MESHCHERYAKOV LABORATORY of INFORMATION TECHNOLOGIES

The activity of the Meshcheryakov Laboratory of Information Technologies (MLIT) in 2025 was focused on ensuring the reliable functioning and growth of the JINR network, information and computing infrastructure within the large research infrastructure project 06-6-1118-2014/2030 “Multifunctional Information and Computing Complex” (MICC), as well as on developing mathematical support and software for the research and production activities of the Institute and the JINR Member States (project 06-6-1119-1-2014/2026 “Mathematical Methods, Algorithms and Software for Modelling Physical Processes and Experimental Facilities, Processing and Analyzing Experimental Data” and project 06-6-1119-2-2024/2026 “Methods of Computational Physics for the Study of Complex Systems”). A distinctive feature of ongoing research directions is close cooperation with all the laboratories of the Institute, institutes of the JINR Member States and other countries.

In 2025, the MLIT staff published over 200 scientific papers, 4 monographs, and more than 150 articles within international collaborations, and presented over 150 reports at international and Russian conferences.

In 2025, MLIT held two important events dedicated to the memorable dates of the Laboratory’s founders: the 115th anniversary of M. Meshcheryakov’s birth and the 95th anniversary of N. Govorun’s birth, which was marked by the publication of an album book about N. Govorun. In addition, the 11th International Conference “Distributed Computing and Grid Technologies in Science and Education”

17 September. MLIT Deputy Scientific Leader T. Strizh delivers a report at a memorial seminar in honour of the 115th anniversary of the birth of M. Meshcheryakov

(GRID'2025), the Quantum Computing and Machine Learning Workshop (QCML), the scientific and practical seminar "HybriLIT Workshop 2025: Towards Efficient Scientific Computing", as well as the traditional JINR IT School, took place, and the Conference on High Energy Physics (CHEP-Yerevan'2025) was held with the participation of MLIT.

MULTIFUNCTIONAL INFORMATION AND COMPUTING COMPLEX OF JINR

The Multifunctional Information and Computing Complex (MICC) represents a key element of the computing infrastructure and plays a decisive role in scientific research that entails advanced computing power and data storage systems. The MICC is an intricate hardware and software complex, the major components of which are the energy supply and climate control engineering systems, the network infrastructure, the data transfer and storage system, the Tier1 and Tier2 data processing grid centres, the cloud infrastructure, the HybriLIT platform, including the Govorun supercomputer, and the monitoring system for all components of the complex. In 2025, to attain the main objectives of JINR flagship projects, the high performance, reliability, and availability in 24 × 7 × 365 mode of all MICC components were ensured.

The Tier1 grid site for the CMS experiment at the LHC was ranked second among seven similar sites worldwide. Tier2/CICC provided the comprehensive processing and analysis of data obtained within the experiments at the LHC, NICA, and in other large-scale scientific projects. Particular attention was paid to support for users from the JINR laboratories and Member States, providing them with indispensable computing resources and tools for work with data. The cloud environment of JINR and its Member States was mainly used for computing within the JINR neutrino programme, which enabled the effective solution of complex problems related to neutrino data analysis. The Govorun supercomputer was employed to perform massively parallel and resource-intensive computations, as well as calculations using artificial intelligence methods within the ML/DL/HPC ecosystem.

JINR Network Infrastructure

The network infrastructure deployed within the MICC project is a central element that ensures external telecommunication channels, communication between MICC users through the JINR local area network, and data exchange within the MICC local area network.

In 2025, the reliable operation of the Moscow backup channel with a bandwidth of 4 × 100 Gbps was ensured. To operate a Tier1 grid site that meets the highest standards of performance and reliability, one must be a full member of the LHCOPN (Large Hadron Collider Optical Private Network) to seamlessly communicate with Tier0 (CERN) and the other Tier1 sites. This connection is provided by the 100 Gbps JINR–CERN direct channel and its 100 Gbps backup channel passing through Moscow and Amsterdam, ensuring fault tolerance and data transmission continuity. The JINR Tier2 connectivity is effectively supported by the LHCONE (LHC Open Network Environment) external overlay network designed for Tier2 grid sites and optimized for their data transfer needs. The National Research Computer Network of Russia (NIKS) provides communication with Russian scientific and educational organizations, as well as integration with individual foreign National Research and Education Networks (NRENs) and the Internet.

In 2025, the overall incoming traffic amounted to 64.14 PB, which is 51% more than in 2024, and the outgoing traffic grew by 13% compared to last year. This increase is due to the growth in transferring data for processing and storage on Tier1. The traffic with the scientific and educational networks, accounting for 88% of the total, is overwhelming. The distribution of the incoming (exceeding 25 TB) and outgoing traffics by the JINR subdivisions in 2025 is shown in Table 1.

Table 1

Subdivision	Incoming traffic, TB	Outgoing traffic, TB
MLIT	1070.0	180.46
VBLHEP	558.29	223.37
HRC	520.92	145.28
DLNP	353.25	120.38
JINR Directorate	190.1	89.69
FLNP	187.27	59.71
FLNR	185.47	35.43
Dubna State University	160.59	55.93
Medical Unit No. 9	120.28	18.7
Public Access Servers	95.52	94.89
Remote Access Node	78.64	11.56
UC	75.93	10.48
BLTP	44.85	29.85
SIMO	39.71	8.06
LRB	39.16	3.33
CPED	29.42	2.62

The local area network (LAN) is built on the JINR backbone network (2 × 100 Gbps) and the distributed multi-node cluster network between the DLNP and VBLHEP sites (4 × 100 Gbps). This ensures the reliable transfer of physics data from the NICA complex for its subsequent processing and analysis on the MICC components.

Throughout the year, the e-mail service processed 4.7 million incoming messages and 950 thousand outgoing messages. The average message processing time was 3.4 s.

In 2025, over 1600 JINR user requests concerning the operation of the network and services were processed. Security checks for incoming e-mails from the @jinr.ru domain were significantly enhanced, and hundreds of new filters were added. The functioning of approximately 30 servers and virtual machines was supported, and over 820 network devices were monitored. About 50 incidents of network security violations were identified and processed.

The JINR LAN comprises 14 328 network elements, 23 746 IP addresses in IPv4 format, 1490 IP addresses in IPv6 format, 5933 users (including 5376 JINR staff members), 5083 @jinr.ru e-mail addresses, 1151 users of electronic libraries, 1021 users of the remote access service, and 171 users of the EDUROAM service. The registration procedures were supplemented with support for new user categories, namely, associated personnel and students.

