Measurements of characteristics of the pulse neutron sources RADEX and IN-06 of the Moscow Meson Factory (INR RAS, Troitsk)

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Abstract. A source of thermal neutrons IN-06 of the Moscow meson factory (MMF) INR RAS started operation in mid-November 2010. We have carried out time-of-flight measurements on 22.4 m flight path of the first IN-06 neutron channel. The neutron source IN-06 has worked in a starting regime, i.e. a proton beam has been moved on its metal tungsten target only during a day, and at night the proton beam has been shifted on a tungsten target of the RADEX setup. Such a mode of operation allowed to carry out measurements at the IN-06, and on the 50-meter flight path of the RADEX setup with a 8-section liquid (n, γ)-detector (49.5 m) and a neutron cylindrical ^{3}He counter (51.5 m). The registration efficiency of thermal neutrons by the He-3 counter was approximately 100 %. It was used on the 22.4 m flight path of the IN-06 and on the 51.5 m flight path of the RADEX. The usage of the ^{3}He allowed to determine parameters of two neutron sources simultaneously and to carry out comparative analysis of their characteristics. Parameters of a proton beam of the linear accelerator were approximately identical for the IN-06 and for the RADEX.

Time of flight spectra were measured by two systems of the experimental information storage: a slow system with a minimal width of the time channel 4 μs and a performance < 10^4 n/s [1] and a fast system with a width of the time channel 121.2 ns and a performance < 10^7 n/s. The fluxes of thermal neutrons, measured on the 22.4 m flight path of the IN-06, were determined from the experimental spectra at different frequencies of neutron pulses. At a frequency of 50 Hz the neutron flux was equal to F=821 n/ cm^{2}s. A small intensity of the source of thermal neutrons IN-06 is the result of not optimal geometry of a target and moderator, and also of possible losses of the proton beam during its transportation to the tungsten target. The flux of thermal neutrons on the 50 m flight path of the central beam of the pulsed source RADEX was determined F =150 n/cm^{2}s at the following conditions: the frequency of 25 Hz, the pulse duration at half height of 60 μs, the pulse proton current of 5 mA, the energy of protons of 209 MeV and a diameter of collimator of 2 cm, installed at a distance of 20 m from a moderator.

Earlier in 1998 [2] and 2004 [3] other groups carried out measurements on the pulsed source IN-06, but at that time it was not possible to determine basic characteristics of the neutron source IN-06 because of different reasons. The measurements of time-of-flight spectra at the RADEX setup were realized since its start in 1996 [4, 5, 6], therefore a large amount of the experimental information, including characteristics of the neutron pulsed source RADEX, was collected. The geometry and other experimental conditions at the IN-06 and at the RADEX differ from each other. A schematic view of experiments at the IN-06 and at the RADEX is presented in Figure 1. The moderator's luminous surface at the RADEX was equal to 113 cm^2. It was caused by internal diameter of a steel neutron guide d = 12 cm.

