Annex 3.

Form of renewal for Project

APPROVED

JINR DIRECTOR

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"_____"2023 г.

PROJECT PROPOSAL FORM

Renewal of a research project of the large research infrastructure project within the Topical plan of JINR

1. General information on the research project of the theme

1.1 Theme code 02-2-1099-2010/2026.

1.2 Project Study of neutrino oscillations in the JUNO experiment (participation of JINR)

1.3 Laboratory DLNP

1.4 Scientific field particle physics

1.5 Title of the project JUNO

1.6 Project leader(s) D.V. Naumov

1.7 Project deputy leader(s) (scientific supervisor(s)) N.V. Anfimov, M.O. Gonchar

2 Scientific case and project organization

2.1 Annotation

JUNO, a reactor antineutrino experiment under construction in China, aims to determine the neutrino mass ordering with median sensitivity corresponding to 3−4 standard deviations alone and measure lepton mixing parameters with record sub-percent precision level. There is also a rich physics program including searches for proton decay, search for SN neutrino, most precise measurement of geo-, atmospheric and solar neutrino fluxes, as well as searches for physics beyond the Standard Model.

The satellite detector TAO will measure reactor electron antineutrino spectrum with unprecedented statistical uncertainty of order of 1% and energy resolution of $\sigma=2\%$ at energy of 1 MeV. Its sensitivity to the sterile neutrino mixing amplitude $\sin^2 2\theta_{14}$ in a range of $2\cdot10^{-2}\lesssim\Delta m^2_{41}\lesssim8$ eV^2 will be comparable to the world leading experiments.

JINR plays a major role in this project:

(i) JINR is responsible for design and production of high voltage units for JUNO large (20 inches) and small (3 inches) photomultipliers (PMTs) with an overall amount exceeding 25 thousand units;

(ii) JINR contributes to the construction of the Top Tracker (TT) detector by developing a mechanical support system, hardware and software for monitoring of T scintillators, tracks reconstruction and data acquisition system (DAQ). Also, JINR provided TT scintillators;

(iii) Mass tests and commissioning of large PMTs with help of JINR's designed and produced brand new scanning stations;

(iv) JINR contributed to the design and construction of JUNO's near detector — TAO: procurement of half of 4100 tiles (130k dices) of silicon photomultipliers (SiPM) and their mass-testing, production and operation of SiPM power supply system (4100 channels);

(v) JINR contributes to the software, leading a development of Global Neutrino Analysis (GNA) package for the oscillation analysis of data, developing simulation, reconstruction and analyses modules;

(vi) JINR has commissioned a data center dedicated to Monte Carlo production, data storage and processing for the JUNO experiment. This data center is expected to be one of three European data centers managing JUNO data;

JINR contributed to the JUNO project about 6M$. We request further 1.3 M$ for three years of the project extension 2024−2026 for a successful participation in JUNO and TAO experiments. The details of this request are presented in relevant parts of the project below.

2.2 Scientific case

Goals

JUNO aims to determine the neutrino mass ordering with median sensitivity corresponding to 3−4 standard deviations alone and measure lepton mixing parameters with record sub-percent precision level. There is also a rich physics program including searches for proton decay, search for SN neutrino, precise measurements of geo-, atmospheric and solar neutrino fluxes, as well as searches for physics beyond the Standard Model.

Relevance and scientific novelty

Neutrino mass ordering

The term "neutrino mass ordering" (MO) refers to establishing an appropriate ordering of masses of neutrino mass states $m_3 > m_1$ or $m_1 > m_3$. There is no easy and cheap way to measure the ordering. The MO can be determined using the following observables.

(i) **Neutrino oscillation** probability is sensitive to the MO in both appearance and disappearance channels. The disappearance channel is insensitive to the CP-violation phase which is currently unknown. On the contrary, the appearance channel suffers from the degeneracy due to an unknown CP-violating phase which biases the MO for neutrino energy of GeV range and the baseline of 700 km. At a larger baseline the degeneracy is relaxed due to an increasing matter effect.

JUNO[1] exploits the disappearance channel using reactor electron antineutrinos. After six years of data taking JUNO should be able to determine the mass ordering at 3 standard deviations alone, i.e. without external constraints on the value of Δm^2_{31}.

NOvA[2] and T2K[3] accelerator neutrino experiments are taking data and currently both favouring the normal mass ordering ($m_3 > m_1$) at about 1 and 1.6 standard deviations respectively. By 2025 NOvA expects a determination of MO varying between 0.5 and 5 standard deviations. The interval corresponds to the degeneracy due to an unknown CP-violating phase.

The DUNE[4], an accelerator neutrino experiment, should start data taking in 2027 with 50% of the beam power and 50% of the total detector mass. The final upgrade is expected in 2030. DUNE should be able to determine the MO at 5 standard deviations around 2029.

IceCube and its dense extension PINGU would be able to determine the MO using atmospheric

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[1] https://iopscience.iop.org/article/10.1088/0954-3899/43/3/030401

[2] https://novaexperiment.fnal.gov

[3] https://t2k-experiment.org

[4] https://www.dunescience.org

neutrinos. PINGU expected to reach ~4σ median significance after 5 years of data taking. The starting date is unknown.

The comparison of the experimental sensitivities is shown in Figure 1.

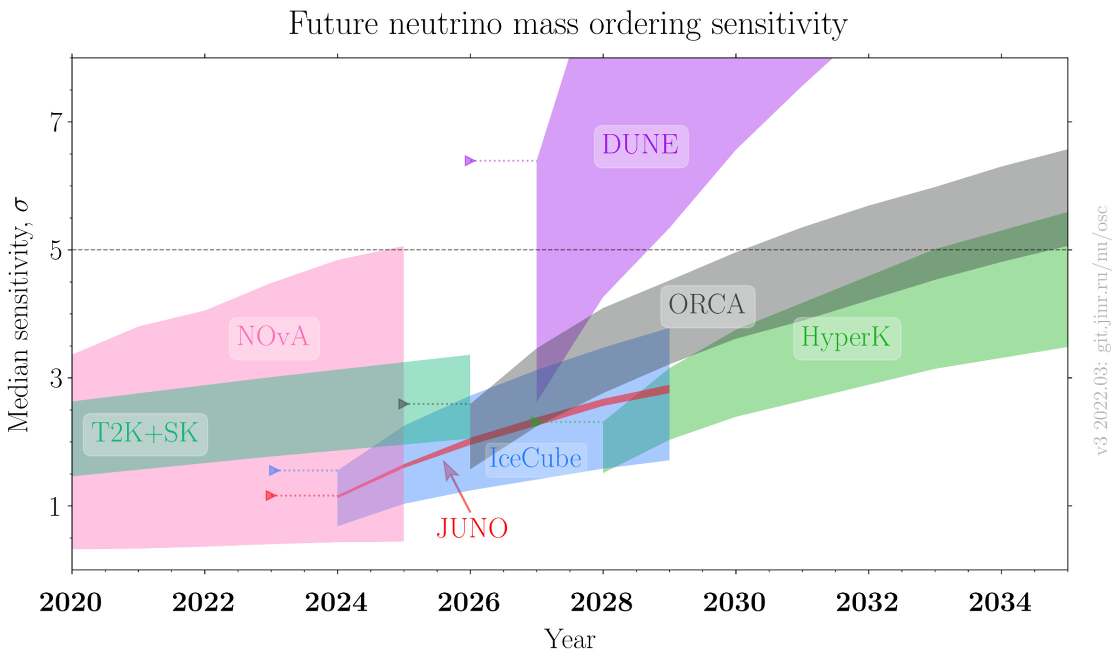

Figure 1. The future sensitivity to the neutrino mass ordering by reactor, accelerator and atmospheric neutrino oscillation experiments.

(ii) **Neutrinoless double beta decay** probability is sensitive to the MO. If observed the effective neutrino mass $m_{\square\square}$ is expected to be of the order $(2.6)\cdot10^{-2}$ eV for the inverted mass ordering, and $(2.6)\cdot10^{-3}$ eV for the normal mass ordering. Current experiments do not provide competitive limits on the MO.

(iii) **Cosmology** provides limits on the sum of neutrino masses Σm_ν. One expects that $\Sigma m_\nu \geq 0.06$ eV for the inverted MO and $\Sigma m_\nu \geq 0.1$ eV for the normal MO. Current bounds on Σm_ν does not provide yet a competitive limit, while a further increase in the Σ_ν determination accuracy is proved to be significant. The key players here are CMB-S4[5] and CORE[6] experiments. Their start data taking dates are not known to us.

(iv) **Beta decay experiments** are also sensitive to the MO since each neutrino mass eigenstate produces a kink in the energy spectrum. The corresponding measurement is extremely challenging since a record energy resolution is required to resolve these kinks. The KATRIN experiment will not provide a competitive limit, while the Project-8[7] experiment, which will use the Cyclotron Radiation Emission Spectroscopy in order to determine the mass of the electron antineutrino, might be able to provide the competitive limit. We refrain from discussing the time scale.

Let us note, that while sensitivities of individual experiments might be below the 5σ discovery significance, the joint analysis of their data is known to improve the overall sensitivity to the MO at a rate more significant than the usual statistical averaging of the data. The main reason for that is a significant breaking of the degeneracy in parameters determination when data from different categories (i)-(iv) are combined.

This consideration was one of our motivations to develop the JINR global analysis framework

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[5] https://arxiv.org/pdf/1610.02743.pdf

[6] https://arxiv.org/abs/1706.04516

[7] https://arxiv.org/abs/1309.7093

(GNA). Today, the global neutrino fits favour the normal ordering at 3.4σ[8]. Further details can be found in Ref.[9]

Accuracy of the lepton mixing parameters determination

Current accuracy in the determination of the lepton mixing parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ as well as expected sensitivity of JUNO is summarised in Figures 2–4[10]. JUNO will improve the measurements with sub-percent precision and provide the leading precision. JUNO is also sensitive to the value of $\sin^2 2\theta_{13}$ with precision of 11.7%. The leading measurement of $\sin^2 2\theta_{13}$ with accuracy of 2.8% is provided by the Daya Bay experiment.

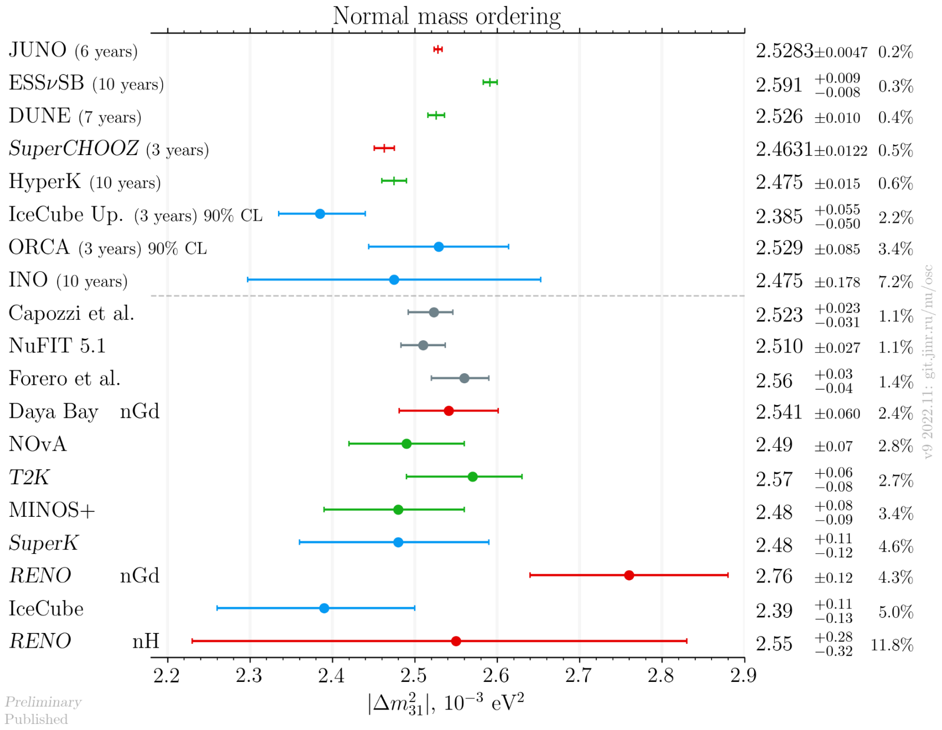

Figure 2. Accuracy of the measurement of the neutrino oscillation parameter Δm^2_{31}.

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[8] https://globalfit.astroparticles.es/2018/07/03/neutrino-mass-ordering/

[9] https://arxiv.org/pdf/1806.11051.pdf

[10] See https://git.jinr.ru/nu/osc for references.

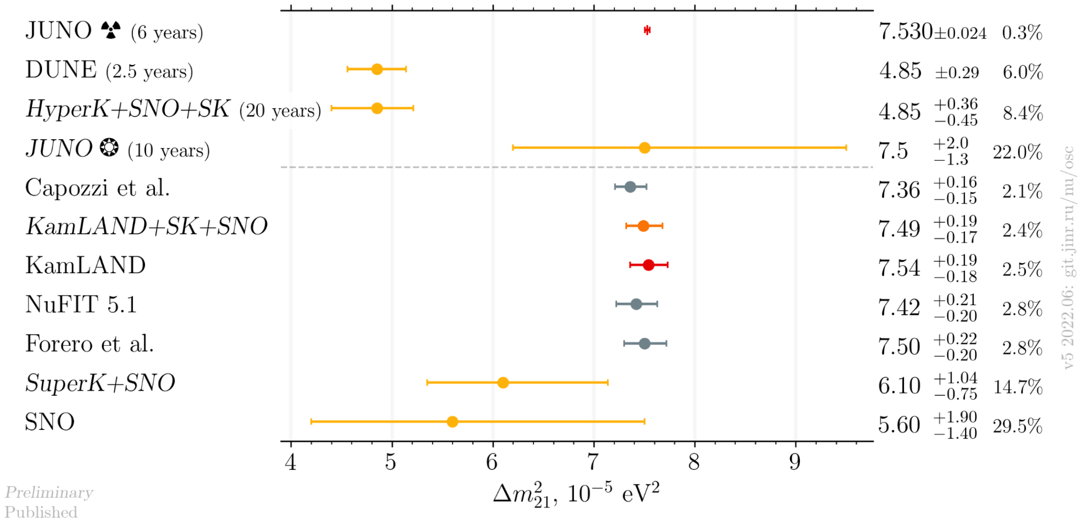

Figure 3. Accuracy of the measurement of the neutrino oscillation parameter Δm^2_{21}.