MICC Engineering Infrastructure

In 2025, work on the replacement and enhancement of the MICC engineering infrastructure, designed to ensure the reliable, uninterrupted, and fault-tolerant operation of information and computing systems and data storage resources, was in progress. During the year, work to install new servers of various configurations and network switches was performed.

At present, the MICC computing facilities are placed in one computing hall of 900 m^2 of floorspace on the 2nd floor of the MLIT building. In 2025, a substantial upgrade of the engineering infrastructure of two modules, related to the transition to the cooling of the cold corridor by inter-row air conditioners, was carried out.

JINR Grid Environment (Tier1 and Tier2 Sites)

In 2025, the successful operation of the JINR grid sites continued. Both grid sites provided data processing and analysis within JINR's participation in the LHC projects at CERN, as well as tasks on modelling, processing, and storing data from the BM@N, MPD, and SPD experiments at the NICA accelerator complex.

The JINR grid environment comprising the Tier1 (JINR-T1) and Tier2 (JINR-LCG2) sites ensures the functioning of the computing complex, the data storage system, grid services, the data transfer service, and the information service (monitoring of servers, storage, data transfer, information sites).

The key task of the year was the migration of the Tier1 and Tier2 computing resources to the AlmaLinux 9.6 operating system (OS) due to the end of the life cycle of CentOS 7. For the mass transfer of compute nodes, a fully automated reinstallation pipeline was developed and implemented. During October–November, 629 of the 920 nodes were successfully migrated. Additionally, a tool for exporting and validating node configurations was created.

In 2025, the performance of Tier1 was enhanced by 32%, and it currently embraces 468 compute nodes (23 360 cores) with a performance of 427.92 kHS23. Data storage is provided by the 15 PB dCache system and the robotic tape storage with a capacity of 100 PB. To work with tapes, a 2.24 PB disk array is used to cache data.

Top view of upgraded Modules 1 and 2, transferred to the cold corridor cooling with inter-row air conditioners, in the MICC machine hall

In 2025, the JINR Tier1 site took second place in terms of the number of events processed (Fig. 1) and the total normalized CPU and actual time for data processed in the ranking of world Tier1 sites that process data from the CMS experiment at the LHC (Table 2) according to the statistics available at https://accounting.egi.eu.

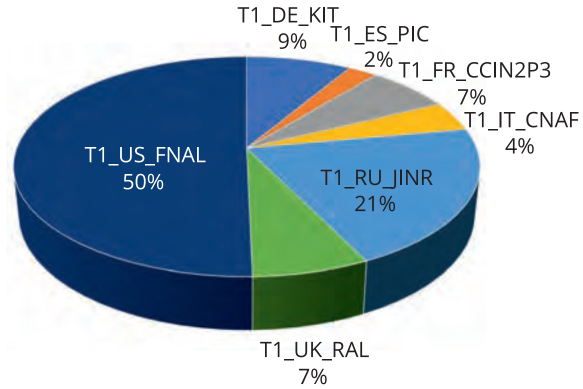

Fig. 1. Distribution of events processed in 2025 on the world Tier1 sites of the CMS experiment at the LHC

Table 2

Tier-1	Total CPU time (kHS23 h)	Total actual time (kHS23 h)
US-FNAL-CMS	4 089 705.009	4 920 606.964
RU-JINR-T1	2 106 701.086	2 871 833.526
UK-T1-RAL	1 347 308.725	1 671 293.034
DE-KIT	1 247 756.876	1 448 471.493
ES-PIC	1 232 820.775	1 266 032.136
FR-CCIN2P3	943 818.023	1 066 548.004
IT-INFN-CNAF	642 358.043	900 642.478

As in previous years, the JINR Tier1 site performed the tasks of modelling and processing data from the BM@N, MPD, and SPD experiments at NICA (Fig. 2).

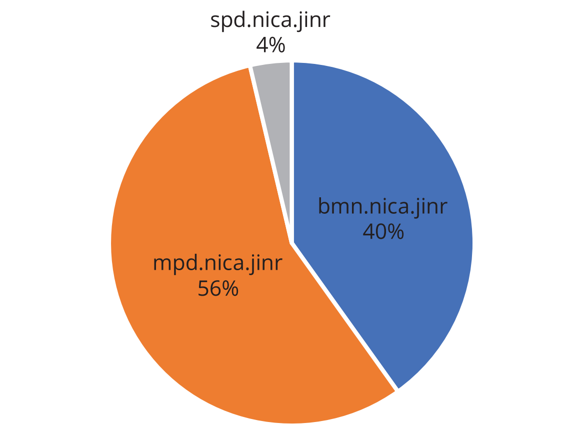

Fig. 2. Distribution of the normalized CPU time by tasks of the BM@N, MPD, and SPD experiments on the JINR Tier1 site

The Tier2 site embraces 485 compute nodes (10 356 cores) with a total performance of 166.8 kHS23. Data storage is provided by the 4.84 PB dCache system for the CMS and ATLAS experiments and the 1.5 PB EOS-Alice system.

The Tier2 site, which in 2025 remained virtually the only one receiving tasks from the Russian grid segment (RDIG), completed over 5 million tasks, which amounted to 99.92% of the total RDIG CPU time (Fig. 3).

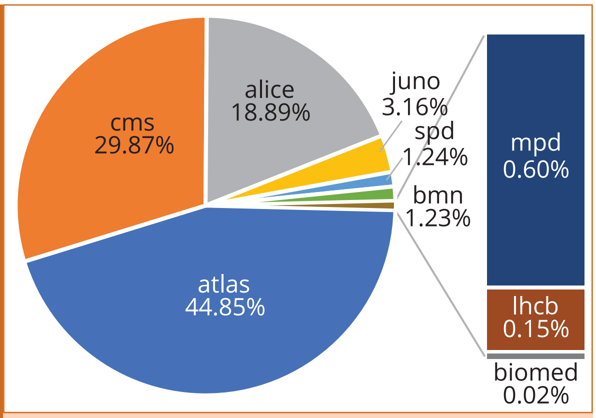

Fig. 3. Distribution of the normalized CPU time by experiments registered on the JINR Tier2 site

A prototype of a distributed environment for modelling, processing, and analyzing SPD experiment data is developed on the PANDA software. The primary contribution to the functioning of the distributed data processing and storage environment for the SPD experiment is made by the JINR MICC, providing the Tier1/Tier2 resources, a certification centre, the EOS storage, and cloud service machines that host all control services of the experiment [1]. In 2025, two new centres, namely, at Samara University and SPbSU, joined computing. Throughout the year, over 1 billion Monte Carlo events with a total volume of approximately 500 TB were generated. To manage the formation of centralized processing tasks, a specialized system containing an interface for submitting tasks to the distributed computing environment was developed and put into operation. In 2025, the experiment received a dedicated 7 PB EOS storage system, to which all of the experiment's data was transferred over the summer. In addition, virtual machine monitoring systems and data processing and management systems were put into operation, the IAM (Identity and Access Management) authorization service was integrated with data storage systems, and a new user authentication method using JWTs (JSON Web Tokens) without the use of X.509 certificates was tested.

