JOINT INSTITUTE FOR NUCLEAR RESEARCH

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RESEARCH PROGRAMME AND MAIN 2016 RESULTS OF THE VEKSLER AND BALDIN LABORATORY OF HIGH ENERGY PHYSICS

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Dubna 2016

The activity of the V. I. Veksler and A. M. Baldin Laboratory of High Energy Physics in 2016 was focused on implementation and further development of the NICA project (the Nuclotron-NICA, MPD and BM@N subprojects) and participation in current research at the Nuclotron and in various experiments at world-class accelerator centers.

THE MOST IMPORTANT RESULTS IN THE DEVELOPMENT OF THE NICA COMPLEX

Development of the LHEP accelerator complex in 2016 was aimed at the further construction of systems and elements for the NICA complex.

During the two Nuclotron runs were carried out the works aimed both to enhance the capabilities of the accelerator complex for the current research programme, and to test the equipment and operation modes of the constructed facilities for the NICA complex parts – the booster and collider.

Very important step has been taken in 2016 in realization of the NICA as megascience project of the Russian Federation: an agreement between the Government of the Russian Federation and the Joint Institute for Nuclear Research on the establishment and operation of the Complex of Superconducting Rings for Heavy Ion Colliding Beams NICA was signed on the 27th of April 2016.

Project Nuclotron/NICA

Civil construction

In frame of the civil works carried out by the Strabag company, all preparatory works has been finished and construction of the collider ring and MPD experimental building were started (see figure 1).

Figure 1: Construction area of the future NICA complex

Injection complex for light ions and polarized beams

Substantial progress was achieved in 2016 in the modernization and development of the light ion and polarized particle injection complex:

- new RFQ pre-injector for the linear accelerator LU-20 was designed in co-operation with ITEP and MEPhI and fabricated in VNIITP (Snezhinsk). Its control and diagnostic systems were provided with participation of the specialists from INR RAS. In 2016 new pre-accelerator was put in operation and used during the Nuclotron runs [1, 2].

- Work on the commissioning of the new source of polarized ions (SPI) has been finished and the source also was put in operation. During 2016 Nuclotron runs SPI was used for production of non-polarized and polarized deuterons. Obtained beam polarization was ~70% in the vector mode and the beam intensity reached ~10^9 d/cycle [3, 4].

- The beam polarimetry system was installed, tested, and debugged in the operating mode during the 52nd and 53rd Nuclotron runs.

Figure 2: New linear accelerator and source of polarized ions

Heavy ions injection complex

Heavy ion linear accelerator (HILac) of the NICA collider injection complex which has been developed and constructed in cooperation with German company Bevatech OHG, was fully commissioned and tested in October 2016 and now is ready for operation (see figure 3). HILac is the first heavy ion accelerator of new generation in the JINR member states institutions. In particular, the high-frequency power supply system of HILac based on the solid-state transistor amplifiers of ~1MW level power. Such technical solution is used for the first time in the world. The test of the HILac properties was done with C^{2+} ion

beam obtained from the laser source (charge to mass ratio corresponds to ions of gold in the charge state of 32+). The design energy and transmission coefficient close to the projected have been obtained [5, 6].

Figure 3: Heavy ion linear accelerator of the NICA collider complex

Construction of the ESIS heavy ion source "KRION-6T" was going according to the plan. New superconducting solenoid designed to operates at the magnetic field of 6.2 T was created and successfully tested. First operation of the source in the heavy ion injection chain is planned at the end of 2017.

Superconducting Magnet fabrication and test workshop

An official ceremony of launching of the high-technology line for assembling, test and certification of superconducting magnets for the NICA booster, collider and SIS100 accelerator was held on the November 28th. 360 magnets for the NICA complex and 310 magnets for FAIR accelerator SIS100 will be prepared at the factory. The mass production of the booster magnets has been started. 100% of the yokes for the booster magnets were produced and delivered, 13 magnets were already tested. Work is going on.

Mobile Cryogenic Target

New mobile movable cryogenic targets which can be filled by the liquid hydrogen, deuterium or helium-4 was fabricated It can be used in the different experiments at the Nuclotron beams.

MPD set up

R&D works on the MPD subsystems have been almost completed. The TDR for most of the basic subdetectors has been prepared and now is under evaluation by the DAC. The

preparation for the detector element mass production is going on.

Status of the MPD magnet construction

Work is going on in frame of the contract signed between ASG Superconductiors S.p.A., Italy and JINR. The status of the subsystems readness are presented in the Table 1.

Table 1.

Type of work	Contractor	Duration	Status
Cryostat production and common supervising	JINR — ASG Superconductors S.p.A., Genova, Italy	2015-18	in progress
Consultations for Cryostat production	JINR — Neva-Magnet, St.Peterburg, Russia	2015-18	in progress
MPD Yoke production and control assembly	JINR — Vitcovice Heavy Machinery, Ostrava, Czech Republic	2016-17	in progress
Forging production for MPD Yoke	JINR — SPETSMASH, Kazan', Russia	2015-16	completed
transport system design	JINR-TSU, Tbilisi, Georgia	2016	completed

TPC status

The clean room for TPC assembly was commissioned on 30th of October. The design of assembly tooling for the TPC has been prepared and manufacture is going on. Mass production of the TPC readout chambers was started. Mass production of Read Out Chambers is going on, 4 chamber out of 24 were produced, 1 tested. FE electronics development and works aimed on the preparation of the gas, cooling and laser systems are in progress.