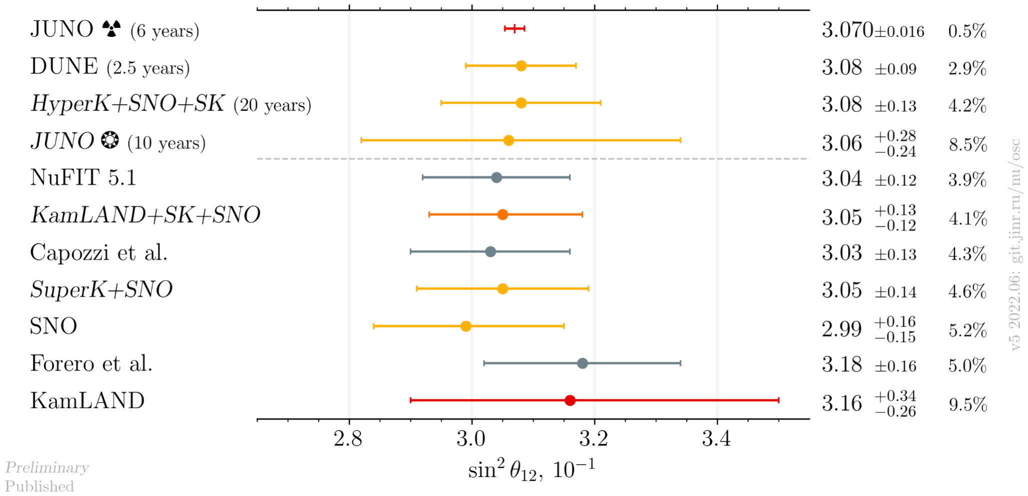

Figure 4. Accuracy of the measurement of the neutrino oscillation parameter $\sin^2 2\theta_{12}$.

Proton decay

To explain the observed matter-antimatter asymmetry of the universe, baryon number violation is one of the requirements. There is no experimental evidence for baryon number violation.

The decay mode $p \to K^+\nu$ is favoured by a number of SUSY GUTs which typically predict the lifetime of the proton to be less than a few $\times 10^{34}$ yrs. The search for this mode in a large water Cherenkov detector is hindered by the decay kinematics. The momentum of the K^+ in this two-body decay is 339 MeV/c (kinetic energy of 105 MeV), which is below the Cherenkov threshold in water. Today's best limit is $\tau(p \to K^+\nu) > 5.9\times 10^{33}$ yrs at 90% C.L. reported by the Super-Kamiokande collaboration[11].

A liquid scintillator detector is able to observe this channel using a unique triple time coincidence signature of the decay. In general, the LS detector efficiency is significantly higher than that of the Cherenkov detector. Due to the high efficiency in measuring this mode, JUNO's sensitivity

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[11] E. Kearns, talk presented at the ISOUP Symposium (2013).

will surpass Super-Kamiokande in only 3 years since its data taking. In 10 year s JUNO will reach the sensitivity of $8.34\cdot10^{33}$ years at 90% C.L.

SN neutrino

So far, neutrinos from a single SN1987A explosion were detected in 1987 by Kamiokande II (12 events), IMB (8 events) and Baksan (5 events). 25 detected neutrinos in total.

SN observations with neutrinos potentially is a rich source of information about the collapsing mechanisms of stars, strong matter effects for neutrino oscillation, and independent determination of the MO. New generation of large scale detectors able to detect hundreds or thousands of SN neutrinos will determine our understanding of SN processes.

JUNO 20 kt detector will be able to detect about 10 thousand SN neutrinos in different channels in 10 s time window, assuming SN at 10 kpc. For the SN bursts within 1 kpc JUNO will be sensitive to the neutrinos emitted before the collapse of the star.

Also, JUNO will have 5σ sensitivity to diffuse supernova background (DSNB) in ten years of data taking. During the period of 3 years JUNO will reach a sensitivity of 3σ.

Geo-, atmospheric and solar neutrinos

Geo-neutrino, electron antineutrino produced in decays of long-lived radionuclides in the Earth interior, was discovered by KamLAND[12] and BOREXINO[13] experiments. Latest analyses reveal 169 and 53 events attributed to geoneutrinos in KamLAND and BOREXINO data, respectively.

The new emerging field of science, **neutrino geophysics**, requires much larger statistics, see a recent review[14] for more details. JUNO will collect about 400 geoneutrinos per year (40 TNU/year). In ten years JUNO will determine geoneutrino fluxes with 5% precision by collecting the largest sample of geoneutrino interactions.

Detection of atmospheric neutrinos adds sensitivity to the MO determination and octant of θ_{23}. PINGU and ORCA will exploit this opportunity fully, determining this direction of research. JUNO will make a modest contribution to the MO determination on the level of about 1σ via detection of atmospheric neutrinos. When combined with reactor antineutrino measurement, the boost in the sensitivity is expected to be larger that of direct sum due to breaking the degeneracy in the parameter space.

Today the solar neutrino puzzle is understood as due to neutrino mixing accounting for the matter effects. The remaining issues that emerged recently are (i) the solar metallicity and (ii) lack of data in the energy interval corresponding to the transition from vacuum to matter dominated regimes.

JUNO will be able to collect 1000 events every day from ^{7}Be and 10 events from ^{8}B solar reactions. This will shed new light on the solar metallicity and the transition from vacuum to matter dominated regimes.

Beyond Standard Model

There are lots of various searches for BSM physics. It is impractical to mention all of them here, given the short format of the document. We mention only the search for light sterile neutrino. The MiniBooNE experiment claimed to observe a hint for sterile neutrino in 2018[15]. Reactor antineutrino

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[12] H. Watanabe, talk at Neutrino Geoscience 2019, Prague, “Geoneutrino measurement with KamLAND”, https://indico.cern.ch/event/825708/contributions/3552210/attachments/1930535/3197332/HirokoWatanabe_NGS2019.pdf

[13] M. Agostini et al., Borexino collaboration, “Comprehensive geoneutrino analysis with Borexino”, Phys. Rev. D 101, 012009 (2020) DOI: 10.1103/PhysRevD.101.012009

[14] O.Smirnov, "Experimental aspects of geoneutrino detection: Status and perspectives", Progress in Particle and Nuclear Physics 109 (2019) 103712. https://doi.org/10.1016/j.ppnp.2019.103712

[15] Aguilar-Arevalo, A.A.; Brown, B.C.; Bugel, L.; Cheng, G.; Conrad, J.M.; et al. (2018). "Observation of a significant excess of electron-like events in the MiniBooNE short-baseline neutrino experiment". *Physical Review*

experiments observe about a 5% deficit with respect to modern models expectations. If interpreted as a hint for sterile neutrino, the fourth neutrino mass should be of eV range scale. Recently, Neutrino-4 collaboration claimed[16] to observe sterile neutrino with mixing parameters $\sin^2\theta_{14}=0.35$ and $\Delta m^2_{41}=7.5$ eV^2.

Direct searches by Daya Bay, MINOS[17], DANSS[18], Prospect[19], STEREO[20] and other experiments did not find any evidence for the sterile neutrino existence, excluding part of the parameter's space. The large mixing angle claimed by Neutrino-4 is ruled out by Daya Bay. JUNO's satellite detector TAO[21] will be sensitive to sterile neutrino oscillation amplitude $\sin^2 2\theta_{14}$ for a range of mass splitting$2\cdot 10^{-2} \lesssim \Delta m^2_{41} \lesssim 8$ eV^2 and will be able to verify the claim by Neutrino-4.

Reactor antineutrino spectrum

Energy spectrum of reactor electron antineutrinos measured in modern experiments is known to have a deviation from the predictions of the widely used Huber+Mueller model[22]. The feature is located at 4−6 MeV of neutrino energy referred to as a "bump" and currently has no proper explanation. Thus the precision measurement of the reactor electron antineutrino spectrum is needed as an input to the reactor experiments and for understanding of the reasons behind this deviation. The satellite detector TAO will have an unprecedented energy resolution of $\sigma=2\%$ at 1 MeV and will provide the best measurement with statistical uncertainty of 1%.

Methods and approaches

The JUNO experiment

Main objectives of JUNO experiment are (i) determination of neutrino mass ordering; (ii) determination of Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ with sub-percent precision; (iii) search for proton decay; (iv) search for SN neutrino; (v) detection of geo-, atmospheric and solar neutrinos; (vi) searches for physics beyond the Standard Model.

Letters. **121** (22): 221801. arXiv:1805.12028. doi:10.1103/PhysRevLett.121.221801. PMID 30547637

[16] https://arxiv.org/abs/1809.10561

[17] https://arxiv.org/abs/2002.00301

[18] https://arxiv.org/abs/1911.10140

[19] https://arxiv.org/abs/2006.11210

[20] https://arxiv.org/abs/2210.07664

[21] TAO CDR: https://arxiv.org/abs/2005.08745

[22] https://arxiv.org/abs/1106.0687, https://arxiv.org/abs/1101.2663

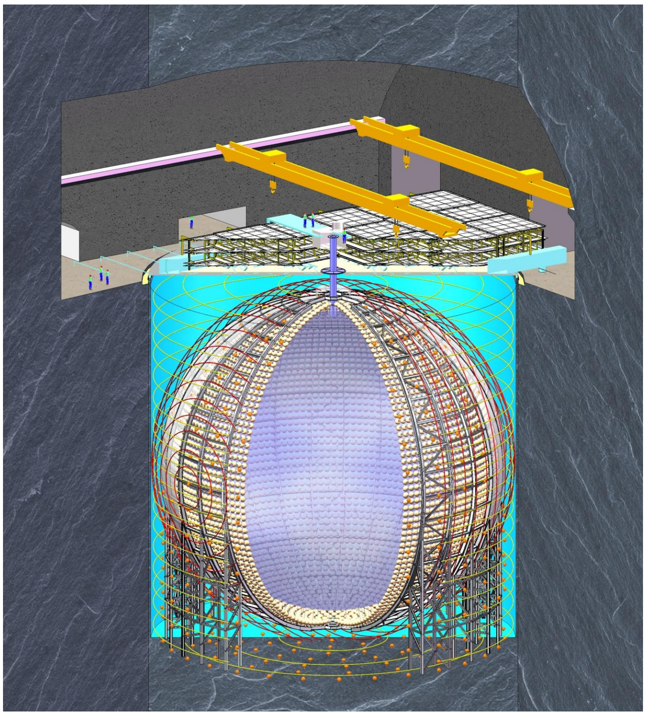

Figure 5. JUNO Central detector and its Top Tracker. The CD acrylic sphere diameter is about 35m. The CD is surrounded by a set of Helmholtz coils to compensate for the Earth Magnetic Field (EMF).

The JUNO central detector (CD), displayed in Figure 5, is a spherical acrylic tank with 35m diameter filled with 20 ktons of liquid scintillator (LS). The scintillation light is detected by about 18k 20'' PMTs (LPMT) and about 26k 3'' PMTs (sPMT) providing about 78% surface coverage. The CD is placed at 52.5 km from Yangjian and Taishan NPP with a total power of 26.6 GW.

In six years of the data taking JUNO will collect about 100k of inverse beta decay (IBD) events determining the antineutrino energy with precision better than σ=3% at 1 MeV of the energy visible in the LS. The precise measurement of the IBD energy spectrum allows the determination of the neutrino mass ordering as can be seen in Figures 6 and 7.

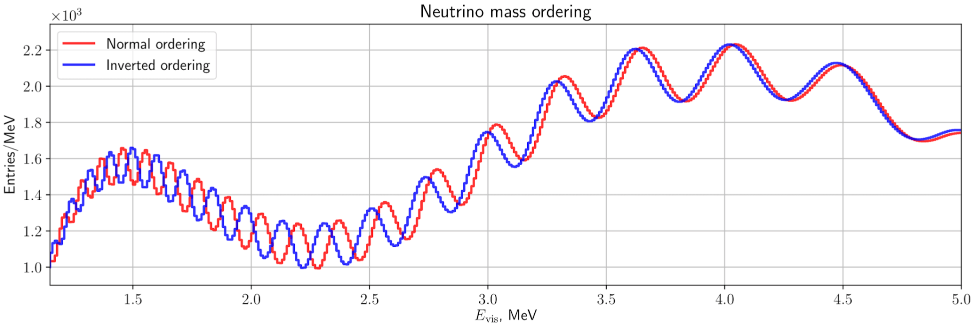

Figure 6. Expected energy spectrum in JUNO CD after eight years of data taking in two models of the mass ordering. The plot corresponds to the true neutrino energy.

