## Proposal for prolongation of the project

# DANSS

## Detector of the reactor AntiNeutrino based on Solid state plastic Scintillator

Theme: **03-2-1100-2010/2018** (**nonaccelerator neutrino physics and astrophysics**)

*Dzhelepov Laboratory of Nuclear Problems (DLNP JINR), Dubna*
*V.V.Belov, V.B.Brudanin, V.G.Egorov, M.V.Fomina, S.V.Kazartcev, A.S.Kuznetsov, D.V.Medvedev, A.G.Olshevsky, I.E.Rozova, N.S.Rumyantseva, Ye.A.Shevchik, M.V.Shirchenko, Yu.A.Shitov, I.V.Zhitnikov, D.R.Zinatulina*

*Institute of Theoretical and Experimental Physics (ITEP), Moscow*
*I.G.Alexeev, A.S.Kobyakin, I.V.Machihilyan, D.N.Svirida, N.A.Skrobova, A.S.Starostin*

*Institute of Experimental and Applied Physics, Czech Technical University in Prague (ÚTEF ČVUT), Prague*
*M.Špavorová, L.Fajt, R.Hodák, Z.Hons, F.Mamedov, P.Přidal, E.Rukhadze, I.Štekl, J.Vlášek.*

*P.N. Lebedev Physical Institute of the Russian Academy of Sciences (LPI RAS), Moscow*
*M.V.Danilov*

*Project leader from JINR V.G. Egorov (egorov@jinr.ru)*
*Project deputy leader from JINR V.B. Brudanin*

# Abstract

Following the Project, a relatively compact neutrino detector **DANSS** with 1 m$^3$ sensitive volume has been developed and created. The detector does not contain caustic, flammable or other dangerous liquids and therefore does not meet any restrictions against location close to industrial power reactors. The DANSS spectrometer is mounted at the fourth unit of Kalinin Nuclear Power Plant (KNPP) in the room #A336 which is located just below the core of the WWER1000 reactor with 3100 MW thermal power. Due to such position, there are more than $10^4$ IBD neutrino interactions per day in the detector body. On the other hand, the detector is shielded against cosmic rays with a big amount of hydrogen-containing materials located above it. Together with high segmentation of plastic scintillator, as well as combined passive and active shielding, all these factors ensure good background suppression down to few percent and provide about 5000 useful events detected per day. A lifting gear allows moving *on-line*, varying the distance to the reactor core from 10.7 to 12.7 m. Due to this feature, the **DANSS** detector is used now to search for short-range neutrino oscillation to a sterile state. It is expected that we get the final answer about existence of so-called “reactor anomaly” in 2018.

In the next 2019–2021 period it is planned to widen the range of the DANSS sensitivity for the oscillation parameters (by higher statistics and, mostly – by detailed investigation of systematic factors). The second goal is precise measurement of the neutrino energy spectrum as a function of time during 2-3 campaigns. These data would produce a basis of reactor neutrino monitoring (actual power and fuel composition). The price of the above activity is estimated as $30,000 per year and covers permanent presence of two JINR physicists at KNPP (Udomlya, Tver region, 285 km from Dubna), maintenance and repair of the spectrometer equipment, assistance of local KNPP personnel and rent of an office in Udomlya.

The next point of our proposal is the JINR limited contribution (within $170,000) to a common (**JINR** + **NEOS** + **Neutrino4**) creation of a new neutrino detector near the research SM3 reactor at NIIAR (Dimitrovgrad, Ulyanovsk region) which could measure neutrino spectrum at 5-18 m distances, thus expanding the oscillation parameters ROI.

In addition, it is planned to develop and create (taking into account accumulated experience) two new neutrino detectors **S$^3$** ***(S-cube)*** based on another scintillator element. Being smaller, simpler and cheaper than **DANSS**, they would have better energy resolution and be able to detect about 300-400 IBD events per day, thus providing reliable reactor monitoring. The price of one of two such **S$^3$** detectors is estimated as ~$270,000 (the second one will be created by ÚTEF ČVUT in Prague and installed then at the Temelin NPP, Czechia).

## 1. Introduction

The goal of the common (JINR + ITEP) project started in 2010 was to develop and create a detector of the reactor antineutrino and then explore it in order to monitor industrial power reactors. After the “Reactor Anomaly” claimed in 2011, one more goal has appeared – search for short-range neutrino oscillation to a sterile state.

