Annex 3.

APPROVED

JINR DIRECTOR

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SCIENTIFIC AND TECHNICAL REASONING FOR THE OPENING / RENEWAL OF THE PROJECT IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the research project of the theme

1.1. Theme code
02-2-1125-2011/2023

1.2. Project
TAIGA

1.3. Laboratory
DLNP

1.4. Scientific field
Particle physics

1.5. The name of the Project
Astrophysical research in the TAIGA experiment

1.6. Project leader
A. Borodin

1.7. Deputy project leader

1.8. Scientific supervisor of the project

2. Scientific rationale and organisational structure

2.1. Annotation

Multi-messenger astronomy and, in particular, high-energy gamma-ray astronomy are key areas of modern astrophysics. The TAIGA astrophysical complex (Tunka Advanced Instrument for Cosmic Ray Physics and Gamma-ray Astronomy) (Fig. 1) is designed to study gamma radiation and charged cosmic rays in the energy range of 10^{13}–10^{18} eV by detecting Cherenkov radiation from extensive air showers (EAS). It is located in the Tunka Valley (51.49° N, 103.04° E), 50 km from Lake Baikal.

TAIGA implements a hybrid approach, combining a wide-angle array of Cherenkov stations (TAIGA-HiSCORE) and imaging atmospheric Cherenkov telescopes (TAIGA-IACT), as well as subsystems for detecting the charged component of air showers (Tunka-Grande / TAIGA-Muon). Such an approach increases the effective area in the 40–1000 TeV energy range while simultaneously improving the suppression of background from charged cosmic rays [1].

During the reporting period, the priority of the data analysis group has been the development and validation of analysis pipelines for mono, stereo, and hybrid events, improving the efficiency of gamma–hadron separation using both classical analysis methods and machine learning, ensuring the reproducibility of analyses (repositories / code review / task tracking), and preparing simulation datasets and a knowledge infrastructure to accelerate software development and maintenance.

These tasks support both the current scientific program (including the reconstruction of energy spectra of observed gamma-ray sources, primarily the standard candle—the Crab Nebula, as well as studies of the energy spectrum and mass composition of cosmic rays) and the further development of the complex (including the expansion of TAIGA-IACT and the preparation of the TAIGA-100 project) [2].

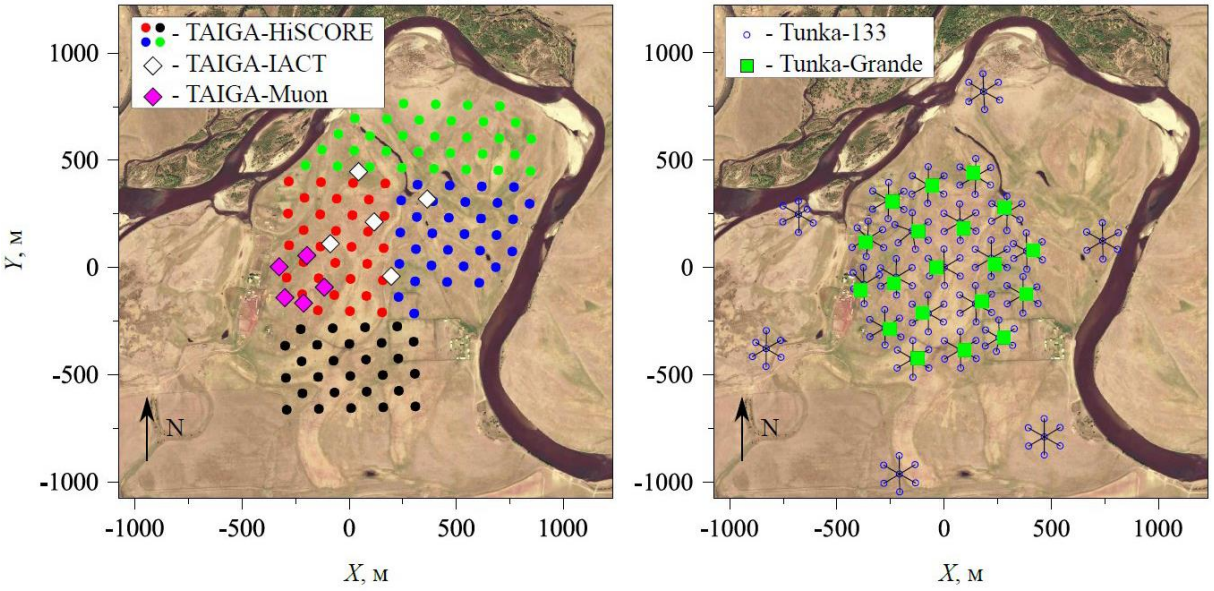

Fig. 1. Layout of the TAIGA detector array. On the left are installations aimed at detecting EAS induced by gamma rays; on the right are installations aimed at detecting hadronic EAS (cosmic rays).