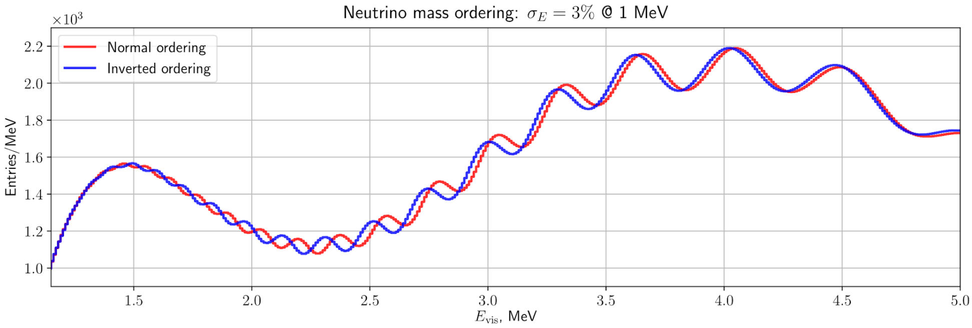

Figure 7. Expected energy spectrum in JUNO CD after eight years of data taking in two models of the mass ordering. The plot corresponds to the reconstructed energy with $\sigma(E)=3\%$ @ 1MeV.

JUNO's sensitivity has no degeneration due to unknown values of CP-violation phase and $\sin^2\theta_{23}$. The main challenge of this method is the energy resolution which should not be worse than 3% at 1 MeV of visible energy.

Another issue is a possible fine structure in the reactor antineutrino energy spectrum. If present, it might potentially bias the mass ordering determination and/or deteriorate the sensitivity of the experiment. In order to eliminate the dependency on the antineutrino spectrum models and possible presence of the fine structure there will be a satellite detector TAO which will measure the energy spectrum of reactor antineutrino with precision even better than in the JUNO CD.

The TAO detector is a spherical barrel of 1.8 meters (see in Figure 8) filled with the 2.8 tonnes of gadolinium-doped LAB liquid scintillator similar to the CD in order to have similar systematic uncertainties. To reach a resolution better than in the central detector, TAO will exploit silicon photomultipliers (SiPM) with photon detection efficiency PDE (about 50%) higher when compared to conventional vacuum phototubes (PMTs). One of the nuisance parameters of the SiPM use is a huge Dark Count Rate (DCR) at room temperature, which can impact the energy resolution and vanish all benefits of high PDE. To suppress the DCR in three orders of magnitude, the setup will operate at low temperatures of −50°C.

Another challenge is the relatively large surface of the detector (about 11 m^2) compared to the size of SiPM (tens of mm^2). In total, about 130 thousand SiPM dice of 12x6 mm^2 packed in 4100 of 32 element 5x5 cm^2 arrays (also called tiles) will be used. This large number of SiPM channels will be read out by means of 4100 32-channel ASICs or 4100 channels of discrete ADC which read out the array as a single element. JINR's responsibility is to provide power for the 4100 arrays with adjustable voltage in the range of 120V. Another important task is to test all SiPMs tiles where JINR is playing the major role.

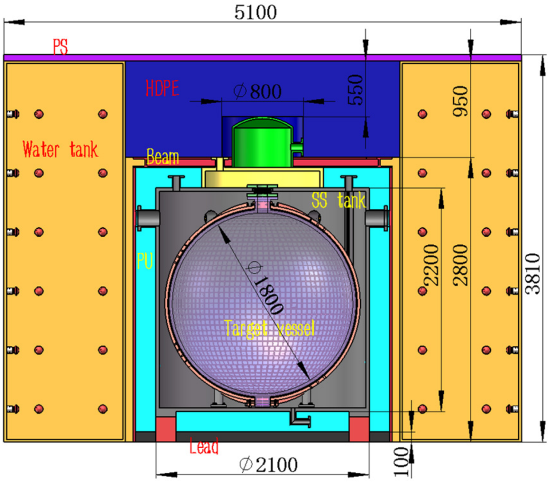

Figure 8. Schematic view of the TAO detector.

To contain the gamma energy from the positron annihilation of the inverse beta decay reaction, a 25-cm selection cut will be applied for the positron vertex from the acrylic vessel, resulting in 1 ton fiducial volume. The IBD event rate in the fiducial volume will be 2000 (4000) events per day with (without) detection efficiency taken into account which will result in more than 4 million of events collected during 6 years of data taking. It will provide a reference reactor electron antineutrino spectrum with statistical uncertainty of order of 1% and energy resolution of σ=2% at 1 MeV.

VETO-system

The muon veto system of the JUNO detector will consist of the water cherenkov detector and the Top Tracker (TT). The TT detector consists of 3 layers of plastic scintillator and will be built of the modules previously used in the OPERA experiment as the Target Tracker detector. JINR took an active part in the construction of the Target Tracker for the OPERA experiment and the data analysis during the experiment. Now JINR participates in the creation of the Top Tracker detector of the Veto system of JUNO. The supply of a former OPERA detector was already accounted as a JINR in-kind contribution. The JINR group:

- is responsible for the design, fabrication and construction of the mechanical support of the TT detector;
- is responsible for monitoring of the performance of the TT modules during the period of their storage;
- takes part in a development of the data acquisition system software;
- takes part in the offline software development for the analysis of the TT data.

Assembly, installation and commissioning of the Top Tracker detector at the JUNO site will begin in 2023 and will take 5-6 months. The participation of 4-5 JINR specialists is required for this period.

The TT detector will be placed on top of JUNO, above the pool. It has three layers, and each layer consists of 21 «walls» which are composed of 8 TT modules, 4 by 4 in X and Y direction. The walls have a weight of about 1 t and a size of 7 by 7 m^2, so one layer is about 1000 m^2. The TT detector layers will be supported by a mechanical structure (see in Figure 9). Its design has been developed by JINR and validated with the prototypes made in Dubna. The procedure of the wall assembly as well as the necessary auxiliary tools has been also developed and validated at JINR. Everything was approved by a dedicated JUNO Review Committees. The support structure will be produced by the Chinese industrial company during 2023. The TT assembly should start in September2023 and complete in February 2024.

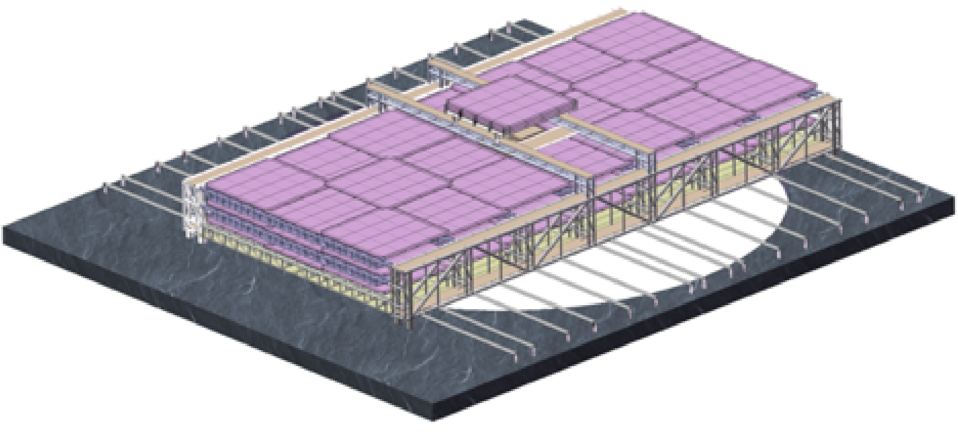

Figure 9. A general view of the TT detector.

To cope with a high signal rate (>50kHz per PMT) in the JUNO experiment, the TT detector will be equipped with new DAQ electronics: Front End (FE) cards, based on MAROC3 chip (designed by LAL, France) are being developed at IPHC in Strasbourg, new Readout Board (RB) are under design at CAEN (Italy) and additional units to suppress background at a hardware level: Concentrator Board (CB) and Trigger Board (TB) — both under development at IPHC (Figure 10). JINR is responsible for the development of DAQ software which has to provide efficient data collection from the detector. The full acquisition chain test bench is installed at IPHC in Strasbourg and available for remote connection. This test bench is used for DAQ software development and testing.

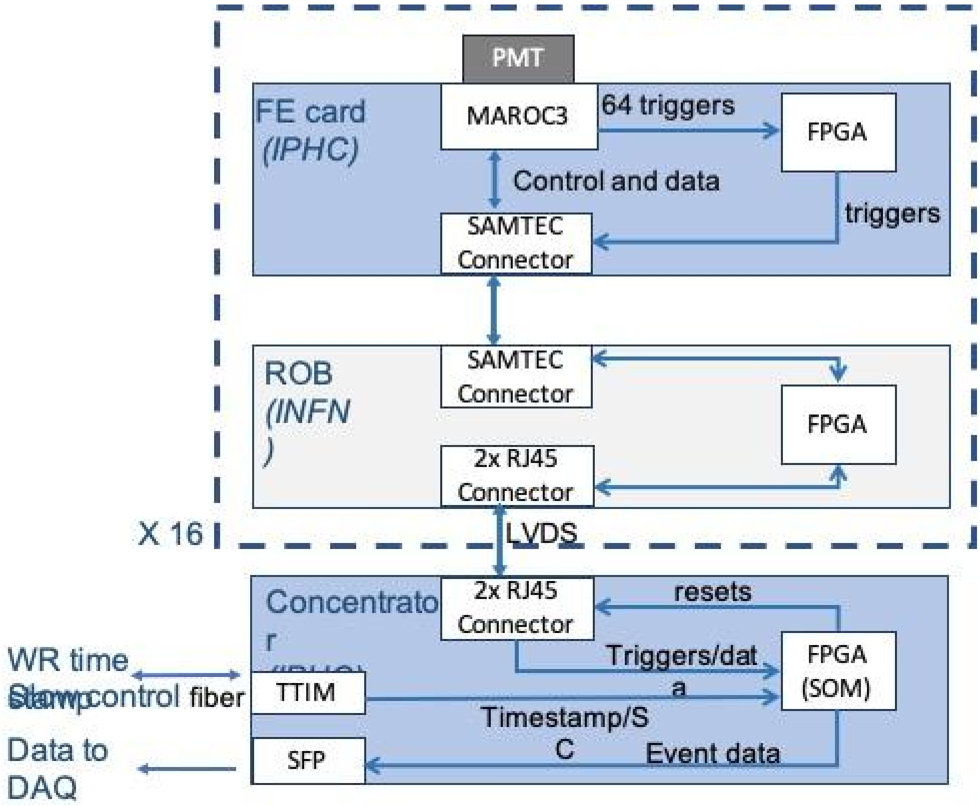

Figure 10. A scheme of the JUNO TT DAQ.

The DAQ and Slow Control (SC) software for JUNO TT is being written in Go programming language. The software consists of two independent parts — DAQ and CS servers.

The DAQ Server receives the status of the data collecting process: "Ready to start run" or "Run" or "Run stop" etc from Juno global DAQ by HTTP protocol and propagates it to all the receivers. It also acts as an event builder which combines the segments of data collected by the CBs in one event and sends the chunk of events ordered in time to the global DAQ system by ZeroMQ protocol. The communication between the DAQ server and CBs is done via TCP link.

The communication of the SC server with CBs is done through UDP protocol. The SC server is responsible for collecting and storing the information about CB's conditions, it is also sent to CBs commands needed for their proper configuration. Web client is a GUI for a TT DAQ. It is supposed to be a main interface to the future JUNO TT shifters.

The TT detector via providing a precise position of the muon tracks in the CD, can help to study the production of the cosmogenic isotopes like ^{9}Li/^{8}He in the interactions of the cosmic muons with the scintillator of CD. The layout of the TT detector (there are only 3 layers) and the presence of the random signals from the radioactivity, however, make this task not easy.

The algorithm for the muon track reconstruction in the TT is under development at JINR. Currently, the Monte Carlo simulation of the detector (partly at JINR, partly at IHEP computing batch system) is used. After equipment of the JINR TT prototype with a 3d layer and especially with a set of the real DAQ electronics, the algorithms can be validated with the data set very similar to the real data of the JUNO experiment. The combination of the TT data with the information from the Water Cherenkov detector to suppress the fake tracks due to an accidental noise in the TT can increase the efficiency of the muons reconstruction. The development of the related algorithms is under way as well. The goal is to combine information from the WP and CD about a rough position of the muon track.

Oscillation Analysis

The group from JINR is one of the key groups in JUNO providing statistical analysis of reactor antineutrino data and sensitivity estimation. A dedicated software GNA[23] (Global Neutrino Analysis) was developed (C++) in order to provide a common base for the oscillation analysis of the reactor antineutrino data in Day Bay and JUNO experiments. The GNA was further extended to support experiments with accelerator[24] neutrinos and atmospheric neutrinos. It was in particular used as a parallel analysis tool in the final analysis of the data of the Daya Bay experiment[25] and the sensitivity of the JUNO experiment[26] with satellite detector TAO.

The GNA provides efficient lazily evaluated models of the JUNO and Daya Bay experiments and tools to perform minimization and statistical evaluation. We plan to further extend the project to accommodate the latest data on the performance of the JUNO and TAO detectors (efficiency, energy characterization, etc.) as well as the data on the antineutrino flux from the Chinese and world Nuclear Power Plants.

A related project was started recently, called dagflow[27]. It's purpose is to provide a similar to GNA tools in Python: an experimental model is built as a directed acyclic graph, evaluated lazily. The goal is to publish the complete code of the oscillation analysis of the Daya Bay data within the "data preservation" initiative.

We will perform the following studies:

- Estimation of the sensitivity of the JUNO experiment with satellite detector TAO to the neutrino oscillation parameters in details during the first 100 days of data taking.
- First measurement of neutrino oscillation parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ at JUNO.
- Sensitivity estimation of the TAO detector to the parameters of the sterile neutrinos Δm^2_{41} and $\sin^2 2\theta_{14}$.
- First search for the sterile neutrino oscillations in the data of the TAO detector.

