# LABORATORY OF INFORMATION TECHNOLOGIES

In 2019, the studies on two topics of first priority, namely, "Information and Computing Infrastructure of JINR" and "Methods, Algorithms and Software for Modeling Physical Systems, Mathematical Processing and Analysis of Experimental Data" were carried out by the Laboratory of Information Technologies (LIT) within the framework of the direction "Networks, Computing, Computational Physics". The LIT staff participated in research on 26 topics of the JINR Topical Plan within cooperation with other JINR Laboratories. The LIT activity is aimed at developing the JINR network, information and computing infrastructure, mathematical support and software for research and production activities underway at JINR and its Member States on the basis of the JINR Multifunctional Information and Computing Complex (MICC).

In 2019, employees of the Laboratory of Information Technologies published 220 scientific papers in refereed scientific journals and presented 135 reports at international and Russian conferences.

## INFORMATION AND COMPUTING INFRASTRUCTURE OF JINR

In 2019, one of the major directions of the LIT activities was the development of the Multifunctional Information and Computing Complex (MICC) of JINR [1]. It comprises the following: the development and improvement of the JINR telecommunication and network infrastructure; the modernization of the MICC engineering infrastructure; the modernization, development and creation of new components of the MICC for data storage, processing and analysis, namely, the development of the IT infrastructure of the NICA megascience project, the extension of capacity and volume of data storage systems of the grid components, i.e., Tier-1 and Tier-2, the extension of the cloud component and creation of an integrated cloud environment for JINR experiments, the enlargement of the HybriLIT heterogeneous computing platform, including the "Govorun" supercomputer.

**JINR Telecommunication Channels.** In 2019, a significant modernization of the JINR network infrastructure was carried out.

The project of increasing the bandwidth of the Moscow–JINR telecommunication channel from 100 to 3 × 100 Gbit/s was implemented; the bandwidth of the backbone of the Institute local area network was increased to 2 × 100 Gbit/s, and a distributed computing cluster network between the DLNP and VBLHEP sites with a capacity of 400 Gbit/s with double redundancy to increase the reliability of the backbone network was built.

At present, the external distributed network of JINR (Fig. 1) is represented by the JINR–CERN direct channel and a backup channel passing through MMTS-9 in Moscow and Amsterdam, ensuring the operation of LHCOPN (JINR–CERN) for the connection between Tier-0 (CERN) and Tier-1 (JINR) and the LHCONE external superimposed network designed for the JINR Tier-2 center, as well as by direct channels for the connection with the collaboration of RUHEP research centers and networks RUNNet, RETN using the RU-VRF technology.

The distribution of incoming and outgoing traffics over the JINR subdivisions in 2019 (exceeding 25 TB by the incoming traffic) is shown in the table.

In 2019, the overall incoming traffic of JINR, including the general-purpose servers, Tier-1, Tier-2 and the computing complex, amounted to about 56 PB. The traffic with scientific and educational networks accounting for 96.4% of the total is the major one.

**JINR Local Area Network (LAN).** In 2019, the work on the development and improvement of the network components of the JINR IT infrastructure was continued. The Cisco ACI factory based on the equipment Cisco Nexus 9504 and Cisco Nexus C9336C-FX2, allowing one to connect the MICC components

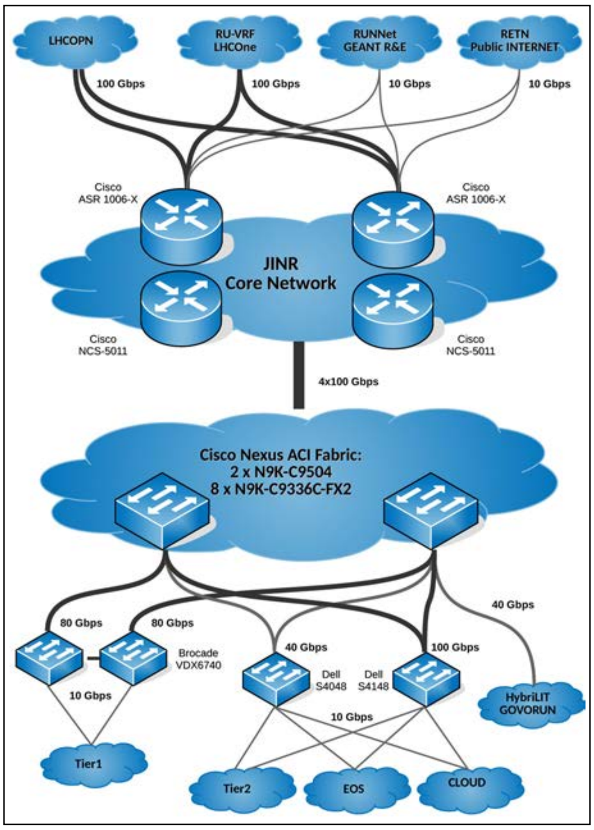


Fig. 1. Scheme of the external JINR distributed network

at speeds of up to 100 Gbit/s and more, was put into operation. To ensure the necessary bandwidth and the possibility of redundancy, the factory is connected to the JINR backbone network by 4 channels of 100 Gbit/s.

The Tier-1 network was transferred to the ACI factory and has the overall connection of 160 Gbit/s (4 channels of 40 Gbit/s). The EOS distributed file system, the HybriLIT heterogeneous platform, the "Govorun" supercomputer, WEB services, Tier-2 and the networks of "Cloud computing" were connected to the ACI factory.

The modernization of the network cluster of virtual services of the JINR network operations center (NOC) was in progress. The NOC virtualization cluster was created using the Proxmox open source software under the license with the open source code GNU AGPL v3, which enables the free use of the code in creating cluster solutions. The cluster serves virtual machines of network services of the JINR network, such as DNS, DHCP, RELAYs, different network databases, as well as a number of LIT and UC services.

The functionality of the system for the network traffic analysis was expanded with the help of new scripts, which can identify infected and hacked user computers. The support of the Wi-Fi eduroam network at LIT, the "Dubna" hotel, the House of International Meetings, the House of Scientists, and the UC hostel is provided. The status of 560 hosts, more than 150 services and conditions is monitored in the network monitoring system.

| Subdivision | Incoming, TB | Outgoing, TB |
|---|---|---|
| VBLHEP | 414.4 | 689 |
| LIT | 414.3 | 182 |
| DLNP | 369.6 | 500.5 |
| Dubna State University | 212.8 | 110.5 |
| FLNP | 173.6 | 266.5 |
| FLNR | 156.8 | 175.5 |
| Hotel and Restaurant Complex | 145.6 | 71.5 |
| JINR Directorate | 100.8 | 266.5 |
| Remote access node | 95.2 | 32.5 |
| BLTP | 61.6 | 58.5 |
| University Centre | 44.8 | 26 |
| Medical-Sanitary Unit 9 | 39.2 | 13 |
| Social Infrastructure Management Office | 39.2 | 32.5 |
| Telephone Communications Site (TCS) | 28 | 13 |
| LRB | 28 | 19.5 |

Several types of notifications, namely, e-mail messages and SMS alerts, are used.

JINR LAN comprises 8169 network elements and 15 505 IP-addresses, 7512 network users, 2465 users of the mail.jinr.ru service, 1531 users of electronic libraries, and 358 users of the remote access service.

**MICC Engineering Infrastructure.** In 2019, the work on the improvement of the MICC engineering infrastructure, designed to ensure the reliable, uninterrupted and fault-tolerant operation of the information and computing system and the network infrastructure, was in progress. Using the integrated approach to building the MICC engineering infrastructure allowed one to elaborate algorithms of the equipment operation and interaction of separate systems both in a normal operation mode and in emergencies, which ensured the uninterrupted performance regardless of external factors. The system of uninterruptible power supplies provides guaranteed power to connected consumers, the automatic launch of diesel-generator units (DGU), the automatic load transfer from the main external power supply network to DGU and vice versa, and allows one to send messages to the dispatcher post in case of an emergency with DGU.

