MAIN DIRECTIONS OF SCIENTIFIC INVESTIGATIONS IN THE FIELD OF NUCLEAR FISSION AND EXPERIMENTAL SETUPS AT THE PIK REACTOR

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ABSTRACT

In spite of the 75 years of the intensive theoretical and experimental investigations, nuclear fission, which is one of the most complicated and practically important nuclear reactions, still needs further detailed scientific investigations. Nuclear reactor **PIK** [1-5] (**Fig.1**), with its extreme neutron flux parameters, will place unique possibilities to organize and successfully perform such investigations. The description of the three experimental setups for research in the nuclear fission physics are planned to be installed in the reactor **PIK** is presented.

1. INTRODUCTION

First of all, it is planning to devise the steady-state installations for production of the high flux monochromatic polarized neutron beam (radial horizontal channel **HEC-1**) and setup for neutron multiplicity measurements (inclined channel **NEC-2**).

There are presented experimental setups [6] proposed for the reactor PIK in order to carry out experimental researches in the physics of nuclear fission:

- Crystal-diffraction polarizing monochromator of slow neutrons (**Fig. 2**).
- Multirotor chopper-monochromator of polarized neutrons (**Figs. 3, 4**).
- Polarizing ^{3}**He** filter resonance neutron beam.
- 4π-Detector of neutron multiplicity measurements accompanying the fission of heavy nuclei at low excitation energies (**Figs. 5, 6)**.

The following basic researches in the physics of nuclear fission are planned at the reactor **PIK**:

- Researches of the space parity violation effect in polarized slow neutron fission of heavy nuclei and P-even effects connected with P-odd one [7].
- Investigations of the exited nuclear system descend from the barrier top to the rupture into two fragments and light particles with γ-rays and prompt neutrons (TRI and ROT-effects) [8,9].
- Study of the deformed nucleus rupture dynamics through the search and property investigations of so called scission neutrons [10].
- Investigation of correlated distributions of masses, charges, velocities and kinetic energies of the heavy nucleus fission induced by thermal neutrons.
- Correlation researches in fission, using a study of multiplicity distributions of fission neutrons and study of the angular and energy correlations of neutrons, gamma rays and third particles in the fission of heavy nuclei at low excitation energies.

Fig.1. General view of the Reactor Complex **PIK**.

2. THE STUDY OF NUCLEAR FISSION IN LOW ENERGY NEUTRON RESONANCES

2.1 The main motivating reasons and high-intensity beam HEC-1

Among the most urgent problems of the physics of fission of heavy nuclei at low excitation energies to be solved using resonance neutrons, first of all it should be called the problem of structure and properties of transition states in a vicinity of the top of the fission barrier. In the last years, an attention was attracted to detailed study of the recently discovered TRI- and ROT-effects of T-odd asymmetry of emission of light charged and neutral particles and gamma-quanta in ternary and binary fission of heavy nuclei by slow polarized neutrons [8, 9]. Besides, motivating reasons are study of the fission mechanism of heavy nuclei by polarized resonance neutrons, practical importance of estimating partial contributions of different spin states of fission nuclei into the fission cross-section, and investigations of mechanism and dynamics of fission nucleus discontinuity [10]. At last, motivation for these researches is lack of the theory of this practically important nuclear process, and necessity in the data for nuclear power and for transmutation of nuclear waste.

The high intensity resonance neutron flux in the horizontal channel of **HEC-1**, the axis of which is directed to the center of the reactor **PIK** active zone [1-5], provides unique opportunities for a variety of current research trends in the field of fundamental nuclear physics (in particular, in the nuclear fission), and in the field of solid state physics. An accessible neutron flux intensity in the energy range **(0 ÷ 0.6) eV** at the exit of the channel is available up to ~ $\mathbf{10^{11}\ n/cm^2 \cdot s}$, and in the range **(1 ÷ 5) eV** it is up to ~ $\mathbf{5 \cdot 10^9\ n/cm^2 \cdot s}$. These intensities are approximately two times higher than intensities currently available at the most powerful research reactor of the Institute Laue - Langevin (ILL) in Grenoble (France).