Event reconstruction

We are planning to reconstruct muon tracks with the help of spherical functions. In this case we can describe a signal from muon track that passed through the detector with a limited number of parameters which is much less than the number of PMTs and in that way we can speed up our reconstruction procedure. We are using the following reconstruction procedure:

- simulation of reference muons: vertical muons with step 0.5 m along Ox-axis;
- making dependence of detector response snapshots for muon tracks on distance;
- making detector response snapshot for muon track that should be reconstructed;
- rotating reference muons while the signal from the detector from input muon will not be the same as for the reference muon;
- found rotation angles — direction of incoming muon track.

With this method it is possible to reconstruct single and multiple muon tracks by the sum of spherical functions from different muon tracks. Rotation of calibration muons and muon track parameters are defined with the chi-square functional.

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[23] https://git.jinr.ru/gna/gna, https://arxiv.org/abs/1903.05567

[24] Physics of Particles and Nuclei Letters volume 19

[25] https://arxiv.org/abs/2211.14988

[26] Talk Neutrino 2022, to be published soon

[27] https://git.jinr.ru/dag-computing/dag-flow

Muon track reconstruction procedure with the help of spherical functions has the following advantages:

- information from the PMTs is collecting during 300 ns (only first hit in other methods) which is safe from the noise and PMTs inefficiency, because noise signal is distributed uniformly on the sphere and compensated by the calibration coefficient during the fit;
- existence of other signals does not have a big influence on reconstruction quality;
- this method allows us to apply different muon track combinations for one event for multiple muon track reconstruction;
- with this method we can reconstruct the electromagnetic shower produced by the muon interactions with the scintillator.

Computing and storage resources

JINR is one of the sites of JUNO Distributed Computing Infrastructure (DCI) which is intended to be used for storage, processing and analysis of enormous amount of data gathered by JUNO. Along with two other European Data Centers the JINR is expected to play three roles within JUNO DCI: Raw Data Center, Regional Data Center and Simulation Production Data Center.

- Raw Data Centers receive the raw and reconstructed data, providing a distributed permanent multiple backup of the raw data, permanent storage and management of data needed during the analysis process, and offer a data service integrated in JUNODCI. They also participate in subsequent reconstructions of raw data.
- Regional Data Centers provide Grid-enabled disk storage to host a partial copy of the reconstructed data and concentrate on tasks such as simulation, end-user analysis and high-performance parallel analysis.
- Simulation Production Centers provide resources for Simulation production and end-user analysis. In case raw data reprocessing is needed these centres will also take part in the task, without needing to maintain a long duration copy of the raw data and will rely on the closest available Raw Data Centre site to provide it.

JINR Data Center for JUNO DCI is based on the resources of MLIT Multifuncional Information and Computing complex (MICC). A dedicated Memorandum of Understanding was signed between JINR and IHEP which outlines the amount of CPU and storage (disks, tapes) resources to be provided each year.

Methodologies

PMT High Voltage

One of the main JINR contributions to the construction of the JUNO experiment is the design and production of the HV electronics for all the JUNO PMT: ~20000 LPMT and ~27000 sPMT in the CD and ~2000 LPMT in the Cherenkov Veto. During previous years of the project, the JINR has completed the design, prototyping, and extensive tests of the HV Units (HVU) to be used in the JUNO experiment.

The designed HVU is a programmable module, which provides the bias voltage to the voltage divider, specific to the type of PMT (HAMAMATSU, MCP, or HZC) used in JUNO. The high voltage is generated by a custom module that converts a 24V DC voltage to a high DC voltage using a cascade of Cockroft-Walton multipliers. Such a system does not need any HV cables or connectors. The module is equipped with an embedded microcontroller. It monitors all operations and provides an RS485 half-duplex interface to the electronics Global Control Unit. The total number of modules produced for JUNO is ~20000 for LPMT, 3500 for sPMT (1 HVU for 8 sPMT) and some reserve.

Since the HVU is a part of electronics located underwater near PMT and has no chance for repair or exchange, special attention was paid to the reliability of the design, components, and production processes. This includes prototyping, components selection, development of factory test protocols, and temperature-accelerated ageing tests. In addition, materials used in the HVU were tested for radioactivity.

The whole production was already finished (25000 pieces) and now HV Units are installed in the JUNO detector together with the rest of underwater electronics and PMTs. We will also continue to work on the firmware of the HVU and general JUNO slow control software development. Resources requested are for possible contract amendment and additional test equipment. They correspond to ~10% of the resources previously requested for production.

PMT testing and installation

The JUNO central detector contains about 20000 large 20-inches PMTs. Five thousand PMTs were produced by Hamamatsu company and 15 thousand tubes by NNVT (China). NNVT tubes use micro-channel plates to amplify photoelectrons and Hamamatsu exploits a standard dynode system. All PMTs passed testing in the warehouse, where 4 containers and 2 scanning systems are placed.

The container is a tool where PMT is tested by means of uniform flashed illumination from LED or picosecond laser. The instrument was developed by German collaborators, and it is a standard 20 feet light-tight container in-lined with a magnetic shield where 36 PMTs can be simultaneously tested. It is extracting, so-called, integral measurements of a PMT's characteristics as PDE, gain, TTS, SPE and Dark noise rate at the operating voltage. One of the containers is equipped for PMT long-term stability testing, where 36 PMTs of different types experienced accelerating ageing to predict and guarantee their performance for the whole of JUNO's operation period of 20 years.

The scanning system is a much more sophisticated tool developed at JINR and can extract the same parameters from 168 points on PMT's surface. The scanning is providing better knowledge of the PMT performance, but is slower compared to container testing. A very important PMT performance parameter is its operation in presence of a magnetic field. The instrument is placed inside the black room surrounded by Helmholtz coils to vary and compensate for the Earth's Magnetic Field. All PMTs were tested in the containers and about 4000 PMTs were qualified by the scanning system for almost three years in 2020-2022.

Currently, the PMTs are relocated next to the JUNO site in Kaiping. After the shipment, all PMTs should be tested for operation with the help of dark noise. This allows realising consistency with measurement in the warehouse. The PMTs are tested in the big black room and oriented in the position at which the Earth's magnetic field will not introduce signal dropping. Then PMTs are moved to the Detector Cavern and go for the installation. After installation, PMT is connected to the underwater box equipped with supply and readout electronics. The Underwater box will support a group of 3 PMTs. The next step is to make sure that all cables are properly connected. The test will happen in an environment of the safety backlight illumination. The HV is applied at the minimum voltage to detect an increase of the PMT current to guarantee the contact.

We plan to provide help in installation and testing during 2024.

SiPM Power System

One of the main JINR responsibilities in the TAO detector is to develop and provide power to ~4100 SiPM tiles (arrays). With the participation of Marathon LTD, we designed and produced a SiPM power supply VME unit that operates 128 SiPM tiles with a maximum current of 500 uA (see Figure 11). Each tile consumes less than 1 uA at −50°C and maximum current provides testing at room temperature where power consumption reaches hundreds of uA. The scope of the power module shown in figure allows setting up to 20 units per crate and in total, we need two crates crowded with 32 modules (~4100 channels). The whole system includes power distribution lines which are 3M 68-lines shielded cables. In total, we need 900 meters for the outer part and 300 meters to distribute inside the cryostat. The production and procurement plan includes 40 VME units, 1200 meters of cable, 3 VME crates, and a dozen of feed-through boards. We plan to build up the system during 2023-2024 and put it in operation in 2024.

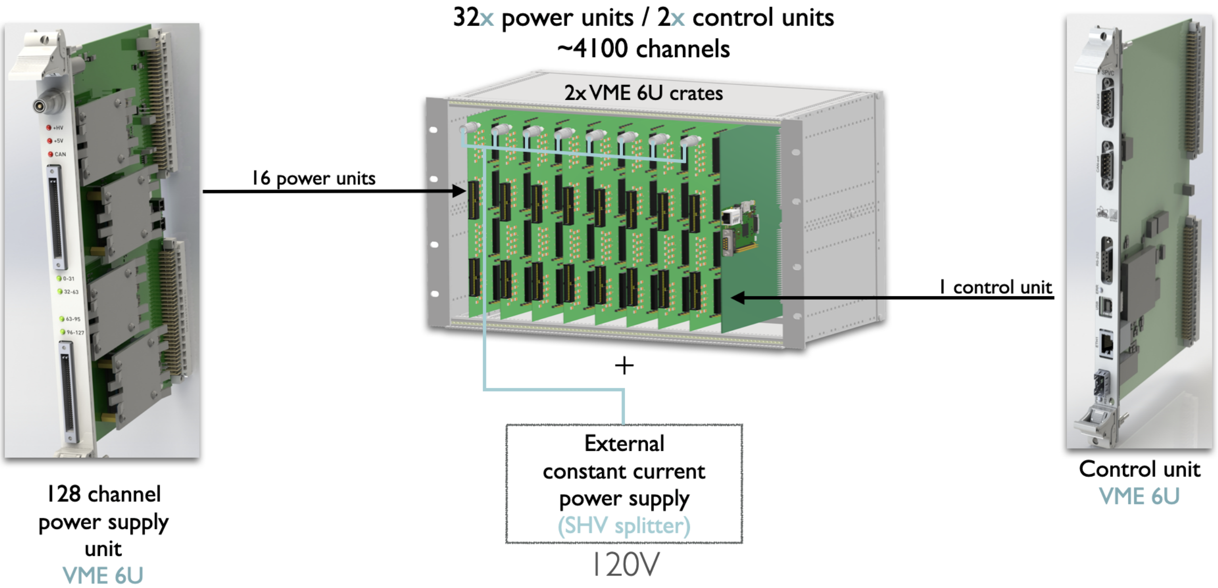


Figure 11. The SiPM Power supply system.

SiPM Mass-testing

In total, we have to test about 4100 SiPM tiles and their performance at −50 C. The first step is a visual check of resin (epoxy) surface quality for dust and bubbles. The second step is to simultaneously test 16 arrays which are put on a large testing PCB (see Figure 12). Each array is supplied by an individual voltage source that allows precisely controlling the current of each array. In dark conditions, by using 16 self-stabilised LEDs, we can arrange the scan of 16 arrays simultaneously by using 16-channel ADC. Each LED is calibrated using reference SiPM sitting next to each array. The LEDs are placed above arrays and spot the light on 5x5 cm^2. The large PCB is moved by two-step motors providing precise positioning reference SiPM to scan the light field. To test all SiPMs on 16 arrays we have to provide 32 scans for 8x4 SiPM arrays. Each scan requires ~10^4 of acquisitions per SiPM which need about 30 minutes for a full scan of 16 arrays. Including cooling down and current measurements, each batch is tested for 3 hours. To test all arrays we need 4-6 months. This technique allows the characterization of SiPM: PDE, Gain, Cross-talks, afterpulses, SPE, and IV-curve. The setup will be put into operation in 2023. We plan to finish testing during 2023-2024.

Figure 12. General view of inside part of the SiPM Scanning system: left — Design, right — real device.

TAO assembling and commissioning

The TAO detector will operate inside the cryostat at low temperature. After the SiPM and electronics testing, we proceed with the installation. The assembly procedure is the following:

- SiPM tiles installation to the copper shell and put inside the cryostat.
- Inside wiring.
- Feedthrough connection and installation.
- Outer cabling and connection.
- DAQ and power rack installation.

Commissioning includes:

- Powering up all SiPMs and electronics.
- Software installation and testing.
- Test run of the setup.
- Calibration.

We plan to spend 2024 assembling and commissioning the TAO detector and put it into operate late 2024.

Expected results (2024-2026)

1. Reconstruction (2024):
    a. Reconstruction of muon tracks and electromagnetic showers with electronics simulation.
    b. Reconstruction of clipping muons in central detector.
    c. Efficiency and quality of reconstructed muon tracks.
    d. Adaptation of muon track reconstruction procedure to real data.
2. VETO TT
    a. The assembly and the commissioning of the Top Tracker detector of Juno setup will be completed.
    b. First physics results on the measurement of the cosmic muons flux with help of the Target Tracker will be obtained.
3. Large PMTs (2024):
    a. PMT testing with HV-units.
    b. PMT installation to the JUNO Central Detector.
4. Filling and running JUNO late 2024 — early 2025.
5. TAO:
    a. All SiPM for TAO are tested and installed to the detector.
    b. Production and commissioning of the TAO SiPM power system 2024-2025
    c. Filling and running TAO: late 2024 — early 2025.
6. Oscillation analysis (2026):
    a. First measurement of neutrino oscillation parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ in the JUNO experiment.
    b. First constraints on the parameters of the sterile neutrino oscillations $\sin^2 2\theta_{14}$ and Δm^2_{41} based on the data from the detector TAO.

SWOT-Analysis

	Helpful	Harmful
Internal	**STRENGTHS**	**WEAKNESSES** ● Failure to achieve sufficient energy resolution at one of the detectors.

	● Neutrino mass ordering determination by method different from other experiments. ● Precision oscillation parameters measurement. ● Geo-neutrinos measurement. ● Other neutrino physics (solar, atmospheric, etc.) ● All PMTs are tested and ready for installation. ● JINR’s responsibility for two major subsystems PMT HV power and SiPM power system. Providing PMT and SiPM mass-testing. Contribution to VETO-system. ● JINR has a leading role in analysis.	● Insufficient detector/structure integrity. ● Insufficient electronics/HV reliability. ● Delay with detector installation.
External	**OPPORTUNITIES** ● BSM physics. ● SuperNova burst. ● Diffuse SuperNovae background. ● Systematic errors' reduction due to new measurements or theory improvement. ● Development of new methods and technologies. ● Cooperation with Chinese institutes on application developments	**THREATS** ● Major accident with cavern infrastructure. ● Export/Import/Travel restrictions in the Russian Federation and China.