Work to create a specialized computing system, SPD OnLine Filter, is underway [2]. A methodology for middleware integration testing was elaborated and implemented, allowing all systems included in the software complex to work together. A system that enables the effective emulation of data taking from the SPD data acquisition system (SPD DAQ Emulator) was developed.

Since 2019, a distributed heterogeneous computing environment based on the DIRAC platform has been functioning. Resource integration within this environment is based on standard data access protocols (xRootD, GridFTP, etc.) and pilot tasks. Thanks to this, the user is provided with a unified environment for launching tasks, managing data, building processes, and monitoring their execution.

In 2025, a mass data transfer system using DIRAC tasks was implemented. The developed approach enabled transfer rates of up to 10 Gbps. Moreover, it became possible to transfer data to storage systems accessible only locally. FTS (File Transfer Service) was integrated into the DIRAC platform, making it possible to transfer large data volumes between storage entities and efficiently copy data from CTA (CERN Tape Archive) tapes to disks.

A set of tools to analyze the mapping between the DIRAC file directory and storage systems accessible via the root protocol was developed. It enables the automated deletion of files and directories that are not listed in the file directory. The developed toolkit also allows aligning file and directory structures between the file directory and local storage systems. A new approach to visualizing the directory and file structures of experiments using the DIRAC file directory was implemented.

In total, 600 thousand computational tasks with an overall duration of 408 astronomical years or 3.68 MHS06 days were completed in 2025. The major users of the DIRAC computing resources in 2025 were the BM@N and MPD experiments (Fig. 4). With the discontinuation of the VOMS service, the SPD experiment ceased using DIRAC at JINR.

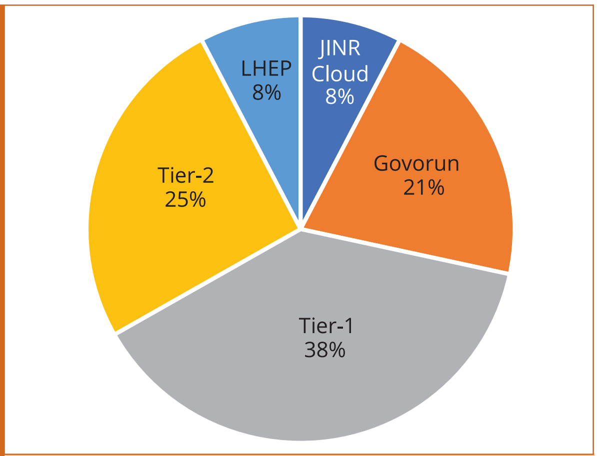

Fig. 4. Share of use of various components of the MICC and cluster at VBLHEP in a distributed heterogeneous environment based on the DIRAC platform

Heterogeneous Infrastructure

In 2025, the HybriLIT platform, which is a component of the JINR MICC designed to conduct massively parallel and resource-intensive calculations, as well as research using artificial intelligence methods and approaches, was actively evolving [3]. The next stage of modernization of the Govorun supercomputer was completed. The computing resources of the supercomputer's GPU component were enhanced by integrating two new compute nodes on top of the unique RSC Exastrim AI server solution with liquid cooling. These nodes were created specifically for the Govorun supercomputer considering its architectural features. Each node contains eight NVIDIA H100 graphics accelerators. As a result, the peak

17 September. A delegation from the INPhE MEPhI Department visited JINR to discuss personnel training for the Institute's laboratories and research projects

performance of the GPU component of the Govorun supercomputer grew by 36%, reaching 1.4 PFlops for double-precision operations, and the supercomputer's total capacity amounted to 2.2 PFlops for double-precision operations and 58 PFlops for half-precision calculations for artificial intelligence tasks.

In 2025, the software and information environment of the HybriLIT platform was supplemented with a new service designed to evaluate the efficiency of utilizing the supercomputer's computing resources (http://hlit.jinr.ru/accounting_and_statistics_processing_systems/). The service enables performance monitoring, the accumulation and analysis of computing resource usage statistics for different user groups, as well as the identification of resource usage trends. To control sorting in the system's elements, selectors that allow sorting data by year and compute queue or by both parameters simultaneously are available (Fig. 5). The new service is built on the Yandex DataLens Business Intelligence system. The data source for the service is the SLURM task scheduler database.

Within a joint project between MLIT, BLTP JINR, and FBHI "Medical Unit No. 9" of FMBA of Russia, a polygon for working with medical data from computer, magnetic resonance, and functional magnetic resonance imaging for the DICOM and Nifti formats was deployed in the JupyterLab environment on the basis of the ML/DL/HPC ecosystem (http://hlit.jinr.ru/polygon-ct-mri/). To visualize medical data, the PyDicom, Nipype, and PySurfer libraries, allowing for the construction of 3D images of the human brain, were installed on the polygon. The polygon is designed for the testing of various visualization software packages and software development to implement a new mathematical approach to image reconstruction.