Within the previous period of the project realization, the unique neutrino spectrometer **DANSS** (https://arxiv.org/pdf/1606.02896.pdf [physics.ins-det]) was developed, created and started to operation. Some features of the detector make it free of numerous disadvantages being inherent in similar devices:

- based on a solid state plastic scintillator, the detector has no restrictions on location close to a commercial power reactor

- placed at a distance of 10 meter from the WWER1000 reactor core, it is irradiated with extremely high neutrino flux $5\times10^{13}$ 1/cm$^2$/s;
- the detector is shielded against cosmic rays with a big amount of hydrogen-containing materials located above it (~50 m of water equivalent) which suppresses hadronic component completely;
- high segmentation of the detector body provides more reliable identification of the neutrino events;
- regular (3 times per week) variation of the detector position (Up-Middle-Down) avoid numerous systematic errors which are inherent in the most of other oscillation experiments.

Finally, a regular data taking with the **DANSS** spectrometer operating in the planned mode was started at the end of 2016.

To reach all the physical goals it is proposed to prolong the project for years 2019-2021 and within that period to perform the following:

1. accumulate statistics enough to widen the sensitivity region of the oscillation parameter values in the range of $\sin^2(2\theta_{new}) \approx 0.01$ with $\Delta m^2_{new} \approx (0.1 - 5.0)$ eV$^2$;
2. investigate detailed dependence of the neutrino spectrum from the reactor power and the fuel composition during 2-3 full reactor campaigns (one campaign takes 18 months);
3. make necessary steps towards measurement of the neutrino spectra at shorter and longer distances (5-18m) from the point-like reactor SM3 at the NIIAR (in collaboration with **NEOS** and **Neutrino4**);
4. develop and create two new smaller and simpler neutrino detectors **S$^3$** (***S-cube***) with improved parameters to be exploited at the KNPP and Temelin NPP (CZ).

The cost of realization of p.1-2 are estimated as $30,000 per year, p.3 – as $170,000, and p.4 – as $270,000.

## 2. Status of the research

### 2.1. Status of the competitive projects

All actual competitive projects could be divided to two (almost non-intersecting) groups, according to their goals:

- the projects on the neutrino monitoring of the industrial reactors and
- the projects searching for the short-range neutrino oscillations.

The first group (with applied goal) includes the projects discussed annually at ***AAP*** workshops (Workshop **A**pplied **A**ntineutrino **P**hysics), the former be held in India [1], the previous ones reviewed in [2]. These projects are: **NUCIFER** [3], **CORMORAD** [4], **PANDA** [5], **NEOS** [6], **WATCHMAN** [7], **ANGRA** [8], **NULAT** [9], **IDREAM** [10], **VIDARR** [11], **SoLid** [12], **CHANDLER** [13]. The most developed of them are French **NUCIFER** and Korean **NEOS**, and the last of them is the only one which succeeded to get signal-to-background ratio higher than unity. All the rest projects either have been canceled or are still at the R&D stage, or have faced the problem of background which is much higher than the effect being searched for. It should be mentioned that the most of these projects use liquid scintillator and therefore no of them were allowed to approach to a commercial reactor nearer than to 25-30 m.