The JUNO experiment is expected to be a revolutionary step forward in scale and precision among both the reactor neutrino experiments and liquid scintillator experiments. JUNO detector will be 20 times larger than the current largest reactor antineutrino detector KamLAND. Experiment requirements include maximal PMT coverage and σ=3% energy resolution at 1 MeV of released energy. Therefore the detector construction has a number of technical challenges:

- Creating an acrylic sphere to hold 20 kt of liquid scintillator which is inflammable.
- Protection of PMTs against the shock wave.
- Potting and connecting PMTs and electronics underwater at depths up to 35 meters.
- At least 20 years working time (30 years expected).

All these items indicate high reliability and safety requirements. The potential risks are minimised by extensive subsystem testing and putting high reliability requirements on the detector components and electronics.

2.3 Estimated completion date

2045

2.4 Participating JINR laboratories

DLNP, MLIT, VBLHEP, BLTP

2.4.1 MICC resource requirements

Computing resources	Distribution by year				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB)					
- EOS	5000	10000	15000	20000	25000
- Tapes	5000	10000	15000	20000	25000
Tier 1 (CPU core hours)					
Tier 2 (CPU core hours)					
SC Govorun (CPU core hours)					
- CPU					
- GPU					
Clouds (CPU cores availability)	3500	5000	6300	7100	7500

The requested numbers are needed for the processing and storage of the JUNO data and were approved by the parties within “Memorandum of Understanding for Collaboration in the Deployment and Exploitation of the JUNO Computing Grid” signed between IHEP and JINR on September 1, 2022.

2.5. Participating countries, scientific and educational organizations

Organization	Country	City	Participants	Type of agreement
IHEP	China	Beijing	Yifang Wang + 10	MoU
SYSU	China	Guangzhou	Wei Wang + 10	MoU
SINP MSU	Russia	Moscow	Alexander Chepurnov, Maxim Gromov	MoU
INFN	Italy	Catania, Rome	Giuseppe Adronico +1 Stefano Maria Mari +1	MoU MoU
FZJ-IKP	Germany	Jülich	Livia Ludhova +4	MoU
EKUT	Germany	Tübingen	Tobias Lachenmaier +1	MoU

2.6. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

Institute for High Energy Physics, Beijing, China

3. Manpower

3.1. Manpower needs in the first year of implementation

№№ n/a	**Category of personnel**	**JINR staff, amount of FTE**	**JINR Associated Personnel, amount of FTE**
1.	research scientists	10	-
2.	engineers	5	-
3.	students	-	5
	Total:	**15**	**5**

3.2. Available manpower
3.2.1. JINR staff

No.	Category of personnel	Full name	Division	Position	Amount of FTE
1.	scientific staff	Dmitry Naumov	DLNP	Deputy DLNP, Project leader	0.5
2.	scientific staff	Maxim Gonchar	DLNP	Head of sector	1.0
3.	scientific staff	Alexander Olshevsky	DLNP	Head of Department	0.3
4.	scientific staff	Nikolay Anfimov	DLNP	Head of sector	0.4
5.	scientific staff	Alexander Selyunin	DLNP	Researcher	0.2
6.	scientific staff	Arseniy Rybnikov	DLNP	Researcher	0.7
7.	scientific staff	Anastasia Bolshakova	DLNP	Researcher, PhD	0.5
8.	scientific staff	Vyacheslav Tchalyshev	DLNP	Senior Researcher, PhD	0.4
9.	scientific staff	Vladislav Sharov	DLNP	Researcher	0.6
10.	scientific staff	Igor Nemchenok	DLNP	Head of Group	0.2
11.	scientific staff	Svetlana Biktemerova	DLNP	Researcher	0.4
12.	scientific staff	Artem Chukanov	DLNP	Senior Researcher, PhD	0.5
13.	scientific staff	Elena Naumova	DLNP	Researcher	1
14.	scientific staff	Denis Korablev	DLNP	Researcher	0.8

15.	scientific staff	Oleg Smirnov	DLNP	Senior Researcher, PhD	0.3
16.	scientific staff	Maxim Gromov	DLNP	Researcher, PhD	0.5
17.	scientific staff	Sergey Dmitrievsky	DLNP	Senior Researcher, PhD	0.5
18.	scientific staff	Vitalii Zavadskiy	DLNP	PhD Student	0.5
19.	scientific staff	Andrey Sadovsky	DLNP	Senior Researcher, PhD	0.5
20.	scientific staff	Yuri Gornushkin	DLNP	Head of sector	0.5
21.	scientific staff	Alexei Krasnoperov	DLNP	Senior Researcher, PhD	0.1
22.	scientific staff	Vitaly Shutov	VBLHEP	Senior Researcher, PhD	0.1
23	scientific staff	Nikita Tsegelnik	BLTP	Trainee Researcher	0.2
24.	engineers	Sergei Sokolov	DLNP	Senior engineer	0.4
25.	engineers	Vasily Gromov	DLNP	Leading engineer	0.5
26.	engineers	Dmitry Fedoseev	DLNP	Electronics engineer (1st class)	0.5

27.	engineers	Alexey Chetverikov	DLNP	Electronics engineer (2nd class)	0.5
28.	engineers	Ksenia Kuznetsova	DLNP	Engineer	0.5
29.	engineers	Albert Sotnikov	DLNP	Electronics engineer (1st class)	0.4
30.	engineers	Tatiana Antoshkina	DLNP	engineer	1.0
31.	engineers	Dmitry Dolzhikov	DLNP	engineer	1.0
32.	engineers	Nikita Balashov	MLIT	1st category software engineer	0.2
33.	engineers	Nikolay Kutovskiy	MLIT	Senior researcher	0.2
	Total:				**15.9**

3.2.2. JINR associated personnel

No.	Category of personnel	Partner organization	Amount of FTE
1.	research scientists	-	-
2.	engineers	-	-
	Total:	**-**	**-**

4. Financing

4.1 Total estimated cost of the project

The total cost estimate of the project (for the whole period, excluding salary).
The details are given in a separate table below.
1300 k$

4.2 Extra funding sources

Expected funding from partners/customers – a total estimate.
—

Project Leader __________/___________/

Date of submission of the project to the Chief Scientific Secretary: _________
Date of decision of the laboratory's STC: _________ document number: _________

Year of the project start: ________________

(for extended projects) – Project start year: _______

Proposed schedule and resource request for the Project

Expenditures, resources, funding sources			**Cost (thousands of US dollars)/ Resource requirements**	**Cost/Resources, distribution by years**		
				1st year	2nd year	3rd year
		International cooperation	750	250	250	250
		Materials	280	100	100	80
		Equipment, Third-party company services	150	50	50	50
		Commissioning				
		R&D contracts with other research organizations	60	20	20	20
		Software purchasing	60	20	20	20
		Design/construction				
		Service costs (*planned in case of direct project affiliation)*				
Resources required	**Standard hours**	Resources				
		−workshop and design,	150	50	50	50
		−accelerator/installation,				
		−reactor,…				
Sources of funding	**JINR Budget**	JINR budget *(budget items)*	1300	440	440	420
	Extra fudning (supplementary estimates)	Contributions by partners Funds under contracts with customers Other sources of funding				

Project Leader_________/________________/

Laboratory Economist __________/_________________/

APPROVAL SHEET FOR PROJECT

Study of neutrino oscillations in the JUNO experiment (participation of JINR)

The JUNO project

Renewal of the project for 2024−2026

Theme: 02-2-1099-2010/2026

Leader: Dmitry Naumov

AGREED

JINR VICE-DIRECTOR	SIGNATURE	NAME	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	NAME	DATE
CHIEF ENGINEER	SIGNATURE	NAME	DATE
LABORATORY DIRECTOR	SIGNATURE	NAME	DATE
CHIEF LABORATORY ENGINEER	SIGNATURE	NAME	DATE
LABORATORY SCIENTIFIC SECRETARY THEME LEADER	SIGNATURE	NAME	DATE
PROJECT LEADER	SIGNATURE	NAME	DATE
APPROVED BY THE PAC	SIGNATURE	NAME	DATE

Annex 4.

Project report form

PROJECT REPORT

1. General information on the project

1.1. Scientific field physics of elementary particles

1.2. Title of the project Study of neutrino oscillations in the JUNO experiment (participation of JINR)

1.3. Project code JUNO

1.4. Theme code 02-2-1099-2010/2026

1.5. Actual duration of the project

1.6. Project Leader(s) Naumov D.V.

2. Scientific report

2.1. Annotation

JUNO, a long baseline reactor antineutrino experiment under construction in China, aims to determine the neutrino mass ordering with median sensitivity corresponding to 3−4 standard deviations alone and measure lepton mixing parameters with record sub-percent precision level. There is also a rich physics program including searches for proton decay, search for SN neutrino, detection of geo-, atmospheric and solar neutrinos, as well as searches for physics beyond the Standard Model.

The satellite detector TAO will measure reactor electron antineutrino spectrum with statistical uncertainty of order of 1% and energy resolution of $\sigma=1\%$ at energy of 1 MeV. Its sensitivity to the sterile neutrino mixing amplitude $\sin^2 2\theta_{14}$ in a range of $2\cdot 10^{-2} \lesssim \Delta m^2_{41} \lesssim 8$ eV^2 will be comparable to the world leading experiments.

During the period 2021-2023 the JINR group has contributed to the construction of the detector and overall preparation of the experiment:

(i) JINR designed and produced 25000 pcs of high voltage units for JUNO large (20 inches) and small (3 inches) photomultipliers (PMTs).

(ii) JINR developed and produced the stainless steel structure for the muon tracker, designed the data acquisition system and developed a dedicated software.

(iii) JINR designed and produced magnetic field shields for the large PMTs of the OSIRIS detector.

(iv) Mass tests and commissioning of large PMTs: with help of JINR two scanning stations were designed and produced, JINR provided scanning for almost 4000 PMTs and PMT long-term stability tests.

(v) JINR contributed to the design and construction of JUNO’s satellite detector — TAO: procurement of half of 4100 SiPMs tiles (130k dices) and their mass-testing methods, production and testing of pilot version of SiPM power units, design of the power system.

(vi) JINR contributes to the software and analysis. Two groups from JINR have done the analysis of the JUNO sensitivity to a) neutrino mass ordering determination and b) neutrino oscillation parameters Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{12}$.

(vii) JINR shares its computer resources within JUNO distributed computer infrastructure. During the period of 2021-2022 the fraction of the total JUNO jobs processed at JINR increased from 30% to 50%.

The Daya Bay is a medium baseline reactor antineutrino experiment in China, which completed the data taking in late 2020. In 2022 it had completed the analysis of the full dataset and estimated the most precise values of the neutrino mixing parameters $\sin^2 2\theta_{13}$ and Δm^2_{32}. The group from JINR took part in the analysis as a parallel group.

2.2. A detailed scientific report

2.2.1. Description of the mode of operation and functioning of the main systems and equipment

-

2.2.2. A description of the conducted experiments (for experimental projects).

-

2.2.3. A description of the research undertaken and the results obtained.

JUNO detectors construction

The assembly of the largest liquid scintillator detector JUNO has been started in China in 2022. For this detector the JINR has constructed the PMT High Voltage power supply system. All of the system units (>25'000) were produced, tested and are ready for installation. The JINR team has also done R&D for the power supply for the silicon photomultipliers (SiPM) of the TAO detector. The power supply units were designed and prepared for production in China. Also, the design of the station for the mass testing of the SiPMs was developed.

PMT Mass-testing

The JUNO central detector contains about 20000 large 20-inches PMTs. All PMTs passed testing in the warehouse, where 4 containers and 2 scanning systems are placed.

The container is a tool where PMT is tested by means of uniform flashed illumination from LED or picosecond laser. The instrument was developed by German collaborators, and it is a standard 20 feet light-tight container in-lined with a magnetic shield where 36 PMTs can be simultaneously tested. It is extracting, so-called, integral measurements of a PMT's characteristics as PDE, gain, TTS, SPE and Dark noise rate at the operating voltage. One of the containers led by JINR group is equipped for PMT long-term stability testing, where 36 PMTs of different types experienced accelerating aging to predict and guarantee their performance for the whole of JUNO's operation period of 20 years.

The scanning system (see Figure 1, left) is a much more sophisticated tool developed at JINR and can extract the same parameters from 168 points on PMT's surface. The scanning is providing a better knowledge of the PMT performance, but is slower compared to container testing. An important PMT performance parameter is its operation in presence of a magnetic field. The instrument is placed inside the black room surrounded by Helmholtz coils to vary and compensate for the Earth's Magnetic Field (see Figure 1, right). All PMTs were tested in the containers and about 4000 PMTs were qualified by the scanning system for almost three years in 2020-2022.

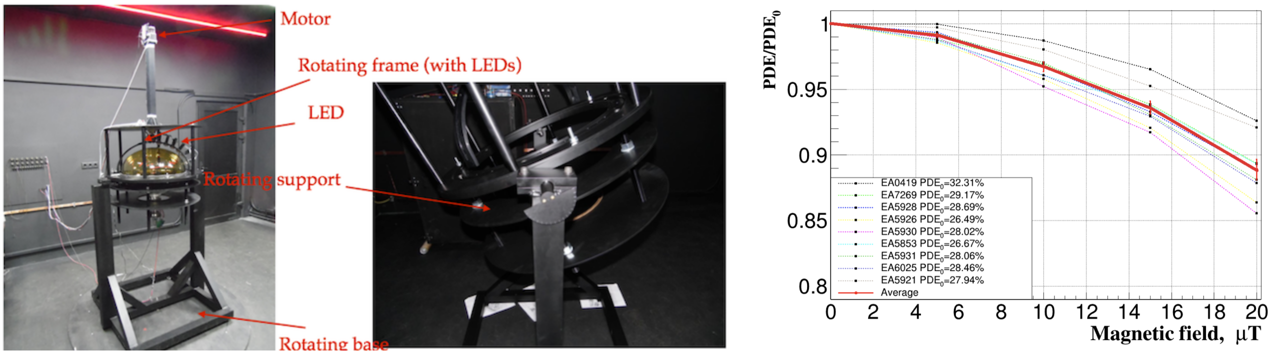


Figure 1: The scope of the scanning system (left). The Photon Detection Efficiency of Hamamatsu R12860 tubes vs Magnetic Field (right).