The MICC existing climate control system is a complex of the interconnected equipment with different air and liquid cooling schemes, with the help of which the corresponding temperature regime ensuring the MICC functioning in a $24 \times 365$ mode is created. At present, the MICC climate control system has the following components: free cooling of the server equipment of the machine hall with cooled air; raised floor supply of cold air with a forced exhaust of hot air by ventilation panels; cooling of the cold corridor of the Tier-1 module by inter-row conditioners; liquid cooling of the elements of the "Govorun" supercomputer. According to the type of heat removal, the MICC climate control system refers to the mixed type that combines systems with the evaporation of a coolant and systems with an intermediate coolant.

Additional opportunities and new requirements to the cooling system are associated with the commissioning of the "Govorun" supercomputer in 2018, which required the creation of a precision liquid cooling system balanced for constant work with a high-temperature coolant. In accordance with the equipment placement conditions, an optimum operation mode of the computing rack at a constant coolant temperature of $+45\,^{\circ}$C at the entrance to the computing nodes (with a peak value of up to $+57\,^{\circ}$C) was chosen. The work in a "hot water" mode for this solution allowed one to apply a year-round free cooling mode using only dry cooling towers, which cool liquid with the help of ambient air on any day of the year, and also to completely get rid of the freon circuit and chillers. As a result, the average annual PUE (Power Usage Effectiveness) indicator of the system, reflecting the level of energy efficiency, is less than 1.06.

**JINR Grid Environment.** The JINR grid infrastructure [2] is represented by the Tier-1 center for the CMS experiment at the LHC and the Tier-2 center, which provides processing of data from the experiments ALICE, ATLAS, CMS, LHCb, BES, BIOMED, MPD, NO$\nu$A, STAR, and others.

In 2019, the Tier-1 data processing system for CMS was increased to 10 688 cores, providing a performance of 151.97 kHS06. The storage system comprising disk arrays and long-term storage of data on tapes was expanded. The total usable capacity of disk servers was increased to 10.4 PB; the IBM TS3500 tape robot is 11 PB. In terms of performance, Tier-1 (T1_JINR) is ranked second among other Tier-1 centers for the CMS experiment (Fig. 2, *a*). More than 301 493 million events were processed, which accounts for 20% of the total number of processed events (Fig. 2, *b*) and 18% of the total CPU load of all Tier-1 centers for the CMS experiment.

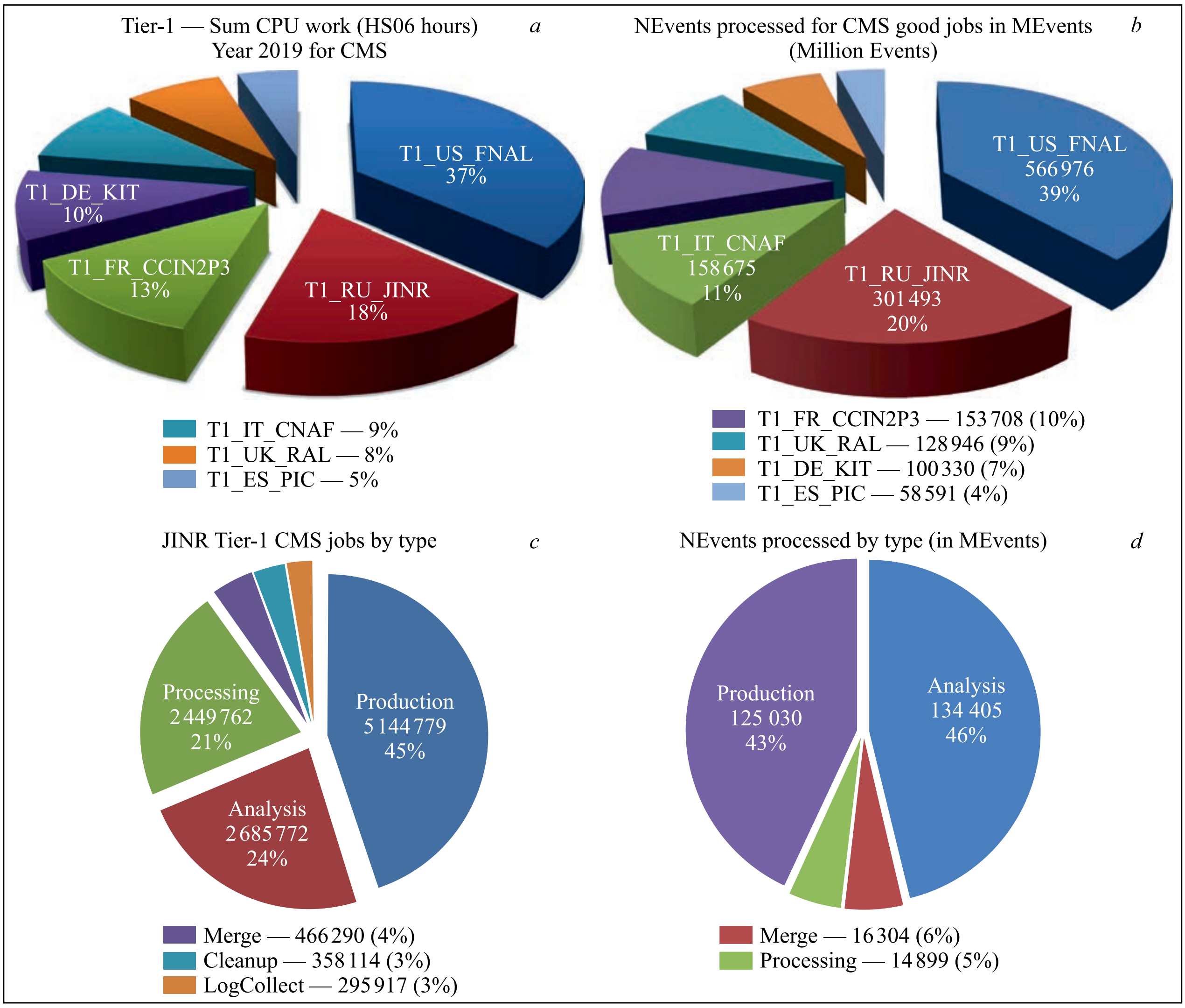


Fig. 2. Contribution of the world Tier-1 centers to the processing of CMS experimental data in 2019: *a*) distribution by the normalized CPU time in HS06 hours; *b*) number of processed events (in millions of events). Statistics on the use of the JINR Tier-1 center by the CMS experiment by different types of data stream processing in 2019: *c*) distribution of jobs; *d*) distribution of events by type of processing