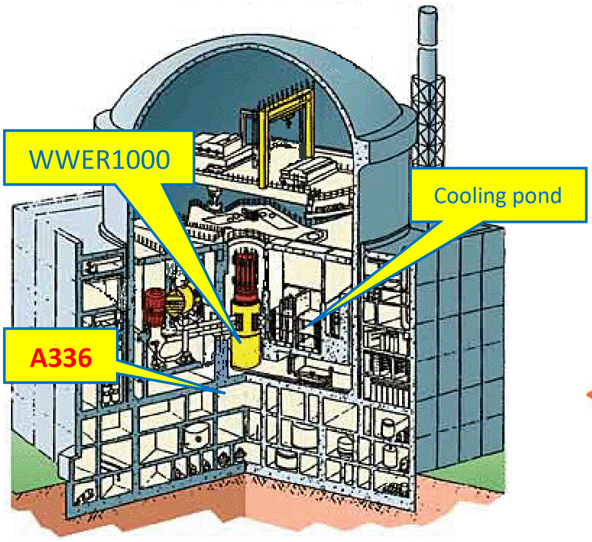
What about the “sterile oscillation” projects, some of them are aimed to a precise measurement of theoretically well-known neutrino spectra from artificial radioactive sources by means of an existing big underground neutrino detectors: **SOX** [14] (BOREXINO + $^{144}$Ce/Pm), **CeLAND** [15] (KamLAND + $^{144}$Ce/Pm), **BEST** [16] (SAGE + $^{51}$Cr). From all of them, the most promoted seems the **SOX** project which is ordering an intensive $^{144}$Ce source at the “Mayak” enterprise in Russia, the transportation to Italy is in preparation (expected in March 2018). If the **SOX** collaboration succeeds to overcome an embargo initiated by the Italian “Green movement” – then the source will be moved to Gran Sasso lab in time. Taking into account relatively short half-life of $^{144}$Ce (285 days), it becomes clear that the **SOX** experiment has a real chance to get any result before the end of 2018.

The rest part of the oscillation projects (**PROSPECT** [17], **Heutrino4** [18], **STEREO** [19]) exploits small research reactors with the power not higher than 30-100 MW. In this case, a liquid scintillator is allowed to be used, but, as usual, an overburden is not thick enough to suppress hadron component of cosmic background (the existing buildings with research reactors are not as massive and do not contain big water reservoirs as industrial NPPs

### 2.2. The DANSS position between the similar projects

Our project takes the leading place between all ones mentioned above. In the previous years, we have developed, created and started the neutrino spectrometer **DANSS** [20] which is free of numerous disadvantages being inherent in similar devices.

First, instead of liquid scintillator, our detector uses solid-state polystyrene-based scintillator. As it does not contain flammable, explosive, caustic, volatile or toxic liquids, there are no restrictions on its location close to the commercial reactor. As a result, the detector is mounted in the room #A336 which is located just below the core of the WWER1000 reactor with 3100 MW thermal power (Fig. 1). Due to such position, there are more than $10^4$ IBD neutrino interactions per day in the detector body. Moreover, being in the bottom part of the building, the detector is shielded against cosmic rays with a big amount of hydrogen-containing materials located above it – the reactor cauldron, theck concrete walls, cooling pond for the spent fuel, reservoirs with boric acid, etc. The total thickness of this gratis overburden is 50 m of water equivalent which removes completely the hadronic component of cosmic rays being the most dangerous source of background events similar to IBD.



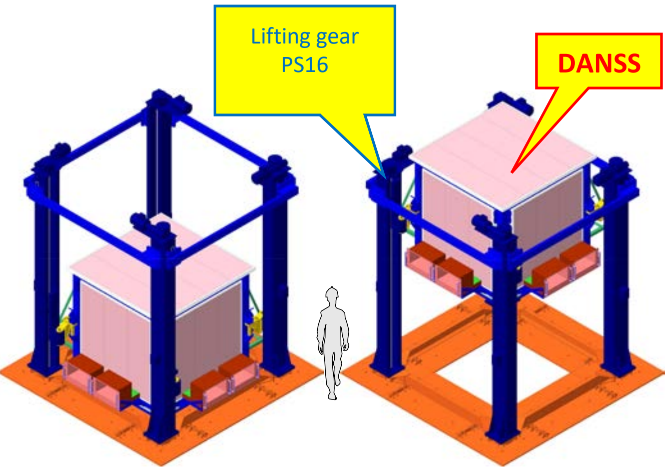


***Fig.1.*** *Left: location of the A336 room below the reactor core. Right: the* ***DANSS*** *detector installed on the lifting gear PS16.*

Second, the sensitive **DANSS** volume is highly segmented – it consists of 2500 independent scintillator strips with a total volume of 1 m$^3$ (Fig. 2). The segmentation provides detailed 3D spatial pattern of energy deposit for each event and thus improves identification. Together with combined passive and active shielding, it allows the background suppression down to a level of few percent.