The regular maintenance of all components of the HybriLIT platform, including the Govorun supercomputer, was carried out. For the compute queues of the Govorun supercomputer for various user groups, queues were reconfigured to meet current user needs, data Storage-on-Demand systems were created and modified, and queues were maintained

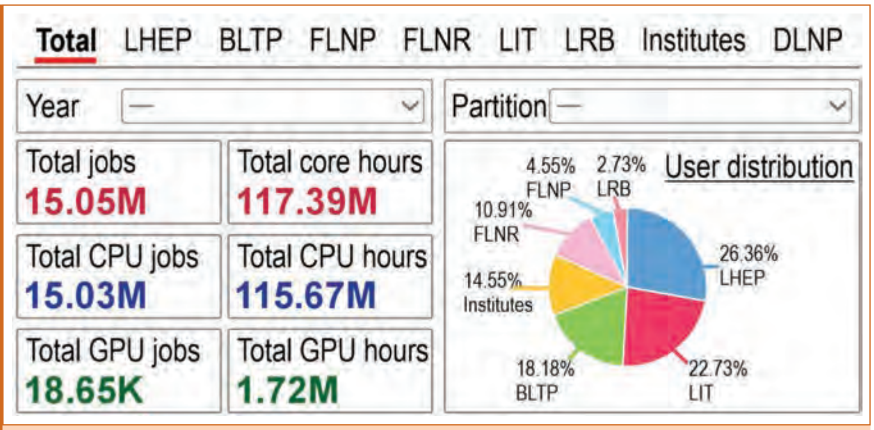

Fig. 5. The Govorun supercomputer accounting system. A main page element

25–26 November. The HybriLIT Workshop 2025 in working order; i.e., the operation of compute nodes and services was checked and promptly restored. Additionally, within the transition of the platform to AlmaLinux OS 9.6, work to install and configure the XCAT software product, designed for quickly deploying and configuring the operating system on the compute node, was completed, and settings for virtual machines (platform user interfaces) were prepared. The total number of Govorun supercomputer users is currently 357. Throughout 2025, approximately 6.8 million tasks were executed, which corresponds to 34 million core hours.

Cloud Infrastructure

In 2025, work on developing the JINR cloud infrastructure, which is a universal component of the MICC designed to provide computing resources and host information and computing services, was underway. The Institute's scientific projects, particularly the Baikal-GVD and JUNO neutrino experiments, as well as the NICA experiments, were the primary and most resource-intensive consumers of these resources (Fig. 6). At the same time, the service is institute-wide and is used by a vast range of users. During the year, resources were provided to over 100 active users, supporting the operation of 857 virtual machines that utilize a total of 5472 CPU cores. The HTCondor batch cluster with a number of grid services that comprise the Neutrino Computing Platform (NCP), the git.jinr.ru collaborative software development service, the jupyter.jinr.ru interactive programming environment, and the newdle.jinr.ru, webanalytics.jinr.ru, and docs.jinr.ru information and application web services were operated and supported in the cloud infrastructure.

One of the uppermost areas of work during the reporting period was the modernization of the cloud infrastructure's monitoring system. Work on the transition to the use of the standard monitoring tools included in the cloud platform started. As part of this work, standard metric collectors were deployed, and the corresponding visualization dashboards were integrated into the mon-service.jinr.ru monitoring service. A separate instance of the VictoriaMetrics time-series database management system was deployed for the current test period, and metrics are collected in parallel across both the previously used and new databases.

Within the distributed information and computing environment (DICE) based on the cloud resources of organizations from the JINR Member States, the main work was related to maintaining the operability and availability of these resources.

MICC Data Storage Systems

One of the essential elements of the MICC is the data storage system. The primary storage systems used are dCache and EOS for disk storage, and Enstore and CTA for tape storage.

In 2025, substantial work related to the transition to AlmaLinux OS 9.6 was carried out to refine, modify, support, and maintain the Enstore-based magnetic tape data storage and transportation system. Considerable work to optimize tape recording, dictated by the increased data flow in 2025, was performed. As a result of code optimization, the transfer time was reduced by approximately 25%, and with the introduction of the Python 3 system distribution, read/write speeds approached the theoretical maximum: 400 Mbps per tape device.

As part of work on organizing a regional data centre for the JUNO experiment on the basis of the MICC, a data storage system whose architecture is built on the dCache software was developed [4].

