Experiments with massive uranium targets - on the way to technologies for Relativistic Nuclear Energy

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There are two main reasons that hinder the wide dissemination of nuclear power in the world (today its share in global energy balance <5%):

1. Unsettled in the modern concept of nuclear energy utilization problem of spent nuclear fuel (SNF).
2. Lack of inventories of raw materials (uranium-235) for hundreds of years.

Modern fast and thermal reactors operate at a controlled fission chain reaction with mean neutron energy about her, or substantially below 0.2 MeV. Subcritical multiplying systems, initiated by accelerators (electronuclear system or Accelerator Driven Systems - ADS) can, in principle, to work with much more hard neutron spectrum. However, the vast majority of ADS scheme is proposed use the same "reactor" neutron spectrum, implemented in sub-critical systems with a *keff* ~ 0.94 ÷ 0.98.

Analysis of the various areas of nuclear power shows limitations of the capabilities of traditional reactors and classic ADS in addressing global energy challenges.

In the fission neutron spectrum, the threshold minor actinide burning is ineffective because of their high threshold (~ 1 MeV). Transmutation of long-lived radioactive waste from the spent fuel is very bad closed due to multistep reactions that lead to the emergence of new long-lived radioactive isotopes.

Stocks of the main fuel of modern nuclear energy - ^{235}U in the energy equivalent of no more than oil and gas. Large reserves of thorium and natural (^{238}U) uranium can provide the energy future for thousands of years, but in the existing and even in advanced reactors or in classic ADS, they as it was mentioned above practically do not "burn".

Thus it becomes clear that the only real prospect of radical solutions to the problems of modern nuclear power is the use of more hard than fission's, the neutron spectrum.

For practical realization of this path has been worked out principally new scheme electronuclear method, based on the **relativistic nuclear technologies (RNT)**.

This scheme is aimed at creation extremely hard neutron spectrum inside of the multiplying system. It is expected that such a spectrum would permit to "burn" for energy production natural (depleted) uranium or thorium, and simultaneously utilize the long-lived components of spent nuclear fuel of nuclear power plants.

RNT scheme is based on the implementation of the following basic principles.

1. Using the deep subcritical active core (AC) of natural (depleted) uranium or thorium the size of which provides minimal leakage of neutrons. (Below this core is called the quasi-infinite).

2. An increase in energy of incident particles up to ~ 10 GeV instead of 1 GeV as in the traditional ADS schemes.

3. Using as a target for incident beam the material of AC.

4. Using a scanning divergent incident beam to reduce by several orders of power release density in the central region of AC serving as neutron productive target

5. Creation of compact powerful linear accelerator based on Russian original scheme BWLAP.

6. Application as a load of AC encapsulated fuel elements from uranium or thorium, as well as spent nuclear fuel, without its preliminary radiochemical reprocessing.

7. Using the technology of high temperature helium coolant for primary circuit.

The quasi-infinite active cores from natural uranium (thorium) are deeply subcritical. Only in a deep subcritical multiplying system it is possible to obtain the neutron spectrum determined by an external neutron source, i.e. to get substantially more hard spectrum than one created by chain fission reaction.

In difference of traditional reactor and ADS schemes the neutron spectrum in the RNT AC volume is determined apart (n,f), (n,γ) and (n,n' γ)-reactions by large set of competing inelastic processes, in particular, by multi-step cascade reactions as well as by threshold (n,xn)-reactions. The hardest part of the neutron spectrum is formed by high energy neutrons generated at first stages of intra-nuclear cascades. The obtained neutron spectrum allows "burning" out the AC material and the minor actinides placed in this system.

The soft part of the neutron spectrum (with energies below 1MeV), which is formed by prompt fission neutrons and the above-mentioned inelastic processes, will cause the production of low concentrations of ^{239}Pu (^{233}U). This must lead to the substantial increase opportunities RNT system in energy production.

A significant increase in the energy of incident particles up to 10 GeV allows an order to reduce the required current of the accelerator at the same beam power and greatly increase a fraction of the energy beam, which goes on generation of hard neutron field in the AC. This is determined, in particular by the increasing role of meson production in growth of neutron multiplicity and the hardness of the neutron spectrum with increasing beam energy in quasi-infinite multiplying system.

1. The results of the first experiments on the basic physics of RNT

In June 2009, by initiative of CPTP «Atomenergomash» a series of experiments with the target assembly «Quinta» irradiated by deuteron beam from JINR Nuclotron with energies of 1 and 4 GeV were carried out. This assembly shown in Fig. 1 consists of the uranium target placed in a lead blanket thickness of 10 cm with the input beam window size of the 150x150 mm. The target consists of three sections of hexagonal aluminum containers with an inscribed diameter of 284 mm, each of which is placed for 61 cylindrical uranium block. Blocks of 36 mm diameter and a length of 104 mm made of metallic natural uranium and placed in sealed aluminum housing. Unit weight is 1.72 kg and the total mass of uranium in one section is 104.92 kg. In front of the target and between its sections as well as behind it there are 4 detector probes.

For comparative experiments in the assembly was also used a lead target, structurally identical to the uranium one.