***Fig. 2.*** *Left: mounting of 2500 scintillator strips. Right: the* ***DANSS*** *detector on the movable platform in the down position.*

Third, the **DANSS** detector with all the shielding, acquisition electronics and auxiliary devices is mounted on a movable platform. A lifting gear PS16 moves it *on-line* by 2 meter per 4 minutes, varying the distance to the reactor core from 10.7 to 12.7 m. Due to this feature, the **DANSS** detector is used now to search for short-range neutrino oscillation to a sterile state. In the most of other similar projects it is done (or planned to be done) by means of precise measurement of the neutrino energy spectrum at fixed position and then comparing it with a calculated spectrum. In this case the reliability and precision of the calculation model used for the reactor neutrino is quite questionable.

We use alternative, model-independent conception. Instead of comparing spectrum itself, we analyze evolution of the spectrum with distance. In this way, we completely avoid systematic errors caused by an incorrect model (no models are used at all), insufficient knowledge of the detector efficiency, fuel composition, power long-term variations, acquisition dead time, etc. If one moves the detector frequent enough (we do it three times per week) then the long-term variation of the fuel composition and burning intensity within the core become not important as well.

Unfortunately, mounting and starting of the **DANSS** spectrometer to operation took much longer time than was expected. In particular, almost one year was lost waiting the next reactor OFF period in order to perform welding works in the room A333 (according to the local rules, the welding is forbidden when the reactor is operating). Later, latent mechanical defect caused a breakage of a lifting system, and again more than a month was lost. In order to remove a small water leakage inside the detector cooling system, we had to dismount and then mount again almost all the shielding, which took about 3 months. Such annoying problems are unavoidable when a new experimental setup is being created. Nevertheless, the spectrometer is in a regular operation starting from October 2016, although some small shortcomings were repaired up to February 2017.

Since that time, every systems work well, and we expect to accumulate statistics enough to confirm or disprove existence of the “Reactor Anomaly” till next Summer. It should be mentioned that only those periods can be analyzed correctly when the reactor power was stable between 3000 and 3100 MW – otherwise an active geometry of the core has irregular shape and the results could be disturbed.

Fig. 3 presents some examples of time and energy spectra measured with 50 PMTs (of-course, similar information obtained with 2500 MPPCs is under analysis as well). Time distribution includes three parts: exponential moderation of neutrons with $\tau_m \approx 3$ μs, exponential capture of neutrons in Gd with $\tau_c \approx 14$ μs, and (almost) constant asymptotic corresponding to random coincidences. It can be seen that the background events (when the reactor is OFF) behaves also “neutron-like” with the same characteristic times, but the origin of the neutrons is different. We suppose that these neutrons originate from surrounding heavy materials irradiated with cosmic muons. Additional evidence of this hypothesis is a quite different shape of the “OFF” energy spectrum. Correct accounting of this background, as well as random events, requires the further investigation.

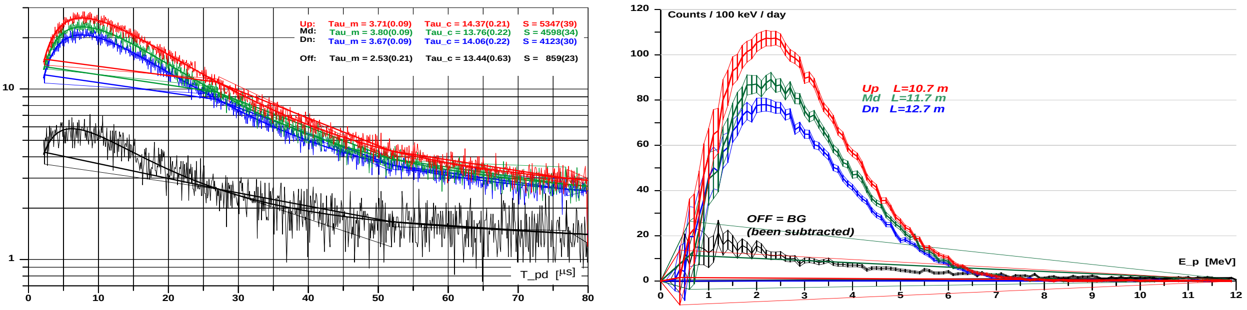


***Fig.3.*** *Time and energy spectra measured at different distance L to the reactor core: Up (L=10.7 m), Md (L=11.7 m), Dn (L=12.7 m). Background spectra for the reactor OFF period are drawn with black color.*

Preliminary analysis of a part of accumulated data is shown in Fig. 4. It can be seen that even with such incomplete data set we can exclude at 99% CL significant part of oscillation parameters $\Delta m^2_{new}$ and $\sin^2(2\theta_{new})$. At the same time, it is clear that the excluded region (as well as the best fit point) depends on the selection conditions and therefore more data and more detailed investigations are needed.