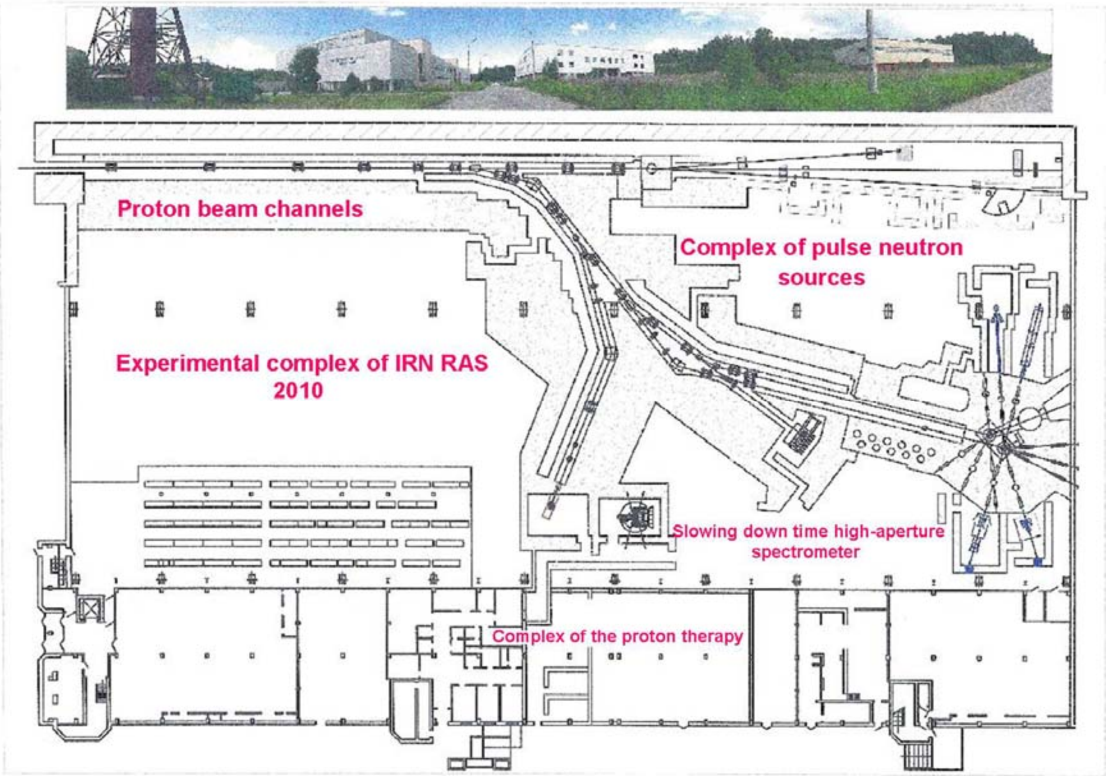

Fig. 1. A general scheme of pulsed neutron sources RADEX and IN-06 placement in experimental complex (building 25) of Institute of Nuclear Researches of the Russian Academy of Sciences.

A collimator 50 cm of a length made of a mixture of paraffin and boron carbide with an aperture of 6 cm in diameter was positioned at a distance of 20 m from moderator in the hole of neutron guide. The resonance filter made of manganese oxide with a thickness of 1 cm and NaCl of the same thickness were installed behind the collimator. Filters allowed to determine positions of a neutron flash and to estimate background at the energy of 336 eV and of 2.4 keV. The width of neutron flashes was approximately 60 μs, a time delay of 200 μs. An additional lead collimator was used at a distance of 45 m from moderator. This collimator had an aperture of 6 cm in diameter. The carbon collimator with a length of 1 m with an internal aperture of 6 cm in diameter was located before the iron protection at a distance of 40 m inside the vacuum neutron guide with a diameter of 17 cm. The powder of Sm_2O_3 packed into the aluminum container was used as a radiator-sample. It was positioned in the center of a liquid (n,γ)-detector.

To determine position of the neutron flashes and their durations, the ^{3}He counter with the efficiency of ~100 % was used. The internal cavity of the counter, filled with ^{3}He at the pressure of 8 atmospheres, has thickness of 3.5 cm and internal diameter of 12 cm. Sometimes this ^{3}He counter was moved to the central neutron channel of the RADEX setup where a collimator with an aperture diameter of 2 cm was installed at a distance of 10 m from the moderator surface. It reduced the pulse count of ^{3}He counter approximately be a factor of 10 that allowed to observe neutron flashes without overloads using "old" slow measuring system.

The measurement conditions of the TOF spectra on the first neutron beam of the IN-06 were the following. Two collimators with rectangular apertures with the area of 17 cm * 8 cm = 136 cm^2 at the entry of the first collimator and 11.5X6.5 cm = 75 cm^2 at the exit of the second collimator with a length of 1.7 m and 0.95 m before the mirror neutron guide were at a distance of 0.6 m from vertical water moderator (22X22 cm = 484 cm^2 area and thickness of 5 cm). The full length of the mirror neutron guide with a cross section of 11.5 cm *6.5 cm = 75 cm^2 was about 12 m. The neutron guide had a vacuum level of approximately 10^{-2} Top. The length of the flight path in measurements was 22.4 m. The core with 2 cm in diameter made from the pressed powder of technical diamond was placed at the end of the flight path. The cylindrical ^{3}He counter [1] was installed in a trap of cadmium sheet and plates made from a mix of paraffin and boron carbide. It was placed on the neutron guide axis and irradiated with neutrons from the moderator surface with the area of 136 sm^2. In front of the detector on the neutron guide wall a collimator made of 2 mm thickness cadmium with window area of 10 sm * 3.4 sm = 34 sm^2 was placed. The diamond sample was used for measurements of a dispersion spectrum at 90^o and 180^o to the neutron guide axis. Presence of a diamond sample on the neutron beam resulted in reduction of a flux of thermal neutrons by illuminated surface of He^3 detector approximately to the value of 15 %.