TOF status

The workshop for the TOF mass production has been prepared. All 28 TOF module housing was made in close collaboration with NC PHEP BSU and "Artmash" (Minsk, Belarus) and delivered. Mass production of full-scale modules for MPD TOF has been started. It is planned till the end of the year to assemble 40 mRPC for 4 modules. The total amount of modules for barrel TOF is 28. Different stages of TOF production are shown on the figure 4.

ECAL status

Significant success concerning the realization of the ECAL subsystem was obtained in 2016. In particular:

- new modification of the module was developed;
- the entities capable to produce the main ECAL elements were found;
- an Agreement between JINR and Tsinghua University was signed on the participation of Tsinghua physics group in the MPD experiment, preparation of workshop in China for the mass production of the ECAL modules for MPD and production of the first 10 test modules;
- new methods of data analysis – clusterization, reconstruction of an event and particle identification have been developed and included in the analysis software.

Figure 4: a) MRPC assembling process; b) TOF module assembling; c) Soldering of the signal cables; d) Control of MRPC quality and uniformity of gaps.

Progress with STS

Following results aimed on the development of the silicon tracker workshop were achieved during 2016 :

- serial deliveries of silicon sensors from CIS (Germany) and Hamamatsu (Japan) for the second stage of BM@N was started;
- 40 “Igolkin-type” carbon fiber non-central frames for the BM@N was produced at CERN;
- first test stand for the in-beam tests of the assembled demonstrator boards with silicon sensors was launched;
- the developing and production of jigs for module assembly was finished. Three technicians have been trained for the module assembly;
- Memorandum of Understanding about participation of CBM STS group in creation of four wide-aperture silicon stations for BM@N has been signed;
- active negotiations on the possible collaboration aimed on the creation of systems based on the innovative sensors MAPS for the ALICE and NICA/MPD were conducted with the CERN colleagues.

BM@N set up

BM@N set up - the 1st stage of the NICA project is now under preparation to data taking in 2019. Two technical runs were carried out on the extracted deuteron beams of the Nuclotron in July and December of 2016. 1st configuration of the BM@N central tracking system which includes 6 GEM stations and 1 silicon strip plane was put in operation and successfully tested during these runs. 5 GEM detectors have a size 66 x 41 cm^2 and 1 detector has size 163 x 45 cm^2, it is largest ever produced GEM detector. It is planned to equip BM@N with 6-8 more such detectors in 2017. Large drift chambers, small-angle calorimeter, elements of TOF system for the hadron identification, detectors for beam profile and structure measurement as well as the triggering system and integrated DAQ system were commissioned during 2016 (see figure 5).