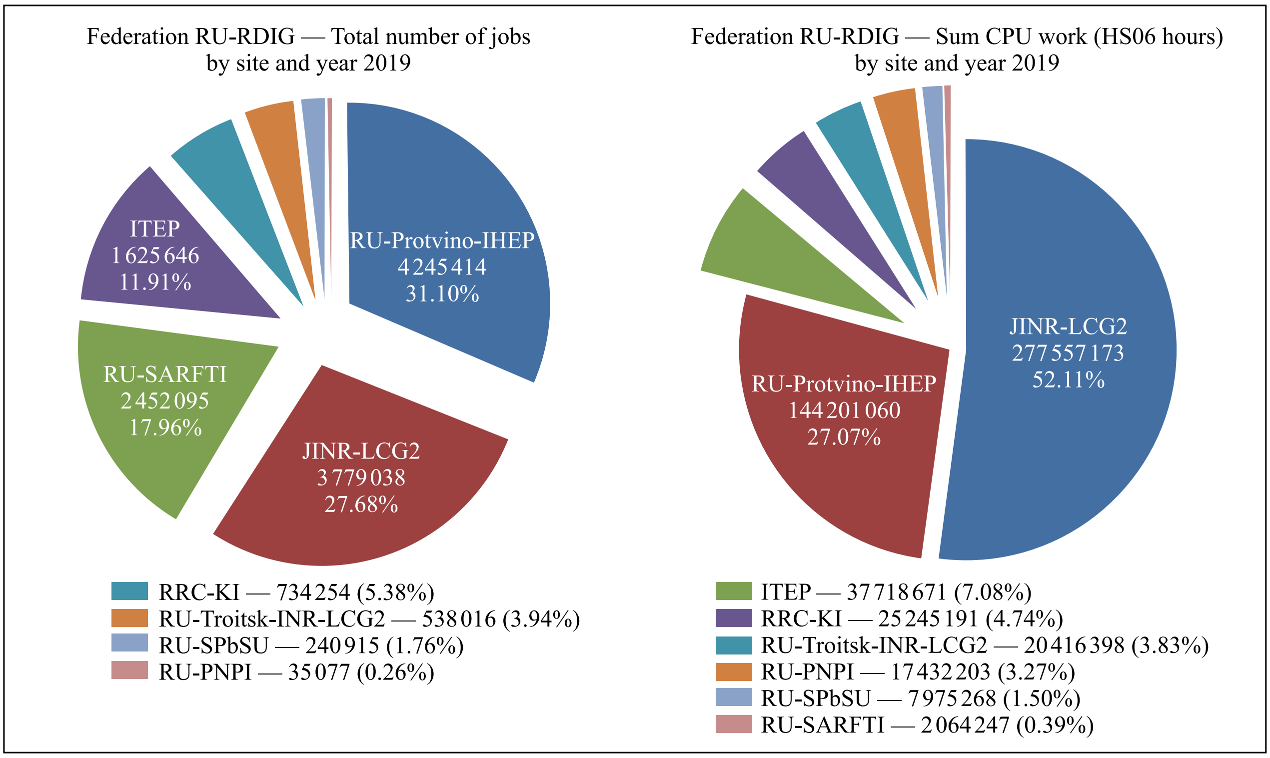


Fig. 3. Statistics of the work of Tier-2 sites of the organizations being part of the Russian Consortium RDIG

Figure 2, *c*, *d* shows the number of jobs and events processed at the JINR CMS Tier-1 center in 2019 by different types of data stream processing (reconstruction, modeling, reprocessing, analysis, etc.).

One of the main functions of Tier-1 centers is to provide data exchange with all world sites operating for the CMS experiment and storage of raw experimental and simulated data. In 2019, the overall volume of CMS data exchange with the tape robot was 9.6 PB, of which 2.1 PB of new files were recorded. The disk storage was used more actively: the total volume of CMS data and the results of their processing, taking into account the DCAP protocol, was 119.7 PB, of which the output stream was 33.4 PB.

In 2019, the computing resources of the Tier-2 center amounted to 4128 cores, which currently provides a performance of 55.489 kHS06. The total usable capacity of disk servers is 2789 TB for ATLAS, CMS, and ALICE and 140 TB for other virtual organizations. The JINR Tier-2 web site is the best one in the Russian Consortium RDIG (Russian Data Intensive Grid). In 2019, 3 779 038 jobs were processed, which accounts for 52.11% of the total performance of RDIG CPU (Fig. 3).

Figure 4 shows the data on using the JINR Tier-2 site by virtual organizations within grid projects in 2019.

The MICC allows users to perform calculations outside the grid environment. It is necessary for experiments, such as NO$\nu$A, BES, NICA/MPD, etc., as well as for local users of the JINR Laboratories. JINR and grid users have access to all computing facilities via a unified batch processing system. The distribution by time and jobs performed on the computing cluster by the JINR subdivisions and user groups is shown in Fig. 5.

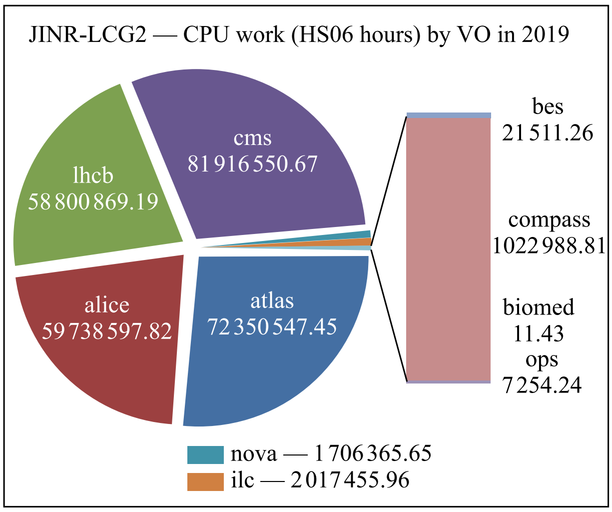


Fig. 4. The use of the Tier-2 grid site by virtual organizations (VO) of the global grid infrastructure: distribution by the normalized CPU time in HS06 hours

Systems of data storage and access, such as dCache, EOS, and XROOTD, ensure joint work with data for JINR local users, as well as WLCG (Worldwide LHC Computing Grid) users and other virtual organizations. JINR joined a group of research centers that develop a WLCG data lake prototype for HL-LHC. The data lake prototype was built as a distributed EOS storage system and is used for storing and accessing big arrays

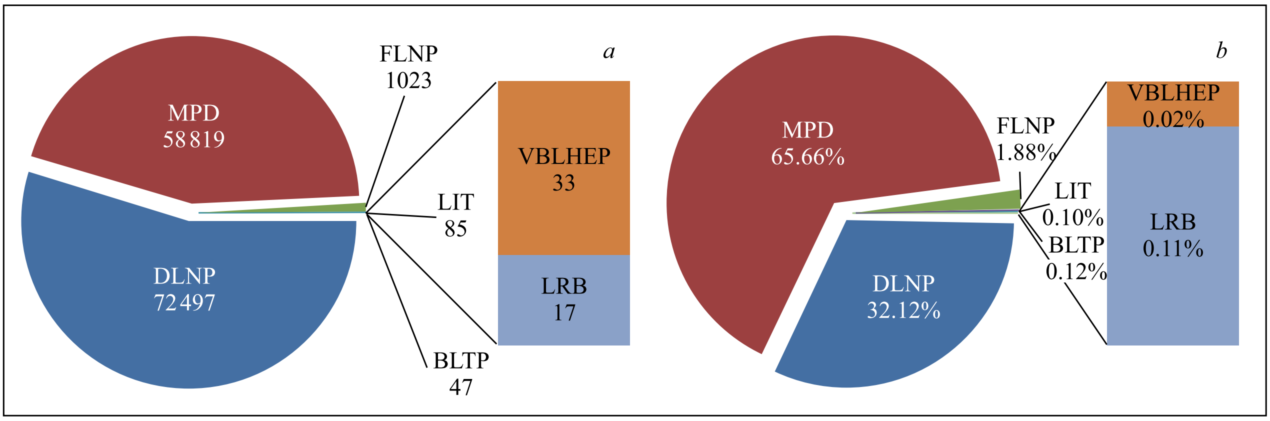


Fig. 5. Statistics of the use of the computing cluster: distribution by time (*a*) and jobs (*b*) performed on the computing cluster by the JINR subdivisions and user groups

of information. The EOS system was successfully integrated in the MICC structure. At present, 3740 TB of disk space is available for EOS. The NICA experiments have already been using EOS for data storage. EOS is visible as a local file system on the MICC working nodes and allows authorized users (by the kerberos5 protocol) to read out and write data.

