired model that predict spin-1 resonances. Lower mass limits of 5.15 (4.56) TeV/c^2 are set in the $Z'_{\rm SSM}$ (Z'_ψ) models (Fig. 8). The observed upper limit on narrow spin-1 resonances is translated into the limits on generalized couplings of Z' to up and down quarks in several classes of new physics models. For spin-2 graviton resonances in the Randall–Sundrum model of extra dimensions, lower limits on the graviton mass of 2.47–4.78 TeV/c^2 are set for values of the coupling parameter $k/M_{\rm Pl}$ between 0.01 and 0.1.

For spin-1 resonances that act as a mediator between SM particles and dark matter (DM), exclusion limits are set in the mass plane of the mediator and DM particles. For large values of $m_{\rm DM}$, mediator masses below 1.92 (4.64) TeV/c^2 are excluded in a model where the mediator is a vector (axial vector) with small (large) coupling to leptons. For $m_{\rm DM} = 0$, these limits are reduced to 1.04 and 3.41 TeV/c^2, respectively.

The JINR group participated in CSC studies at the GIF++ test beam at CERN in 2021. The tests were carried out at H4 muon SPS beam line with GIF++ 12 TBq ^{137}Cs gamma source. The chamber operation in the high background conditions and with gas mixtures with different CF_4 contamination was studied. The project "Upgrade of the CMS Detector" was prepared and approved for operation in the HL-LHC configuration. The main goal of the project is the contribution to the construction of the High Granularity Calorimeter (HGCal) and the upgrade of the Forward Muon Station ME1/1. It is planned to

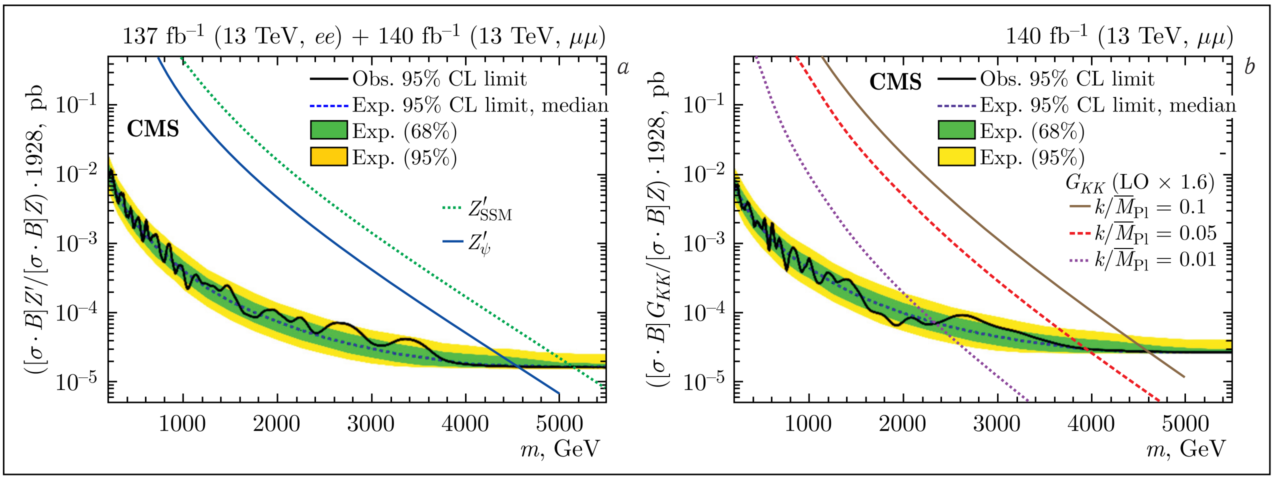

Fig. 8. The upper model-independent limits at 95% CL on the production cross section for a spin-1 (a) and spin-2 (b) resonances, relative to the product of the production cross section and the branching fraction of a Z^0 boson, multiplied by the theoretical value of 1928 pb. Simulated predictions for the spin-1 Z'_{SSM} and Z'_{ψ} resonances, as well as for the spin-2 resonances for coupling parameters k/M_{Pl} of 0.01, 0.05, and 0.10, respectively, are shown for comparison

continue the construction of the system for testing HGCal active elements in 2022. The production of the HGCal cooling panels was started.