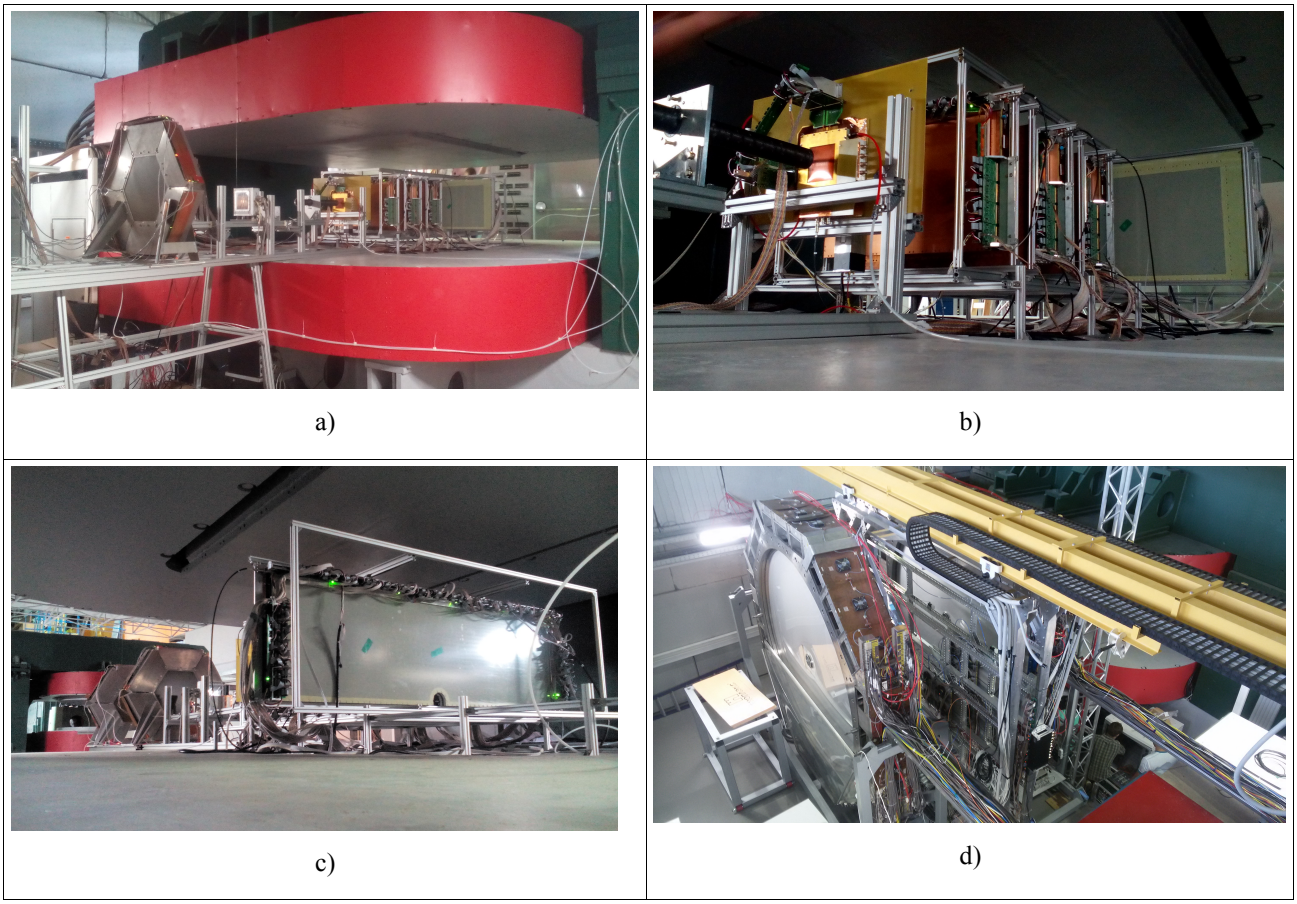

Figure 5: Different views of the BM@N setup during 2016 runs.

EXPERIMENTS CARRIED OUT AT NUCLOTRON DURING THE 2015 RUNS

DSS

In frame of the DSS experiment the following results have been obtained in 2016:

- the upgraded version of the polarimeter was put in operation at the internal target. Determination of the beam polarization based on the measuring of the asymmetry in the deuteron-proton elastic scattering has been commissioned during the 52nd (June 2016) run at Nuclotron.
- The analysis of the experimental data on the angular dependence of the cross sections of elastic deuteron-proton scattering at deuteron energies of 1300 and 1400 MeV obtained at internal target has been performed. Preliminary results were reported at international conferences.
- Data for the deuteron-proton non-mesonic breakup in coplanar geometry at an energy of 400 MeV obtained at internal target has been proceeded. Preliminary results were reported at international conferences.

- The theoretical calculations for the interpretation of the obtained experimental data on deuteron-proton elastic scattering have been performed within framework of the relativistic multiple scattering model taking into account the excitation of delta-isobar in the intermediate state.

Alpom-2

The measurements of analyzing powers in the reaction p + CH_2 and n + CH_2 in the energy range up to 7.5 GeV/c and 4.5 GeV/c, respectively were performed during the Nuclotron runs. Results on the neutron asymmetry were obtained for the 1st time (see figure 6).

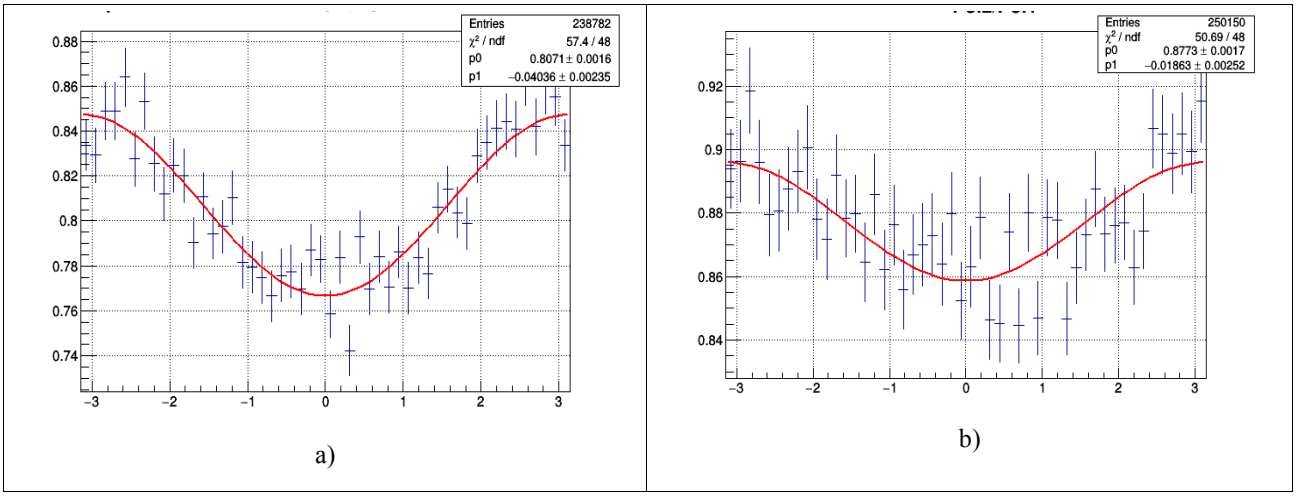

Figure 6: Proton (a) and neutron (b) asymmetry.

