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

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Abstract. It is considered an essentially new scheme of the electro-nuclear method - nuclear relativistic technologies (RNT). This is based on the formation and use an extremely hard neutron spectrum inside deep subcritical active core. It is shown that the development and application of RNT may be promising for solving the problem of utilization of spent nuclear fuel and the global challenges of energy. The results of the first experiments carried out at JINR, indicate a validity of the basic principles of RNT, in particular, doubling the gain of the power of the deuteron beam, irradiating the massive (315 kg) uranium target, with increasing the beam energy from 1 to 4 GeV.

1. Introduction
There are two main reasons that hinder the wide dissemination of nuclear power in the world:
- unsettled in the modern concept of nuclear energy utilization problem of spent nuclear fuel (SNF);
- 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 $\text{keff} \sim 0.94 \div 0.98$.

In the fission neutron spectrum, the threshold minor actinide burning is ineffective because of their high threshold ($\sim 1$ 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.

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)[1].

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].

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.

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.

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.

2. The results of the first experiments on the basic physics of RNT
In June 2009 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 [2]. 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. In front of the target and between its sections as well as behind it there are 4 detector probes. 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.
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.2 shows the time dependence of neutron yield from a uranium target irradiated by deuterons with energies of $Ed = 1$ and 4 GeV (indicated by 2 and 3 respectively), as well as from geometrically identical lead target for $Ed = 4$ GeV (labeled by 1). The incident deuteron beam (duration of pulse $\sim 500$ ms, repletion rate $\sim (8 \div 9)$ 1/s) had fine temporary structure defined by features of the beam extraction from the Nuclotron.

Analysis of the time spectra of DN presented in Fig.2 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 $(8.7 \pm 1.2)$ and $(10.3 \pm 1.5)$ 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.

In November 2009, at Nuclotron new experiment was carried out with the target set-up "Energy + Transmutation" ("E+T") [3] 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.3). Beside that the lead-uranium assembly was placed in thick (~300 mm) and dense ($\rho = 0.7$ g/cm$^3$) 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.4 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.

**Fig.2.** The time dependence of the neutron yield from the geometrically identical lead and uranium targets. 1 - (Pb+d) for $Ed = 4$ GeV; 2 and 3 (U+d) for $Ed = 1$ and 4 GeV.
Fig. 3. The time dependence of neutron yields from different target assemblies for $Ed = 4$ GeV.

In Fig.3 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.

Fig. 4. Comparison of neutron energy dependence of the weight ratios of 5-th to (6+7-th) DN groups from 238U(n,f)-reaction and similar values extracted from DN time spectra measured in present work.

In Fig.4 the systematic of weight ratios of the abovementioned groups in dependence on neutron energy for 238U(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+238U) assembly «E+T» at $Ed = 4$ GeV.
As follows from Fig. 4 for the uranium target assembly «Quinta» the values of the “mean neutron energy” $<E_n>$ inducing of $^{238}$U fission are about 15 and 25 MeV for $Ed = 1$ and 4 GeV correspondingly. But for the «E+T» target assembly $<E_n>$ is much lower and is only $\sim 3$ MeV at $Ed = 4$ GeV.

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.

3. Towards 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”[4] with the first priority of execution.

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 m.
Target length – 1 m.
Central zone content – U, Th, Pb.
Central zone diameter – 0.2 m.

Fig. 5.

Project "E&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.

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

1. Quasi-infinite uranium target assembly "Buran" a mass of $\sim 21$ tons, which will be a full-scale nuclear-physical model of the active core of RNT reactor (Fig.5).

2. The upgraded uranium target setting "Quinta"(Fig.6) weighing about 500 kg, which simulates the central zone the target assembly "Buran".

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 \((n,\gamma)\)-process) of \(^{239}\text{Pu}\) 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.

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. Layout of the upgraded target setup with measuring equipment is shown in Fig.7. In the near future the results will be published.

4. Conclusion

This article presents the basic physical and technical principles of the original electronuclear scheme RNT. It is shown that using RNT can be achieved by a significant increase in the power of relativistic particle beam initiating a subcritical active core. There are considered optimal conditions for the energy gain in the RNT. First results of experiments conducted on JINR Nuclotron with model AC indicate the validity of the basic physical principles of RNT. However, requires further experiments with the greater mass of AC at higher energies of incident particles to convincingly justify the application of innovative perspectives RNT for energy production and utilization of spent nuclear fuel of modern nuclear power plants.

References

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