It is necessary to note, that two independent tungsten targets (top with water cooling used in our measurements and bottom with liquid deuterium moderator) exist in accordance with the technical project IN-06 specialized in the work with thermal and cold neutrons. 12 vacuum neutron guides come to these two targets, some of them for improvement of background conditions look not at the target, but at the peak of neutron flux density in the moderator. One of those 12 neutron guides has a diameter of 1 m, other three having a standard diameter of 200 mm get out the experimental building and might be lengthened up to 500 meters. The cooling system of the IN-06 was built up for an average current of 1 mA, that at designed protons energy of 600 MeV and pulse-repetition frequency of 100 Hz corresponds to the average target power of 0.6 MW. The name “IN-06” derives from this fact.

Thus, the IN-06 setup has a serious potential of development (by number of operated neutron guides three times more, by density of neutrons flux twice times more), which will be involved in the nearest years. As the IN-06 will come close to the designed parameters, this source approach to other similar installations of our country (the pulsed reactor IBR-2 in JINR, Dubna, and the reactor "PEAK" in Saint Petersburg INP which is currently under construction) by the majority of characteristics and surpass in separate parameters. It could classified among ten best installations of the world.

Two systems of data acquisition were used for storage of the TOF spectra. A slow system on the basis of PC-386 and dialogue program ROM, which simultaneously allowed to measure TOF spectra from the 8-sectional liquid (n, γ) detector and from a He^3 cylindrical counter. In parallel with this system the special single-channel high-speed system on the basis of notebook through USB 2.0 port was used. In the first system the width of the time channel was 4 μs in 4096 time channels. In the second system it was 121.2 ns in 160000 channels, that allowed to observe thermal neutrons spectra in the energy range of thermal neutrons from 0.006 up to 0.2 eV (in time interval t = 20000 – 3500 μs = 0.0165 s) at the frequency of neutron fluxes of 50 Hz. The maximum of thermal neutron peak was observed at the energy of 0.06 eV. The following ratio was used to define the flux of thermal neutrons F on the surface of He^3 detector (22.4 m):

$$F = \frac{N}{S*T},$$

where N – the total number of registered thermal neutrons during the time T = t*R = 0.0165s* 50964 = 841s = 14 minutes at the registration efficiency of 100 %; R – start number of the time analyzer; S - area of the illuminated surface of the detector.

In such measurements a number of registered thermal neutrons was equal to N = 22636714 at R = 50964. The average flux of pulsed thermal neutrons on the illuminated surface of the He^3 detector with the area of S = 34 sm^2 was determined to be 821 n/s*sm^2. The maximal peak flux of thermal neutrons at the energy 0.06 eV was F_{max} = 2460n/s*sm^2.

Below we briefly give a description of the new high-speed system of data acquisition. In Figure 2 and Figure 3 are presented Photo of the system and the general electronic scheme. A prototype of the time - digitizer converter (TDC) has been developed to modernize the data acquisition system made in CAMAC standard for TOF measurements. A start signal and a signal from the detector are connected through the entrance cable header of CP50 type. The device consists of the USB-controller FT245R, the programmed integrated chip (PIC) XC9572XL, the signal shapers on the basis of Schmidt triggers and generator with 66 MHz frequency. In the PIC the 8-digit shift register (SR), registered at the input signal from the detector and also the auxiliary logic containing a counter of time channel number and a final automatic device, formed read and write signals for the USB-controller are realized.