PARTICIPATION IN EXPERIMENTS AT EXTERNAL ACCELERATORS

Experiments at the Large Hadron Collider

ALICE

New results of the 1D femtoscopic correlation analysis for K^+K^- pair production in Pb-Pb collisions at 2.76 TeV (per nucleon pair) were obtained and compared with the prediction of R.Lednicky and V.Luboshitz (Sov. J.Nucl.Phys.35,1982**).** Figure 7.a shows the typical correlation function for K^+K^- pair productions. The curve is the fit with Lednicky-Lyuboshitz formula and describes well the data including ϕ meson peak. Figure 7.b shows the source radii of K^+K^- pairs and of identical kaons ones versus pair transverse momentum, k_T. The good agreement between two different methods is seen [7, 8].

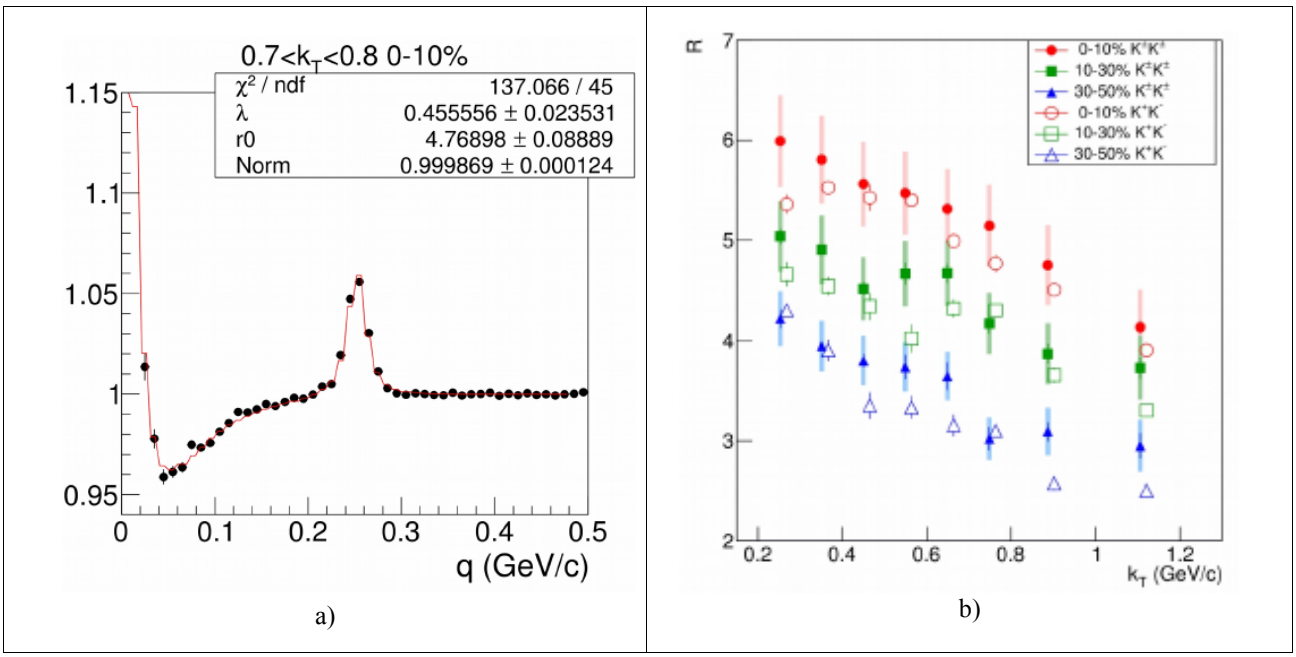

Figure 7: a) Correlation function of K^+K^- pairs. The curve is Lednicky-Lyuboshitz prediction b) The source radii versus k_T.

New results were obtained with the JINR team participation for the J/ψ and ρ^o production in ultraperipheral Pb-Pb collisions (UPC) at 5.02 TeV. The J/ψ resonance peak was studied and cross section was obtained taking into account the background [9, 10].

The tests of the modules of the PHOS ALICE electromagnetic calorimeter were performed in beams of electrons at PS and SPS CERN accelerators in the energy range of 1 - 160 GeV. This study aimed to make the optimal choice for the upgrade of photodetectors and readout electronics. The goal of the upgrade is to provide the calorimeter functioning at the room temperature without the worsening of the energy resolution and the improvement of the time resolution. Currently PHOS is running at the temperature of -28 C° and has the time resolution of σ_t = 4-5 ns.

Silicon photomultipliers area of 6x6 mm^2 (four parallel connected 3x3 mm^2 size SiPM) showed some energy resolution worse than APD 10x10 mm^2, but significantly better than APD 5x5 mm^2. Increased SiPM area twice would get the same resolution as the 10x10 mm^2.

The time resolution for SiPM is σ_t = 0.15 ns to energy of 1 GeV. It is possible to use two SiPM as photodetectors, one for the range 0 to 10 GeV, the other for the range 10 - 160 GeV.