2.2. Scientific justification (purpose, relevance and scientific novelty, methods and approaches, methodologies, expected results, risks)

The key idea is to combine within a single complex two fundamentally different methods for detecting Cherenkov radiation from extensive air showers (EAS)—namely, imaging and non-imaging (timing) techniques. These include imaging atmospheric Cherenkov telescopes (IACTs), which record Cherenkov images of EAS, and wide-angle Cherenkov detectors. The main advantage of operating IACTs together with wide-angle Cherenkov installations is the ability to identify gamma-ray–induced events against the background of EAS produced by charged cosmic rays, using data from one or several IACTs while incorporating information on the energy, core position, and arrival direction of the shower axis reconstructed from the wide-angle array.

At the group level, a software package (framework) is currently being actively developed to perform comprehensive data processing for the observatory. This includes the formation of datasets from simulated and raw experimental data, construction of a modular processing pipeline, optimization of gamma–hadron separation criteria based on these datasets, and ultimately the evaluation of detection efficiency and reconstruction of the energy spectrum of the studied source. The need for such a framework is обусловлена the complexity of the data processing, as the level of hadronic background relative to the gamma-event flux is high and, under TAIGA-IACT observational conditions, can reach up to five orders of magnitude (depending on observation conditions).

Relevance.

1. For energies ≳10 TeV, the efficiency of stereo observations and the quality of shower parameter reconstruction strongly depend on detector calibration and response, as well as on the criteria for gamma–hadron separation. In TAIGA-IACT, a stereo data analysis methodology has been developed (including simulation, reconstruction of direction/axis/energy/X_{max}, optimization of gamma–hadron separation criteria, and estimation of the effective area), which makes it possible to detect weak sources above 10 TeV within reasonable observation times on the order of hundreds of hours [3].
2. A current trend in IACT astronomy is the transition from manual parameterizations to approaches based on machine learning and deep learning, as well as hybrid feature sets. Based on TAIGA data, results have been published both for classical analyses (including the Crab spectrum) and for neural network–based approaches to gamma–hadron separation [4].
3. The development of data processing methods using large language models. In global practice, agent-based systems are currently being активно adopted, enabling automation of data format synchronization, documentation generation, and software development for rapid hypothesis testing. In particular, members of the HESS and CTA collaborations have demonstrated the applicability of tools based on instruction-tuned large language models for supporting engineering and data analysis in the context of CTAO [5]. These systems show that agent-based approaches can understand project documentation and codebases, interactively generate, verify, and refine program code, interact with external APIs and user queries, and automatically correct errors through iterative self-validation cycles, significantly accelerating data analysis. Such approaches reflect the evolution of general data analysis methodologies and define requirements for developing dedicated RAG/agent-based frameworks for TAIGA, oriented toward integration with experimental documentation, code repositories, and automated validation of results.
4. Existing experimental data indicate that, for significant progress in the PeV gamma-ray astronomy domain, the areas of current installations must be increased by one to two orders of magnitude. One possible implementation is an installation with an area of about 100 km², provisionally referred to as TAIGA-100. The group plans to actively participate in the development of a working prototype of the TAIGA-100 installation at the TAIGA astrophysical complex [6,7], which will include the main detector components of the new facility: large-area water Cherenkov muon detectors, wide-angle Cherenkov detectors for extensive air showers, and scintillation detectors for charged particles in EAS.**Научная новизна.**

Scientific novelty at the group level in data processing consists of:

1. The unification of mono/stereo/hybrid analysis pipelines with automated optimization of gamma–hadron separation criteria and calculation of the effective area;
2. Systematic comparison of gamma–hadron separation methods (threshold cuts on Hillas parameters, random forest, fully connected neural networks, and CNNs applied to images) using large simulated datasets, with subsequent transfer of the optimized settings to experimental data;
3. Development of camera geometry transformations (transition from a hexagonal to a rectangular coordinate grid) to isolate different components of the EAS signal;
4. Construction of a knowledge base and development of RAG/agent-based systems oriented toward engineering and analytical data processing tasks.