PMT HV

During previous years of the project the JINR has completed the design, prototyping and extensive tests of the HV Units (HVU) to be used in the JUNO experiment.

Since HVU is a part of electronics located under water near PMT and has no chance for repair or exchange, special attention was paid to the reliability of the design, components and production processes. This includes prototyping, components selection, development of factory test protocols and temperature accelerated ageing tests. In addition, materials used in HVU were tested for radioactivity.

All of the tests were passed successfully and HVU was found to be compliant with JUNO requirements. The design of HVU has been approved by the Collaboration in a series of reviews, which examined full correspondence to the requested parameters, especially the reliability. Finally, the Production Readiness Review was passed and the production contract was signed with the electronics factory in Shenzhen (see Figure 2). The full production was finished by late 2021 (25000 pieces) and HV Units are being installed now at JUNO detector together with the rest of underwater electronics and PMTs.

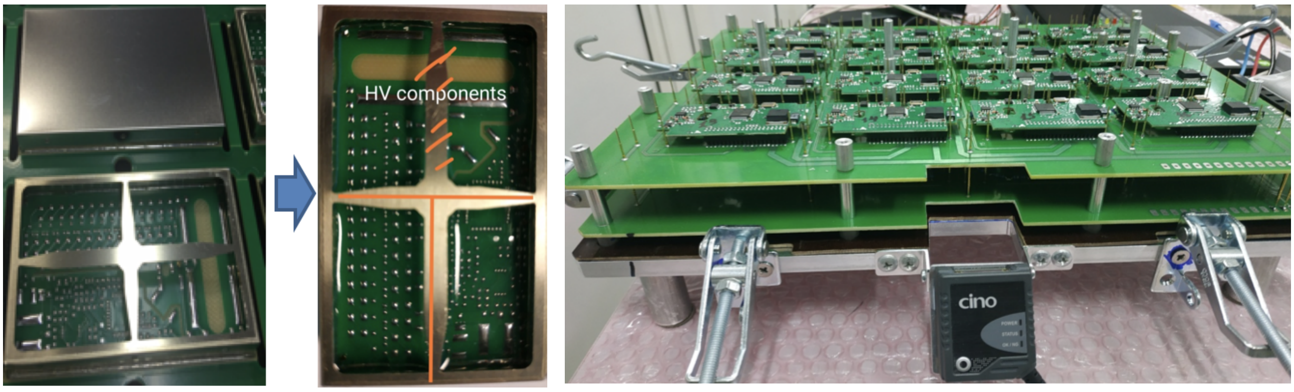


Figure 2. High voltage unit and mass-testing equipment.

Protection against Earth Magnetic Field

Magnetic field shields for the large PMTs of the OSIRIS facility are manufactured and delivered to Germany. The amorphous alloy tape of domestic origin is used as an Earth magnetic field screen. The 64 screens made using potassium-free carbon fiber texture as a base will be used in the detector. The 12 screens made using cheaper fiberglass (some potassium is acceptable) will be used in the muon veto.

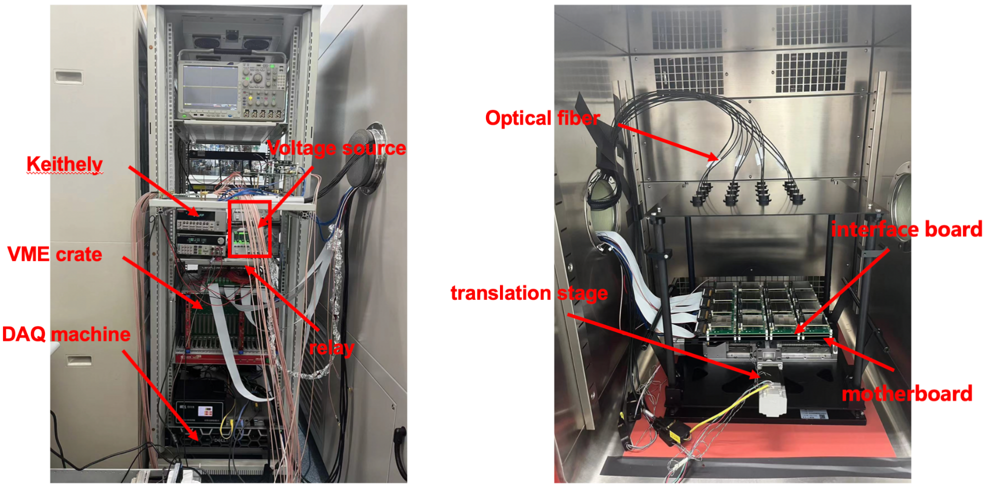
A paper on the magnetic shield for large photomultipliers of the OSIRIS facility of the JUNO detector submitted to JINST ([2212.02562]). The presented magnetic shield could be used in Serappis, the proposed upgrade of the OSIRIS facility for the detection of solar pp-neutrino (Eur.Phys.J.C 82 (2022) 9, 779, [2109.10782]).

Veto: Top Tracker

The stainless steel structure for the Top Tracker is produced. The Top Tracker assembly and installation procedure are developed. The core part of TT DAQ software already exists. It is under intensive tests and debugging via a remote test bench in Strasbourg. More functions will be added later. The integration with Juno global DAQ starts in June 2023. The paper on the Top Tracker description has been prepared for publication.

SiPM mass testing

The TAO detector will exploit almost 4100 32-channel SiPM arrays (tiles) operating at the temperature of –50°C to read out the scintillation light. Potential SiPM candidates operating at temperatures below 0°C were studied [N. Anfimov et al. Study of silicon photomultiplier performance at different temperatures. NIMA 997:165162, 2021]. The methods and design of the setup for SiPM tiles mass tests at –50°C were developed and tested at DLNP JINR. The results were accepted for use by the JUNO collaboration and successfully passed Final Design Review (FDR). The technique allows testing a single array and will be scaled up to test 16 tiles together. To test simultaneously multiple tiles the optical fiber splitter has been designed (see in Fig.3) [Rybnikov, A.V. et al. Optical Fiber Splitter for Photodetector Testing. Phys. Part. Nuclei Lett. 19, 797–802 (2022)]. The setup for the mass testing was produced and assembled at IHEP and is under commissioning now (see in Fig. 3).



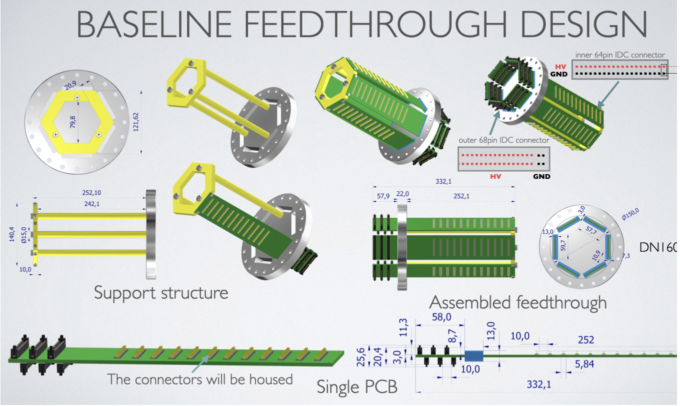
outside of cryogenic chamber

Inside of cryogenic chamber

Figure 3. SiPM Mass-testing setup at IHEP.

SiPM power system

A multi-channel SiPM power supply VME module for 128 channels has been developed. The module allows biasing detectors from 0 to 200V with a maximum current load of 500 mA. Current and short-circuit monitoring is implemented. The modules are designed to power 4100 SiPM arrays in the TAO detector. Pilot versions have been produced (see Figure 4), tested and passed FDR. All components for modules production were procured and await the manufacturing in China. We also developed the feedthrough to guide all power lines inside the cryostat (see Figure 4) and find suitable cables for transferring up to 200V at −50°C in LAB.



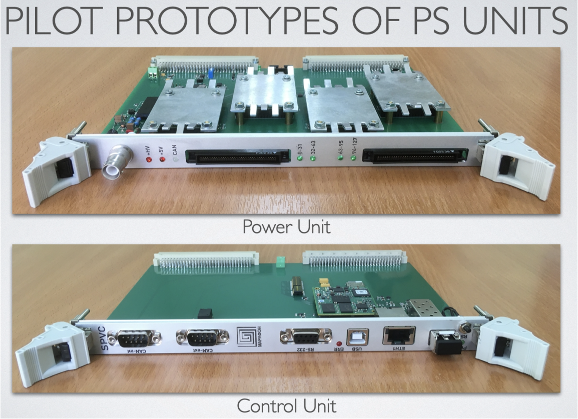


Figure 4. The scope of the feedtrough design and assembly (left). A photograph of the power module and its control unit (right).

Solar neutrinos

JINR scientists took part in the proposal to use the upgrade of the OSIRIS facility (Serappis) for the detection of the Solar pp-neutrino flux with high precision (EPJC 82, 2109.10782). A possibility to use a magnetic field shield combined with a light concentrator is considered for the Serappis detector. Together with the manufacturer we are developing the process of argentum deposition on the carbon fiber texture.

The sensitivity of the JUNO experiment

It is shown that JUNO will be able to measure the neutrino oscillation parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ with precision below 0.5% during 6 years of data taking (Chin.Phys.C 46 (2022) 123001 [2204.13249]). Moreover the precision of 1% will be reached already after 100 days of data taking.

A new estimation of the JUNO sensitivity to neutrino mass ordering taking into account the data from the satellite detector TAO and recent knowledge of the detector and experimental setup was released. The sensitivity reaches 3σ after 6 years of the data taking (see in Figure 5). The result was obtained via two methods: based on the Asimov data set (with no fluctuations) and based on the MC with fluctuations. The methods provide consistent results. The draft of the paper is under the collaboration review.

Two groups from JINR provided their own analysis for each of the studies, passing all the steps of the analysis preparation, cross checks and review.

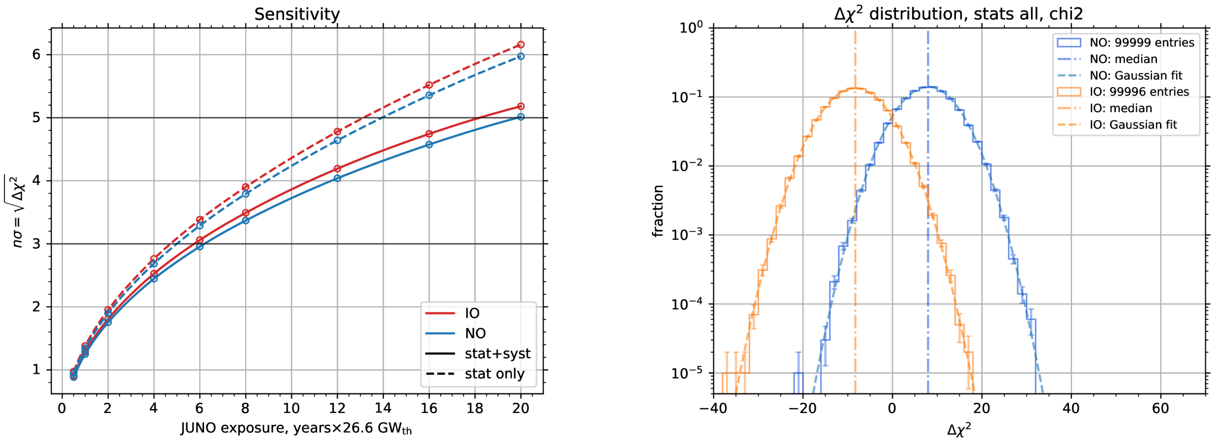


Figure 5. Sensitivity of the JUNO experiment versus exposure (left). The distribution of the test statistic for 6 years of data acquisition (right).

Event reconstruction

The results of a study of application of methods of machine learning the the reconstruction of the primary vertex and energy in the JUNO detector were published (NIMA1010, [2101.04839]). The group from DLNP JINR has made a major contribution to the energy reconstruction and performed the overall coordination of the analysis.

The new algorithms for the reconstruction of the energy of positron for the JUNO detector were developed by the JINR group (Eur.Phys.J.C 82 (2022) 1021). It is shown that the algorithms may reach the desired energy resolution of $\sigma=3\%$ at 1 MeV.

An algorithm of muon tracks and electromagnetic shower with the help of spherical functions has been developed and tested. We wrote a procedure of closest muon tracks separation, proposed a new method of muon tracks reconstruction quality estimation, and also we made preliminary conditions for Li/He isotopes isolation with taking into account muon track reconstruction quality.

With our method we can reconstruct a single muon track with precision ~25 cm (maximal distance between true and reconstructed muon track in central detector).

Computing infrastructure

During 2022 the usage of the computing resources increased a lot. Out of 2.04 millions of jobs performed within JUNO distributed computing infrastructure JINR processed the largest fraction (46%) of jobs (see in Figure 6). In 2021 JINR's cluster processed 31% out of all JUNO jobs.

JINR is providing CPU nodes with large memory per CPU (15 GB) making JINR the only provider to perform memory demanding simulation, e.g. high energy muons. As for storage the JINR provides 1 PB quota of effective disk space (2 PB of raw disk space due to 2x replication) for JUNO (65% of which is used) and 650 TB (1.3 PB) for Daya Bay (92% is used).