In these experiments, the first time in the study of accelerator driven systems the integral characteristics of fission in AC were examined by measuring the time spectra of delayed neutrons (DN). They were recorded with a detector assembly "Isomer-M" and stilbene detector.

The photo of target assembly is shown in Fig.2 and the scheme of the experiment is given in Fig.3.

The "Isomer-M" consists of 11 ^{3}He-proportional counters (SNM-33 and SNM-44) mounted in a block of plexiglass moderator with dimensions of 50×50×60 cm.

Each neutron counter is equipped with a preamplifier and discriminator. Massive combined shielding of ^{3}He-counters (CH-B-Cd) has provided the suppression of the neutron background to the level of 1.7% in the measurements with the uranium target at the energy of 4 GeV deuterons. Experimentally measured the "Isomer-M detection efficiency for neutrons from Pu-Be-source with an average energy spectrum of 4.4 MeV was (11.4 ± 0.1)%. The result of modeling of the neutron count intensity from this source, performed with the use of computer code MCNPX v. 2.5 for the real geometry of the experiment gives (4.77E-05 ± 5E-07) p/s in good agreement with measured value (4.86E-05 ± 3E-07) p/s.

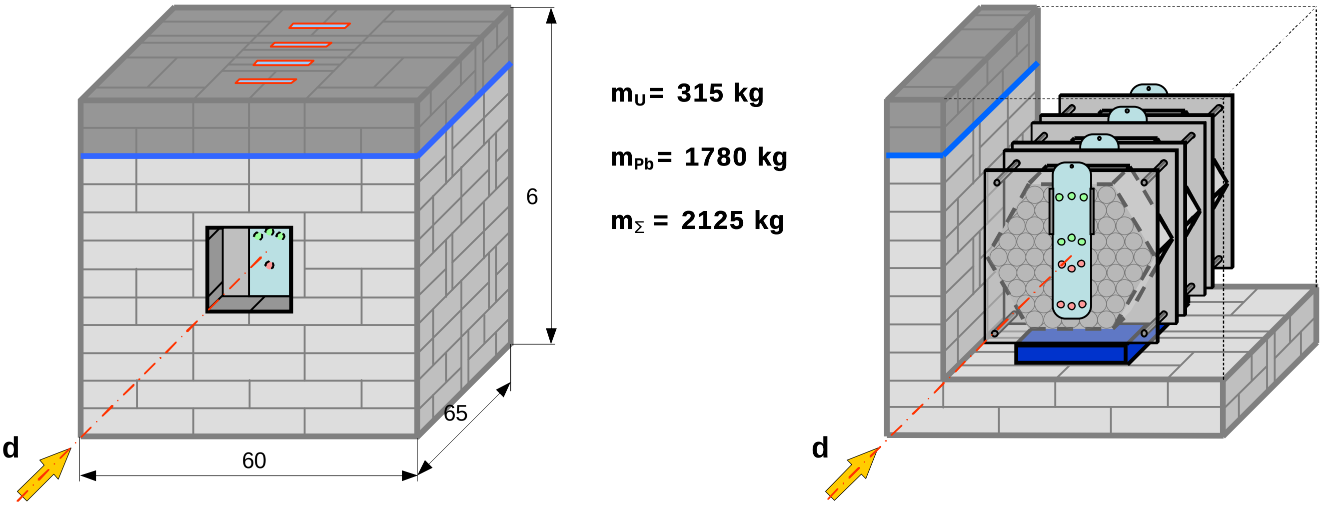

Fig.1. Target assembly “Quinta”.

Fig.2. The “Quinta” assembly at an irradiation position on NUCLOTRON beam F3 focus.

The scintillation neutron detector based on stilbene crystal of the sizes Ø 35 mm × 40 mm was placed over (in axial plane) of setup «Isomer-M».

Along with the measurements of the DN yield during experiments the methods of measuring spatial-energy characteristics of neutron fields inside and on the surface of the target assembly were tested using sets of activation detectors.