CMS

In 2016 the JINR group has taken part in data taking, processing and physics analysis of data collected during the LHC run with the proton beams at energy of 13 TeV and the luminosity up to 1.52×10^{34} sm^{-2} s^{-1}. The new limits on the masses of new dilepton resonances were obtained from 2015 data, 95% CL lower limit on the masses of spin-1 Z' of sequential standard model (SSM) is 3.37 TeV. The preliminary results of 2016 in the dimuon channel with an integrated luminosity of 13 fb^{-1} extend this limit up to 3.75 TeV.

Experiments at the CERN Super Proton Synchrotron

COMPASS

With considerable participation of the JINR group the multiplicities of charged pions and unidentified hadrons produced in deep-inelastic scattering were measured by the COMPASS. Data were obtained with 160 GeV muon beam and an isoscalar target (^{6}LiD). Precise measurements of charged kaon multiplicities in deep inelastic scattering were performed and published [11]. This data cover the kinematic domain 1 $(GeV/c)^2 < Q^2 < 60$ $(GeV/c)^2$ in the photon virtuality, $0.004 < x < 0.4$, $0.1 < y < 0.7$, $0.20 < z < 0.85$, and $W^2 > 5$ $(GeV/c)^2$ in the invariant mass of the hadronic system. The results from the sum of the z-integrated K+ and K− multiplicities at high x point to a value of the non-strange quark fragmentation function larger than obtained by the earlier DSS fit (see figures 8.a and 8.b).

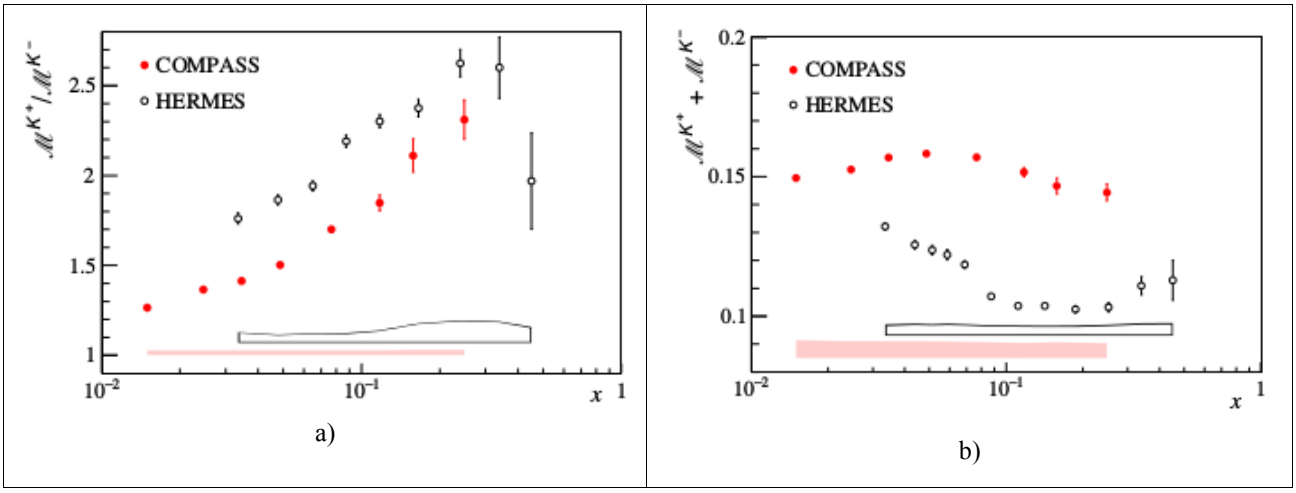

Figure 8: a) Ratio of z-integrated multiplicities, M^{K+}/M^{K-}. b)Sum of z-integrated multiplicities, $M^{K+} + M^{K-}$. COMPASS data (full points) are compared to HERMES data (open points).

One of the main achievement of the JINR group in 2016 is a completion of works on assembly and installation of a new electromagnetic calorimeter (ECAL0) into the COMPASS set-up (see figure 9). This calorimeter, suggested and developed at JINR, is a unique device of the "shashlyk"-type (scintillator, lead), in which the most advanced photodetectors – Micro-pixel Avalanche Photo Diodes (MAPD) with ultra-high pixel density (up to 15 thousand pixels / mm^2) were used, instead of the traditional photomultiplier tubes.