At the collaboration level, during 2023–2026, stereo data processing has been actively developed, and corresponding publications on reconstruction, sensitivity, and spectra in stereo mode have been released [3].

Methods and approaches / methodologies.
The methodological basis includes:

- simulation of extensive air showers (EAS) and detector response, reconstruction of parameters (direction, core position, X_max, energy), estimation of effective area, and optimization of gamma–hadron separation criteria;
- standard IACT observation modes, including wobble mode for background estimation; [8]
- ML approaches (random forests and neural networks) for event classification by primary particle type;
- engineering methods for detector maintenance (e.g., measurements of attenuation length for water Cherenkov detectors), based on established community methods for monitoring detector health and the requirements of each installation.

The main research directions of the facility include problems of gamma-ray astronomy and cosmic ray physics:

2.2.1. Study of the energy spectrum of gamma rays from Galactic sources and search for new gamma-ray sources.

It is planned to reconstruct the gamma-ray spectrum from Galactic PeVatrons (Dragonfly, J2227+610 (G106.3+2.7), J2031+415 (Cygnus Cocoon), Cygnus X-3, CTA-1), which are important for understanding the origin of cosmic rays.

2.2.1.2. Monitoring of gamma-ray flux from nearby extragalactic sources.

Studying the shape of the gamma-ray spectrum at energies above 8–10 TeV from extragalactic sources will allow constraints to be placed on the density of the extragalactic background light (EBL) and enable searches for axion-like particles.

2.2.1.3. Search for TeV gamma rays from gamma-ray bursts and gamma rays correlated with high-energy neutrinos.

Within the development of multi-messenger astronomy at the TAIGA facility, a search is being conducted for TeV gamma rays associated with gamma-ray bursts and events registered by neutrino observatories. For this purpose, an automated alert processing system based on GCN and AMON has been implemented, including alerts from the FERMI, SWIFT, and INTEGRAL satellites, as well as from the IceCube neutrino telescope. A software system, TAIGA GCN Monitor, has been developed, enabling automatic generation of observation tasks and pointing of TAIGA-IACT telescopes toward the source with a typical response time of less than 2 minutes. Over the past two years, about 15 alerts have been processed, including 8 gamma-ray bursts and events associated with IceCube neutrino alerts. These studies aim at the search for correlated γ- and ν-signals [1].

The commissioning of a 10 m diameter telescope with a 200 GeV energy threshold will significantly expand the capabilities of the array for detecting gamma rays from gamma-ray bursts, enabling the observation of sources at redshifts of 0.3–4.

2.2.1.4. Search for cosmic accelerators in which protons are accelerated to energies of 100–10,000 TeV.

To search for such accelerators, studies will be carried out of the properties of the charged cosmic-ray spectrum in the energy range 100–10,000 TeV. The fraction of protons and helium nuclei among charged cosmic rays will be measured. The separation of the light component of cosmic rays in this range is performed using hybrid events, i.e., extensive air showers simultaneously detected by the TAIGA-IACT atmospheric Cherenkov telescopes and the wide-angle TAIGA-HiSCORE array. Using this method, the spectrum of the light component of cosmic rays has been obtained [9], which is in good agreement with the results of the LHAASO experiment [10]. Further extension to higher energies is also possible.

2.2.1.5. Study of the mass composition of cosmic rays in the transition region from Galactic to extragalactic cosmic rays.

According to current understanding, the transition from Galactic to extragalactic cosmic rays occurs in the energy range of 10^{17}–10^{18} eV. Evidence for this transition is provided by a break in the cosmic-ray energy spectrum, the so-called “second knee.” However, measurements from different experiments place the position of this break at different energies, ranging from 10^{17} eV to 3×10^{17} eV, which complicates its astrophysical interpretation. There is also no consensus among experiments regarding the behavior of the cosmic-ray mass composition in this region. It is possible that this energy range includes a contribution from cosmic rays originating from new types of Galactic sources, the so-called B-component proposed by M. Hillas.