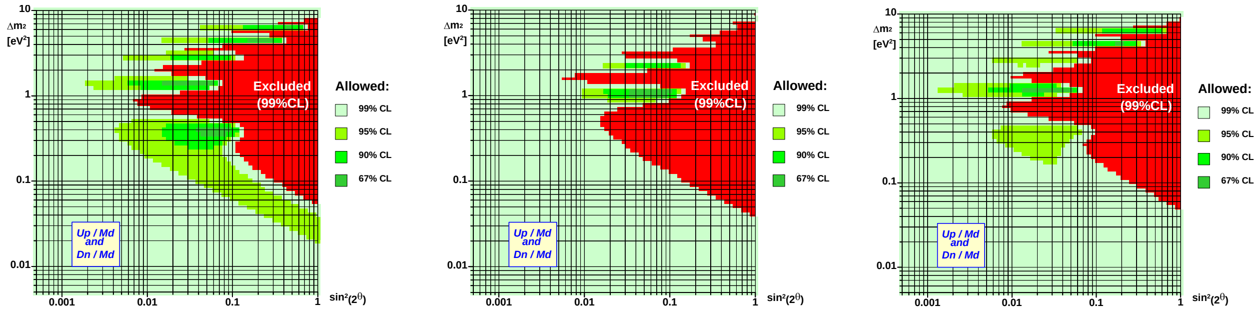


***Fig.4.*** *Allowed and excluded regions of oscillation parameters obtained from the* ***DANSS*** *data analysis under different selection conditions (shown for illustration only).*

Parallel to our works with the **DANSS** spectrometer, we have performed some *R&D* devoted to the next vesion of the neutrino detector – $\mathbf{S^3}$ *(S-cube)*. The weak points of the **DANSS** are relatively poor energy resolution and excessive complexity. The first of them is caused by low quality of scintillator strips produced in Kharkov with extrusive technology. The second one initially was not really unnecessary because our neutrino detector with such structure was the first in the world, possible problems were not known *a priori* and therefore some of the systems were doubled. Today we see our main mistakes, we have more experience and understand that for the reactor diagnostics it is possible to create another detector which could be better, simpler and cheaper.

Instead of long narrow scintillator strips, in the new **S$^3$** detector it was decided to use shorter and wider plates with the same 1 cm thickness (40×20×1 cm) produced by Czech firm NUVIA (ENVINET). After our numerous tests, the firm has optimized chemical composition of the scintillator and produced 160 such plates – the number enough to build two **S$^3$** detectors. One of them will be made in Prague and the second one – in Dubna. Several tests performed with one of the plates in 2017 demonstrate that with appropriate PMT it is possible to get 80 photoelectrons per 1 MeV (instead of 20-23 in **DANSS)** and thus double the energy resolution.

## 2.3. The bibliography

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## 3. Description of the proposed investigations

In the next project period (years 2019-2021) it is proposed to work in three directions:

- continue searching for short-range neutrino oscillations (measure $E\nu$-spectrum as a function of the distance),
- perform neutrino diagnostics of the reactor (measure $E\nu$-spectrum as a function of the campaign time),
- create two new neutrino detectors **S$^3$** ***(S-cube)*** and start them to operation.

### 3.1. Searching for short-range neutrino oscillations

It is expected that in 2018 we get the final answer about existence of so-called "Reactor Anomaly", i.e., oscillation of the reactor neutrino to the fourth, sterile state with the following parameters: $\Delta m^2_{new} \approx 2$ eV$^2$ and $\sin^2(2\theta_{new}) \approx 0.17$. The most probable answer will be negative.