**Cloud Environment.** In 2019, the work on expanding the JINR cloud environment [3] and combining computing powers of organizations of the Institute Member States into a unified information and computing environment was in progress. For efficient use of local computing resources, cloud infrastructures were or are created in each of the organizations participating in the unification, and clouds of each of the partner organizations of the JINR Member States are integrated into a distributed platform based on the DIRAC Interware (Distributed Infrastructure with Remote Agent Control) [4]. The distribution of jobs by clouds of the Member States's organizations is presented in Fig. 6.

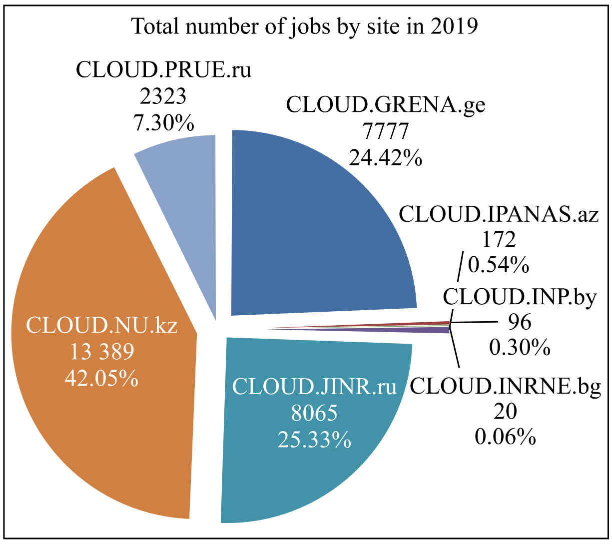


Fig. 6. Distribution of jobs by clouds of the Member States' organizations

The resources of the cloud infrastructure were enlarged to 1564 CPU cores and to 8.5 TB of the total RAM. Figure 7 shows the information on consuming the resources of the cloud infrastructure in 2019: DLNP, LIT, and the NO$\nu$A experiment are the major users of the cloud infrastructure.

The service that provides access to the MICC resources for carrying out a wide range of scientific calculations via a problem-oriented web interface [5], which ensures extended capabilities for launching jobs and notifying the user about the job status, was developed and improved in the JINR cloud. Access to the calculation results was changed: when the job is completed, the output is downloaded to an external file storage, where it becomes available at the automatically generated unique URL for user download, further analysis and/or visualization.

The studies, carried out in collaboration with FLNP within the international program "UNECE International Cooperative Program (ICP) Vegetation" for monitoring and predicting air pollution processes in Europe and Asia, were in progress [6]. In 2019, a mobile application, which allows automatically filling in information about places of moss samples in accordance with the standards of UNECE ICP Vegetation, was elaborated. The application is integrated with the system of managing data of the ICP Vegetation, so that all information about sampling locations can be imported into the system. Predictions of some heavy metals for Norway, Romania, and Serbia were made using deep neural networks. The methodology was worked out not only on a regional scale, but also in predicting pollution on a city scale.

**Heterogeneous Infrastructure.** The heterogeneous infrastructure of the JINR MICC consists of two elements, i.e., the "Govorun" supercomputer and the education and testing polygon, combined by a unified software and information environment into the HybriLIT heterogeneous platform (http://hlit.jinr.ru/). The resources of the platform are used to solve problems that require massively parallel calculations in different

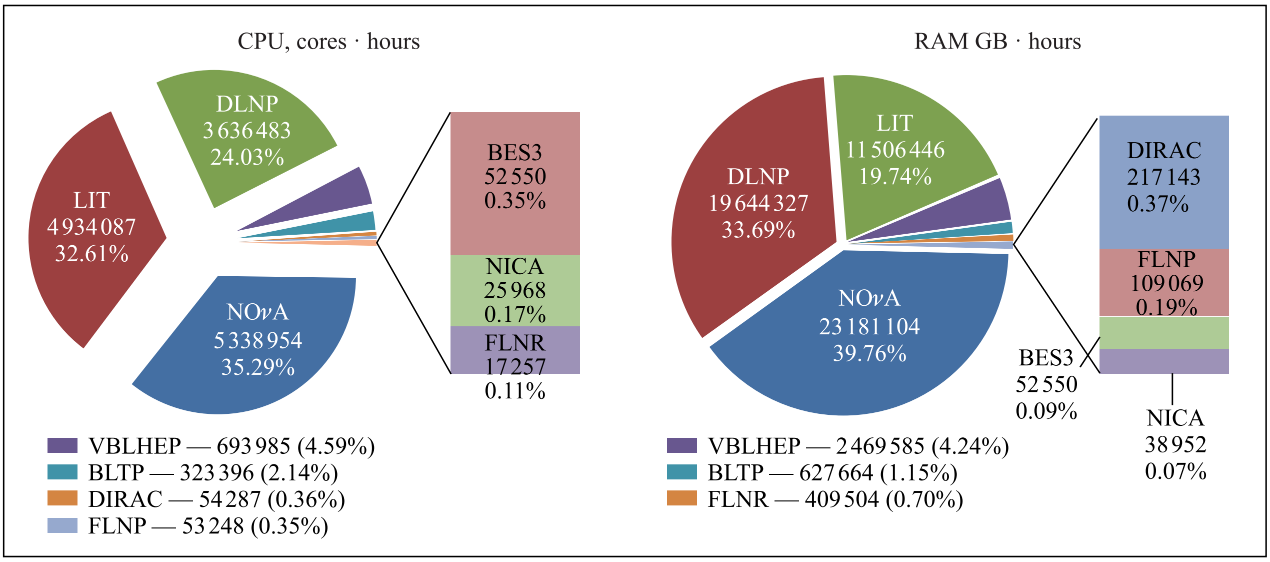


Fig. 7. Consumption of the resources of the cloud infrastructure in 2019

fields of nuclear physics and high-energy physics, condensed matter physics, radiobiology and others underway at JINR, including the development of computing for the NICA megaproject.

Based on the rapid development of IT technologies and user requests, the supercomputer was modernized, i.e., the transition to new processors Intel®Xeon®Scalable gen 2 (models Intel®Xeon®Platinum 8268) and novel high-speed solid-state disks Intel®SSD DC P4511 with the NVMe interface and a capacity of 2 TB was carried out. As a result of the modernization, the performance of the CPU component increased three times, and the total peak performance of the supercomputer reached 860 TFlops for double-precision operations and 1.7 PFlops for single-precision operations, which in turn allowed the CPU component of the "Govorun" supercomputer to take the 10th place in the TOP50 list of the most powerful supercomputers in Russia and the CIS.

The CPU component of the supercomputer is implemented on the high-density architecture "RSC Tornado" with direct liquid cooling, which ensures a high density of computing nodes, i.e., 150 nodes per computing rack, and high-energy efficiency of about 10 GFlop/W.

The "Govorun" supercomputer is a hyperconverged software-defined system and has unique properties for flexibility of customizing the user's job, ensuring the most efficient use of the computing resources of the supercomputer. To speed up the work with data, an ultrafast data storage system (UDSS) was implemented on the "Govorun" supercomputer under the Lustre file system. The total capacity of UDSS is currently 256 TB, and the data input/output rate is 300 GB/s.

The operation of the first version of the "Govorun" supercomputer made it possible to carry out a number of resource-intensive calculations in the field of lattice quantum chromodynamics, to qualitatively increase the efficiency of modeling the dynamics of collisions of relativistic heavy ions, to accelerate the process of generation and reconstruction of events for the experiments of the NICA megascience project, to calculate radiation safety of JINR experimental facilities, and to significantly speed up studies in the field of radiation biology and other scientific and applied tasks. The results of the given scientific studies were published in more than 50 leading world scientific journals (http://hlit.jinr.ru/users_publications/). In 2019, more than 260 000 jobs were performed on all computing components by all groups making calculations on the supercomputer. The distribution of the computing resources usage by user groups is shown in Fig. 8.