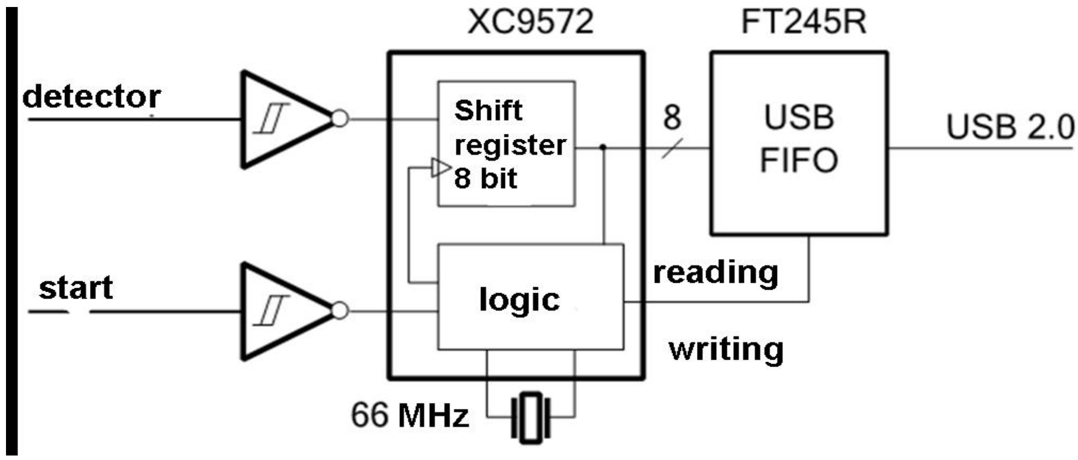

Fig. 2 Functional scheme of the DAQ device

Maximum number of time channels	524272
Maximum number of events in the channel	2^{32}-1
Width of the time channel	121.2 ns
Minimal period of pulses repetition	140 ns
Minimal duration of pulses registration	1 ns
Level of the entrance signal	TTL, 5 volt, positive polarity
Connection interface with computer	USB 2.0

The experimental data come through the bi-directional 8-digit bus to the chip which groups them into the continuity of the protocol USB and transfer them into computer. This chip has buffers FIFO of information reception and transfer with a volume of 256 and 128 bytes respectively for carrying capacity smoothing. The data exchange between TDC and computer is carried out in the following way:

1. The command processor transfers into TDC a value specifying a number of time channels;
2. TDC passes into sleep mode of a start pulse;
3. From the moment of start pulse arrival the shift register starts to work and then the transfer of the information to the computer takes place byte-by-byte;
4. After transfer of a required number of time channels the TDC forms a status byte, informing the program about successful or mistaken transfer of data frame at buffer FIFO overflow.

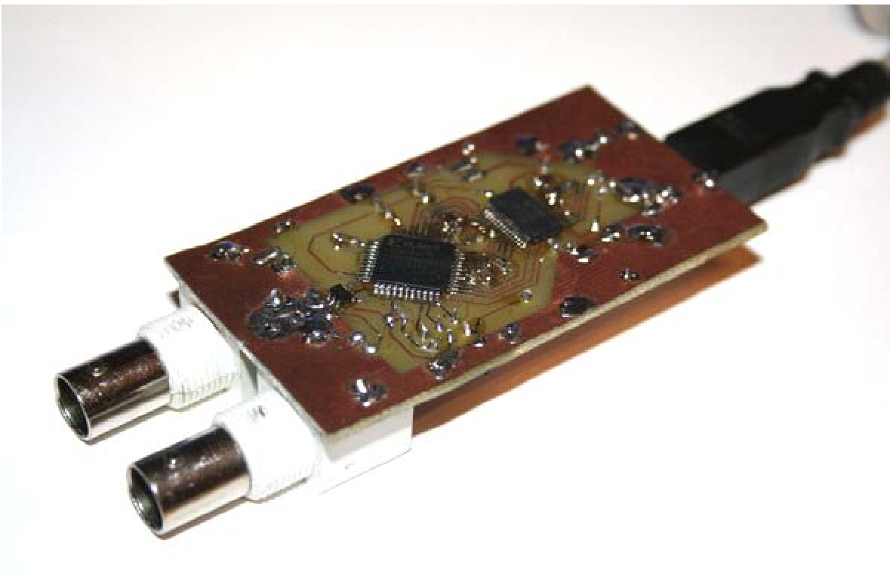

Fig. 3 Photo of the device

A possibility of TDC dumping in initial condition with a command of the command processor is additionally realized. With the exception of storage memory from the TDC structure and load shifting into the computer, the significant simplification of the device was achieved. The maximal data stream, given by the TDC, comes to 8 Mbytes per second. At the same time modern multinucleate processors with a set of vector instructions are available to process at least two orders of magnitude larger data streams. This fact allows construct even faster multichannel TDC, based on the above-mentioned principle, limited only by cash bandwidth of the USB-controllers. The model of TDC was successfully tested with the linear accelerator of protons of the INR of Russian Academy of Science during the beam time at the RADEX and IN-06 setups and also at the isotope complex.