However, it does not mean that there no such oscillation with other parameter values. Our MC simulations indicate that for the **DANSS** conditions (distance varying from 10.7 to 12.7 m) in one-two years it is possible to reach sensitivity of $\sin^2(2\theta_{new}) \approx 0.01$ with $\Delta m^2_{new} \approx (0.1 – 5.0)$ eV$^2$. To do that, we should just continue the measurements with the **DANSS** spectrometer, studying the spectrum evolution with distance and from time to time performing calibration tests with radioactive sources. The price of the above activity is estimated as $30,000 per year and covers permanent presence of two JINR physicists at KNPP (Udomlya, Tver region, 285 km from Dubna), maintenance and repair of the spectrometer equipment, assistance of local KNPP personnel and rent of an office in Udomlya.

In order to widen the sensitivity to the region of lower and higher values of $\Delta m^2$, one needs to expand the region of distances. The limited height of the room A336 at the KNPP makes it impossible. Another solution is the following. It was proposed that we combine experience and efforts of the JINR physicists with those of Korean **NEOS** and Russian **Neutrino4** experiments and build common new neutrino detector near the research SM3 reactor at NIIAR (Dimitrovgrad, Ulyanovsk region) which could measure neutrino spectrum at 5-18 m distances. The **NEOS** physicists will provide their liquid scintillator and some other elements of their spectrometer (which is no more in operation) and the crew of **Neutrino4** will perform all mechanical and other mounting works at NIIAR. Contribution of the JINR will be limited by purchasing of 200 scintillator detectors (50×50×5 cm) for the muon veto system. In addition, being the international institution, the JINR will take responsibility for collaboration meetings and contacts with Korean side, as well as for transportation of the NEOS elements to Russia. еще один спектрометр, используя элементы и наши наработки. The total amount required from the JINR for this collaboration is estimated as $170,000.

### 3.2. Measurement of the neutrino energy spectrum depending on the reactor power and the fuel composition during the reactor campaign

For this task, as in previous case, we have just to continue the measurements with the **DANSS** spectrometer during at-least two complete 1.5-year campaigns. It is expected that the total neutrino flux decreases smoothly by 5-7% per campaign, whereas its energy becomes slightly higher. Results of the measurement would demonstrate perspectives of a real neutrino monitoring (which is important not only for the power industry, but also for non-proliferation of fissile materials) and compare he models used for the spectra calculations.

### 3.3. Creation of two $S^3$ (*S-cube*) detectors and starting them to operation

The $\mathbf{S^3}$ detectors, contrary to **DANSS**, are developed by other authors group. Instead of ITEP and LPI RAS (Moscow), an active part in these works is taken by physicists of Institute of Experimental and Applied Physics, Czech Technical University in Prague (ČVUT, ÚTEF). Nowadays, taking into account results of *R&D*, the concept of $\mathbf{S^3}$ seems to be the following.

80 polystyrene-based scintillator plates of 40×20×1 cm dimension produced by the firm NUVIA with the "*between glass*" technology, form a cube of 40×40×40 cm (Fig. 5). The neighboring plates are interlayed with Gd-containing film produced by the same firm on the Tyvek basis.

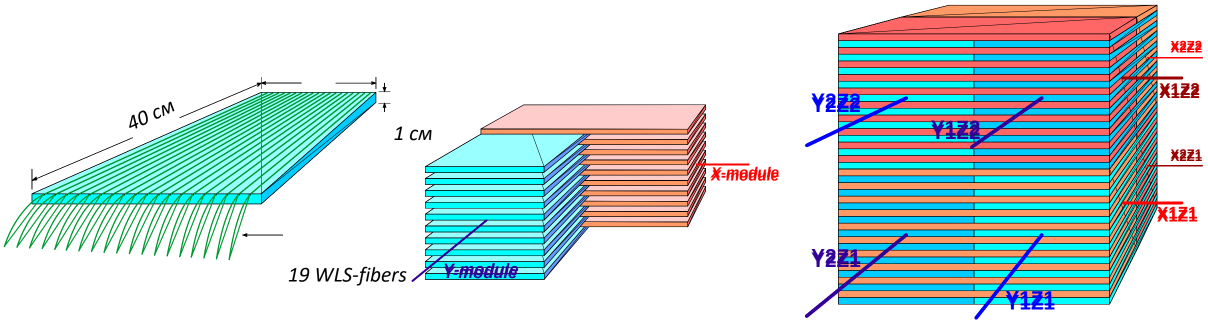

***Fig. 5.** Scintillator plates combined to intersecting X- and Y-modules with the total volume of 64 liter.*

Contrary to **DANSS**, the plates have no any special carrying frames (the **DANSS** experience shows that it is not needed). Instead of internal copper shielding layer used in DANSS, a 5 cm thick scintillator plates will be installed. These plates play a role of moderator for external fast neutrons and a role of gamma-catcher simultaneously. The rest shielding is similar to the one of the **DANSS**.