Experiments at the CERN Super Proton Synchrotron

COMPASS. The JINR group made a significant contribution to the preparation of the setup and data taking for measurements of semi-inclusive processes using a polarized deuterium target and a 190 GeV muon beam, including support of the hadron calorimeter, the coordinate detector systems, and DAQ.

When analyzing the data, the study of transversity was performed by measuring the polarization of Λ hyperons produced in SIDIS off transversely polarized protons [22]. Within the experimental uncertainties, no significant deviation from zero was observed. When studying the spin-exotic $J^{PC} = 1^{-+}$ amplitude in single-diffractive dissociation of 190 GeV/c pions into $\pi^-\pi^-\pi^+$ using a hydrogen target [23], the $\pi_1(1600) \to \rho(770)$ amplitude was confirmed, which interferes with a nonresonant 1^{-+} amplitude. The results obtained are consistent with the basic assumptions for the isobar model for $J^{PC} = 1^{-+}$ amplitudes.

NA61/SHINE. Measurements of double-differential spectra and mean multiplicities of $\Xi(1530)^0$ and anti-$\Xi(1530)^0$ resonances produced in inelastic $p + p$ interactions were performed at NA61/SHINE [24]. The results were obtained from a sample of $2.6 \cdot 10^7$ minimum-bias events at the CERN SPS using a proton beam of 158 GeV/c momentum ($\sqrt{s_{NN}} = 17.3$ GeV). The $\Xi(1530)^0$/anti-$\Xi(1530)^0$ ratio at mid-rapidity was found to be $0.54 \pm 0.07 \pm 0.08$. Theoretical calculations within EPOS show similar values, but there are discrepancies when compared with the predictions of URQMD and the hadron-resonance gas model in the canonical formulation.

The JINR group is responsible for the upgrade of the time-of-flight (TOF) system based on a Multigap Resistive Plate Chambers (MRPC) with analog reading developed at VBLHEP. The mass production of MRPC was completed in 2021 [25]. Together with colleagues from the RAS Lebedev Physical Institute, tests of the developed MRPC with analog reading were carried out, which demonstrated stable operation and a time resolution of (51.0 ± 0.9) ps, which meets the requirements of the experiment.

NA62 (NA48/2). The NA62 experiment at CERN is dedicated to the study of a very rare kaon decay into a charged pion, neutrino and antineutrino. As part of this experiment, JINR and CERN groups are jointly responsible for the operation of the NA62 Magnetic Spectrometer and for the development of all software.

Searches for the lepton number violating decay $K^+ \to \pi^-\mu^+e^+$, and the lepton flavor violating $K^+ \to \pi^+\mu^-e^+$ and $\pi^0 \to \mu^-e^+$ decays were performed [26] using the data taken by the NA62 experiment at CERN in 2017–2018. The upper limits of the branching ratios at 90% confidence level were obtained: $\mathrm{Br}(K^+ \to \pi^-\mu^+e^+) < 4.2 \cdot 10^{-11}$, $\mathrm{Br}(K^+ \to \pi^+\mu^-e^+) < 6.6 \cdot 10^{-11}$ and $\mathrm{Br}(\pi^0 \to \mu^-e^+) < 3.2 \cdot 10^{-10}$. These results are improved by an order of magnitude over previous results for these decay modes.

Preliminary results of the $K^+ \to \pi^0 e^+ \nu\gamma$ decay analysis based on the NA62 data were presented at the conference [27]. The paper is being prepared for the publication.

The analysis of the experimental data taken in 2014–2021 is planned to be performed in 2021 for studying the following decays: $K^+ \to \pi^+\pi^-\mu^+\nu$, $K^+ \to \mu^+\mu^-\mu^+\nu$, $K^+ \to e^+e^-\mu^+\nu$, $K^+ \to \mu^+\mu^-e^+\nu$, $K^+ \to e^+e^-e^+\nu$, $K^+ \to \pi^+e^-e^+\gamma$. Work will be carried out to search for the light sgoldstio signatures. The JINR group will maintain the NA62 spectrometer straw detector during the next NA62 experimental run. The slow control system will be further improved. Software for straw modules and complete detector calibration, the DAQ system, as well as the simulation and analysis of experimental data will be developed in the future.