For definition of background components the samples of metal cadmium with a thickness of 1mm and indium of 3 mm thickness were installed in the neutron beam before the He^3 detector. The measured experimental energy spectra (22.4 m flight path of the first channel of the IN-06) by means of "old" slow system of data acquisition with a time channel width of 4 µs in 4096 channels (t =16384 µs) are presented in Figure 4.

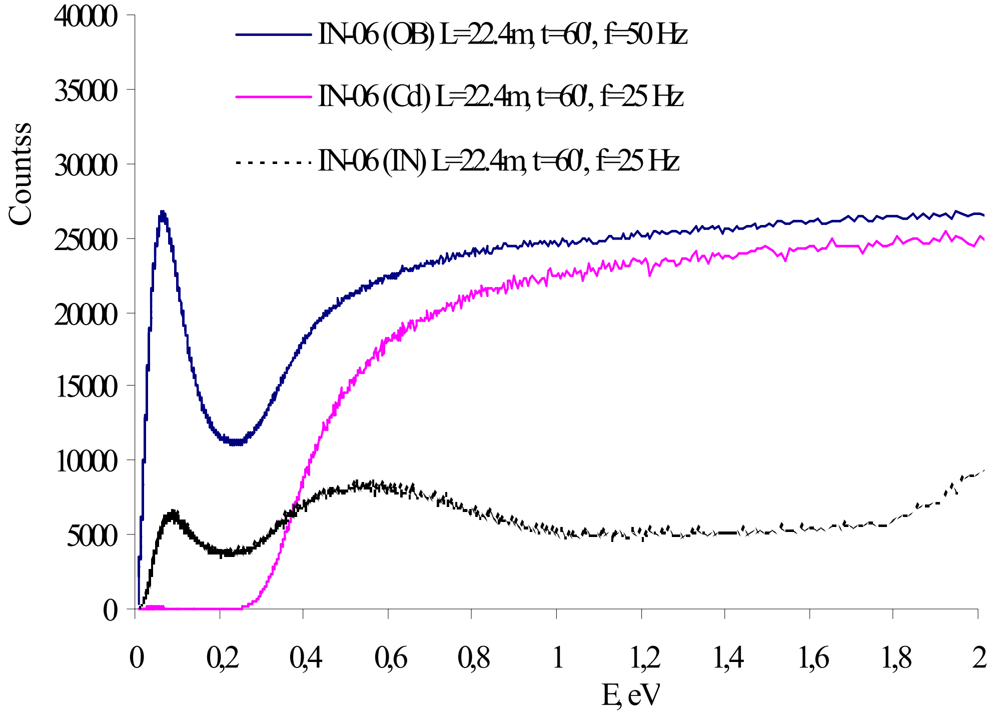

Fig 4. The energy spectra measured at 22.4 m flight path of the first channel of the IN-06 (time channel width 4 µs in 4096 channels t =16384 µs)

Spectra with samples of indium and cadmium in the neutron beam are reduced to the common monitor count of the open beam under burst and in the first 100 channels behind neutron burst, where the proximity effect of samples in spectra is very small. As one can see from Figure 4, background components in spectrum of thermal neutrons for the open beam are negligible (about 0.01 %). This is a kind of spallation neutron sources on the basis of proton accelerators and non-multiplying targets from tungsten. For comparison we note that in reactors, even based on the pulsed action such as the IBR-2 (FLNP JINR), presence of delay of neutrons and small subcriticality between bursts results in a level of background components up to 10 %. To the neutron energy region higher than 0.4 eV the background level in this area for the given measurements is about 20 %.

Figure 5 shows the TOF spectra with a sample of cadmium and without it in the neutron beam, measured on the 22.4 meter flight path of the first channel of the IN-06 source by means of fast data acquisition system with a time channel width of 121 ns in 321240 channels (t = 39500 μs). As well as in case of the parallel measurements carried out with the slow data acquisition system, spectra of the similar form were obtained but with the more pronounced Braggs dip in the thermal part of the energy spectra of diamond sample at the energies of 0.0133 eV (14000 μs), 0.0049 eV (23000 μs), $3.7*10^{-3}$ eV (26000 μs). As there was no special monitor counter, integral sums under burst and in the first channels after burst were used for reducing to monitor count of the open beam.