As seen from the given diagrams, the main users of the supercomputer are users from BLTP, LIT, and VBLHEP. At the same time, it should be noted that 85% of the resources of the supercomputer are used for the NICA megaproject, both for theoretical calculations and for event generation and reconstruction [7] using the DIRAC Interware (Fig. 9).

In 2019, the average load on the computing components was the following: Skylake — 95.61%, KNL — 57.12%, DGX — 84.59%.

An offline computer complex for data modeling, processing, analysis, and storage within the NICA project, which consists of territorially distributed online and three offline clusters connected by the high-speed computer network with a bandwidth $4 \times 100$ Gbit/s, was created. The NICA computing and information offline cluster at LIT was organized on the basis of the JINR MICC as a distributed scalable hybrid cluster, which allows organizing computing for the NICA project efficiently and without additional labor costs at the request of a different class of jobs and users. The main objective of the LIT offline cluster is to create a two-level (disk-tape) storage system for the NICA experiments, as after the first stage of these experiments, significant storage volumes will be required (from 2.5 to 70 PB per year).

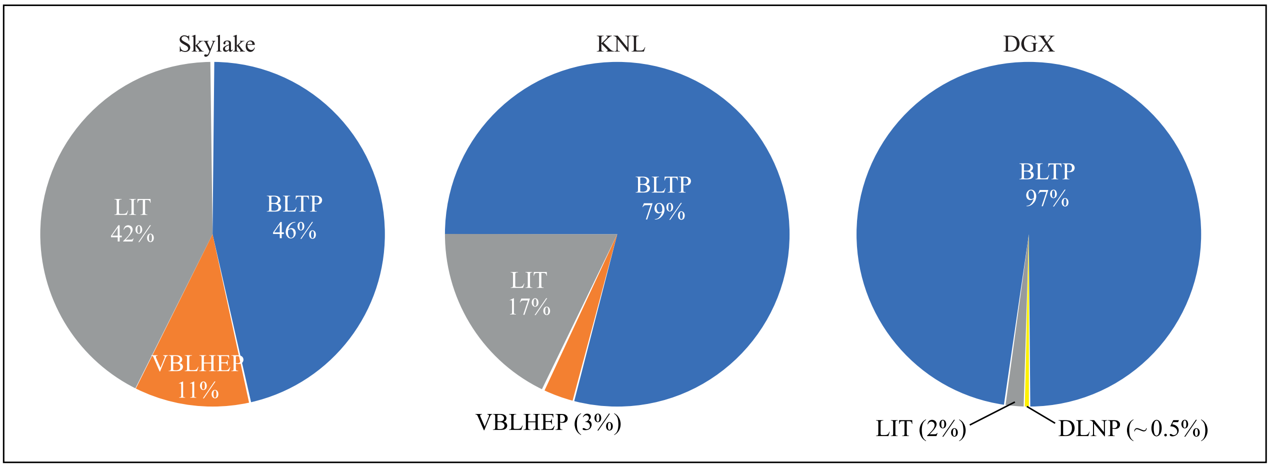


Fig. 8. Distribution of resources among user groups by the computing components of the supercomputer, while the Skylake component contained 40 computing nodes with two CPUs Intel®Xeon 6145, the KNL component contained 21 computing nodes with the processor Intel®Xeon Phi™ 7290, and the DGX component was implemented on the basis of 5 servers NVIDIA DGX-1 with 8 GPUs NVIDIA Tesla V100 in each

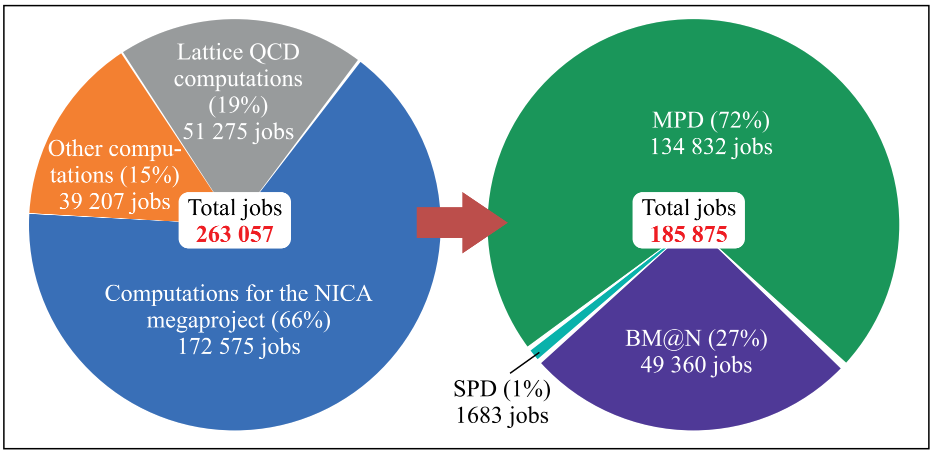


Fig. 9. Number of jobs performed for the NICA megaproject: the share of jobs related to theoretical studies within lattice quantum chromodynamics was 19%, the event generation and reconstruction for all NICA experiments amounted to 66%. At the same time, the share of MPD, out of these 66% of jobs, was 72%

At present, the following computing resources of the JINR MICC were combined using the DIRAC Interware: Tier-1/Tier-2, the "Govorun" supercomputer, the JINR cloud and storage resources, such as UDSS Lustre, dCache, and EOS [7]. More than 120 000 jobs were performed on the MICC components using the DIRAC platform within the framework of data generation by the Monte Carlo method for the MPD experiment. The distribution of simulation jobs by the MICC components via DIRAC is illustrated in Fig. 10.

**Monitoring System.** To ensure a reliable performance of the MICC, a multilevel monitoring system was created and expanded; it operates in a 24 × 365 mode and allows monitoring climate control and power supply systems, the local network equipment, telecommunication channels and computing nodes, jobs, disk and tape storage systems. It is based on different technologies, such as Nagios, Icinga2, Grafana, and systems that are developed at LIT. At present, the monitoring system controls all types of the MICC equipment. The