NA64. The JINR group taking part in the NA64 experiment is responsible for the development, construction and commissioning of coordinate detectors based on thin-walled straw tubes. It participates in the development of the software system for their online monitoring, simulation and reconstruction, and takes part in the reconstruction and analysis of data aimed at searching for the dark photon. By the start of the run in 2021, the setup had been significantly upgraded, supported by the RF earmarked grant and JINR. Straw detectors with an operating area of 20×20 cm, one of the key elements of the tracking system, were equipped with new electronics. This allowed for significantly reducing the background level, setting lower thresholds and increasing the efficiency. For the operation on the muon beam, JINR produced seven new 60×120 cm straw chambers.

During two runs performed in 2021, $\sim 7 \cdot 10^{10}$ events were collected in search of the dark A' production in the invisible mode at the electron beam energy of 100 GeV [28] and $6 \cdot 10^{9}$ events in search of the dark Z' boson to study the muon $(g{-}2)$ anomaly [29]. At present, the data collected in both runs are being analyzed. The JINR group commissioned two new large straw detector stations operating together with hadron calorimeters.

Experiments at RHIC

The participation of the JINR group in the STAR project is aimed at studying the properties of nuclear matter at extreme densities and temperatures, and phase transitions during collisions of heavy ions in a wide range of energies at the Relativistic Heavy Ion Collider (RHIC). The research programme also includes the study of the structure functions of quarks and gluons in collisions of longitudinally and transversely polarized protons.

The final run of the BES II programme in the range of 3–200 GeV was carried out in 2021. This makes it possible to study the phase diagram of nuclear matter in a wide temperature range $T_{\rm ch} = 60{-}160$ MeV and baryon densities $\mu_B = 25{-}720$ MeV. In central Au + Au collisions, a non-monotonic change in the magnitude of the product of the kurtosis coefficient and the dispersion of the distribution of the number of net-protons was detected with a change in the collision energy with a significance of 3.1σ [30].

The polarization of Ξ and Ω hyperons measured for the first time in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [31] is in reasonable agreement with a multiphase transport (AMPT) model. Studies of spin effects and structure functions of partons (PDF) continued. Although PDFs became more precise, there are still kinematic regions where more data are needed: measuring the ratio of the production cross sections of vector bosons W^+/W^-, the limits were set on PDF for sea quarks d^-/u^- [32].

EVENTS

On 15 January, the third meeting of the Cost and Schedule Review Committee of the NICA Complex Project, formed at JINR by the decision of the Committee of Plenipotentiaries of the Governments of the JINR Member States, was held. The Committee noted the outstanding progress on the NICA Project implementation in the ongoing difficult situation of the COVID-19 global pandemic. In particular, the Committee highlighted the commissioning of the Booster, the installation of MPD magnet elements, the construction of a complex of power substations, and progress in the construction of a new cryogenic compressor station.

On 19–20 April, the 7th BM@N Collaboration Meeting was held in Dubna. More than 40 reports were presented. The participants discussed the progress in the construction of detectors and plans for upgrading the facility.

On 21–23 April, the 7th Collaboration Meeting on the MPD Experiment was held in a mixed format. More than 190 senior scientists, students and engineers from all over the world — from China to Mexico — took part in the meeting. During the three days of plenary sessions, almost 50 reports were presented on the construction of MPD detector systems and physics analyses.

On 15–16 September, an International Round Table on Applied Research and Innovations at NICA was held at VBLHEP. It gathered around 300 participants from 19 countries. A Memorandum of the Round Table was adopted. The document reflects a considerable interest of the scientific community in the issues of organization of applied research at the NICA complex and the opinion of participants about a number of strategic issues on the further development of works. For further elaboration of the outlined initiatives, the NICA Project management formed an Expert Committee on Applied Research and Innovation at ARIADNA (Applied Research Infrastructure for Advanced Developments at NICA fAcility) channels.

On 3–8 October, the 8th BM@N Collaboration Meeting was held in Dubna. The meeting brought together about 100 participants from leading scientific centres, who presented 40 reports.

On 12–14 October, the 8th MPD Collaboration Meeting was held via videoconference. More than 150 participants from 15 countries attended the meeting online and in person.

On 16–17 November, the 4th meeting of the Cost and Schedule Review Committee of the NICA Complex project was held. The Committee highlighted significant advances in the launch of the Booster, the completion of civil works and the construction of cryogenic systems. The Committee also revised the deadlines and proposed to postpone the launch of the basic configuration of the complex to the end of 2023.

On 19 November, new deadlines for the implementation of the project were agreed at the 7th meeting of the Supervisory Board of the NICA Complex project.

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