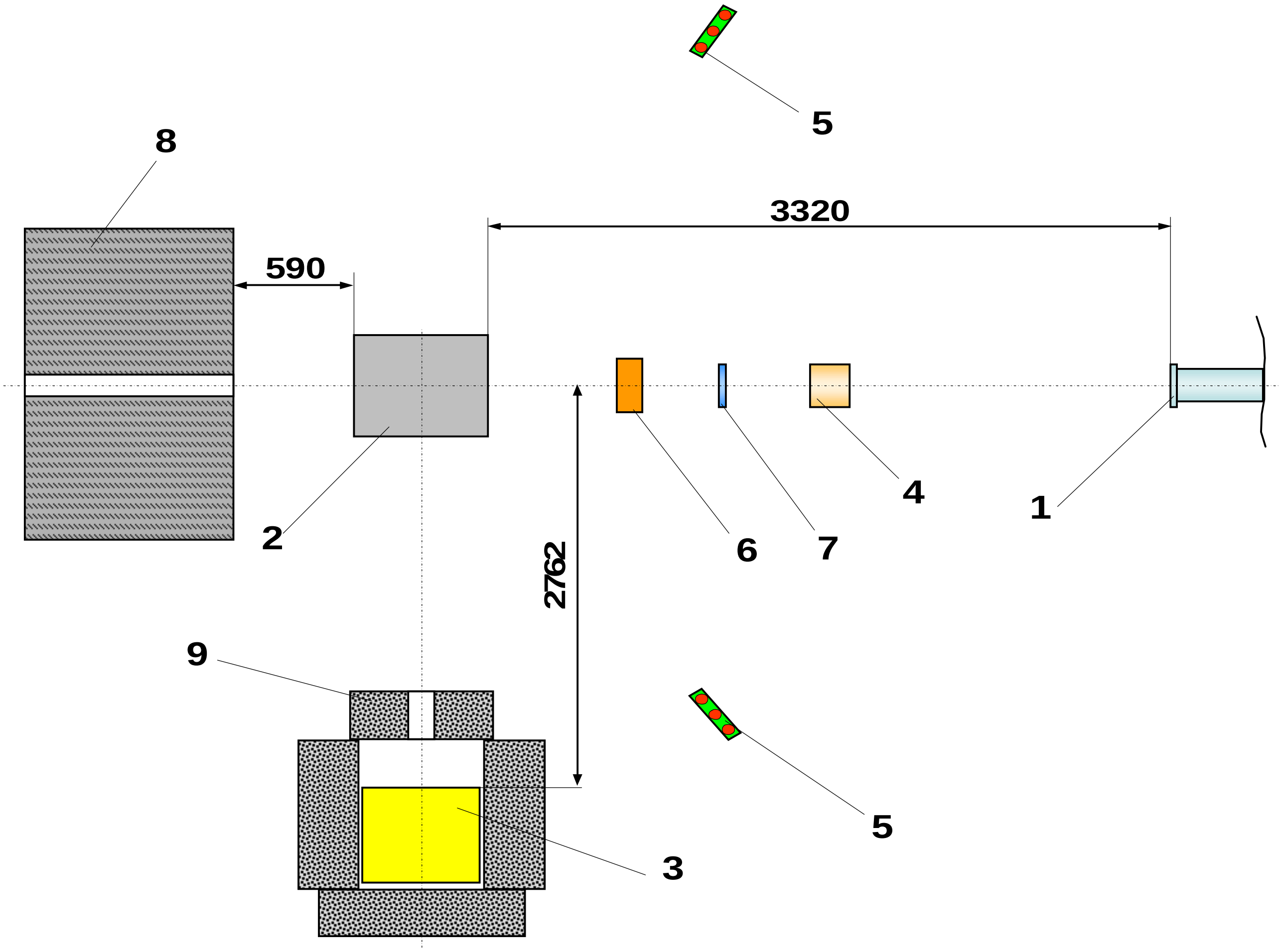

Fig.3. The scheme of experiment: 1- deuteron beam, 2- target assembly «Quinta», 3- detector of delayed neutrons «Isomer-M», 4-6 - on-line (7 –off-line) beam monitoring system, 8-9 – shielding.

Monitoring of beam intensity and its position on the target was performed by means of three independent systems:

1) on-line system measuring an intensity, time structure and position on the target of extracted beam in each accelerator burst realized on the basis of the ionization chamber, a profilometer and two scintillation telescopes;

2) off-line system obtaining the integral beam flux on the target by means of STD;

3) off-line system getting the integral beam intensity on the target with aid of Al foil.

The results of three system monitoring coincide in value of integral deuteron current within the error of 15% for all four energies.

Fig. 4 shows the time dependence of neutron yield from a uranium target irradiated by deuterons with energies of E_d = 1 and 4 GeV (indicated by 2 and 3 respectively), as well as from geometrically identical lead target for E_d = 4 GeV (labeled by 1). The incident deuteron beam (duration of pulse ~ 500 ms, repletion rate ~ (8 ÷ 9) 1/s) had fine temporary structure defined by features of the beam extraction from the Nuclotron.

Neutron yield during burst duration (including the prompt fission neutrons) registered on-line detectors with a large pile-up, and remained out of our analysis.

In the time interval from 0.9 s till 7.6 s after the start of the deuteron pulse the summed count of neutrons from the lead target is 0.84% on the corresponding count for the uranium target at the energy of deuterons of 4 GeV. It is obvious that delayed neutrons from the lead target are related only with the yield of light radioactive fragments since the fission cross-section of lead is extremely small. Thus, most of DN in the assembly «Quinta» with uranium target were produced in fission of the uranium nuclei.

Analysis of the time spectra of DN presented in fig.4 shows that with increasing deuteron energy from 1 to 4 GeV, the number of fissions, and hence the total energy release in the uranium target increases (8.7 ± 1.2) and (10.3 ± 1.5) times from the data obtained by the "Isomer-M" and stilbene detector respectively. So the beam power gain has to grow at least two times. Note that the error values given are determined mainly by accuracy of monitoring the deuteron beam current.