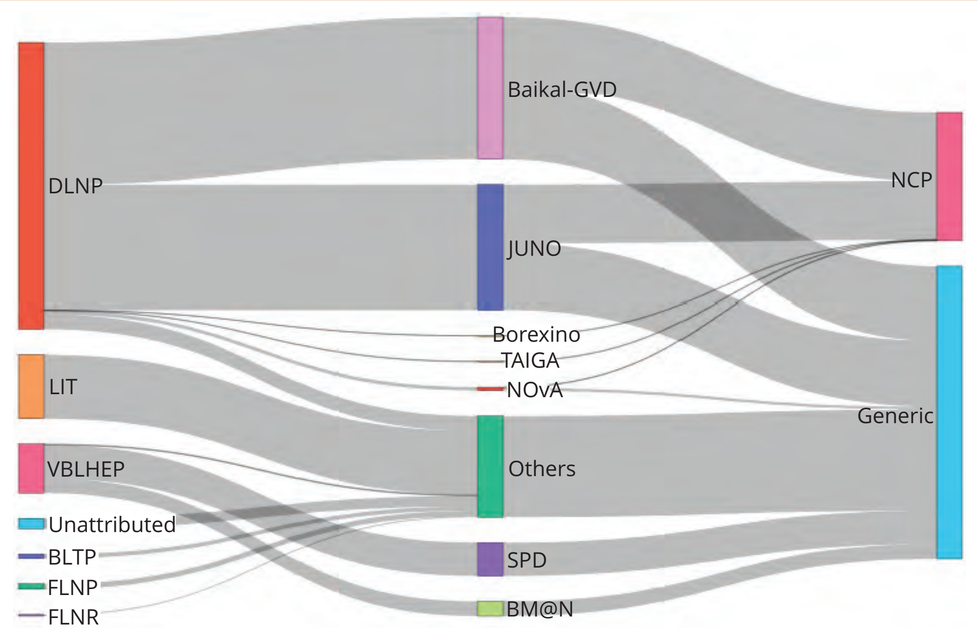

Fig. 6. Structure of JINR cloud resource usage

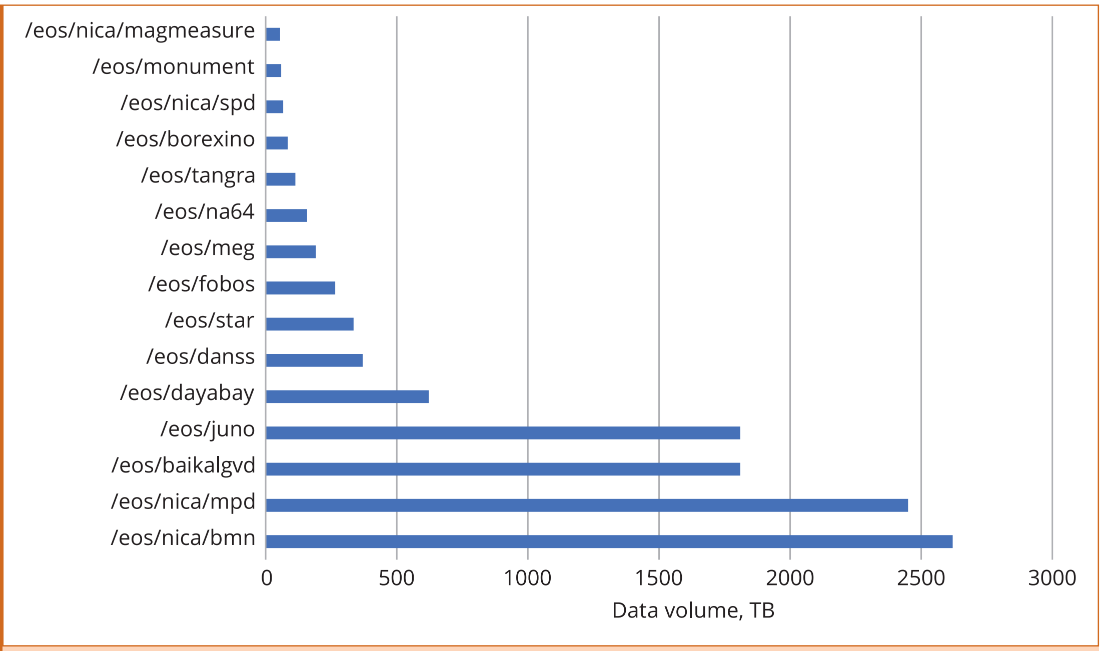

Fig. 7. Distribution of the volume of data stored in the system as of December 2025 (exceeding 50 TB)

In addition to the EOS systems allocated for the MPD and SPD experiments, each with a capacity of 7 PB, a shared storage system based on EOS was organized at the MICC. It is considered as a common distributed data storage system for all MICC users with a capacity of 20.5 PB. Both individual users and user/experiment groups are registered in the shared EOS system. The distribution of the volume of data stored in the system as of December 2025 (exceeding 50 TB) is shown in Fig. 7.

Monitoring System

In 2025, the LITmon monitoring system, which represents the primary tool for MICC operators and allows for up-to-date information on the status of all engineering systems of the complex, was maintained and developed. The general monitoring system embraces an accounting system that provides statistical data on resource usage by user tasks (Fig. 8). The system enables the accounting of resources and

Fig. 8. General information screen of the Tier1 CMS grid site task accounting system

their use both within the distributed data processing system and locally.

To enhance the MICC reliability through early warnings about potential emergencies, the concept of an LSTM (Long Short-Term Memory) neural model to automate the procedure of classifying system log messages, which is necessary for the subsequent prediction of possible hardware and software failures in the major components of the computing complex, was proposed within the development of the monitoring system. Data acquisition and processing programs, as well as an interface for data analysis, were elaborated.

MULTIPURPOSE HARDWARE AND SOFTWARE PLATFORM FOR BIG DATA ANALYTICS

Within the task of establishing a Big Data user infrastructure based on CPU computing resources and hardware accelerators (GPUs), a pool of servers with various locally installed and configured artificial intelligence models, accessible to users through the Open WebUI web server via an API or as an assistant in software development environments (such as Visual Studio Code), was created using software means for organizing calculations and open-source libraries of analysis, modelling, and visualization tools.

A mechanism for monitoring and analyzing the security of network connections to resources hosted in the JINR MLIT cloud environment was worked out. A neural network model that reconstructs normal URL structure patterns, where a considerable deviation between the original and reconstructed requests serves as a potential threat indicator, was implemented. Unlike traditional methods, neural network models trained on normal traffic can detect unknown cyberattacks without first examining malicious samples. This approach is relevant for the task of detecting anomalous requests to web services hosted in the JINR network. Experimental results demonstrate the efficiency of the proposed neural network architecture: the accuracy of normal traffic reconstruction reached 98%, and the accuracy of anomaly detection amounted to 97.6%. The obtained results and models are planned to be used in software tools for ensuring the security of JINR websites and digital services (Web Applications Firewall).

JINR DIGITAL ECOSYSTEM

In 2025, work on maintaining and developing institute-wide scientific and administrative services, as well as on integrating them with each other and into the JINR Digital Ecosystem, was in progress.

The PIN-2 system was put into operation and refined based on the results of its trial operation. An electronic personnel training system, initially aimed at organizing remote testing on radiation safety for the Institute's staff members, was put into test operation. The DocMS document development and management service was fully commissioned and is used by the Institute's subdivisions and collaborations (certificate No. 22025690887 on the state registration of the computer program "DocMS Document Management Platform").

As part of support for administrative services in the MLIT area of responsibility, the following services were developed: the Dubna EDMS, ISSC, DES Shell, HR JINR, GIS JINR, Document Database, Advance Reports, JINR Staff at CERN, ADB2, NICA EVM, Data Exchange Gateway. The above services were migrated to new servers, the monitoring of their operation was introduced, and their security against attacks was enhanced.

To provide parallel and sequential document approval, the Dubna EDMS core was modernized, resulting in a reduction in the average approval time for direct procurement coordination under items 5 and 6 for VBLHEP and DLNP by approximately 2.5 times. The Dubna EDMS user interface was updated considering modern ergonomics and design concepts. Preparations for the phased transfer of the Document Database system's functionality to the Dubna EDMS were made, and a number of modules to transfer the approval of JINR orders to the EDMS were elaborated.

The development of the JINR Publications Repository (certificate No. 202569021 on the state registration of the computer program "Software Complex for Managing Digital Objects of the JINR Scientific Publications Repository") was underway. The software base was modernized, and enhancements to the user interface and data visualization (in particular, mathematical formulas) were made. The automation and integration of publication metadata from eLIBRARY (including those not previously linked to JINR) and a specialized list of JINR FLNP publications were implemented. Work to improve the quality of metadata was completed, and algorithms for correcting annotations and linking authors to articles were elaborated. To improve the speed and security of the system, the service architecture was redesigned.

Within the JINR geographic information system, data import and editing mechanisms for entering building outlines and floor plans were implemented. Information on various buildings, premises, and workplaces in them for VBLHEP, LRB, and MLIT was entered into the GIS. A subsystem for analyzing and reporting on the placement of JINR staff members in buildings, rooms, and subdivisions was put into operation. The functionality for reserving workplaces and rooms for staff members and subdivisions was worked out and put into operation.