2.2 The polarizing crystal-diffraction monochromator of neutrons

Most of aforementioned studies usually require neutrons with energies in the electron-volt range and high degree of their polarization. These requirements are met by using a crystal-diffraction monochromator [6] with the polarizing crystals of Geissler (Cu_2MnAl) or CoFe type. In the first case, polarized neutron flux density in the **HEC-1** channel can be obtained up to several units of $\mathbf{10^7\ n/cm^2 \cdot s}$. When using the second type of crystal polarizer, one obtains a high neutron energy resolution but at the much less neutron flux intensity. The operation of the crystal-diffraction monochromator is based on the property of crystal structures to reflect coherently neutrons only with a specific wavelength that satisfies the Bragg condition. The monochromator becomes polarizing if it is used with a reflective ferromagnetic crystal magnetized to saturation.

The intensity of polarized neutron flux for a given energy range can be substantially higher by using the polarizing **^{3}He** filter. In this case, the polarization of the beam, as is was shown in the experiments at the IIL (Grenoble), can reach ~70%. But in this case, in order to obtain neutrons with required energies, it is necessary the use the additional devices (e.g., a crystal monochromator or mechanical chopper of a beam for time-of-flight measurement of the neutron energy) that significantly reduces intensity of the neutrons. In our project, the usage of both options is envisaged. The layout of the polarizing crystal-diffraction monochromator in the main hall of the reactor **PIK** at the **HEC-1** beam is shown in **Fig. 2**. The layout of the neutron multi-rotor mechanical monochromator is presented in **Fig. 3**.