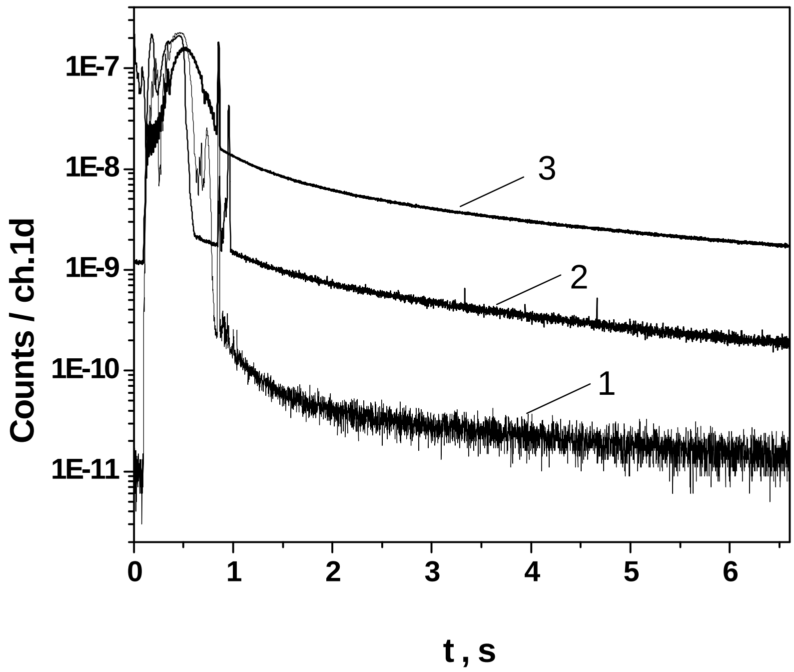

Fig.4. The time dependence of the neutron yield from the geometrically identical lead and uranium targets. 1 - (Pb+d) for E_d = 4 GeV; 2 and 3 (U+d) for E_d = 1 and 4 GeV.

In November 2009, at Nuclotron new experiment was carried out with the target set-up "Energy + Transmutation "("E+T") irradiated by 4 GeV deuterons. The "E + T" set-up consists of a central lead target surrounded by 200 kg blanket from metallic natural uranium (see fig.4). Beside that the lead-uranium assembly was placed in thick (~300 mm) and dense (ρ=0.7 g/cm3) polyethylene box serving as a reflector and a moderator. In parallel with measurements made on the program of the collaboration "Energy plus Transmutation" it was performed measurements of the time dependence of neutron yields. In fig.5 it is shown the time dependence of neutron yields from the target set-ups «Quinta» and «E+T» obtained by detector assembly «Isomer-M» at incident deuteron energy 4 GeV.

In fig.5 it is shown the time dependence of neutron yields from the target set-ups «Quinta» and «E+T» obtained by detector assembly «Isomer-M».

It is seen from the above picture that at the same beam energy the DN yield and respectively the number of fissions in the «E+T» target assembly is approximately by 2 orders of magnitude smaller than for the «Quinta» one. This could be related with the usage of the intermediate lead target in the set-up «E+T» and also with the small thickness of the uranium blanket. Beside a presence of the thick layer of polyethylene surrounding the target assembly has to make a resulting neutron spectrum softer in comparison with the same for «Quinta» set-up. All these factors could lead to decreasing of the number of fissions in the «E+T» set-up.

In fig. 6 the systematic of weight ratios of the abovementioned groups in dependence on neutron energy for ^{238}U(n,f)- reaction is presented together with the respective ratios (horizontal lines with error corridors) extracted from analysis of the DN time spectra measured for the uranium target assembly «Quinta» at the deuteron energy of 1 and 4 GeV as well as for the (Pb+^{238}U) assembly «E+T» at E_d = 4 GeV.

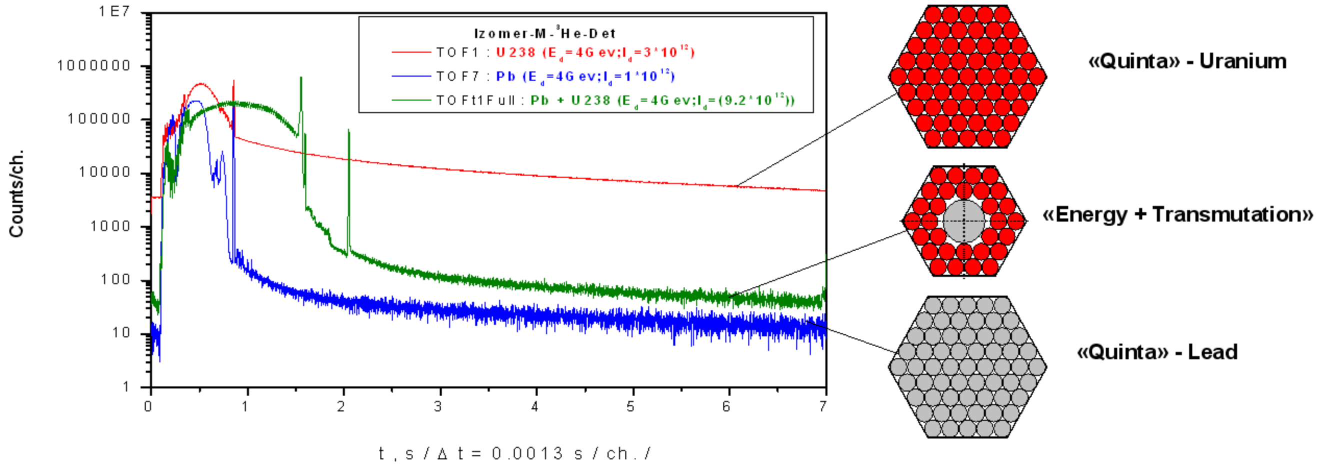

Fig.5. The time dependence of neutron yields from different target assemblies for E_d = 4 GeV.