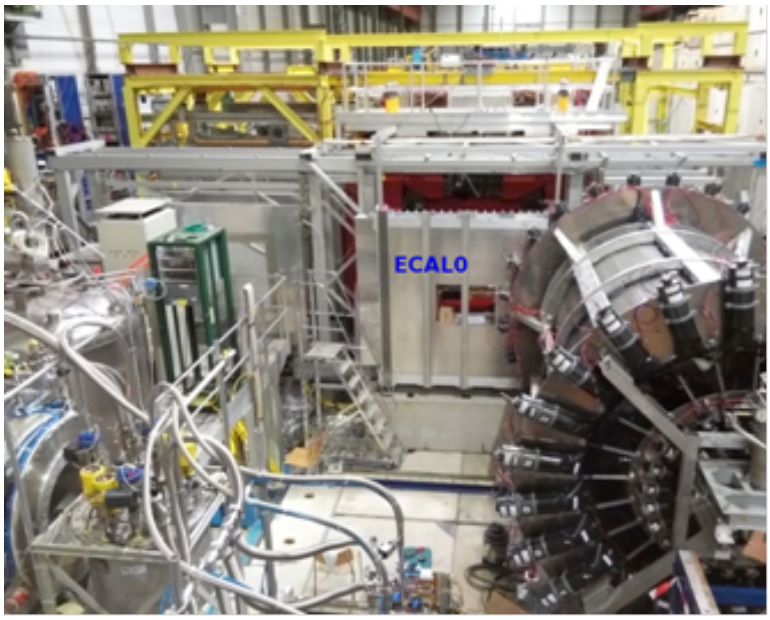

Figure 9: ECAL0 in the COMPASS setup.

NA61/SHINE

A group of the VBLHEP of JINR was responsible for processing and analysis of the experimental data on light nuclei production in central Pb+Pb interactions. During the data taking transverse momentum spectra, rapidity distributions and particle ratios were measured. Result of data analysis shown that an obtained yields are compared to predictions of statistical models. Obtained phase-space distributions of light nuclei were compared to those of protons in the context of a coalescence approach. The coalescence parameters B_2 and B_3, as well as coalescence radii for *d* and ^{3}He were determined as a function of transverse mass at all energies [12].

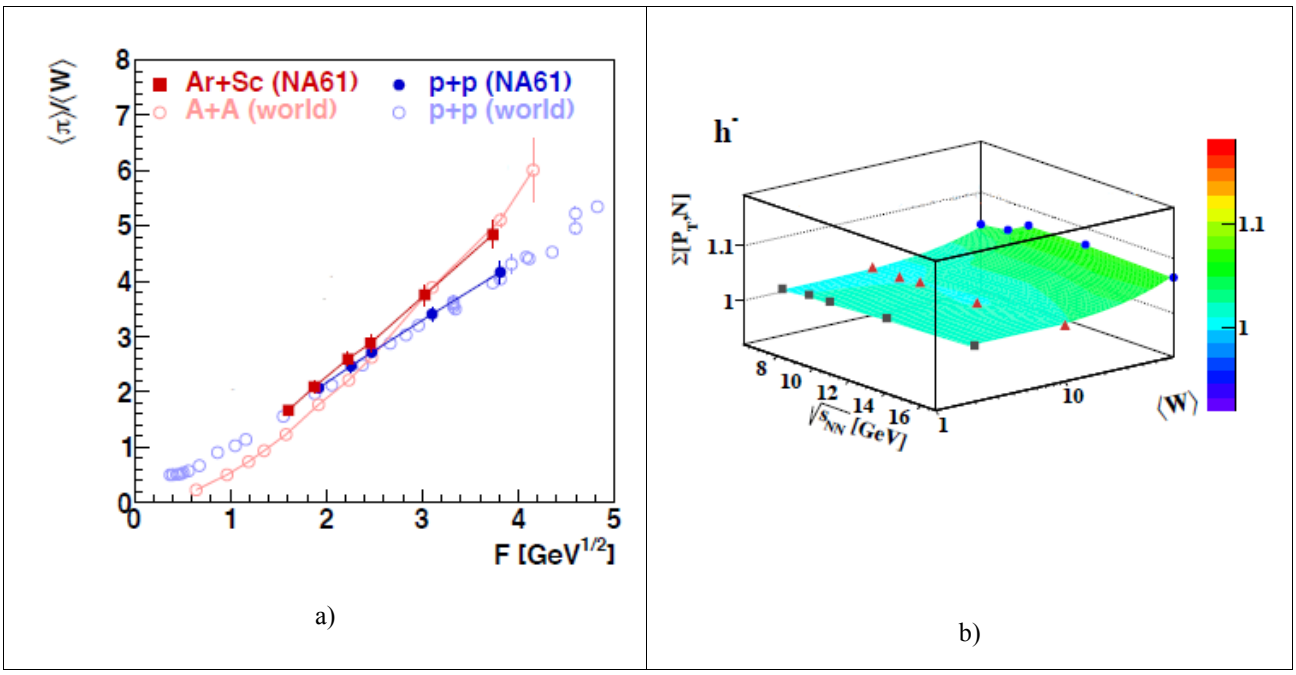

Figure 10: a) Kink plot: mean pion multiplicity divided by mean number of wounded nucleons as a function of Fermi collision energy measure F. b) Σ[P_T, N] in inelastic p+p (grey squares), 0-5% Be+Be (red triangles), and 0-5% Ar+Sc (blue circles) collisions obtained by NA61/SHINE at forward-rapidity, 0 < y_π < y_{beam}, and in p_T < 1.5 GeV/c.

Detailed study of fluctuations in *p+p*, *Be+Be* and *Ar+Sc* collisions for critical end-point search is in progress (see figure 10). Transverse momentum fluctuations in observed interactions show no structures which could be related to the critical point [13].