METHODS, ALGORITHMS AND SOFTWARE FOR MODELLING PHYSICAL SYSTEMS, MATHEMATICAL PROCESSING AND ANALYSIS OF EXPERIMENTAL DATA

One of the main activities of MLIT is to provide mathematical, algorithmic, and software support for experimental and theoretical research underway at JINR. In 2025, within Theme 1119, a number of works and investigations aimed at the elaboration and enhancement of mathematical methods and software for modelling physical processes and experimental facilities, processing and analyzing data from experiments in elementary particle physics, nuclear physics, neutrino physics, radiobiology, etc. were performed. Highly appreciated contributions were made to the research programme of the BM@N, MPD, and SPD projects and to the development of software for data processing systems and physics object reconstruction for the Baikal-GVD, JUNO, ATLAS, and CMS projects. Active participation in the physics analysis of CMS experiment data was ongoing.

A summary of selected results is presented below.

Development of Data Processing Systems, Creation and Enhancement of Information and Computing Systems to Support JINR Research Projects

Within the enhancement of the Baikal-GVD experiment data processing and analysis systems, the refactoring and multithreading of key C++ programs were performed [5].

In 2025, work on detecting and eliminating bottlenecks in the SpdRoot software package was completed [6]. Proposed fixes, such as memory operation optimization and the elimination of undefined behaviour in functions, reduced the average event reconstruction time in SPD.

Within the participation of MLIT specialists in the ATLAS experiment at CERN, work on advancing the ATLAS TDAQ system and the Event Picking service of the EventIndex system was underway [7]. The experience and knowledge gained in elaborating databases for the ATLAS experiment were applied to the experiments at the NICA accelerator complex. Based on the analysis of the corresponding systems in four LHC experiments, the design of the BM@N experiment data quality monitoring (DQM) system was developed [8].

An AI assistant that uses the DeepSeek large language model was integrated into the FITTER_WEB web application, developed for processing data obtained from the YuMO small-angle spectrometer at FLNP. The correctness of automatic C++ code generation for a number of functions employed in data fitting in neutron physics was demonstrated [9].

Development and Enhancement of Physical Event Reconstruction Algorithms and Particle Identification Methods

The detailed geometry of tracking detectors (CSC, GEM, FSD, VSP, SiBT, SiProf) for the current configuration of the physical setup for the upcoming run (Run 9) of the BM@N experiment, which is used for modelling in the BMNROOT environment, was developed and implemented [10]. The geometric models were considerably refined on the basis of updated diagrams and drawings.

Work on the development of a neural network model for separating reconstructed charged particle tracks by events in individual time slices for the SPD experiment started. The model is based on a graph attention neural network (GANN), which was employed to cluster particle tracks by events in SPD time slices. The analysis of the model's results shows that the GANN exhibits high clustering efficiency, achieving 98.5% precision and over 95% recall.

The data shift problem in particle identification by machine learning methods in the MPD experiment was investigated [11]. A methodology for data shift evaluation was elaborated and tested.

An innovative graph neural network model with an attention mechanism and two-stage aggregation for particle trajectory reconstruction after training on Monte Carlo data simulating measurements from the TPC detector of the MPD experiment was developed. The model demonstrated high performance, achieving 96.2% accuracy along with 92.6% in both purity and efficiency metrics. The track reconstruction efficiency exceeded 90% for track integrities below 80%. The model exhibited an unprecedented event processing speed (~80 ms/event) compared to classical methods (~10 ms/event) [12].

A Kolmogorov–Arnold network (Enhanced KAN) architecture for physics experiment data analysis and reconstruction was elaborated [13]. The problem of unstable KAN training using Adam-family methods was solved by setting the weights of the proposed basis functions close to zero. The efficiency of the KAN in resolving multi-Gaussian signals was demonstrated. A method for the fast approximation of the magnetic field in a detector setup using the Enhanced KAN was also implemented, and its efficiency was illustrated by the example of the magnetic field in BM@N.

As part of work on muon reconstruction in the High Granularity Calorimeter (HGCAL) of the CMS experiment, the passage of cosmic muons through a test setup designed to test detector layers was simulated. The reconstruction procedure was implemented by approximating the responses on one layer by a straight line and searching for clusters and then tracks in HGCAL.

A working Monte Carlo model of the OLVE-HERO orbital detector prototype was created, primary beam generation and event processing procedures were implemented, and a dataset for detector response analysis was generated. Separately, the simplified Monte Carlo model of the calorimeter used to calculate background conditions was expanded and enhanced [14].

Development and Enhancement of Methods for Physical Process Modelling and Data Analysis

Work on investigating the excess number of events detected by the CMS experiment on Run 2 data in the dimuon mass spectrum in the invariant mass region of 28 GeV in the class of events with the presence of at least one *b*-jet was completed [15].

Using Run 3 data (2022 and 2023) from the CMS experiment, studies to search for the Higgs boson produced in vector boson fusion were performed. The decay mode into two *b*-quarks was used. Correction factors for the high-level trigger were calculated, requirements for the selection of the fusion process of vector bosons and events with two *b*-jets were formulated, and its criteria were optimized.

An investigation on the search for dark matter within the inert doublet model using the full statistics of Run 2 and the first Run 3 data from the CMS experiment, corresponding to an integrated luminosity of 136 and 36 fb^{-1}, respectively, was completed.

A study of multiparticle correlations in *pp* interactions at 13 TeV LHC (Run 2) was conducted using the factorial moment method. A method for reconstructing the dependence of factorial moments by multiplicity in pseudorapidity intervals on the size of the interval, considering the detector's hardware function, was developed.

As an alternative approach to simulating the responses on the reading elements of the GEM detector of the BM@N experiment, the idea of applying machine learning algorithms, in particular, a conditional generative-adversarial network (C-GAN), was proposed and implemented [16].

Development of Computational Physics Methods

To solve equations within the coupled channel method with complex potentials describing nuclear reactions with massive nuclei, software complexes that implement the high-order finite element method (FEM) were developed. It was shown that the FEM and the *R*-matrix method were more stable than the widely used modified Numerov method and allowed including more vibrational and rotational couplings. The calculations of the $^{48}Ti + ^{208}Pb$ and $^{51}V + ^{248}Cm$ reactions demonstrated that multi-phonon and high-spin states significantly smoothed out the barrier distributions, improving the agreement with experimental data [17]. New third- and fourth-order FEM schemes with multivariate Hermite interpolation polynomials of a *d*-dimensional hypercube to solve boundary value problems (BVPs) for an elliptic equation with mixed partial derivatives on hyperparallelepipedal meshes were elaborated. Benchmark BVP calculations confirmed the declared order of accuracy of the developed FEM schemes [18].