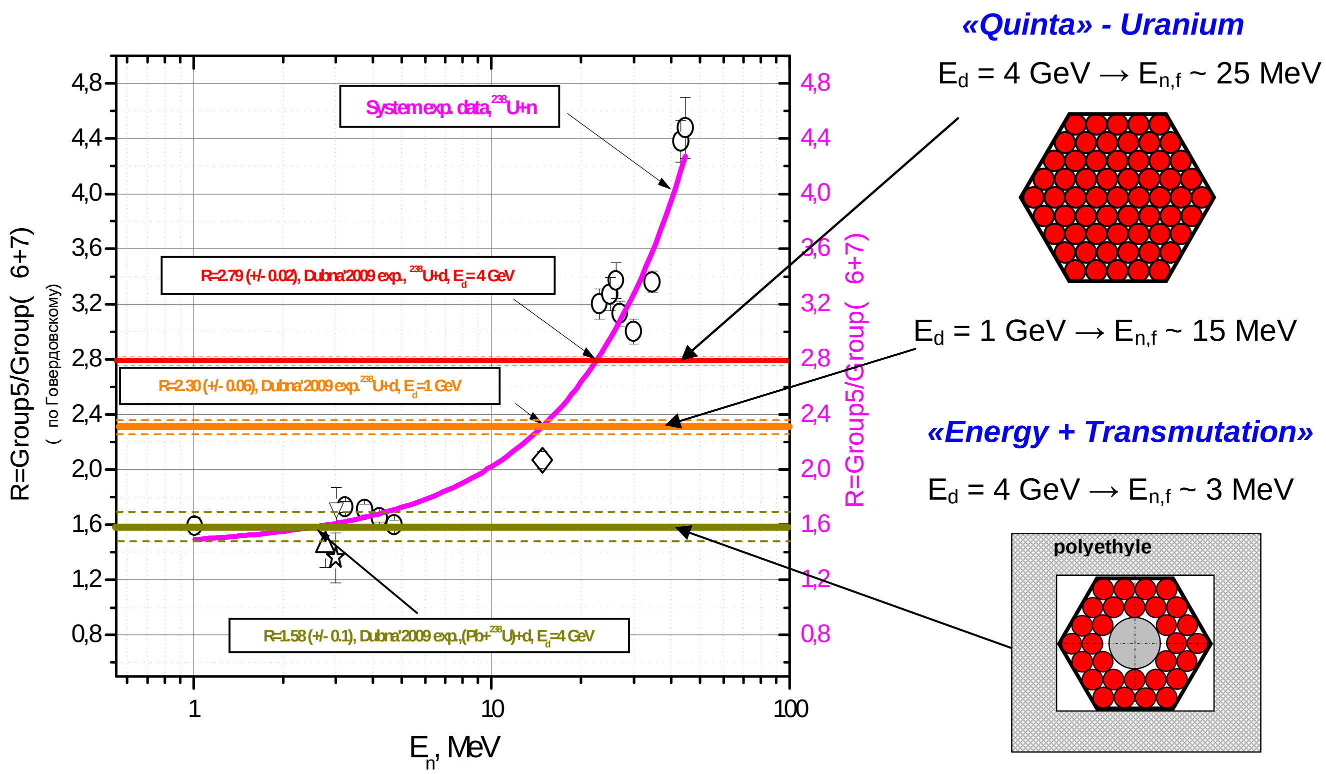

Fig. 6. Comparison of neutron energy dependence of the weight ratios of 5-th to (6+7-th) DN groups from ^{238}U(n,f)-reaction and similar values extracted from DN time spectra measured in present work.

As follows from fig.6 for the uranium target assembly «Quinta» the values of the "mean neutron energy" $\langle E_n \rangle$ inducing of ^{238}U fission are about 15 and 25 MeV for E_d = 1 and 4 GeV correspondingly. But for the «E+T» target assembly $\langle En \rangle$ is much lower and is only ~ 3 MeV at Ed = 4 GeV.

The DN decay spectra observed in our measurements are formed in fission of target nuclei induced by the neutron flux $\varphi\ (E_n)$ inside of target assemblies. Roughly the DN spectrum is determined by product of the fission cross section $\sigma nf\ (E_n)$, the DN multiplicity $\upsilon d\ (E_n)$ and the flux $\varphi\ (E_n)$. For ^{238}U(n,f)-reaction the product of $\sigma nf\ (E_n)\ \upsilon d\ (E_n)$ varies within several percents over a wide range of E_n, at least, up to 15 MeV. Therefore, the value of <E_n> obtained above can be considered as the realistic mean energy of neutrons initiating fission for studied target assemblies

These results reflect a significant difference in the neutron spectra $\varphi(E_n)$ inside the target assembly "Quinta" and "E + T" associated with the fundamental difference in their design. "E + T" set-up is similar to the classic ADS but Quinta assembly represents simplified prototype RNT scheme.