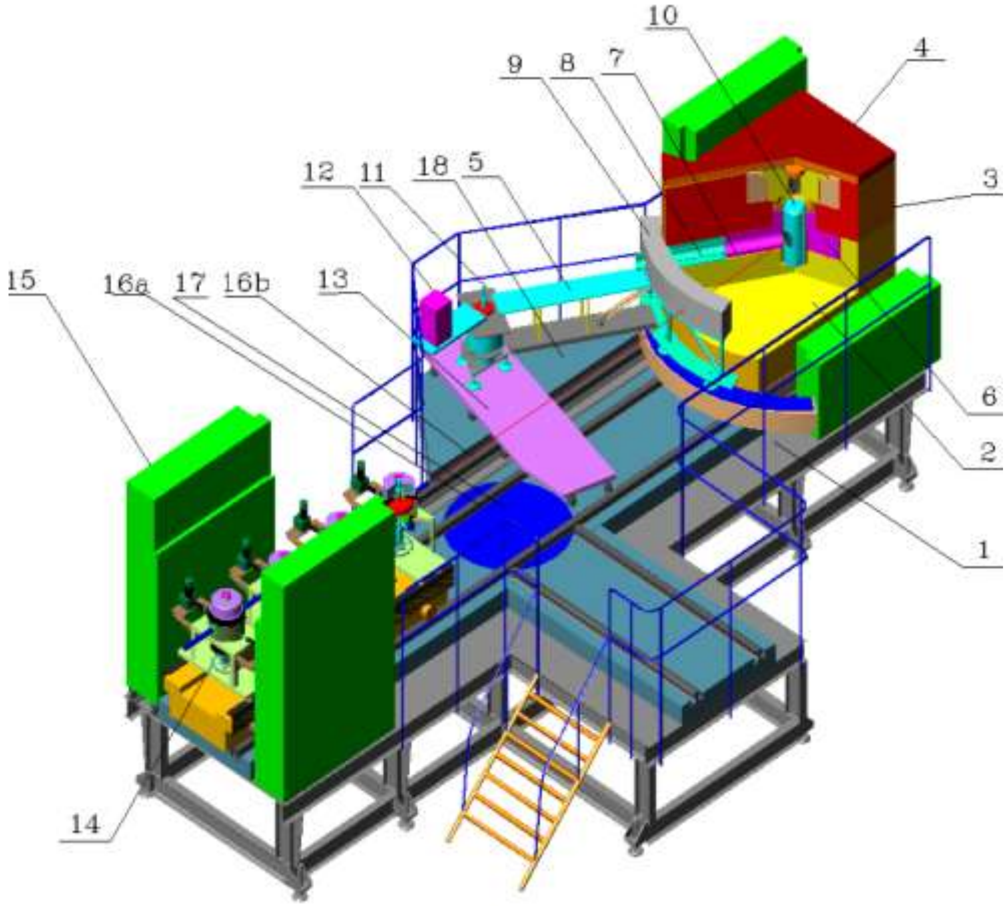

Fig. 2. Schematic view of the polarizing crystal-diffraction monochromator (PCDM) at the **HEC-1** beam: 1- rack, 2 – bottom part of the PCDM shielding, connected to the trolley, 3 - upper part of the fixed shielding, 4 - shielding cover; 5 - swing arm of PCDM; 6 - part of the shielding of rotating together with an arrow, 7 - flipper and spin-rotating device, 8 - output collimator, 9 - mobile shield of Ni and Pb blocks rotates on an air cushion together with an arrow, 10 - crystal-polarizer container, 11 - crystal analyzer with goniometric device, 12 - detector, rotated on the separate arrow, 13 - support plate for sliding of the arrow end on air cushion, 14 - the neutron multi-rotor mechanical monochromator (MRMM), 15 - blocks shielding of MRMM-installation, 16 - track ways for basic settings (a) and for two units of shielding (b), 17 - the turn-table.

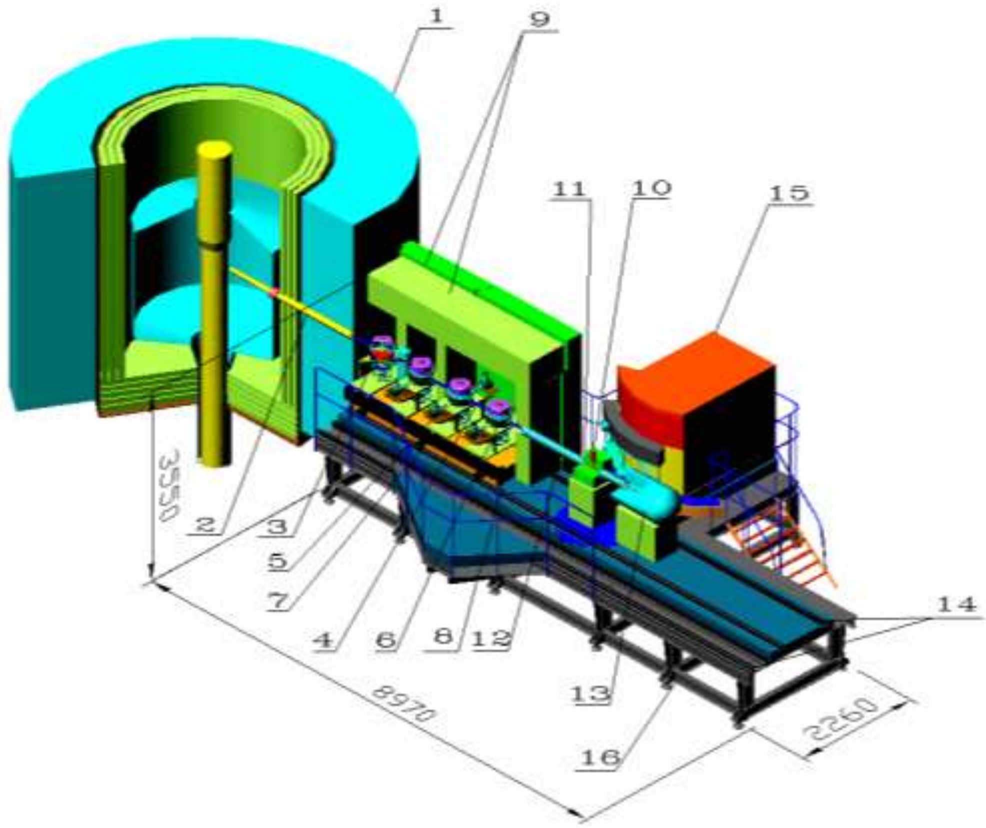

Fig. 3. Layout of the neutron multi-rotor mechanical monochromator (MRMM) at the **HEC-1** beam in the main hall of the reactor PIK:
1 - wall of the reactor PIK, 2 - channel **HEC-1**, 3 - rotor, 4 - collimator, 5 - optical sensor, 6 - vacuum chamber, 7 - supporting frame of the mechanical rotor installation, 8 - sliding platform, 9 - demountable blocks of concrete shielding, 10 - neutron detector, 11 – shielding of the detector, 12 - neutron guide, 13 - neutron trap, 14 - track, 15 - set of polarizing crystal-diffraction monochromator (PCDM) in the shielding, 16 - supporting rack.