Each 10 plates are combined to an X- or Y-module – our experience of the **DANSS** data analysis certainly shows high importance of such stratified structure for the background suppression. Collection of the light signal is done with WLS fibers glued in the grooves with a step of 1 cm. Two alternative versions are considered (up to now we are not sure which version is better), one of them will be realized by ÚTEF in Prague and the other – by ОИЯИ in Dubna.

According to the first version, the rear (blind) end of each WLS fiber is mirrored with a special paint. At the opposite (front) side nine even fibers are coupled to the Hamamatsu MPPC S13360-3075PE with dimensions 3×3 mm (one MPPC per plate), whereas ten odd fibers are combined with similar ones from the rest 9 plates of the Module and coupled either as a single bunch to the Hamamatsu compact PMT H13543-20, or as 10 smaller bunches to separate segments of the matrix PMT H8711-20. As a result, the PMT (one per Module) produces a signal proportional to the total energy deposit in the Module, whereas the MPPC signals provide a spatial pattern of the energy distribution between the plates.

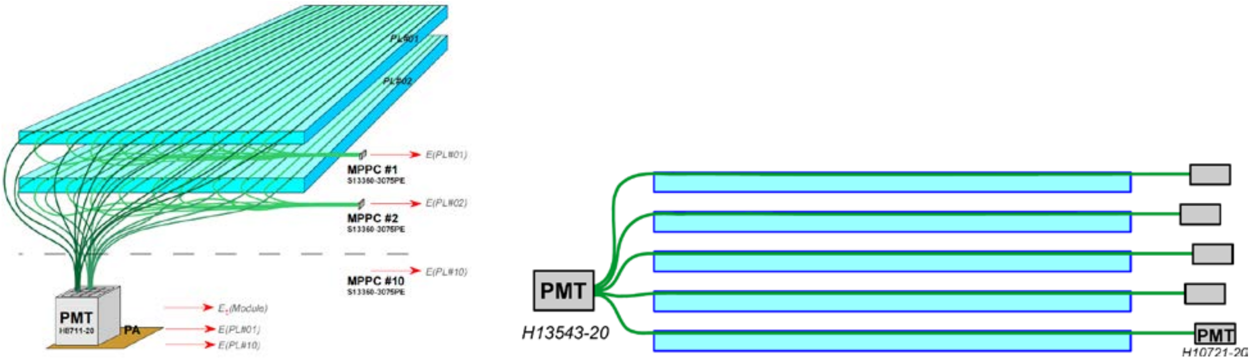

***Fig. 6.*** *Two alternative versions of light collection from a module. Left: 1 PMT + 10 MPPC. Right: 1 PMT + 10 PMT.*

The alternative version supposes two-side collection of the light signals from each fiber. All 19 fibers of one side are coupled to a compact PMT H10721-20 (one per plate), and all fibers of the opposite sides of 10 plates of the Module are combined together and coupled to the PMT H13543-20, registering the total energy deposit in the Module.

The performed tests demonstrate that for both versions of **S$^3$** the energy resolution could be improved by a factor of 2 with respect to **DANSS**. Being installed in the similar A336 room (at the Kalinin NPP or at the Temelin NPP), the **S$^3$** will detect about 300-400 neutrino events per day which is quite enough for the reactor diagnostics.

The total price of one **S$^3$** detector (to be done by JINR) is about $270,000.