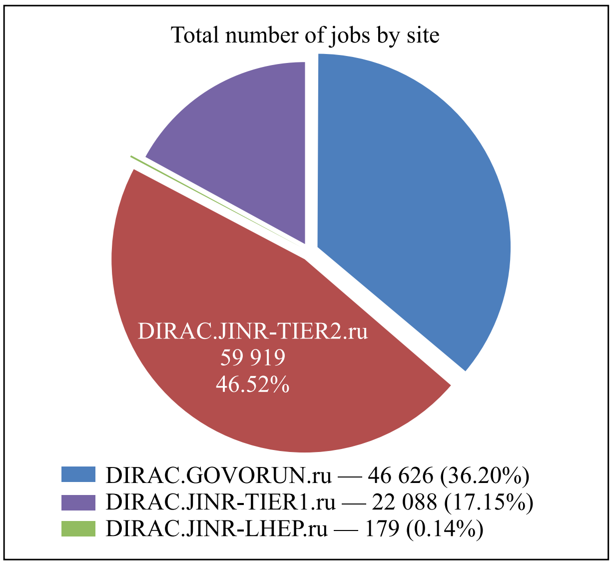


Fig. 10. Statistics on simulation jobs for MPD on the MICC components

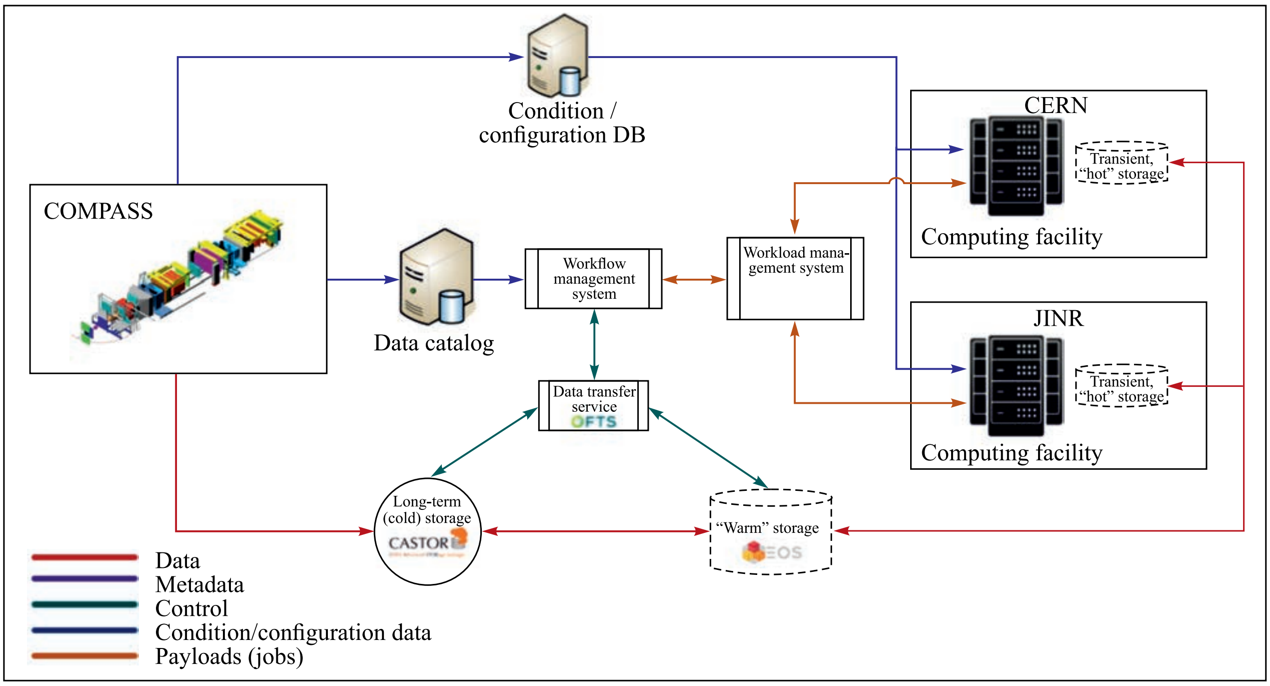


Fig. 11. System architecture and data workflows for data processing of the COMPASS experiment

number of nodes included in monitoring amounts to more than 2000.

In 2019, the work on finalizing the software package [8] for processing data from the COMPASS experiment, which has been operating in a production mode since August 2017, was in progress. The following data processing chains were implemented: reconstruction of real data, filtering of events. In 2019, a chain of job processing for the Monte Carlo modeling and reconstruction was implemented. Two grid nodes, namely, CERN and JINR, take part in data processing on a regular basis. In 2019, the Stampede 2 and Frontera supercomputers from the Texas Advanced Computing Centre (USA) were also connected to this system. The current architecture of the system and the workflow of processing are shown in Fig. 11.

One of the important subjects of analysis in different fields is streaming data, i.e., continuously incoming new information, on which it is necessary to carry out a historical analysis and to make operational decisions. At present, using Big Data technologies seems to be the most effective for studying streaming data. A prototype of the analytical platform was created at LIT for these purposes. The following services are deployed: 1) Apache Spark for analyzing incoming data in memory; 2) streaming data processing and storage system Apache Kafka for uninterrupted data transfer and intermediate storage; 3) Mesos for managing the resources of the computing cluster; 4) Elasticsearch for primary profiling and analysis, as well as incoming data storage; 5) Docker server for deploying supporting services.

The work on the further development of the APT EVM project management system for NICA was in progress. An English version of the system, required for presenting information to the Supervisory Council, was elaborated. A summary report, necessary for the timely coordination of planned expenses with the Russian Federation agreement on additional financing of the NICA project, was formed. The ongoing support and development of the system were carried out.

A number of works on the extension and current maintenance of the "Dubna" electronic document system (EDS) were completed: new documents were worked out and put into operation; a module for gathering statistics was developed; modules of the subsystem for electronic archive storage and search for contracts of capital construction and repair and construction works were elaborated.

The development upon users' requests and the ongoing maintenance of the following systems: Personal Information System (PIN), Information Search System (ISS), JINR Document Base and others, were carried out.

In 2019, the ongoing maintenance of 1C programs, training and support of users, the elaboration of new modules were carried out. A conference management module, which enables full financial accounting of JINR events, was developed and put into operation; in addition, to simplify the payment of participation, a specialized web site of accepting Internet payments (acquiring) was created.

A system of additional analytics of the Topical Plan, which allows taking into account expenses in frames of individual projects within one theme, was created as part of the development of management accounting. The given system was successfully tested in three Laboratories.

In 2019, a new version of the LIT portal (http://lit.jinr.ru) was created in the CMS Drupal environment. The JINR Information System of Scientific Certification (ISSC) was elaborated and put into operation (https://dissertations.jinr.ru/); it is designed to submit documents by applicants of scientific degrees to JINR Dissertation Councils, as well as for further work with these documents by scientific secretaries and Council members. The maintenance of the "Visit Center" portal (https://visitcentre.jinr.ru/) and the web site of "Physics of Elementary Particles and Atomic Nuclei" (PEPAN) and "Letters to PEPAN" journals (http://pepan.jinr.ru/) was performed. The traditional development, creation and maintenance of web sites of conferences, symposia at the request of the Laboratories and other JINR subdivisions were carried out.

A review devoted to the analysis of information acquisition and processing devices used in high-energy experiments, as well as of the classification and the need of information systems and databases in the NICA project experiments, was published together with VBLHEP [9]. The study singled out systems and components, the implementation or adaptation of which is vitally necessary to the NICA experiments.

In 2019, the work related to the development of an interface for the interaction of the jAliEn middleware and central services of the ALICE experiment was performed. The code integrated into the jAliEn environment and enabling to identify users, create working sessions, as well as send jobs to central services, by using Java Websocket, was developed [10].

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

One of the main activities of LIT is to provide mathematical, algorithmic and software support for experimental and theoretical studies conducted at JINR. A summary of some of the results is presented below.

When processing Big Data, the problem of finding sets of identical records in the whole volume of the information array often arises. As a new approach to connecting records, a study on the application of locality-sensitive hashing methods to search for the nearest lines in terms of the edit distance was carried out. A method to speed up the connection of records in Big Data was developed. A high performance of the given approach to reducing the dimension and searching for the nearest neighbors in the multidimensional vector space was shown [11].

Within the framework of the JINR NICA project, the three-dimensional modeling of the collider multipole corrector and the vertical output magnet was carried out. The magnet parameter influence on the field distributions in the magnet working areas was studied [12].

A workable prototype of the Geometry Database for the BM@N experiment was developed on the basis of the experience of the Geometry Database design for the CBM experiment [13]. The developed information system includes a database, intuitive and compact GUI tools and API tools as a set of ROOT macros. The Geometry Database is being prepared for production.

Research related to the study of the main characteristics of the MPD detector of the NICA accelerator complex, using data on proton–proton interactions obtained by simulating this detector with the help of the Monte Carlo method, was carried out [14]. The obtained results can be used to justify the necessity to build this detector and develop a high-level trigger system including machine learning techniques.

New effective tracking methods based on the graph neural network (GNN) are actively developed and tested for the GEM detector of the BM@N experiment at NICA. This approach was well adapted for solving the known fake hit problem inherent to strip detectors like GEM with the help of minimum branching tree algorithms [15].