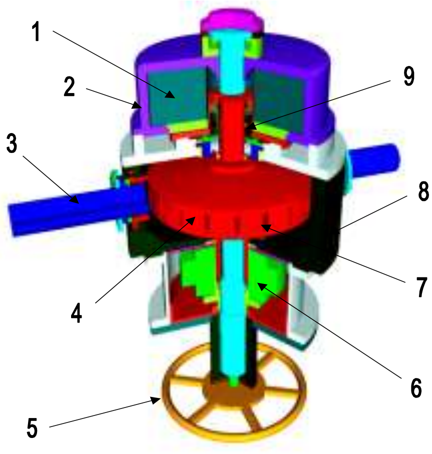

Fig. 4. General view of one rotary installation:
1 - coil of the electromagnet, 2 - moveable yoke of the electromagnet, 3 - collimator, 4 - rotor, 5 - adjusting wheel, 6 - stator of induction motor, 7 - a through crack, 8 - the body of the vacuum chamber, 9 - horizontal displacement damper of the rotor.

2.3 The neutron multi-rotor mechanical monochromator

Mechanical neutron monochromator [6] selects mechanically the narrow portion of the wide spectrum of neutrons. The monochromator consists of 4 modules of the same type that will be placed along the collimated neutron beam of the **HEC-1** channel (**Fig. 3**). Each module is a massive (≥30 kg) Ø30 cm rotor made of a durable steel alloy, enclosed in the vacuum casing and vertically suspended in the magnetic field (**Fig. 4**).

Along the diameter of the rotor, 10 rectangular slits 8×30 mm in size are evenly spaced around the circumference. By applying an electrical current to the electromagnet, the rotor is suspended and then is driven in rotation at speeds up to 18,000 revolutions per minute (rpm) with rotating magnetic field that occurs in the stator of the frequency induction motor.

Stabilization of the rotor in space, its speed of rotation, as well as the mutual phasing of the various rotors of the monochromator, are carried out by the special electronic systems for automation and control. Specified position of the rotor can be maintained with an accuracy of 3 μm in height and ~ 5 μm in the horizontal plane, the synchronous period of rotation with an accuracy of $2{\cdot}10^{-6}$ c, and the given phase of rotation of rotors with an accuracy ~ 0.02° at a speed of 10,000 rpm.

The transmission of the monochromator reaches ≈ 10%, and the use of four rotors almost completely suppresses the background in between bursts of intensity. To reduce the background of scattered neutrons, a shielding wall of heavy concrete is placed between the modules.

All the monochromator are enclosed in a shielding block with external dimensions of (370×220×230) cm^3 (**Fig. 3**). The time-of-flight technique is applied for the measurement of neutron energy within the allocated interval of energies ΔE_n. The start signal is produced by the optical sensors of the first rotor once per rotation, so that between the two start signals the neutron detector registers 20 bursts of neutrons with energies in the interval ΔE_n each.

The energy resolution of the instrument depends on the speed of rotation of the rotors and the neutron energy. In particular, at a speed of 15,000 rpm and neutron energy $\mathbf{E_n \approx 1\ eV}$, which is configured with monochromator, the energy resolution is $\mathbf{\Delta E_n/E_n \sim 0.05}$.

On the basis of the tests already conducted, we have obtained the following estimates of the intensity of monochromatic beams of neutrons depending on neutron energy in comparison with other well-known pulsed neutron sources (at a fixed time-of-flight base ~ 9 m):

WWR-M, HC-7 (Gatchina): $\mathbf{\Phi n \approx 9{\cdot}10^4}$ **neutrons/cm²·s·eV,**

PIK, HEC-1 (Gatchina): $\mathbf{\Phi n \approx 1{\cdot}10^6}$ **neutrons/cm²·s·eV,**

IREN (Dubna, Russia): $\mathbf{\Phi n \approx 1{\cdot}10^6}$ **neutrons/cm²·s·eV,**

LANSCE (USA): $\mathbf{\Phi n \approx 5{\cdot}10^6}$ **neutrons/cm²·s·eV.**

On the **HEC-1** beam line, it is supposed to accommodate two of the experimental setups described above, namely: the four-rotor mechanical monochromator and the crystal-diffraction polarizing monochromator. The working place can accommodate only one of two installations. An axis of the **HEC-1** channel is located at a height of 2.3 m above the floor, which requires special construction of the overpass-rack on the quite powerful supports. These two installations are presented in **Figs. 2, 3**. Mechanical monochromator is shown in detail in the working position (**Figs. 3, 4**). Moving facilities in standby status is on rails and with a turning circle.