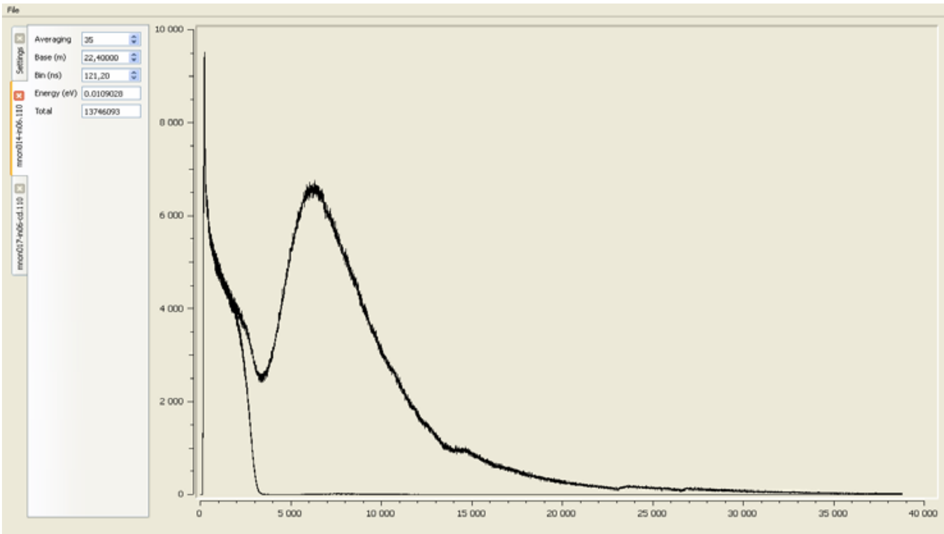

Fig 5. TOF spectra of the open beam and TOF spectra with cadmium sample, measured on the 22.4 m flight path of the first channel of the IN-06 source (time channel width 21 ns in 321240 channels, t = 39500 μs)

As Figure 5 indicates the main part of neutron spectrum is located within the limits of 20 ms at the 22.4 m flight path. Therefore for the majority of experiments at the IN-06 a frequency of neutron burst with a repetition of 50 Hz is affordable. For special experiments with solid-state subjects and cold neutrons the frequency of 25 Hz or even 10 Hz might be needed due to the presence of recycled neutrons.

The maximum frequency of the accelerator 100 Hz allowing double statistic set speed, could be adjust to the IN-06 only for limited number of tasks on the 11 m flight path. This is one of differences of external environment of the source IN-06 having the thermal and cold neutron spectrum from the neutron source RADEX, where a high frequency of neutron burst repetition is available due to the resonance neutron spectrum. In some cases at short neutron bursts (about 0,5 ms) and at increase of intensity of neutrons in thermal energy region less than 100 keV, realization of different neutron-nuclear studies is possible at the frequency of 100 Hz.

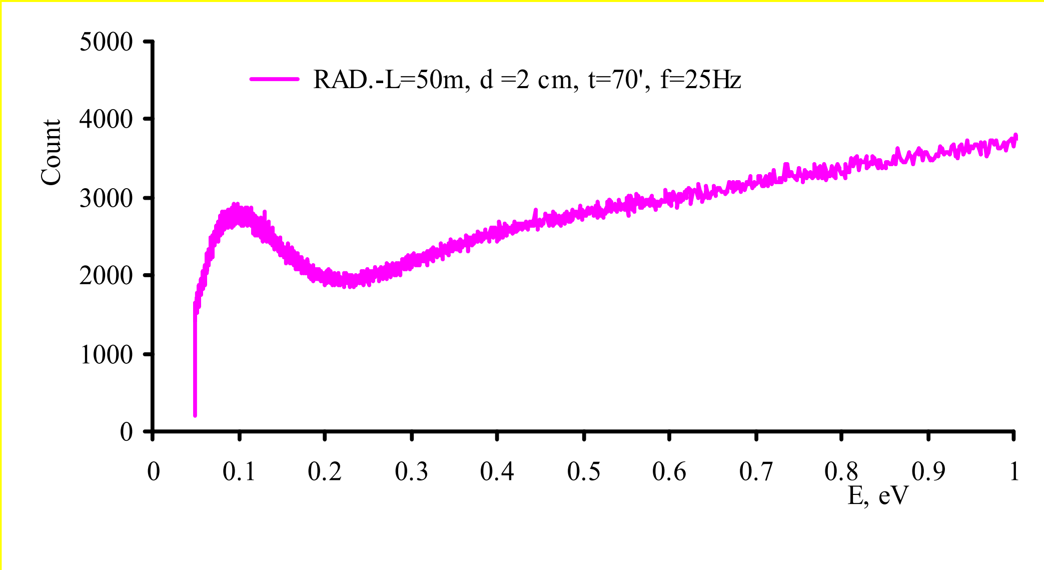

Fig. 6. Energy dependence in the TOF spectrum of the open beam, measured on the 50 m flight path of the central channel of the RADEX setup (time channel width 4 μs in 4096 channels t = 16384 μs)