In collaboration with FLNR and BLTP, an investigation of the $^{7}Li + ^{10}B$ scattering reaction and the $^{7}Li + ^{10}B \rightarrow ^{6}Li + ^{11}B$ reaction at a beam energy of E_{LAB} = 58 MeV based on experimental data obtained at FLNR was carried out. The results indicate the existence of a proton–neutron halo in the structure of the $^{6}Li_{0+}$ excited state (3.56 MeV) [19]. The ratio of isotope yields obtained in reactions with an incident ^{18}O ion at an energy of 35 MeV with heavy ^{181}Ta and light ^{9}Be targets was investigated relying on the transport-statistical approach.

The TANGELO software package for simulating quantum computing was supplemented considering relativistic corrections to Coulomb interactions when calculating chemical compounds involving superheavy elements. The computational algorithm is based on the hybrid quantum-classical adapt-VQE scheme and is implemented for the quantum-chemical computation of wave functions and ground state energies of heavy lead and superheavy flerovium monoxides [20].

A numerical study on the influence of frequency and radius parameters on the structure and properties of standing waves in a ball of finite radius, approximating 3D oscillons in the φ^4 model, was performed jointly with the University of Cape Town [21].

In cooperation with Sofia University, a high-precision numerical method for searching for new solutions to the problem of three equal-mass bodies under collisionless conditions and with central symmetry was developed. The method is based on Newton's method with initial approximations obtained by the grid-search method. [22].

An investigation on the structure of vesicles of the phospholipid transport nanosystem (PhTNS) and PhTNS-based medical drugs using small-angle neutron scattering data was conducted together with FLNP and the Institute of Biomedical Chemistry of the RAS. The influence of impurities and other factors on the size of vesicles and their structure was analyzed [23].

In collaboration with VBLHEP and DLNP, work on the three-dimensional computer modelling of the magnetic system of the MSC-230 cyclotron with a 4.5 kA current winding, considering a new version of its winding, was carried out [24].

The operator approach to stochastic systems, within which the master kinetic equation is represented in the form of a Schrödinger-like equation with a Hamiltonian dependent on the creation and annihilation operators, was considered. Approximate values for the probabilities of being in the first and second states were obtained for the pure creation process [25].

A potential model with non-local interaction was developed, and a system of equations for describing the spectrum of vector mesons was formulated within the model. The phenomenological choice of the vector meson vertex used will be sufficient to describe the processes of production and dissociation of heavy quarkonia J/ψ (Υ) at heavy ion collision energies in the NICA experiment [26].

A method for efficiently describing the entanglement of a two-qubit system using a specially selected coordinate system in a given cross section of the entanglement space, which simplifies the calculation of nonlocal characteristics, was proposed. The method enables the description of a class of separable states as a semi-algebraic variety [27]. A comparison of a four-dimensional quantum system and a two-qubit system within the generalized Stratonovich–Weyl correspondence formalism was carried out. Based on numerical analysis, it was demonstrated how information about the possible implementation of a virtual two-level subsystem was encoded in the properties of the Wigner function of the states of the corresponding four-level system.

The Tait–Bryan angles method, which is a modification of the well-known Euler angles method describing the rotation of an orthogonal frame in three-dimensional Euclidean space, was generalized to the case of spaces of arbitrary finite dimension. The developed system of elementary unitary rotations allows for the introduction of a convenient parameterization of Grassmannians and a parameterization of algebraically open subsets of conjugation classes of Hermitian matrices [28].

Regularizing correlation functions were constructed for quantum statistical systems that are composed of atoms or molecules and interact with each other through singular non-integrable potentials [29].

A computer simulation of a controllable magnetization reversal in a chain of φ_0 junctions induced by an alternating voltage was performed. It was shown that by applying an external alternating voltage pulse with a frequency coinciding with the eigenfrequency of the LCR circuit, a magnetization reversal could be realized in the selected φ_0 junction; i.e., the possibility of a controllable magnetization reversal was demonstrated [30].

6–10 October. The JINR Autumn School of Information Technologies

EDUCATIONAL ACTIVITY

Within the educational activity, the JINR Spring and Autumn Schools of Information Technologies (IT Schools) were held in 2025. Eighty-six students from various universities in Russia, Belarus, Kazakhstan, and Uzbekistan participated in them. As a result of the IT School series, 28 people have become JINR employees since 2022. More than 50 theses of postgraduates, master's and bachelor's students were prepared and defended in 2025 under the supervision and scientific advice of the MLIT staff. Over 70 non-graduate students are working on JINR projects and came for practice. In 2025, the education and testing polygon of the HybriLIT platform was actively used both for conducting semester-long training courses and within schools and workshops. Semester-long training courses on IT disciplines held at Dubna University and the Dubna branch of Lomonosov Moscow State University (MSU Branch) were attended by more than 400 students. In addition, 11 bachelor's and one master's theses were prepared based on the HybriLIT platform. In 2025, the first student enrolment for the master's programme of the Dubna MSU Branch in direction 01.04.02 "Applied Mathematics and Computer Science" took place. Thirteen students successfully passed entrance exams and started mastering the educational programme entitled "Data Processing Methods and Technologies in Heterogeneous Computing Environments".