Experiments at the Relativistic Heavy Ion Collider, BNL

STAR

The JINR team of the STAR collaboration takes part in the analysis of the BES-I data. The original method of data analysis has been suggested and exploited for search for new phenomena in nuclear matter created in heavy ion collisions. The preliminary STAR data, which are shown in figure 11cover a wide kinematical and dynamical range of particle production, collision energy $\sqrt{s_{NN}}$ = 7–200 GeV, centrality of collisions 5 %–80 % and momentum range p_T = 0.2–12 GeV/c.

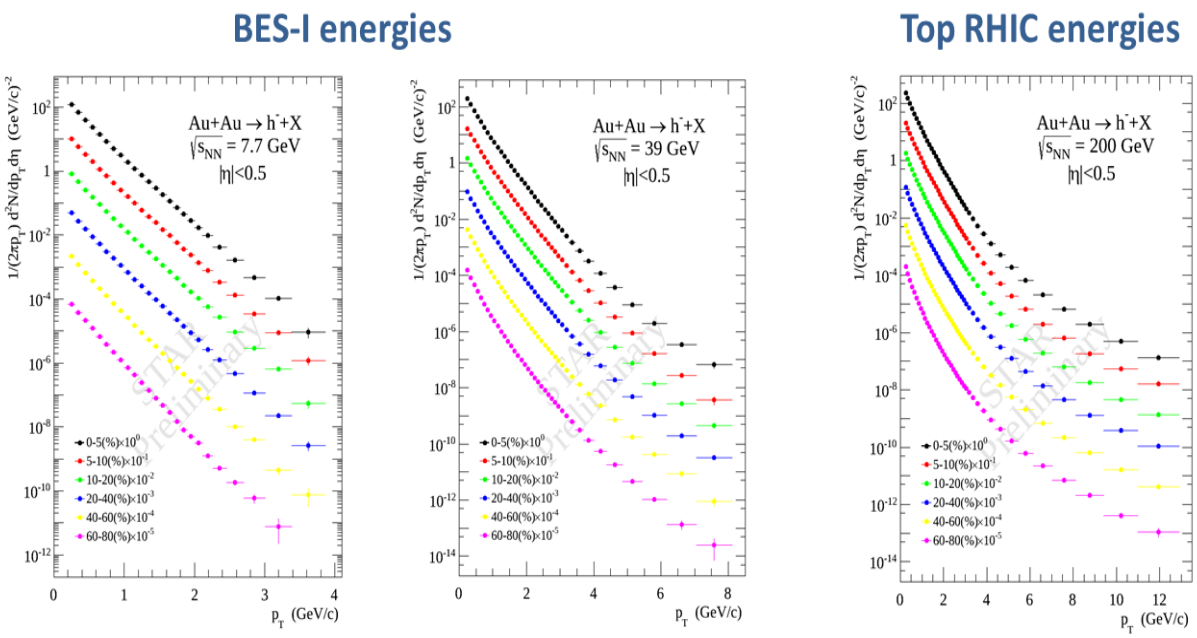

Figure 11: Transverse momentum distribution of negative charged particles production at BES energies 7.7, 39 and 200 GeV as a function of centrality

As it seen from figure 11 the data demonstrate strong energy and centrality dependence of spectra, exponential behavior of the spectra at low p_T and energy $\sqrt{s_{NN}}$, a power behavior of spectra at high p_T and energy $\sqrt{s_{NN}}$. One observes that difference of yields at various energies strongly increases with transverse momentum.

New very important results has been obtained with an active participation of the JINR group in the measurement of interaction between antiprotons. Antiproton pair correlations obtained by the STAR experiment with gold ions at 200 GeV per nucleon were analysed [14]. Results show the attracting nuclear force between two anti-protons. The measurement of the two key parameters that characterize the corresponding strong interaction, namely, the scattering length (f_0) and effective range (d_0) are presented in figure 12. As a direct knowledge from the interaction between two anti-protons, the simplest system of anti-nucleons (nuclei), this result provides a fundamental ingredient for understanding the structure of more sophisticated anti-nuclei and their properties.