To investigate this energy region, a minor upgrade of the TAIGA-HiSCORE array will be carried out, combined data from the Tunka-Grande and TAIGA-Muon installations will be used, and new machine-learning-based approaches for mass composition studies will be developed.

2.2.1.6. TAIGA-100

Active participation in the creation of a working prototype of the TAIGA-100 installation within the TAIGA astrophysical complex, including the main detectors of the new setup: large-area water Cherenkov muon detectors, wide-angle air Cherenkov detectors for extensive air showers, and scintillation detectors for charged particles in extensive air showers.

Expected results.
The following outcomes are anticipated:

- increased statistical significance and an extended energy range of reconstructed spectra for observed sources (Crab Nebula, Mrk 421, etc.);
- improved efficiency of gamma–hadron separation through the extraction of new features and the application of neural-network-based approaches;
- readiness of the software package for an expanded stereoscopic configuration of TAIGA-IACT and for hybrid measurements taking into account the muon component;
- a developed and well-documented knowledge base, as well as RAG/agent-based tools for interactive support of analysis and development;
- implementation of a remote alignment system for composite mirror elements;
- implementation of composite mirror technology, followed by their production and commissioning on the atmospheric Cherenkov telescopes (IACT);
- fabrication and commissioning of a 10 m diameter atmospheric Cherenkov telescope with a 12 m focal length composite mirror;
- development of new wide-angle detectors;

- development, assembly, and commissioning of components of the water Cherenkov muon detector system;
- participation in the deployment and operation of the TAIGA-100 prototype installation;
- preliminary design studies of new detectors within the project framework.

Risks and mitigation measures.
Key risks and corresponding mitigation measures include:

- systematic discrepancies between MC simulations and data (optics/atmosphere/calibration effects) → regular validation using a standard candle (Crab Nebula), calibration of optical transmission and system response, and strict documentation of instrumental response versions;
- degradation of reconstruction and gamma–hadron separation performance when changing configurations (addition of telescopes, modified layouts, new detectors) → modular pipeline design and comparative validation using "frozen" MC datasets corresponding to different configurations;
- ML overfitting and lack of transferability to real data → strict data splitting protocols, systematic uncertainty control, domain validation on independent observation seasons, and benchmarking against classical methods [11];
- risks of hallucinations and errors in RAG/agent-based systems → strict curation of knowledge base sources, isolated code execution, iterative validation and self-correction procedures, and systematic testing for errors and reproducibility.

Additional project risks are associated with potential lack of funding in the context of increasing international competition in gamma-ray astronomy, as well as possible delays in replacing unavailable components with equivalent alternatives during the design and construction of new Cherenkov telescopes, including both small wide-angle instruments and large-aperture mirror systems.

References.

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7. Project of the Astrophysical Complex TAIGA-100. Physics of Atomic Nuclei, 2026, Vol. 89, No. 1, pp. 11–16. DOI: 10.1134/S1063778826600181

8. TAIGA-IACT telescopes for the Multi-Messenger observations, PoS ICRC2023 939, 10.22323/1.444.0939

9. Estimation of the Light Component Spectrum of Cosmic Rays in the Energy Range of 200–10 000 TeV by the Hybrid Method, Bulletin of the Russian Academy of Sciences Physics 89(6), SJR 0.253, https://doi.org/10.1134/S1062873825711638

10. Measurements of All-Particle Energy Spectrum and Mean Logarithmic Mass of Cosmic Rays from 0.3 to 30 PeV with LHAASO-KM2A, Z.Cao (LHAASO collab.), Phys.Rev.Lett. 13 (2024) 131002

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2.3. Estimated completion date

The expected time horizon for the proposed research direction (data processing / ML / infrastructure development and support for the extension of the installation) is 3 years (the next reporting cycle), with annual validation of key scientific results using standard sources and updates of procedures to accommodate the expansion of TAIGA-IACT and hybrid detection channels. The rationale is based on the planned expansion of TAIGA-IACT and upgrades of TAIGA-1 / TAIGA-100, as reflected in publications and the current status of the collaboration. [1]