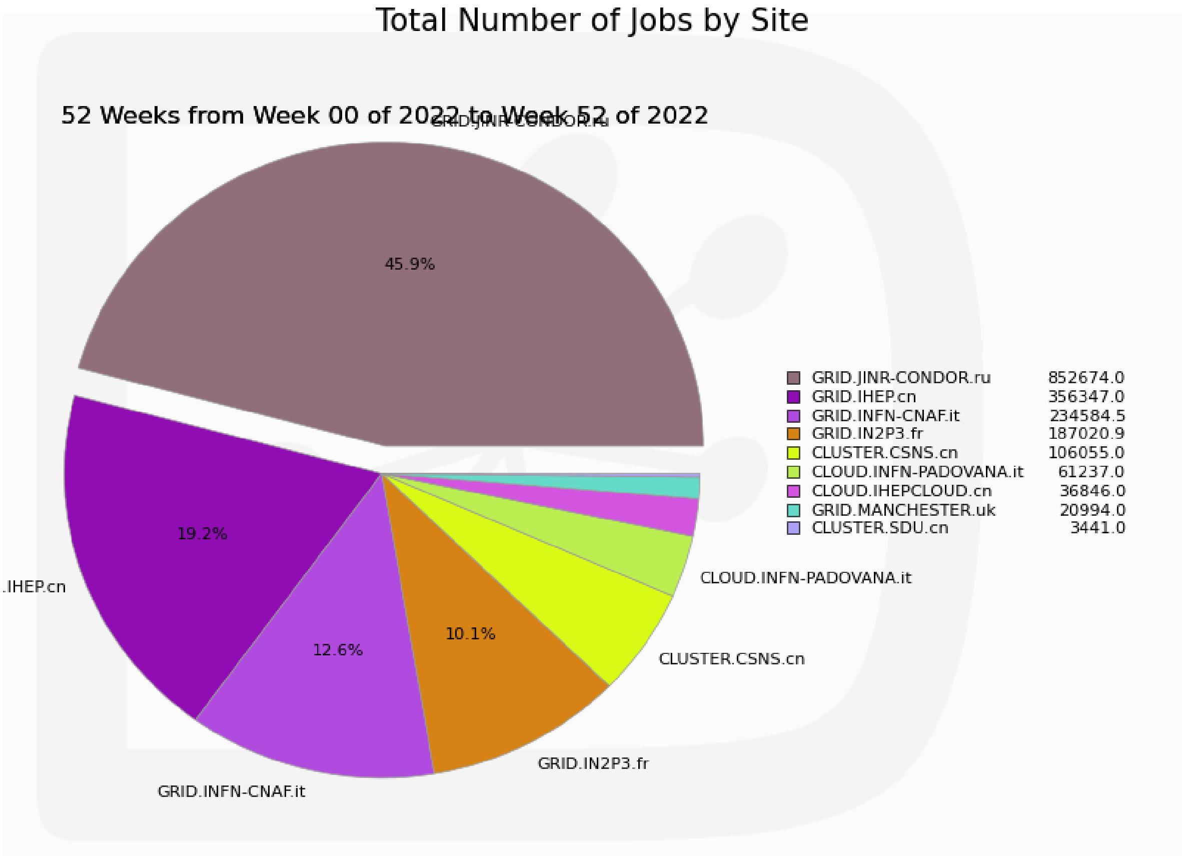


Figure 6. The usage of the shared CPU resources within JUNO distributed infrastructure.

Apart from providing CPU and storage resources the following JUNO DCI services replicas were deployed at JINR to make JUNO DCI more redundant and thus its functioning more reliable as well as to increase an overall JUNO DCI performance:

- WebApp and Configuration Services;
- Secondary VOMS server for JUNO VO;
- Full replica of CVMFS Stratum-1 repositories /cvmfs/juno.ihep.ac.cn and
- /cvmfs/dcomputing.ihep.ac.cn;

- JUNO offline Condition Database.

The final result of the Daya Bay experiment

The Daya Bay experiment has finished operation in 2020. In 2022 the measurement of the neutrino oscillation parameters based on the complete dataset was finished. The obtained result $\sin^2 2\theta_{13}=0.0851\pm0.0024$ and $\Delta m^2_{32}=2.466\pm0.060$ (-2.571 ± 0.060) eV^2 for the normal (inverted) neutrino mass ordering is the most precise to the date measurement ([2211.14988], submitted to PRL). The precision of the measurement of $\sin^2 2\theta_{13}$ will be dominated by the Daya Bay at least for 10-15 years. The observed reactor electron antineutrino survival probability as well as obtained contours are shown in Figure 7.

The group from JINR traditionally participated in the preparation of the result, including the selection of inverse beta-decay events, estimation of the backgrounds and oscillation analysis. Our group was chosen by the collaboration to develop the code for the data preservation of the main analysis.

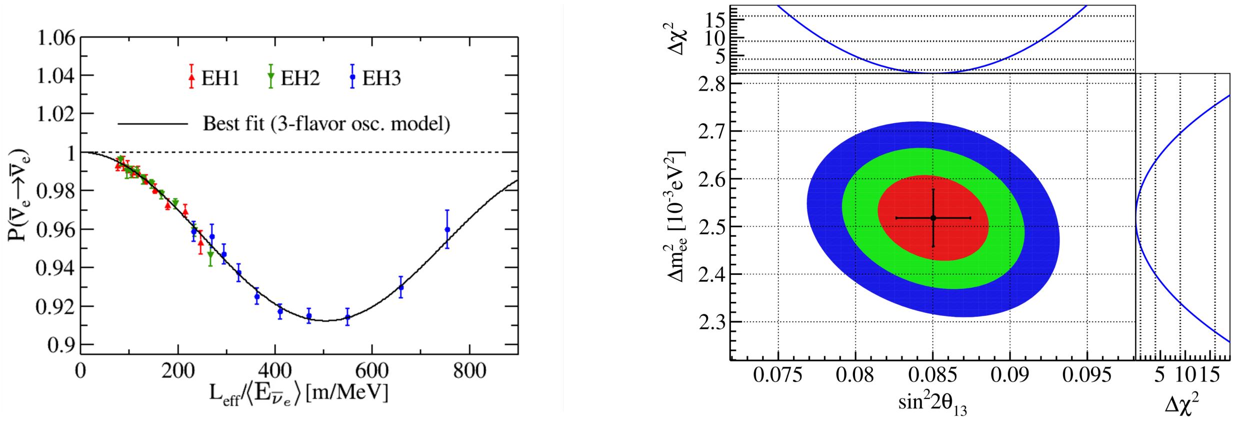


Figure 7. The ratio of the observed events without the backgrounds to the expectation without oscillations (left). The confidence interval for the neutrino oscillation parameters $\sin^2 2\theta_{13}$ and Δm^2_{31} (right).

The value of $\sin^2 2\theta_{13}$ by Daya Bay will be the world leading measurement with uncertainty of 2.8% for decades. The only known planned project which may provide a better precision of 0.5% is SuperCHOOZ, if approved. The detailed comparison is presented in Figure 8.

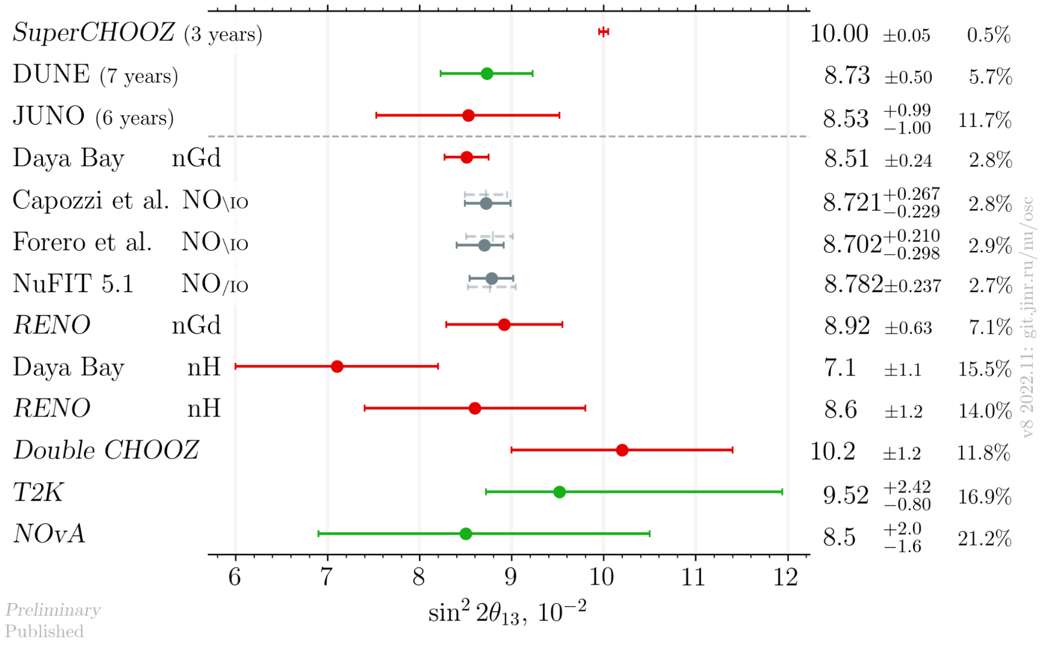


Figure 8. The comparison of the measurement of $\sin^2 2\theta_{13}$.

2.2.4. A list of the main publications of the JINR authors, including associated personnel on the results of the project (list of bibliographical references).

1. Abuselme A.,..., Gonchar M.,..., Malyshkin Yu. et al., Sub-percent precision measurement of neutrino oscillation parameters with JUNO, e-Print: 2204.13249 [hep-ex], Published in: Chin.Phys.C 46 (2022) 12, 123001
2. JUNO Collaboration, JUNO physics and detector, e-Print: 2104.02565 [hep-ex], Published in: Prog.Part.Nucl.Phys. 123 (2022), 103927
3. An F.P.,..., Dolzhikov D.,..., Gonchar M.,..., Naumov D.,..., Olshevkiy A.,..., Treskov K.,..., Zavadskyi V. et al., Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay, e-Print: 2211.14988 [hep-ex], submitted to PRL.
4. Angel Abusleme,..., Dmitrievsky S.,..., Gornushkin Yu.,..., Korablev D. et al., The JUNO experiment Top Tracker, e-Print: 2303.05172 [hep-ex], to be submitted.
5. Arsenii Gavrikov, Yury Malyshkin, Fedor Ratnikov (Higher Sch. of Economics, Moscow and Dubna, JINR), Energy reconstruction for large liquid scintillator detectors with machine learning techniques: aggregated features approach, e-Print: 2206.09040 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 11, 1021, Eur.Phys.J.C 82 (2022), 1021
6. Xu H.,..., Anfimov N.,..., Gromov M.,..., Rybnikov A. et al., Calibration strategy of the JUNO-TAO experiment, e-Print: 2204.03256 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 12, 1112
7. Bieger L.,..., Gromov M.,..., Smirnov O. et al., Potential for a precision measurement of solar pp neutrinos in the Serappis experiment, e-Print: 2109.10782 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 9, 779
8. Qian Z.,..., Gavrikov A.,..., Gonchar M.,..., Malyshkin Yu.,..., Treskov K. et al., Vertex and energy reconstruction in JUNO with machine learning methods, e-Print: 2101.04839 [physics.ins-det], Published in: Nucl.Instrum.Meth.A 1010 (2021), 165527
9. O. Smirnov, D. Korablev, A. Sotnikov et al., Magnetic shielding for large photoelectron multipliers for the OSIRIS facility of the JUNO detector, e-Print: 2212.02562 [physics.ins-det], submitted to JINST.
10. A. Stepanova (Dubna, JINR), M. Gonchar (Dubna, JINR), L. Kolupaeva (Dubna, JINR), K. Treskov (Dubna, JINR), Deep Underground Neutrino Experiment DUNE—Calculation of

Sensitivity to the Measurement of Oscillation Parameters, Published in: Phys.Part.Nucl.Lett. 19 (2022) 5, 505-508

11. Rybnikov, A.V., Anfimov, N.V., Fedoseev, D.V. et al. Optical Fiber Splitter for Photodetector Testing. Phys. Part. Nuclei Lett. 19, 797–802 (2022). https://doi.org/10.1134/S1547477122060255
12. Abusleme, A.,..., Anfimov N,. et al. Mass testing and characterization of 20-inch PMTs for JUNO. Eur. Phys. J. C 82, 1168 (2022). https://doi.org/10.1140/epjc/s10052-022-11002-8