A peak experimentally detected in the ratio of the number of strange kaons to nonstrange pions in the energy region $\sqrt{s_{NN}} = 8{-}10$ GeV was considered within the Nambu–Jona-Lasinio model with the Polyakov loop [16]. As a result of the study, it was shown that the splitting in the mass spectrum of kaons of different signs was observed at low energies of ion collision (at high densities), which might cause a difference in the behavior of the ratio of kaons to pions of different signs; the peak value of the $K^+/\pi^+$ ratio in the model depends on the properties of the substance (strange and baryonic chemical potentials and temperature); the peak position significantly depends on the curvature of the position of the phase diagram.

A set of parameters of the HIJING model (Heavy Ion Jet INteraction Generator) widely used for simulations of nucleus–nucleus collisions was found, and some improvements, which allow one to describe the NA49 and NA61/SHINE collaboration data on proton–proton interactions at momenta of projectile protons in the rest frame of target protons from 20 up to 158 GeV/$c$, were proposed. The modified model was applied to analyze nucleus–nucleus collisions at high energies, and it was shown that the model could describe the main characteristics of those interactions [17].

Parameters of the reactions $p$, $d$, He, $\mathrm{C}+\mathrm{C}$, Ta, and $\mathrm{C}+\mathrm{Ne}$, Cu at momenta of 4.2, 4.5, and 10 GeV/$c$ per nucleon were calculated using the UrQMD model supplemented by the Statistical Multifragmentation Model (SMM). Azimuthal correlations of pions and protons produced in the listed reactions were calculated and compared with the experimental data obtained at VBLHEP on the SKM-200-GIBS and Propane Bubble Chamber installations. A good agreement between the calculations using UrQMD + SMM and the experimental data was achieved [18].

A Monte Carlo study was performed for modeling experimental results on the elastic scattering of $^{15}N$ ions from $^{11}B$, as well as for the analysis of systematic errors arising from the derivation of the elastic scattering cross section from experimental data within the EXPERTroot framework [19]. The developed software will be used for planning and analyzing similar experiments in the future.

Multiple improvements for the reconstruction algorithm of the particle trajectory on a single layer of the cathode strip chambers (CSC) detectors of the CMS experiment were developed [20]. The wavelet-based approach was adopted for overlapping signals delimitation. The tuning of the reconstruction for the special geometry ME1/1 chamber was performed, and as a result, the inefficiencies in the problematic regions were almost eliminated.

The development of discontinuous $hp$-adaptive schemes with parallel algorithms of two-level domain decomposition methods enabled highly precise three-dimensional projection-grid solutions with proved convergence. The advantage of the proposed method over the other known high-order approximation methods was demonstrated numerically [21]. Three-dimensional computations for finding an optimal configuration of the magnetic device with highly uniform magnetic fields for experiments with neutrons were continued as part of the collaboration with co-workers from FLNP.

Algorithms based on the basic element method were developed for the separation of neutron noise from slow power changes of IBR-2M. It was applied to both static and dynamic states of the reactor in the 0–2 MW power range. The algorithm speed is adequate for real-time monitoring [22].

In collaboration with FLNP, on the basis of the method of separated form factors (SFF), the analysis of SANS/SAXS experimental data for samples of various polydispersed vesicular systems, including the phospholipid transport nanosystem, was carried out. To increase the computational performance, the procedure of fitting the parameters of the SFF model to the experimental data of SANS and SAXS was implemented on the HybriLIT cluster using MPI techniques [23].

The $\varphi_0$-Josephson junction model in the "superconductor–ferromagnet–superconductor" system was investigated [24]. For numerical simulation in a wide range of parameters, which requires the significant computer time, a parallel MPI/C++ computer code was developed and implemented on the HybriLIT cluster and the "Govorun" supercomputer.

Numerical studies were performed for implementations of three different types of algorithms for solving band matrix systems of linear algebraic equations (SLAEs) obtained from the discretization of parabolic nonlinear partial differential equations. The results of the performance analysis of the implementations were obtained on the HybriLIT and Avitohol clusters [25].

Molecular dynamic simulations of long-range effects in metal targets irradiated with nanoclusters unveiled in depth the occurrence of fusion of high-temperature moving regions [26]. The temperature in the fusion region rises sharply, exceeding the melting temperature of the target. As a result, structural changes can occur in the crystal lattice at the target depth exceeding the penetration depth of the nanoclusters.

Methods and algorithms were developed for building finite difference schemes for systems of partial differential equations that possess the property of strong consistence [27].

To study constructive models of composite quantum systems, an efficient algorithm was developed [28] and implemented for decomposing the representations of the wreath products of finite groups into irreducible subrepresentations.

A method for reducing the Feynman integrals, depending on several kinematic variables and masses, to a combination of integrals with fewer variables was proposed. The method is based on the iterative application of functional equations proposed by the author [29].

The global indicator for quantization of the "classicality–quantumness" correspondence was introduced [30] and defined as a relative volume of the subspace with the positive Wigner function of the state space of an $N$-dimensional quantum system, and it was exemplified for the Hilbert–Schmidt ensemble of qubits and qutrits.

Computational experiments on quantum teleportation of the two-qubit Bell states done on the five-qubit quantum computer IBM Q were conducted. The comparison with such teleportation performed on the Feynman classical quantum simulator written in Maple was carried out [31].

## APPLIED RESEARCH

To continue the work on the RFBR project, a mobile application for detecting plant diseases, which uses the modern cloud infrastructure and technologies of deep learning to provide a new level of service to the farmers' community, was developed [32]. The application allows users to send photos and text descriptions of sick plants and get the cause of the illness and treatment.

The programs for calculating the dynamics of the beam of the SC230 superconducting cyclotron for proton therapy, developed at JINR DLNP with information and computing support of LIT in collaboration with the Institute of Plasma Physics (Hefei, China), were improved [33]. New algorithms, in which the components of the magnetic field outside the medium plane are calculated to the fourth order, were proposed. An algorithm for finding an equilibrium orbit for a large number of particles with different energies with a good calculation speed was implemented.

Some approaches to the intellectual analysis of the text as applied to the automated monitoring of the labor market were considered. A scheme for building an analytical system based on Big Data technologies was proposed. A system for monitoring the Russian labor market was created on the basis of the given methods [34].

## INTERNATIONAL COOPERATION

The creation of the second segment of the grid infrastructure within the AZ-IFAN grid site is a result of collaboration between LIT and the Institute of Physics of the National Academy of Sciences of Azerbaijan in the field of information technologies in 2019. The grid and cloud infrastructures work in a production mode [35].

In collaboration with colleagues from Bulgaria, microscopic optical potentials and differential cross sections for the quasielastic scattering of exotic nuclei $^{12,14}$Be on $^{12}$C nuclei at 56 MeV/nucleon and on protons at 700 MeV were calculated using different density models [36]. A good agreement of the theoretical results with the available experimental data of both quasielastic scattering and breakup processes was obtained.

Within the framework of the cooperation agreement between JINR and IKF (Frankfurt, Germany), the work, which presents ultrahigh resolution data on fully differential cross sections for single ionization of helium induced by the 1-MeV proton impact, was performed [37]. A reasonable agreement between the first Born approximation (FBA) and the experiment was obtained in the kinematic regime close to the Bethe ridge. Far from this region, the calculated binary peak was shifted with respect to the experiment. To solve this problem, several theoretical mechanisms beyond the customary FBA theory were analyzed. These mechanisms include a 3C model (three Coulomb functions), effective charges, off-shell pair $T$ matrices instead of pair potentials, and semiclassical postcollision interaction. The given combination can explain the observed discrepancy.

## MEETINGS, CONFERENCES

In 2019, the 10th International Conference “Mathematical Modeling and Computational Physics” (MMCP’2019) and the XXVII International Symposium on Nuclear Electronics and Computing (NEC’2019) were organized with the participation of LIT.