2.4. Participating JINR laboratories

DLNP, VBLHEP, FLNP, LIT

2.4.1. MICC resource requirements

Computing resources	**Distribution by year**		
	2027	2028	2029
Data storage (TB) - EOS - Ribbons	-	-	-
Tier 1 (core-hour)	-	-	-
Tier 2 (core-hour)	200 hours GPU (in H100 GPU equivalent)	200 hours GPU (in H100 GPU equivalent)	200 hours GPU (in H100 GPU equivalent)
SC “Govorun” (core-hour) - CPU - GPU	200	200	200
Clouds (CPU cores)	20	20	20

2.5. Participating countries, scientific and educational organisations

Organisation	Country	City	Participants	Type of agreement
SINP MSU	Russia	Moscow	L.A. Kuzmichev, L.G. Sveshnikova, +15 persons; P.A. Klimov, +5 persons; D.M. Podorozhny, +10 persons	Consortium agreement GAMMA, cooperation agreement
API ISU	Russia	Irkutsk	N.M. Budnev, R. Mirgazov, D.P. Zhurov, +29 persons	Consortium agreement GAMMA, cooperation agreement
INR RAS	Russia	Moscow	B.K. Lubsandorzhiev, +5 persons	Consortium agreement GAMMA
IZMIRAN	Russia	Moscow region	V.S. Ptuskin	Consortium agreement GAMMA
NRNU MEPHi	Russia	Moscow	A.A. Petrukhin, I.I. Yashin, +5 persons	Consortium agreement GAMMA
NSU	Russia	Novosibirsk	E.A. Kravchenko, +5 persons	Consortium agreement GAMMA
INR SB RAS	Russia	Novosibirsk	E.A. Kravchenko, +4 persons	Consortium agreement GAMMA
Altai State University	Russia	Barnaul	A.A. Lagutin, R.I. Raykin, N.V. Volkov	Consortium agreement GAMMA
Institute of Nuclear Physics, Ministry of Energy of the Republic of Kazakhstan	PKazakhstan	Almaty	E.S. Mukhametjanov, +5 persons	Additional agreement No. 1 JINR–INP Almaty
University “Dubna”	Russia	Dubna	I.B. Nemchonok, A.M. Morzhukhin	Cooperation agreement

2.6. Co-executing organizations

1. **Skobeltsyn Institute of Nuclear Physics, MSU, Moscow, Russia**
   - Data processing and physics analysis, fabrication of IACT cameras, data acquisition, Monte Carlo simulations.

2. **Institute of Applied Physics, ISU, Irkutsk, Russia**

   - "Tunka" infrastructure, data acquisition, IACT and HiSCORE control electronics, detector deployment, HiSCORE Monte Carlo simulations and data analysis.

3. **Institute for Nuclear Research RAS, Moscow, Russia**

   - Photomultiplier tube testing and data processing.
   - Methodological tasks: IACT design and calibration, data analysis, HiSCORE photomultipliers, Monte Carlo simulations for HiSCORE and IACT.

4. **IZMIRAN, Moscow region, Russia**

   - Theoretical support.

5. **MEPhI, Moscow, Russia**

   - Data analysis, fabrication of IACT camera electronics, Monte Carlo simulations, development and testing of scintillation detectors.

6. **JINR, Dubna, Russia**

   - Design, fabrication, and testing of mechanical parts of IACT at JINR; participation in software development and Monte Carlo simulations for data taking in the Tunka region and autonomous analysis.
   - Production of IACT mirrors and mirror drive systems, measurements, and calibration of detector components.

7. **Novosibirsk State University, Novosibirsk, Russia**

   - Design and fabrication of muon detectors.

8. **Institute of Nuclear Physics SB RAS, Novosibirsk, Russia**

   - Design and fabrication of scintillation muon detectors.
   - IACT electronic components.

9. **Altai State University, Barnaul, Russia**
10. **Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan, Almaty, Kazakhstan**

    - Participation in the development and testing of the OLVE-HERO prototype, Monte Carlo simulations of the OLVE-HERO experiment, prototypes at the Nuclotron, JINR reactor, and Tien Shan high-altitude cosmic ray station, as well as data processing.

11. **University “Dubna”**

- Design and fabrication of composite mirrors and large-aperture optical elements for Cherenkov detectors.