3. INVESTIGATIONS OF CORRELATIONS IN FISSION AT THE BEAM NEC-2

3.1 Main directions of the researches

There are the following urgent problems in nuclear fission researches:

- Mass, charge and energy distribution of fission fragments of a number of heavy nuclei by thermal neutrons.
- Output, angular and energy distribution of fast neutrons and gamma-quanta at fission of heavy nuclei.

The main trend of modern experimental physics researches in nuclear fission are directed to multiparameter experiments, in which it is possible to register several of the most important characteristics of the reaction at the same time.

The presented setup [11] allows to simultaneously detect the main part of energy, released in the fission, for each specific act of fission: kinetic energy, mass fragments and the number of neutrons emitted by each of the fragments. Besides, the fact that this device allows to obtain information about the mechanism of nuclear fission, it is still of practical interest, since the available data on the average neutron multiplicity and its distribution is known with a large uncertainty and for a limited set of nuclei. Similar studies for the forced fission were not made.

Despite significant advances in the theory of nuclear fission, at present in some cases it is impossible to predict the values and characteristics used in technical applications with the required accuracy. For example, in calculations of reactors and other critical systems, the accuracy of determination of the neutron yield should be better than 0.1%. Recently, the attempts to develop the systems intended to detect hidden nuclear materials, which are based on the principle of observation of the various correlations between fission products, have been undertaken. The use of such correlation measurements is possible with the help of the Monte Carlo simulation method. In this case, the experimental data on the angular and energy distributions of prompt neutrons and gamma-quanta of fission are the tool for debugging and verification of the performed calculations. Of course, such information is very important for further studies of the mechanism of nuclear fission. It enables one to define the basic characteristics of the fissioning system, such as: parameters of the level density for the neutron-excess nuclei, deformations of both fragments near the “scission point”, and the properties of the “scission” neutrons.

The installation created at the **PNPI** was designed for investigation of correlations in fission [12] with the help of different methods:

- the study of multiplicity distributions of fission neutrons, depending on the characteristics of fission fragments and fission systems;
- the study of the angular and energy correlations of neutrons, gamma rays and third particles in the fission.

3.2 Brief description of the installation

Neutrons in the installation [11] are detected in a liquid scintillation (with an admixture of gadolinium) detector. Liquid scintillator can be replaced with plastic, which significantly improves the temporal characteristics of the detector. Detector of nuclear fragments is running a double ionization chamber (**IC**) with Frisch grids. Compared with silicon surface-barrier detectors **IC** has several advantages, such as: the absence of radiation damage during long-term measurements or working with high-active isotopes, the best energy resolution and about 30% less amplitude defect.

Thus, the installation consists of two high-efficiency neutron counters and detector of fragments located between these counters (**Fig. 5**). Neutron counters to eliminate the mutual influence on each other separated by a protection (insert). The installation quite simply can be configured to work in the following modes:

1) registration of total number of neutrons in an act of spontaneous fission (4π-geometry, the total registration efficiency ~70%);

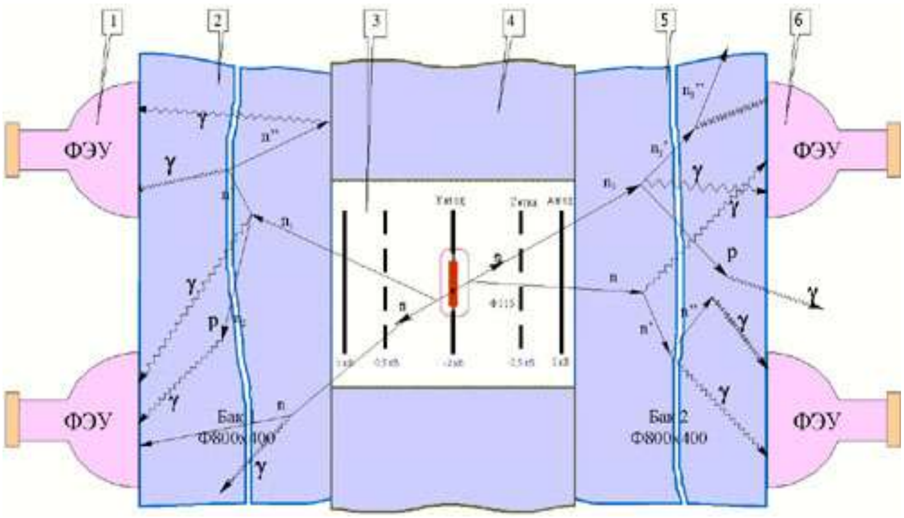

Fig.5. A schematic diagram of the scintillation 4π-detector:
1, 6 - photomultipliers, 2, 5 - neutron scintillation detector, 3 - ionization chamber (**IC**), 4 - annular separation protection (or the annular scintillator insert).