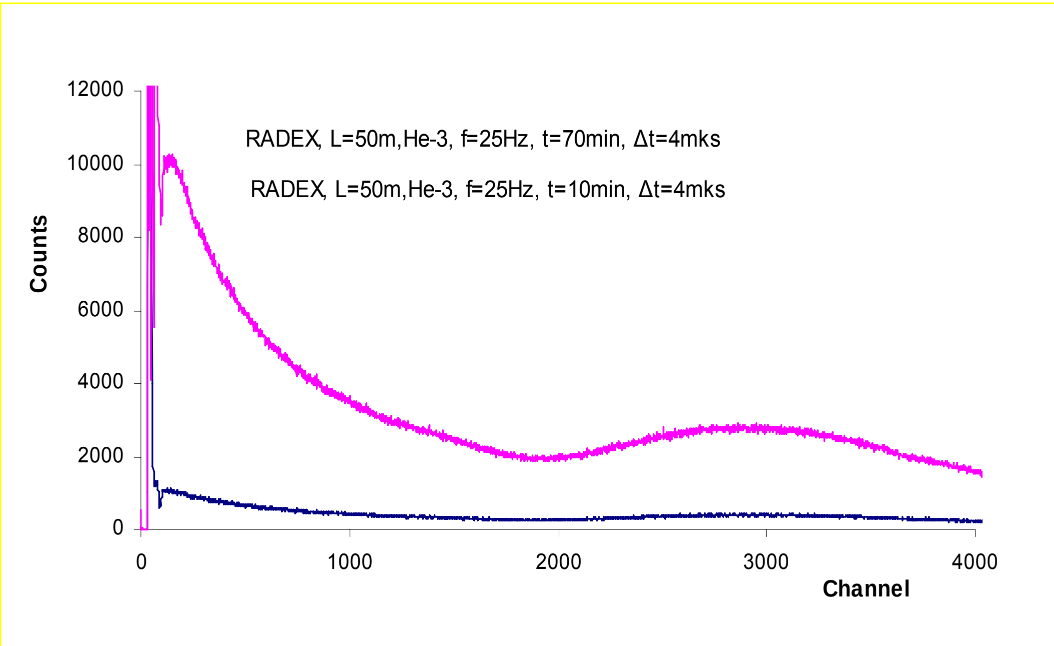

Fig. 7. TOF spectra of the open beam, measured on the 50 meter flight path of the central channel of the RADEX setup (time channel width 4 μs in 4096 channels t = 16384 μs)

Measured time-of-flight spectra at the central flight path of the RADEX setup are presented in Figures 6 - 8. These spectra were used for obtaining flux of thermal neutrons on the 50 m flight path by analogy with the above-mentioned method for the IN-06 source. The flux of thermal neutrons was estimated at the rate of about 150 n/cm^{2}s at the burst frequency of 25 Hz and pulse duration of 60 μs.