## 4. Estimation of human resources

The DLNP JINR participants : continuation of works with the **DANSS** detector (regular shifts, maintenance, data analysis); development, creation and exploitation of the **$S^3$** detector at KNPP (*R&D*, mounting, electronics, data analysis).

| Neutrino spectrometer: | | | **DANSS** | | | | **$S^3$ (#2)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| JINR staff member | | | type of activity | | | | | | | | |
| Name (*the young persons are marked with color*) | *Position* | *% of participation* | *Maintenance* | *Regular shifts* | *Data analysis* | *MC simulations* | *R&D* | *Mounting* | *ACQ electronics* | *Data analysis* | *MC simulations* |
| V.V. Belov | jun. | 100 | + | + | + | | + | + | + | + | |
| V.B. Brudanin | dep. | 10 | *Management of all works* | | | | | | | | |
| V.G. Egorov | sect. | 100 | *Management and participation in all works* | | | | | | | | |
| M.V. Fomina | jun. | 100 | | | + | + | + | + | | + | + |
| S.V. Kazartcev | jun. | 100 | + | + | | | + | + | + | + | |
| A.S. Kuznetsov | ing. | 100 | + | + | | + | + | + | + | + | + |
| D.V. Medvedev | sci. | 30 | + | + | | | | + | + | | |
| A.G. Olshevsky | dep. | 5 | *Management of some works* | | | | | | | | |
| I.E. Rozova | jun. | 50 | | | + | | + | + | + | | |
| N.S. Rumyantseva | jun. | 30 | | | + | | + | + | + | | |
| Ye.A. Shevchik | ing. | 30 | + | + | | | + | + | + | + | |
| M.V. Shirchenko | sci. | 50 | + | + | | | + | + | + | | |
| Yu.A. Shitov | sen. | 50 | | | + | + | + | + | + | | + |
| I.V. Zhitnikov | jun. | 100 | + | + | + | + | + | + | + | + | + |
| D.R. Zinatulina | jun. | 50 | | | | | + | + | + | | |

The ITEP and LPI RAS participants (Moscow) : I.G.Alexeev, M.V.Danilov, A.S.Kobyakin, I.V.Machihilyan, D.N.Svirida, N.A.Skrobova, A.S.Starostin - continuation of works with the **DANSS** detector (data analysis, MC simulations).

The ÚTEF ČVUT participants (Prague): M.Špavorová, L.Fajt, R.Hodák, Z.Hons, F.Mamedov, P.Přidal, E.Rukhadze, I.Štekl, J.Vlášek - development, creation and exploitation of the **$S^3$** detector at Temelin NPP.

## 5. Concise SWOT analysis

### The major strengths of the project:

- based on a solid state plastic scintillator, both **DANSS** and **S$^3$** detectors have no restrictions on location close to a commercial power reactor (later, this idea was supported in **CORMORAD** and **PANDA** projects, but not realized yet);
- placed at a distance of 10 meter from the WWER1000 reactor core, it is irradiated with extremely high neutrino flux $5\times10^{13}$ 1/cm$^2$/s;
- the detector is shielded against cosmic rays with a big amount of hydrogen-containing materials located above it (~50 m of water equivalent) which suppresses completely hadronic component (being the main background source);
- high segmentation of the detector body provides more reliable identification of the neutrino events (the same idea was used later in **Neutrino4** and **NULAT**);
- regular (3 times per week) variation of the detector position (Up-Middle-Down) avoid numerous systematic errors which are inherent in the most of other oscillation experiments (our project was the first with this idea).

### Weaknesses of the project:

- relatively poor energy resolution caused by several factors – low transparency of scintillator strips produced with extrusion technology, longitudinal attenuation in WLS fibers, dead layers, inhomogeneity of the PMT photocathode. This disadvantage will be reduced in the **S$^3$** detector;
- because of complicated internal structure it is impossible to calculate absolute efficiency of the detector with enough accuracy;
- polystyrene-based scintillator contains lower percentage of hydrogen atoms than liquid LAB scintillator (~7.7 $\%_{\mathrm{wt.}}$ vs ~11.5 $\%_{\mathrm{wt}}$), which reduces the IBD signal.

By these reasons both **DANSS** and **S$^3$** detectors should not be used for the precise measurement of absolute neutrino spectra (at-least, such measurements should not be claimed as the main goal).

The only real competition could be faced with the **SOX** experiment because it plans to use a good underground neutrino detector BOREXINO which is in operation for many years and does not require any serious reconstruction. In addition, contrary to the reactor neutrino, the expected neutrino spectrum of $^{144}$Ce/Pm can be calculated with much higher precision. The **SOX** experiment has a real chance to get any result before the end of 2018.