REFERENCES

1. *Petrosyan A., Oleynik D., Zhemchugov A., et al.* Production System of the SPD Experiment // Phys. Part. Nucl. 2025. V. 56. P. 1576–1580; https://doi.org/ 10.1134/S1063779625700893.
2. *Greben N., Oleynik D., Romanychev L.* Workload Management System for SPD Online Filter // Phys. Part. Nucl. Lett. 2025. V. 22. P. 1044–1047; https://doi.org/10.1134/S1547477125701067.
3. *Anikina A., Belyakov D., Bezhanyan T., et al.* Structure and Features of the Software and Information Environment of the HybriLIT Heterogeneous Platform // Lect. Notes Comput. Sci. 2025. V. 15460. P. 444–457; https://doi.org/10.1007/978-3-031-80853-1_33.
4. *Baranov A., Balashov N., Makhalkin A., et al.* GitOps-Managed Distributed Data Storage System on Top of dCache for the JUNO Neutrino Experiment within the JINR Computing Infrastructure // Phys. Part. Nucl. 2026. V. 57, No. 4.
5. *Solovjev A. G. et al. (Baikal-GVD Collab.).* Multi-Threading for Baikal-GVD Core Software Framework // Ibid.
6. *Didorenko A., Voytishin N.* Search for Bottlenecks in SpdRoot Code // Ibid.
7. *Alexandrov E., Alexandrov I., Barberis D., Yakovlev A.* Methods for Automating Error Handling in the Event Picking Service of the ATLAS Experiment // Ibid.
8. *Alexandrov E., Alexandrov I., Chebotov A., Gertsenberger K.* Design of the Data Quality Monitoring System for the BM@N Experiment // Ibid.
9. *Soloviev A. G., Solovjeva T. M., Lukyanov K. V.* AI-Based C++ Code Generation for Fitting Models in FITTER_WEB // Ibid.
10. *Afanasiev S. et al. (BM@N Collab.).* Production of Protons, Deuterons and Tritons in Argon-Nucleus Interactions at 3.2 *A* GeV // JHEP. 2025. V. 2025. P.95; https://doi.org/10.1007/JHEP08(2025)095.
11. *Papoyan V.* Data Shift Problem in Particle Identification // Phys. Part. Nucl. 2026. V. 57, No. 4.
12. *Talochka Y., Ososkov G., Voytishin N.* Graph Neural Network with Attention and Two-Stage Aggregation for Particle Track Reconstruction in the TPC MPD of the NICA Accelerator Complex // Comput. Soft. Big. Sci. 2025. V. 9. P. 22; https://doi.org/10.1007/s41781-025-00153-4.
13. *Talochka Y., Ososkov G., Voytishin N.* Enhanced KAN Architecture for Experimental Data Processing in High-Energy Physics // Comput. Phys. Comun. 2025. V. 316. P. 109801; https://doi.org/10.1016/j.cpc. 2025.109801.
14. *Kalikulov O., Saduyev N., Mukhamejanov Y., et al.* Monte Carlo Simulation of the HERO Orbital Detector Calorimeter // Symmetry. 2025. V. 17, No. 9. P. 1449; https://doi.org/10.3390/sym17091449.
15. *Hayrapetyan A. et al.* Dark Sector Searches with the CMS Experiment // Phys. Rep. 2025. V. 1115. P. 448–569.
16. *Baranov D.* GAN-Based Simulation of Triple GEM Detector in the BM@N Experiment // Phys. Part. Nucl. 2026. V. 57, No. 4.
17. *Wen P. W., Chuluunbaatar O., Gusev A. A., et al.* Role of Multi-Phonon and High-Spin States on the Quasi-Elastic Barrier Distributions of Massive Systems // Phys. Lett. B. 2025. V. 863. P. 139383; https://doi.org/10.1016/j.physletb.2025.139383.
18. *Kovalev O. O., Batgerel B., Gusev A. A., et al.* Symbolic-Numerical Algorithms for Solving Multidimensional Boundary Value Problems by Finite Element Method on Hypercubes // Lect. Notes Comput. Sci. 2025. V. 16235. P. 210–222; doi.org/10.1007/978-3-032-09645-6_12.
19. *Zemlyanaya E. V., Lukyanov K. V., Lukyanov V. K., et al.* Microscopic Analysis of Elastic Scattering and Transfer Reactions in the ^{7}Li + ^{10}B Collision at a Beam Energy of 58 MeV // Bull. Russ. Acad. Sci. 2025. V. 89. P. 1236–1240.
20. *Yushankhai V. Yu., Siurakshina L. A.* Variational Quantum Algorithm for Computational Problems of Quantum Chemistry: From UCCSD-VQA to ADAPT-VQA // Phys. Part. Nucl. 2025. V. 56. P. 1004–1008.

21. *Zemlyanaya E. V., Bogolubskaya A. A., Alexeeva N. V., Bashashin M. V.* φ^4 Oscillons as Standing Waves in a Ball: A Numerical Study // Ibid. P. 1655–1659.
22. *Hristov I., Hristova R., Puzynina T., et al.* Numerical Search for Three-Body Periodic Free-Fall Orbits with Central Symmetry // Commun. Nonlin. Sci. Numer. Simul. 2025. V. 51. P. 109066.
23. *Zemlyanaya E., Kiselev M., Chausova V., et al.* Analysis of Structure of the PhTNS Vesicles Based on Small-Angle Neutron Scattering Data Obtained at the "Yellow Submarine" Spectrometer //. Int. J. Mod. Phys. E. 2025 (accepted); https://doi.org/10.1142/S021830132641003X.
24. *Akishin P. G., Vesenkov V. A., Vlasov A. I., et al.* Medical Superconducting Cyclotron MSC-230. Status of the Project // Phys. Part. Nucl. Lett. 2025. V. 22, No. 4. P. 847–851.
25. *Ayryan E., Buša J., Hnatič M., et al.* Approximate Calculation of Functional Integrals Arising from the Operator Approach // Physica A: Stat. Mech. Appl. 2025. V. 670. P. 130616.
26. *Tawfik A. N., Ahmadov A. I., Friesen A., et al.* Derivation of Meson Masses in *SU*(3) and *SU*(4) Extended Linear Sigma Model at Finite Temperature // Particles. 2025. V. 8, No. 1. P. 9; https://doi.org/10.3390/particles8010009.
27. *Khvedelidze A., Mladenov D., Torosyan A.* Towards Parameterizing the Entanglement Body of a Qubit Pair // Phys. Part. Nucl. 2025. V. 56. P. 1493–1497.
28. *Babich M. V., Bordag L. A., Khvedelidze A. M., Mladenov D. M.* On Multidimensional Analogs of Euler (Tait–Bryan) Angles and Grassmannians // Zap. Nauchn. Sem. POMI. 2025. V. 543. P. 43–55.
29. *Yukalov V. I., Yukalova E. P.* Quantum Systems of Atoms with Highly Singular Interaction Potentials // Laser Phys. 2025. V. 35. P. 045501.
30. *Rahmonova A., Streltsova O., Rahmonov I., Zuev M.* Simulation of a Controllable Magnetization Reversal in a Chain of φ_0 Junctions by an Alternating Voltage Pulse // Phys. Part. Nucl. 2025. V. 56. P. 1592–1598.