Of course, the total neutron energy spectrum below 10 MeV should be enriched by prompt fission neutrons produced in initial fission. And with increasing the radial target size the role of these secondary neutrons in production of delayed neutrons should become more important. For a quasi-infinite target the value of <E_n> should be essentially lower. The value <E_n> obtained above gives some indications that with our intermediate size of the target most of secondary neutrons leave the target volume without producing fission of target nuclei.

It can be stated that the study of the decay spectra of DN predecessors provides an important and sensitive tool for investigation of basic characteristics of fission process in a massive fissile target used as the active core of an ADS system.

The experimental results show promising application of RNT. We note in particular a twofold increase power gain of the deuteron beam, irradiating a massive (315 kg) uranium target when incident energy is increased from 1 to 4 GeV. This is in qualitative contradiction with the results of many current simulations, performed by various authors.

However, the amount currently available experimental data, as well as the level of accuracy of the results of computational and theoretical work in this area are insufficient for appropriate cost-informed policy decision to create full-scale prototype of RNT installation aimed at generation electricity and processing spent nuclear fuel.

2. Towards to the creation of technology for relativistic nuclear energy

June 22, 2010 JINR PACs in particle physics has approved Project “Study of deep subcritical accelerator driven systems and possibilities of their use for energy production and transmutation of radioactive waste" (Energy and Transmutation Energy and Transmutation RAW) with the first priority of execution.

Project "E and T - RAW" is aimed at experimental demonstration of the effectiveness and feasibility of the RNT scheme for processing of spent nuclear fuel and energy production.

The main objectives of the project "E and T - RAW" are:

1. Getting the basic nuclear physics data for the development of the technical conditions (TC) and feasibility study for the establishment of a demonstration pilot of an industrial design RNT system for the production of energy and reprocessing SNF.

2. Deep correction of the theoretical models and transport codes for reliable calculation of the characteristics of Accelerator Driven Systems, which is necessary for the design of a demonstration pilot RNT-installation.

In the framework of the project should be used two target setups:

1. Quasi-infinite uranium target assembly "Buran" a mass of ~ 21 tons, which will be a full-scale nuclear-physical model of the active core of RNT reactor (Fig.7 and 8).

2. The upgraded uranium target setting "Quinta" weighing about 500kg, which simulates the central zone the target assembly "Buran" (Fig.9).

Quasi-infinite uranium target assembly «Buran» with changeable central zone

Target material – depleted uranium in steel case.
Uranium mass – 21 t.
Target diameter – 1,2 ì .
Target length – 1 ì .
Central zone content – U, Th, Pb.
Central zone diameter – 0,2 ì .

Front view (from beam direction) *Rear view*

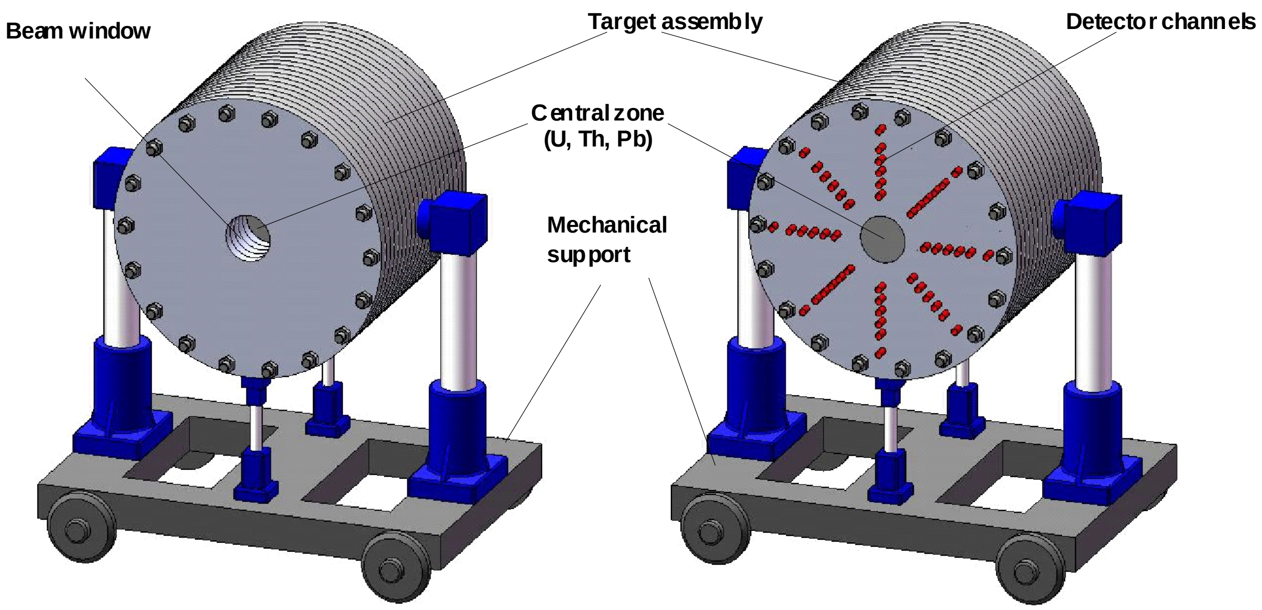

Fig. 7.