2. **3. Staffing**
3. **3.1. Staffing needs in the first year of implementation** (total number of participants)

№№ п/a	**Category employee**	**Core staff Amount of FTE**	**Associated Personnel Amount of FTE**
1.	scientific staff	5	
2.	engineers	2	
3.	professionals	2	
4.	employees		
5.	workers	1	
Total:		**10**	

3.2. Human resources available

3.2.1. JINR core staff (total number of participants)

№№ п/a	**Category of employees**	**Division**	**Position**	**Amount of FTE**
1.	scientific staff	DLNP	A.N. Borodin, Head of Section	1
		VDLHEP	N.V. Gorbunov, Head of Section	0,1
		DLNP	P.A. Bezyazyakov, Senior Researcher	1
		DLNP	V.M. Grebenyuk, Senior Researcher	1
		DLNP	Kh. Karatash, Junior Researcher	1
		LIT	I. Satyshov, Junior Researcher	0,5
2.	engineers	DLNP	A.V. Shaikovsky, Lead Engineer	1
		DLNP	S.Yu. Porokhovoy, Lead Engineer	0,1
		DLNP	A.A. Grinyuk, Engineer	1
			A.N. Shalyugin,	0,1

		DLNP	Senior Engineer	
3.	professionals	DLNP DLNP	A.V. Blinov, Intern Researcher A.D. Ivanova, Intern Researcher	1 0,5
4.	workers	DLNP	M.I. Dzhakupov, Mechanical Fitter	1
Total:				**9,3**

3.2.2. JINR associated personnel (total number of participants)

№№ п/а	Category of employees	Partner organisation	Amount of FTE
1.	Scientific employees		
2.	engineers	University "Dubna"	2
3.	professionals		
4.	workers		
Итого:			**2**

4. Financial support

4.1. Total estimated cost of the project / subproject

Forecast of total estimated project cost for the implementation period 2027–2029: 288 thousand USD, including 45 thousand USD for international collaboration, 93 thousand USD for materials, and equipment and services provided by external organizations.

4.2. Extrabudgetary funding sources

Estimated funding from co-executors/customers - total.

Project Leader Бородин / Бородин А.Н /

Date of submission of the project to DSOA: _____
Date of decision of the laboratory's STC: _____ document number: _____
Year of the project opening: _____
(for renewable projects) -- Project start year: _____

Schedule proposal and resources required for the implementation of the Project

Names of costs, resources, sources of funding			Cost (thousands of dollars) resource requirements	Cost, distribution by year		
				1st year	2nd year	3rd year
		International cooperation (IC)	45	15	15	15
		Materials	93	31	31	31
		Equipment and third-party services (commissioning)	150	50	50	50
		Commissioning work				
		Services of research organisations				
		Acquisition of software				
		Design/construction				
		Service costs (*planned in case of direct project affiliation)*				
Resources required	**Norno-hours**	Resources				
		– the amount of FTE,	27,9	9,3	9,3	9,3
		– accelerator/installation,				
		– reactor,….				
Sources of fundin	**Budgetary resources**	JINR budget *(budget items)*	**288**	**96**	**96**	**96**
	Extrabudgetary (supplementary estimates)	Contributions by co-contractors Funds under contracts with customers Other sources of funding				

Project Leader _____ / Бородин А.К. /

Laboratory Economist _____ / Usova /

APPROVAL SHEET FOR PROJECT

NAME OF THE PROJECT

Astrophysical research in the TAIGA experiment

SHORT NAME OF THE PROJECT TAIGA

PROJECT CODE: 02-2-1099-2010

THEME CODE: 02-2-1099-3-2015/2026

PROJECT LEADER (s) A.N. Borodin

AGREED

JINR VICE-DIRECTOR	SIGNATURE	NAME	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	NAME	DATE
CHIEF ENGINEER	SIGNATURE	NAME	DATE
LABORATORY DIRECTOR	SIGNATURE	R. Yakushev NAME	DATE
CHIEF LABORATORY ENGINEER	SIGNATURE	S. Volkovenko NAME	DATE
LABORATORY SCIENTIFIC SECRETARY	SIGNATURE	I.V. Simonenko NAME	DATE
THEME LEADER	SIGNATURE	A. Olshevskiy NAME	30.04.26 DATE
PROJECT LEADER	SIGNATURE	Бородин А.Н. NAME	DATE
PROJECT LEADER	SIGNATURE	NAME	DATE

- to sign in frame after PAC

APPROVED BY THE PAC	SIGNATURE	NAME	DATE