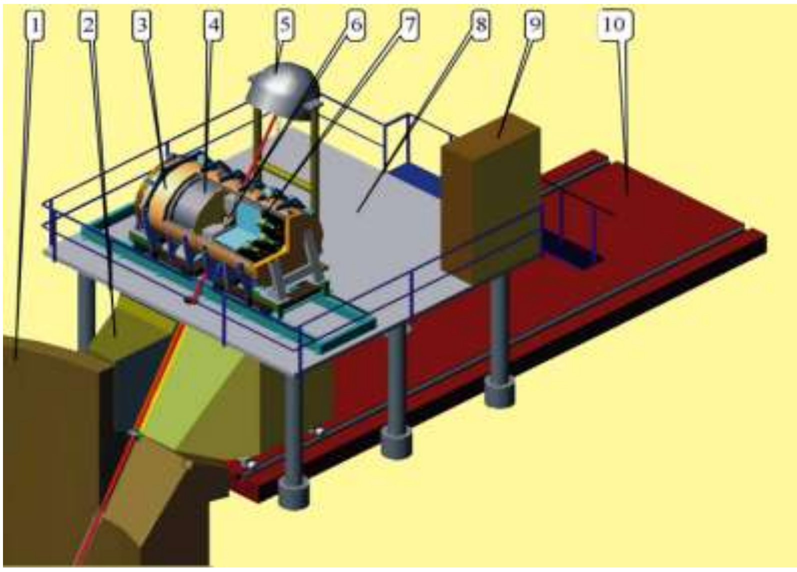

Fig. 6. General view of the installation at the **NEC-2** neutron beam:
1 - reactor **PIK** vessel, 2 - standard beam shutter, 3 - shielding of scintillation detector, 4 - scintillator tank, 5 - neutron beam dump, 6 - ionization chamber, 7 - photomultipliers, 8 - rack, 9 - instrumental stand, 10 - shutter guides.

2) registration of neutrons from the fragments using a single neutron counter, and the other one is at greatest distance (2π-geometry);

3) simultaneous detection of neutrons from each fragment, using two neutron counters (2-2π-geometry).

When operating in the first mode, the protection is removed, neutron counters are shifted, and between them an annular container, filled with nitrate gadolinium solution, is placed. Separated registration of neutrons from complementary fragments is ensured by the fact, that in the laboratory system of coordinates neutrons are emitted predominantly in the direction of scattering of splinters. Thus, selecting only those fragments, the angle of scattering which is close to 90 degrees relative to the plane of the cathode, it is possible to determine the direction of flight of the neutrons.

This installation will be located in the hall of inclined channels on **NEC-2** neutron beam of the reactor **PIK** (**Fig. 6**). It is also assumed that for the study of correlation effects as a function the incoming neutron energy, this installation can be used in the main hall of the reactor **PIK** on the **HEC-1** horizontal channel. As previously described, the system is equipped with monochromators.

4. CONCLUSIONS

We have presented three main experimental setups [6] for research in the nuclear fission physics which are planned to be installed at the reactor **PIK**:

- the polarizing crystal-diffraction monochromator;
- the neutron multi-rotor mechanical monochromator;
- the large liquid scintillation 4π-detector.

A feasibility of the usage of this equipment to solve some current problems in neutron-induced fission has been discussed taking into account an important fact that both the equipment and corresponding experimental techniques already have been tested and used in the measurements carried out at the **WWR-M** reactor of the **PNPI**. It's obvious that the equipment in question should be modernized in order to comply with the modern level of the nuclear electronics.

Unfortunately, there are a number of problems and the reactor **PIK** is still not operational. It is assumed that, the projects [1-5] will result in the completion of the works on the Reactor Complex **PIK**. As a result, in 2017-2018 the first start of the reactor is planned to take place and the reactor will be put into operation in 2019-2020.

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