The main physical problems have to be studied in experiments with setup “Buran”:

1) the determination of the optimal energy and the type of incident particle (proton or deuteron) aimed at achieving of maximal beam power gain;

2) to study the neutron production processes and spatial distribution of neutron spectra;

3) investigation of the incident energy dependence of energy and power gain of the beam;

4) to study the dynamics of production and consumption (due to fission and (n,γ)- process) of 239Pu isotope, depending on its concentration inside of target aimed at determination of its equilibrium concentration;

5) determining the reaction rates of processing the most relevant isotopes from the spent fuel.

The main objectives of the experimental program with target assembly "Quinta" are:

1) determination of the dependence of the beam power gain on energy of incident protons and deuterons;

2) to study the incident energy dependence of the spatial and energy distributions of neutrons, spatial distributions of numbers of fission and plutonium production, as well as the anisotropy of the spectra and multiplicity of leakage neutron;

3) obtaining a set of experimental data to proceed with the modification of existing models and transport codes to improve the reliability of predicting outcomes of future experiments under the “E & T – RAW” project.

Additionally, in the course of the experiments with the setup "Quinta" will be used to study the transmutation rates of the most relevant isotopes from the spent fuel, as well as methodological develop new systems of detectors.

Quasi-infinite uranium target assembly «Buran» with changeable central zone

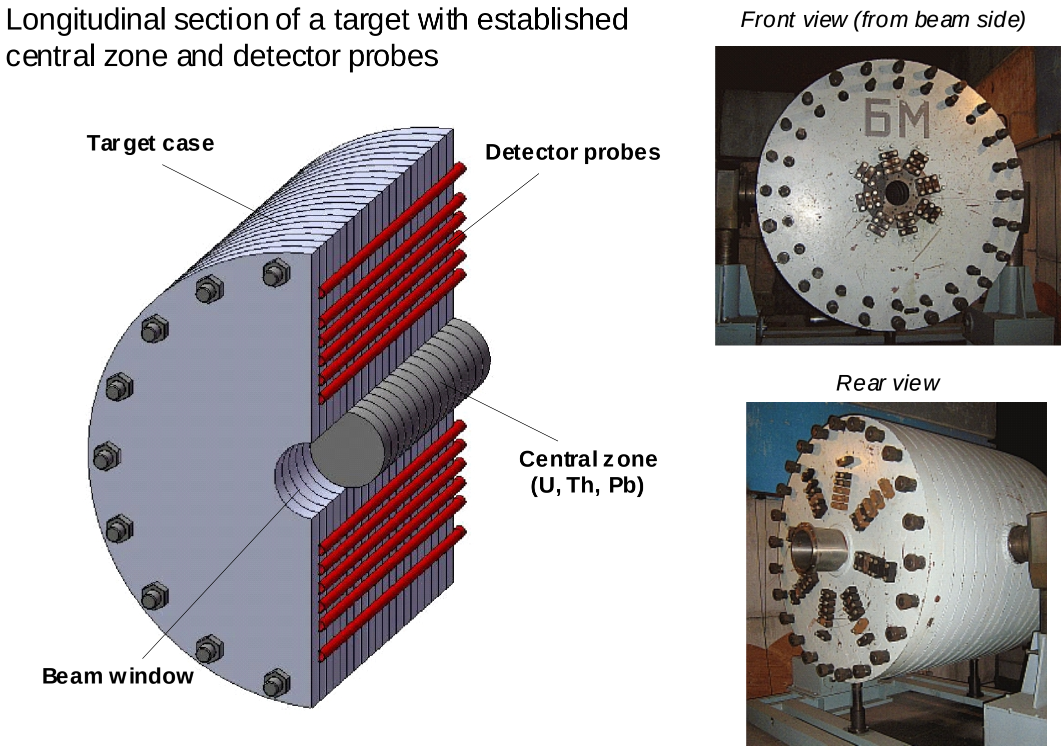

Fig. 8.

In March 2011 the first series of experiments with the upgraded uranium target assembly "Quinta" have been carried out. The target was bombarded by deuterons with energies of 2, 4 and 6 GeV. Preliminary results obtained in these experiments are presented at this conference.

Layout of the upgraded target setup with measuring equipment is shown in Fig.9.