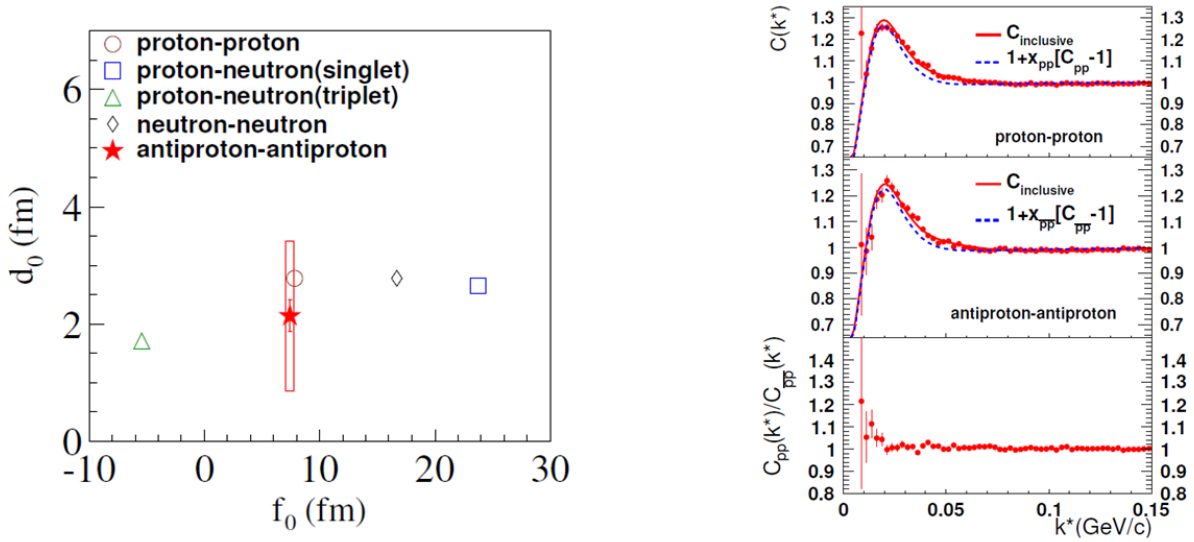

Figure 12. Correlation functions of $N-N$ *and* $\overline{N}-\overline{N}$ *pairs.*

Experiments at FAIR

CBM

In the framework of the CBM-project preparation the following t results have been obtained in 2016:

- The simulation for the central and peripheral Au+Au interactions at the energy of 4 AGeV aimed on the study of the light nuclear fragments (deuterons, tritium, etc.) coalescence has been performed.
- The simulation for the vector meson decays using “vector-finding” approach to reconstruct the tracks of muons in the MUCH CBM has been continued.
- The radiation tests of silicon photo-detectors from various manufacturers (Ketek, Zecotek, Hamamatsu) and registering electronics for the centrality and reaction plane determination the CBM detectors have been performed.

EVENTS

Signing of the agreement between the Moscow region and JINR and the first stone laying ceremony for the mega-Science NICA project

An agreement on cooperation between the Government of the Moscow region and the Joint Institute for Nuclear Research was signed on 25 March in VBLHEP. The agreement was signed by the Governor of the Moscow region A.Yu.Vorobev and JINR Director Academician V.A.Matveev.

International Session-Conference of SNP PSD RAS "Physics of Fundamental Interactions"

From 12 to 15 April 2016, the Section of Nuclear Physics of the Physical Sciences Division of the Russian Academy of Sciences (SNP PSD RAS) and the Joint Institute for Nuclear Research (JINR) was held at JINR, an International Session-Conference of the SNP PSD RAS "Physics of Fundamental Interactions".

The Programme of the Session-Conference covered basic theoretical and experimental aspects of particle physics and related problems in nuclear physics, astrophysics and cosmology.

The NA62 International Collaboration Meeting

The NA62 International Collaboration Meeting was held in the VBLHEP on 22–27 August 2016. The meeting was held annually in one of 32 institutions, representing 12 countries participating in the collaboration. More than 60 experts visited the meeting in Dubna; they were discussing the most pressing issues faced by the collaboration and made outline plans for its activities in the short and medium term. One day of the workshop was set for the meeting of the Steering Committee of the collaboration.

Baldin seminar

The XXIII International Baldin Seminar on High Energy Physics Problems “Relativistic Nuclear Physics and Quantum Chromodynamics”, named “Baldin Autumn”, was held on 19-24 September 2016 in the Big Conference Hall of the Laboratory of High Energy Physics JINR. Since this year is the 90th anniversary of Alexander Mikhailovich Baldin, the Seminar was dedicated to his memory.

The seminar gathered a record number of participants – 250 physicists from 22 countries. There were presented 157 reports, 57 from which were presented at the plenary sessions and 100 – on parallel sections. The reports covered the research results of the most of the world leading physics centers, such as CERN, GSI (Germany), BNL (USA) and many others. The seminar was also supported by the RFBR grant and the grant of the JINR Director. There were a lot of young scientists. More than a quarter of participants were aged less than 35.

Perspectives of Experimental Research at the Nuclotron beams

The 4th International Workshop of the Nuclotron Beam Users «Perspectives of Experimental Research at the Nuclotron Beams» was held on 6 October 2016 in the VBLHEP.

The present status and prospect of the Nuclotron facility which provides unique possibilities for investigations at relativistic ion beams in the kinetic energy range from hundreds of MeV to several GeV per nucleon were discussed.

After reports, on the milestones of the general discussion, representatives of the JINR Member States and consumers of the Nuclotron beams approved the resulting document of the Workshop, determining the development of the user policy and development of the accelerator complex in the nearest future.

BIOMAT

The International Workshop on Biophysics and Materials at NICA «BIOMAT» was held on 12-13 December 2016 in the VBLHEP for the first time. It was dedicated to applied research at the NICA complex. This was initially pertinent to radiobiology, ion beam interactions with materials, and exposure of electronic components, testing of electronic components for space applications. The seminar gathered 60 participants from Belarus, Germany, Egypt, Italy, Poland, the Czech Republic, and Russian research centers. Opportunities for joint research were discussed in the roundtable format.

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