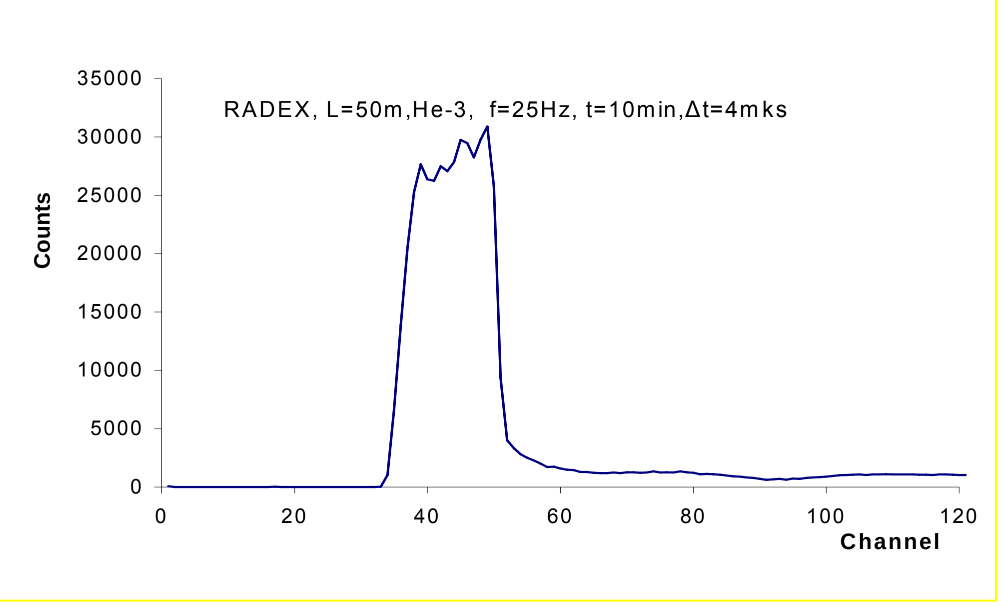

Fig. 8. TOF spectra of the open beam, measured on the 50 meter flight path of the central channel of the RADEX setup (time channel width 4 μs in 4096 channels t = 16384 μs)

After recalculation of the RADEX measurement at the same experimental conditions as on the 22.4 m flight path of the IN-06 source we discovered, that the thermal neutron flux at equal characteristics of the proton beam of the RADEX is approximately 20 times larger, than that of the IN-06.

Conclusion

During start measurements at INR of Russian Academy of Science of the pulsed source of thermal neutrons IN-06 measurements of its basic characteristics were carried out, also in parallel measurements of parameters of earlier started neutron source RADEX were realized. Fluxes of thermal neutrons were determined on the 22.4 m flight path of the IN-06 and on the 50 m flight path of the RADEX, at the average proton beam power of 6 kW and available experimental conditions accordingly $F_{in\text{-}06}$ = 821 n/s*cm^2 and F_{radex} =150 n/cm^{2}s. It turns out, that at the identical proton beam the flux of thermal neutrons at the RADEX is approximately 20 times larger, than at the IN-06. It may be connected with the different orientation of neutron guides of the RADEX and the IN-06 setup (neutron guides of the RADEX look on the neutron production target whereas neutron guides of the IN-06 look on the water moderator).

During preparation to the around-the-clock running conditions the new high-speed data acquisition system was developed and tested. Comparison with the spectra measured by the old measuring system in standard CAMAC, validate the operation of the new data acquisition system. At the same time maximum statistic set speed has been increased by an order of magnitude from 80 kHz for the "old" system up to 8 MHz for the new one. It managed to reduce the time channel width of the new data acquisition system down to 121 ns.

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References

1. Yu. V. Grigoriev, O.N. Pavlova, B.V. Zhuravlev, A.A. Alekseev, A.I. Berlev, E.A. Koptelov, D.V. Hlustin, Zh.V.Mezentseva. / The Investigation of the Resonance Structure of the Neutron Cross-Sections with the Time-of-Flight Spectrometers at the Moscow Meson Factory. // Proc. Int. Seminar ISINN-16, May 23-24, 2008.-Dubna:-JINR. 2009 - P.319-325.
2. Yu. Ya. Stavissky./Neutron facilities of Moscow meson and kaon factories. Proc. of International Collaboration on Advanced Neutron Sources ICANS-XI, October 22-26, 1990, KEK, Tsukuba, Japan, p. 87.
3. A.P. Zhukov, A.D. Perekrestenko, S.F. Sidorkin, N.M. Sobolevskij./Spectra of neutrons of a pulsed source of neutrons IN-06 INR of the Russian Academy of Sciences. // Moscow: INR RAS. Preprint INR №1140/2005. April, 2005.
4. B.A. Benetsky, F.Z. Beketov, M.I. Grachev etc. Preprint INR of the Russian Academy of Sciences № 1058/2001. Moscow: INR of the Russian Academy of Sciences, 2001.
5. A.A. Bergman, A.I. Berlev, Yu.V. Grigoriev. Research of resonant structure of neutron sections on TOF spectrometers with pulse neutron sources of Moscow Meson Factory. Preprint INR of the Russian Academy of Science № 1225/2009.-Moscow: INR of the Russian Academy of Science, 2009.