The International Conference MMCP’2019 was held in the High Tatras (Slovakia) on 1–5 July. Organizers of the conference were JINR LIT, Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) (Bucharest, Romania), the Institute of Experimental Physics of the Slovak Academy of Sciences (Košice, Slovakia), the Technical University of Košice (Slovakia), and Pavol Jozef Šafárik University (Košice, Slovakia).

More than 100 scientists and specialists from JINR and 15 countries (Armenia, Belarus, Bulgaria, the United Kingdom, Germany, Egypt, India, Canada, Moldova, Russia, Romania, Slovakia, the USA, Finland, and the Czech Republic) participated in the conference.

The International Computer School “Machine Learning, Parallel and Hybrid Computations & Big Data Analytics” was held in frames of the conference. In total, 26 students and postgraduate students from Slovakia, Romania, and Russia took part in the school.

The proceedings of the conference (revised selected papers) were published (Math. Modeling and Comput. Phys. (MMCP’2019) // Eur. Phys. J. Web Conf. 2020. V. 226).

## REFERENCES


1. *Dolbilov A. et al.* // CEUR Workshop Proc. 2019. V. 2507. P. 16–22.
2. *Baginyan A. et al.* // CEUR Workshop Proc. 2019. V. 2507. P. 321–325.
3. *Balashov N. et al.* // CEUR Workshop Proc. 2019. V. 2507. P. 185–189.
4. *Balashov N. et al.* // CEUR Workshop Proc. 2019. V. 2507. P. 256–260.

5. *Balashov N., Kutovskiy N., Priakhina D., Sokolov I.* // Eur. Phys. J. Web Conf. 2020. V. 226. P. 03002.
6. *Uzhinskiy A., Ososkov G., Frontasyeva M.* // Adv. Ecol. Environ. Res. 2019. V. 4, Iss. 6. P. 168–176.
7. *Belyakov D. V. et al.* // CEUR Workshop Proc. 2019. V. 2507. P. 316–320.
8. *Petrosyan A., Malevanniy D.* // CEUR Workshop Proc. 2019. V. 2507. P. 94–98.
9. *Alexandrov E. et al.* // Modern Information Technologies and IT Education. 2019. V. 15, No. 3. P. 645–650 (in Russian).
10. *Korenkov V., Kondratyev A., Bondyakov A.* // Modern Information Technologies and IT Education. 2019. V. 15, No. 3. P. 573–585 (in Russian).
11. *Kadochnikov I. S., Papoyan V. V.* // CEUR Workshop Proc. 2019. V. 2507. P. 219–224.
12. *Akishin P. G., Sapozhnikov A. A.* // Discrete and Continuous Models and Applied Computational Science. 2019. V. 27, No. 1. P. 60–69.
13. *Akishina E., Alexandrov E., Alexandrov I., Filozova I., Gertsenberger K., Ivanov V., Priakhina D., Shestakova G.* // Eur. Phys. J. Web Conf. 2020. V. 226. P. 03003.
14. *Zinchenko D. A., Nikonov E. G., Zinchenko A. I.* // Comput. Res. Modeling. 2019. V. 11, No. 1. P. 87–94 (in Russian).
15. *Baranov D., Goncharov P., Ososkov G., Shchavelev E.* // AIP Conf. Proc. 2019. V. 2163. P. 040001; https://doi.org/10.1063/1.5130100.
16. *Friesen A. V., Kalinovsky Yu. L., Toneev V. D.* // Phys. Rev. C. 2019. V. 99. P. 045201. doi: https://doi.org/10.1103/PhysRevC.99.045201.
17. *Uzhinsky V. V., Galoyan A.* // The 69th Intern. Conf. “Nucleus-2019” on Nucl. Spectroscopy and Nucl. Struct. “Fundamental Problems of Nuclear Physics, Nuclei at Borders of Nucleon Stability, High Technologies”, Dubna, 1–5 July 2019. Book of Abstracts. P. 291; Bull. Rus. Acad. Sci.: Phys. (submitted).
18. *Chkhaidze L., Chlachidze G., Djobava T., Galoyan A., Kharkhelauri L., Togoo R., Uzhinsky V.* // FERMILAB-PUB-18-497-TD. arXiv:1808.02661[nucl-ex]; Eur. Phys. J. A. 2019. V. 55. P. 7; https://doi.org/10.1140/epja/i2019-12674-9.
19. *Satyshev I., Belogurov S., Kozlov M., Mauyey B., Ovcharenko E., Schetinin V.* // AIP Conf. Proc. 2019. V. 2163. P. 060003; https://doi.org/10.1063/1.5130109.
20. *Voytishin N. (CMS Collab.)* // CEUR Workshop Proc. 2019. V. 2507. P. 120–124. CMS note CR-2019/268.
21. *Yuldasheva M. B., Yuldashev O. I.* // Comput. Math. Modeling. 2019. V. 30, No. 3. P. 267–284. doi: 10.1007/s10598-019-09453-y.
22. *Korepanova N. V., Dikusar N. D., Pepelyshev Y. N., Dima M.* // Annals of Nuclear Energy. 2019. V. 131. P. 475–482.
23. *Kiselev M. A., Zemlyanaya E. V. et al.* // J. of Surface Investigation: X-Ray, Synchrotron and Neutron Techniques. 2019. V. 13, No. 1. P. 111–116.
24. *Panayotova S., Bashashin M., Zemlyanaya E., Atanasova P., Shukrinov Yu., Rahmonov I.* // Eur. Phys. J. Web Conf. 2020. V. 226. P. 02018;
*Serdyukova S. I.* // Zh. Vychisl. Mat. Mat. Fiz. 2019. V. 59, No. 12. P. 16–176 (in Russian).
25. *Veneva M., Ayriyan A.* // Stud. Comput. Intell. 2019. V. 793. P. 407–419. doi: 10.1007/978-3-319-97277-0_33.
26. *Sharipov Z. A. et al.* // Bull. Rus. Acad. Sci.: Phys. 2019. V. 83, No. 10. P. 1306–1310 (in Russian).
27. *Michels D. L., Blinkov Yu. A., Gerdt V. P., Lyakhov D. A.* // J. Math. Sci. 2019. V. 240, No. 5. P. 665–677.
28. *Kornyak V. V.* // Lect. Notes Comput. Sci. 2019. V. 11661. P. 300–314.
29. *Tarasov O. V.* // Theor. Math. Phys. 2019. V. 200, No. 2. P. 1205–1221.
30. *Abgaryan V., Khvedelidze A., Torosyan A.* // J. Math. Sci. 2019. V. 240. P. 617–633.
31. *Gerdt V. P., Kotkova E. A., Vorob’ev V. V.* // Part. Nucl., Lett. 2019. V. 16, No. 6. P. 975–984.
32. *Goncharov P., Ososkov G., Nechaevskiy A., Uzhinskiy A., Nestsiarenia I.* // Stud. Comput. Intell. 2019. V. 799. P. 151–159; https://doi.org/10.1007/978-3-030-01328-8_16.
33. *Karamysheva T. et al.* // Nucl. Instr. Meth. A. 2019. V. 940. P. 61–65.
34. *Belov S. D., Javadzade J. N., Kadochnikov I. S., Korenkov V. V., Zrelov P. V.* // CEUR Workshop Proc. 2019. V. 2507. P. 469–472.
35. *Bondyakov A.* // Modern Information Technologies and IT Education. 2019. V. 15, No. 3. P. 586–595 (in Russian).
36. *Lukyanov V. K., Kadrev D. N., Zemlyanaya E. V., Lukyanov K. V., Antonov A. N., Gaidarov M. K.* // Phys. Rev. C. 2019. V. 100. P. 034602.
37. *Chuluunbaatar O. et al.* // Phys. Rev. A. 2019. V. 99. P. 062711. doi: https://doi.org/10.1103/PhysRevA.99.062711.