2.2.5. A complete list of publications (electronic annex, for journal publications with journal impact factor).

1. Daya Bay Collaboration, Search for electron-antineutrinos associated with gravitational-wave events GW150914, GW151012, GW151226, GW170104, GW170608, GW170814, and GW170817 at Daya Bay, e-Print: 2006.15386 [astro-ph.HE], Published in: Chin.Phys.C 45 (2021) 5, 055001
2. JUNO Collaboration, Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO, e-Print: 2006.11760 [hep-ex], Published in: Chin.Phys.C 45 (2021) 2, 023004
3. Daya Bay Collaboration, Antineutrino energy spectrum unfolding based on the Daya Bay measurement and its applications, e-Print: 2102.04614 [hep-ex], Published in: Chin.Phys.C 45 (2021) 7, 073001, Chinese Physics C, Volume 45, Number 7, 2021
4. Abuselme A.,..., Gonchar M.,..., Malyshkin Yu. et al., Sub-percent precision measurement of neutrino oscillation parameters with JUNO, e-Print: 2204.13249 [hep-ex], Published in: Chin.Phys.C 46 (2022) 12, 123001
5. JUNO Collaboration, Prospects for detecting the diffuse supernova neutrino background with JUNO, e-Print: 2205.08830 [hep-ex], Published in: JCAP 10 (2022), 033
6. JUNO Collaboration, Damping signatures at JUNO, a medium-baseline reactor neutrino oscillation experiment, e-Print: 2112.14450 [hep-ex], Published in: JHEP 06 (2022), 062
7. Daya Bay Collaboration, First Measurement of High-Energy Reactor Antineutrinos at Daya Bay e-Print: 2203.06686 [hep-ex], Published in: Phys.Rev.Lett. 129 (2022) 4, 041801
8. JUNO Collaboration, JUNO physics and detector, e-Print: 2104.02565 [hep-ex], Published in: Prog.Part.Nucl.Phys. 123 (2022), 103927
9. An F.P.,..., Dolzhikov D.,..., Gonchar M.,..., Naumov D.,..., Olshevkiy A.,..., Treskov K.,..., Zavadskyi V. et al., Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay, e-Print: 2211.14988 [hep-ex], submitted to PRL.
10. Angel Abusleme,..., Dmitrievsky S.,..., Gornushkin Yu.,..., Korablev D. et al., The JUNO experiment Top Tracker, e-Print: 2303.05172 [hep-ex], to be submitted.
11. Daya Bay and PROSPECT Collaborations, Joint Determination of Reactor Antineutrino Spectra from U235 and Pu239 Fission by Daya Bay and PROSPECT, e-Print: 2106.12251 [nucl-ex], Published in: Phys.Rev.Lett. 128 (2022) 8, 081801
12. JUNO Collaboration, The design and sensitivity of JUNO’s scintillator radiopurity pre-detector OSIRIS, e-Print: 2103.16900 [physics.ins-det], Published in: Eur.Phys.J.C 81 (2021) 11, 973
13. Arsenii Gavrikov, Yury Malyshkin, Fedor Ratnikov (Higher Sch. of Economics, Moscow and Dubna, JINR), Energy reconstruction for large liquid scintillator detectors with machine learning techniques: aggregated features approach, e-Print: 2206.09040 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 11, 1021, Eur.Phys.J.C 82 (2022), 1021
14. Xu H.,..., Anfimov N.,..., Gromov M.,..., Rybnikov A. et al., Calibration strategy of the JUNO-TAO experiment, e-Print: 2204.03256 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 12, 1112
15. Bieger L.,..., Gromov M.,..., Smirnov O. et al., Potential for a precision measurement of solar pp neutrinos in the Serappis experiment, e-Print: 2109.10782 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 9, 779

16. JUNO Collaboration, Calibration Strategy of the JUNO Experiment, e-Print: 2011.06405 [physics.ins-det], Published in: JHEP 03 (2021), 004
17. JUNO Collaboration, Radioactivity control strategy for the JUNO detector, e-Print: 2107.03669 [physics.ins-det], Published in: JHEP 11 (2021), 102
18. Qian Z.,..., Gavrikov A.,..., Gonchar M.,..., Malyshkin Yu.,..., Treskov K. et al., Vertex and energy reconstruction in JUNO with machine learning methods, e-Print: 2101.04839 [physics.ins-det], Published in: Nucl.Instrum.Meth.A 1010 (2021), 165527
19. Qian Z.,..., Gavrikov A.,..., Gonchar M.,..., Malyshkin Yu.,..., Treskov K. et al., Vertex and energy reconstruction in JUNO with machine learning methods, e-Print: 2101.04839 [physics.ins-det], Published in: Nucl.Instrum.Meth.A 1010 (2021), 165527
20. N. Anfimov, D. Fedoseev, A. Rybnikov, A. Selyunin, S. Sokolov, A. Sotnikov, Study of silicon photomultiplier performance at different temperatures, Nuclear Instruments and Methods in Physics Research Section A, Volume 997, 2021, 165162, ISSN 0168-9002,https://doi.org/10.1016/j.nima.2021.165162.
21. JUNO and Daya Bay Collaborations, Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector, e-Print: 2007.00314 [physics.ins-det], Published in: Nucl.Instrum.Meth.A 988 (2021), 164823, Nucl.Instrum.Meth.A 988 (2021), 164823
22. O. Smirnov, D. Korablev, A. Sotnikov et al., Magnetic shielding for large photoelectron multipliers for the OSIRIS facility of the JUNO detector, e-Print: 2212.02562 [physics.ins-det], submitted to JINST.
23. A. Stepanova (Dubna, JINR), M. Gonchar (Dubna, JINR), L. Kolupaeva (Dubna, JINR), K. Treskov (Dubna, JINR), Deep Underground Neutrino Experiment DUNE—Calculation of Sensitivity to the Measurement of Oscillation Parameters, Published in: Phys.Part.Nucl.Lett. 19 (2022) 5, 505-508
24. Rybnikov, A.V., Anfimov, N.V., Fedoseev, D.V. et al. Optical Fiber Splitter for Photodetector Testing. Phys. Part. Nuclei Lett. 19, 797–802 (2022). https://doi.org/10.1134/S1547477122060255
25. Abusleme, A.,..., Anfimov N,. et al. Mass testing and characterization of 20-inch PMTs for JUNO. Eur. Phys. J. C 82, 1168 (2022). https://doi.org/10.1140/epjc/s10052-022-11002-8

2.2.6 List of talks given at international conferences and meetings (electronic annex).

1. V.Sharov ”Development of a multi-channel power supply for the TAO and DUNE experiments”, AYSS-2021, 13.10.2021 (oral talk)
2. N. Anfimov. “Methodical activities at DLNP JINR for international neutrino experiments JUNO and DUNE” Conference “Kruger 2022: Discovery Physics at the LHC”, South Africa, December 4-9, 2022.
3. A.G. Olshevsky “Results of neutrino oscillations and the search for sterile states of neutrinos”, International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology, 18-21 July 2022, Dubna (invited plenary talk)
4. Y.M. Malyshkin, plenary, “Status and Physical Potential of JUNO”, NUCLEUS 2021, remote, September 1−11, 2021
5. Y.M. Malyshkin, parallel, “Application of machine learning techniques for event reconstruction in JUNO”, NuFact 2021, Cagliari/online, Italy, September 6−11, 2021.
6. Y.M. Malyshkin, parallel, “Oscillation Physics in JUNO”, NeuTel 2021, online, February 18-26, 2021.
7. M. Gonchar, parallel, "GNA: data flow approach for the neutrino oscillation experiments", Innovative Workflows in Astro and Particle Physics IWAPP (remote), March 8−12, 2021.
8. M. Gonchar, parallel, "Neutrino Oscillation Physics in JUNO", European Physical Society conference on high energy physics EPS-HEP 2021 (remote), July 26-30, 2021

9. M. Gonchar, plenary, "The JUNO experiment: status and prospects", Nucleus-2022, Moscow, 11−16 July, 2022
10. V. Zavadskyi, poster, “Search for Sterile Neutrinos with JUNO-TAO”, Neutrino 2022, May 30−June 4, 2022 (remote).
11. D. Dolzhikov, poster, “JUNO Neutrino Mass Ordering Sensitivity with Subdetectors”, 57th meeting of the PAC for Particle Physics, Dubna, 2023.

2.2.7. Patent activity (if any)

2.3. Status and stage (TDR, CDR, ongoing project) of the project (including percentage of implementation of the declared milestones of the project

1. SiPM Mass-testing — FDR
2. SiPM Power System — FDR

2.4. Results of related activities

Educational activities

1. A. Olshevsky is full professor at Moscow State University (2003 — ongoing) with “Modern research in elementary particle physics.” semi-annual courses.
2. D. Naumov is full professor at Moscow State University with an annual course on the Standard model.
3. N. Anfimov is associate professor at Dubna University (2021 — ongoing) with “Nuclear electronics” and “Electronics in physics” semi-annual courses.

List of defended dissertations

1. N. Anfimov “Development and application of methods for studying photodetectors”, defended 04.03.2021 at JINR

List of defended diploma

1. A. Gavrikov, “Machine Learning Methods for the Event Energy Reconstruction: JUNO Experiment”, HSE, 2022, master’s degree.
2. M. Strizh, “Daya Bay Determination of the arrival direction of antineutrino from a reactor – model and data analysis of the Daya Bay experiment”, MSU, 2021, master’s degree.
3. A. Shaydurova “Application of the Magnus expansion for the calculation of the oscillation probabilities of atmospheric neutrino”, Moscow State University, 2021, master’s degree.
4. V. Zavadskyi “Search for the sterile neutrinos in the Daya Bay and JUNO experiments”, MIPT, 2021, master’s degree.

2.4.2. JINR grants (scholarships) received.

1. N. Balashov — AYSS grants in 2020, 2021, 2023
2. D. Fedoseev — AYSS grants in 2021, 2022
3. A. Chetverikov — AYSS grant in 2023
4. V. Sharov — AYSS grant in 2022
5. M. Zavadskyi — AYSS grant in 2023

2.4.3. Awards and prizes.

1. JINR First Prize for 2021 in the nomination "Research Experimental Works": "Neutrino studies in the OPERA experiment" — A.Olshevsky, Yu. Gornushkin, S.Dmitrievski, D.Naumov, A.Chukanov, A. Krasnoperov.

2.4.4. Other results (expert, scientific-organisational, scientific-propaganda activities).

Expert activities

N. Anfimov is a reviewer in

- Nuclear Instruments and Methods in Physics Research, A — 4 assignments
- Instruments, MDPI — 1 assignment
- PEPAN Letters — 4 assignments

A. Selyunin is a reviewer in

- PEPAN Letters — 2 assignments

D. Naumov is a reviewer in

- EJPC,
- Phys.Rev.
- IOP,
- PEPAN Letters

Scientific-organisational activities

1. Regular excursions to the Green laboratory facilities — A.Selyunin, A.Antoshkin, V. Sharov, N.Anfimov
2. Festival of Science and Technology “Techno Environment at VDNKh” (2021), JINR stand — V. Sharov
3. All-Russian Science Festival “Nauka 0+”, Lecturer at the Kurchatov School (2022) — V.Sharov
4. Marathon “JINR visiting Dubna schools” (2021-2022) — V.Sharov, N.Anfimov
5. Lecture for “Particle physics for kids” (2022) — N.Anfimov
6. Lecture at Vinca Institute. Serbia (2022) — N.Anfimov
7. Seminar “Information technologies in JUNO experiment”, IT School on Data Science, 2021, MLIT — M. Gonchar
8. Baikal School, Baksan School — D.Naumov
9. M.Gonchar — Executive Board member and Institutional Board representative in Daya Bay; Speaker’s Committee member, Online Event Classification group co-convener.
10. D. Naumov — Executive Board member and Institutional Board representative in JUNO, JUNO Publication Committee member, Remote Shift and Maintenance taskforce leader,.
11. A. Olshevskiy — PMT Instrumentation L2 manager in JUNO.

3. International cooperation

Actually participating countries, institutions and organizations

Organization	Country	City	Participants	Type of agreement
IHEP	China	Beijing	Yifang Wang + 10	MoU
SYSU	China	Guangzhou	Wei Wang + 10	MoU
SINP MSU	Russia	Moscow	Alexander Chepurnov, Maxim Gromov	MoU
INFN	Italy	Catania, Rome	Giuseppe Adronico +1 Stefano Maria Mari +1	MoU MoU
FZJ-IKP	Germany	Jülich	Livia Ludhova +4	MoU
EKUT	Germany	Tübingen	Tobias Lachenmaier +1	MoU

4. Analysis of planed vs actually used resources: manpower (including associated personnel), financial, IT, infrastructure

4.1 Manpower (actual at the time of reporting)

No.	Personnel category	JINR staff, amount of FTE	JINR associated personnel, amount of FTE
1.	research scientists	10.9	
2.	engineers	5.2	
	Total:	**16.1**	

4.2 The actual estimated cost of the project

Financial information of the project is accounted for at JINR at the level of the theme: “Study of Neutrino Oscillations (02-2-1099-2010/2023) and will be presented in the corresponding theme report.

4.3 Other resources

Computer resources consumed MICC	Distribution by years		
	2021	2022	2023
Data storage (TB) - EOS	500	1000	1300

Cloud (cores, used permanently)	100	200	290
Cloud (core-hour, on demand)	1 073 000	1 960 000	690 000

5. Conclusion

The JUNO experiment, a long baseline reactor antineutrino experiment in China, aims to determine the neutrino mass ordering and measure lepton mixing parameters with record sub-percent precision level.

JINR has contributed to the construction of the detector and overall preparation of the experiment. In particular, JINR has designed and produced high voltage units for the photomultipliers, developed and produced the stainless steel structure for the muon tracker, designed the data acquisition system, designed and produced magnetic field shields for the large PMTs of the OSIRIS@JUNO detector, designed and produced two stations for large PMT scannings, scanned for almost 4000 PMTs and provided PMT long-term stability tests, and contributed to the design and construction of the satellite detector TAO.

JINR also shares its computer resources within JUNO distributed computer infrastructure, becoming the major data center in the collaboration. JINR also has contributed to the analysis of the JUNO sensitivity to neutrino mass ordering determination and neutrino oscillation parameters. Additionally, JINR participated in the analysis of the full dataset of the Daya Bay experiment, which estimated the most precise values of the neutrino mixing parameters $\sin^2 2\theta_{13}$ and Δm^2_{32}.

Overall, JINR has taken a leading role among JUNO participants outside of China, and fulfilled all its duties.The upcoming period from 2024-2026 is crucial for the success of the experiment as it involves the commissioning of the detector and the commencement of data collection.

6. Proposed reviewers

Yakushev Evgeny, JINR

Theme

_____________/______________/
"_____"___________________ 2023 г.

Project leader (project code)
_____________/____/
"_____"____________ 2023 г.

Laboratory Economist
______/_______/
"_____"____________ 2023 г.