Layout of target assembly "Quinta" at the irradiation position

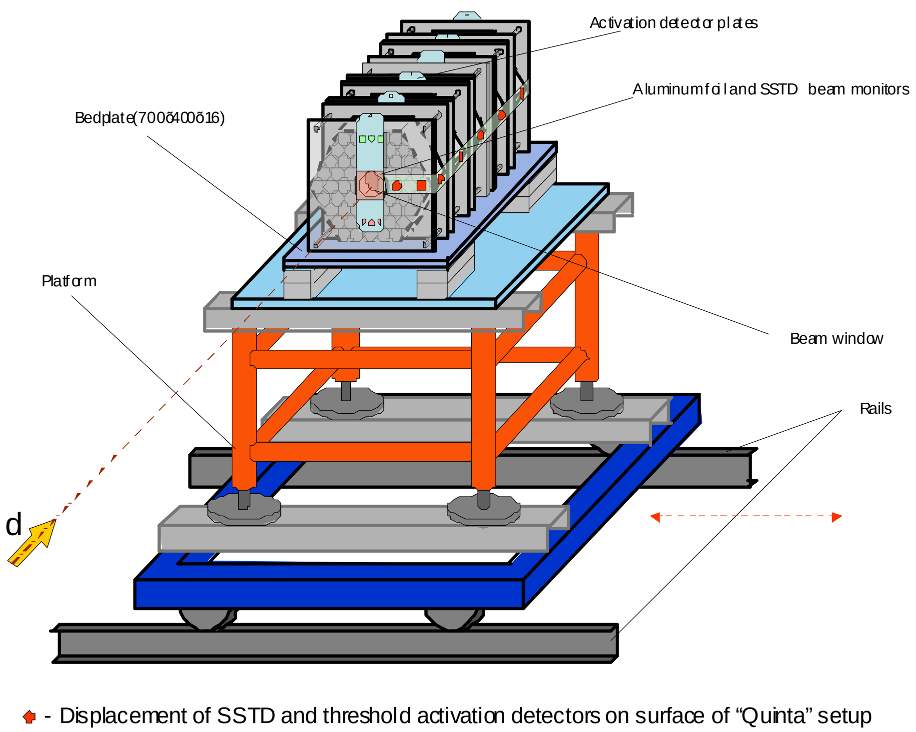

Fig. 9.

The scheme of whole experiment performed at the focus F3 Nuclotron beam is presented in Fig.10 and 11.

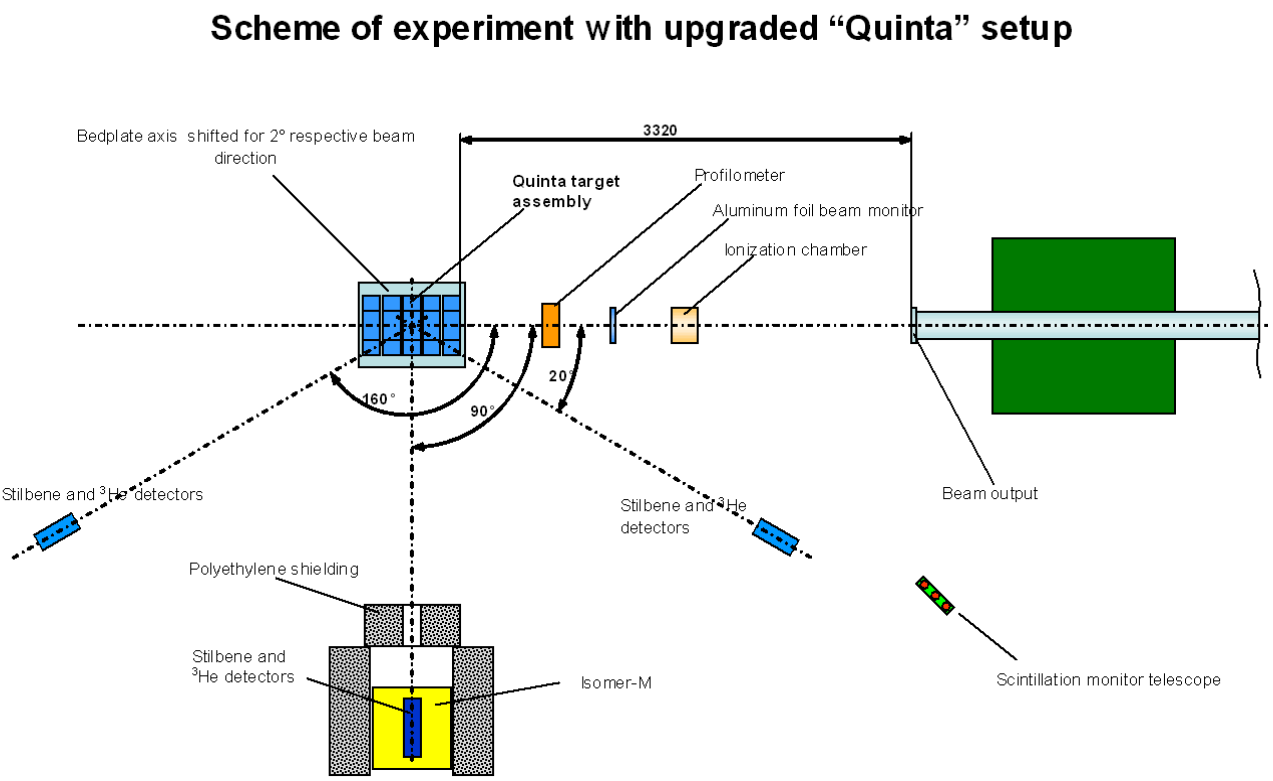

Fig. 10.

Fig. 11.