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Application of low energy accelerators for the investigation of ADS neutronics

H.I. Kiyavitskaya* and I.G. Serafimovich, C.C. Routkovskaia, V.V. Bournos, Yu.G. Fokov, S.V. Korneev, S.E. Mazanik, A.A. Adamovich, A.V. Koulikovskaya
Joint Institute for Power and Nuclear Research-Sosny
of the National Academy of Science of Belarus
Minsk, acad. A.K. Krasin str., 99

A.M. Khilmanovich, B.A. Martsinkevich, T.N. Korbut, S.E. Chigrinov
B.I.Stepanov Institute of Physics of the National Academy of Science of Belarus
68 Nezavisimosti Ave., 220072, Minsk, Belarus

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1. Introduction

The concept of application of high energy accelerators is based on large-scale usage of high energy spallation reactions for neutron production in targets with $A > 150$ (Pb, Bi, W, U, Pb-Bi) with subsequent multiplication of generated neutrons in sub-critical blankets ($k_{eff} \sim 0.9 - 0.98$) [1-4]. In such systems high neutron flux densities ($\Phi \sim 10^{15} - 10^{17} n/(cm^2 \cdot s)$ can be achieved that is one of the main conditions for radioactive nuclides transmutation. The experimental investigations at sub-critical systems are planned only because they are complicated, expensive and time consuming and often may not be realized with application of modern accelerators, since most of them have inappropriate beam parameters. In this regard the experimental research of various aspects of ADS on the basis of low energy accelerators – cyclotrons, microtrons, as well as deuterium and tritium ions accelerators representing neutron generators of high intensity is of great importance [5,6].

2. Interaction of high energy radiation with matter

Interaction of high energy particles in energy range of some MeV - 10 GeV is very complicated process with participation of large number of heavy interacting particles (n, p, π-mesons) in which electromagnetic interactions, nuclear reactions, formation and development of nuclear cascade are taken into account [7]. Transport of high energy radiation through dense media is accompanied mainly by two types of interactions: electromagnetic and nuclear ones. Nuclear interaction results in new particles generation which number and characteristics depend on properties of primary particle initiating nuclear reaction. The extent of development of nucleon-meson (intra-nuclear) cascade depends on medium characteristics, energy and type of primary particle. The development of intranuclear cascade attenuates as new particles generation with lower energy appears and finally results in scattering, moderation and absorption of neutrons. In fissionable media such chain of nuclear reactions includes fission of heavy nuclei by high

*E-mail: anna@sosny.bas-net.by

energy particles and by neutrons of evaporation and fission spectra too. As it was proved by theoretical and experimental researches that main part of spectrum of neutrons emitted from neutron-producing lead target of ADS constitute neutrons in the energy range E<15–20 MeV [5,6]. It proves a possibility to use low energy ion accelerators instead of high energy proton accelerators to investigate neutronics of ADS.

3. Sub-critical facility YALINA

To realize the idea for usage low energy ion accelerators to study neutronics of ADS subcritical experimental facility was developed, designed and constructed. Accordingly to generally accepted principles of ADS-technology [1, 4, 5] the subcritical facility consists of deuterium ions accelerator with Ti ^{3}H or Ti ^{2}H targets (neutron generator), Pb neutron-producing target and sub-critical assembly (Fig. 1).

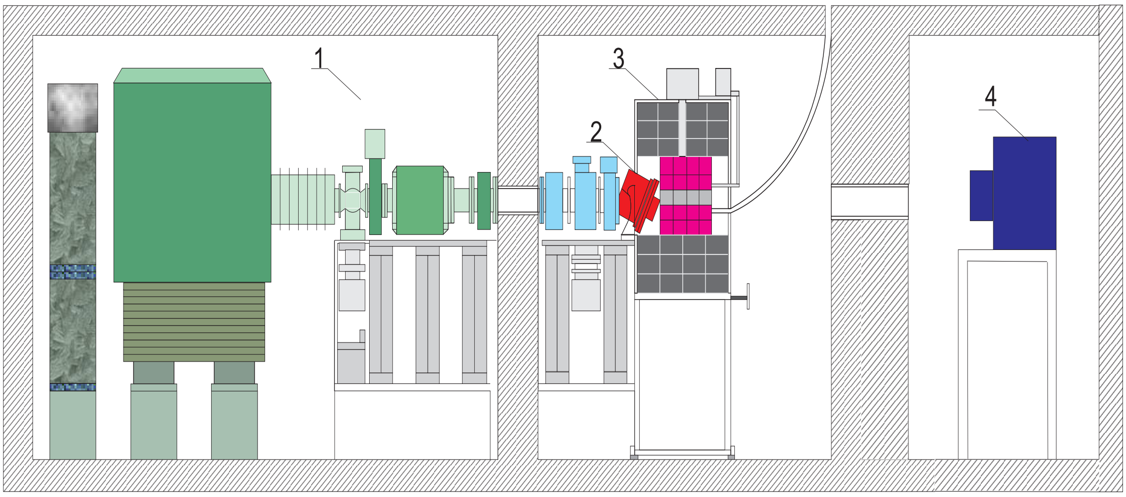

FIG. 1. Sub-critical facility YALINA: 1 - neutron generator; 2 - Ti^{3}H (TiD) target system; 3 - sub-critical assembly, 4 - gamma-spectrometer.

At present there are two assemblies: uranium - polyethylene (thermal neutron spectrum) Yalina-T and booster (fast-thermal neutron spectra) Yalina-B assemblies.

Yalina-T is multiplying system (k_{max} <0.98), located inside graphite reflector of parallelepiped configuration with side dimension 1000 and 1200 mm that is arranged of high purity "reactor graphite" blocks (200×200×500 mm) (Fig.2). The core of the assembly is of parallelepiped configuration too (400×400×600 mm) and consists of "bare" polyethylene subassemblies where fuel rods of EK-10 type (UO_2 of 10% enrichment by U-235) are located. On the whole the fuel subassembly contains 9 blocks (in length) made of polyethylene ($\gamma = 0.923$ g/cm^3) (80×80×63 mm) and 16 fuel pins of EK-10 – type located in channels (D = 11 mm). At the core center Pb target is located made of 12 blocks (in height) with side dimension 80×80×50 mm that reminds fuel subassembly by shape and size. Graphite reflector (thickness ∼500 mm) is covered from outside by Cd – layer (1mm thickness). At the distances R=50 mm, 100 mm, 150 mm from the core center three experimental channels (D=25 mm) are situated for location of samples of radioactive targets and various detectors for measurement of neutron flux density functionals. For the same purpose two axial channels (D=25 mm) are located in graphite reflector at the distances 250 mm and 358 mm; by Z=H/2 one more radial channel (D=25 mm) is located. As a whole, core of the sub-critical assembly contains 20 fuel subassemblies, 4 control rods and Pb target.

YALINA-B core is arranged of rectangular parallelepipeds too. X-Y cross section of YALINA-B is shown in Fig.3. The fast (booster) zone consists of 36 lead subassemblies, the

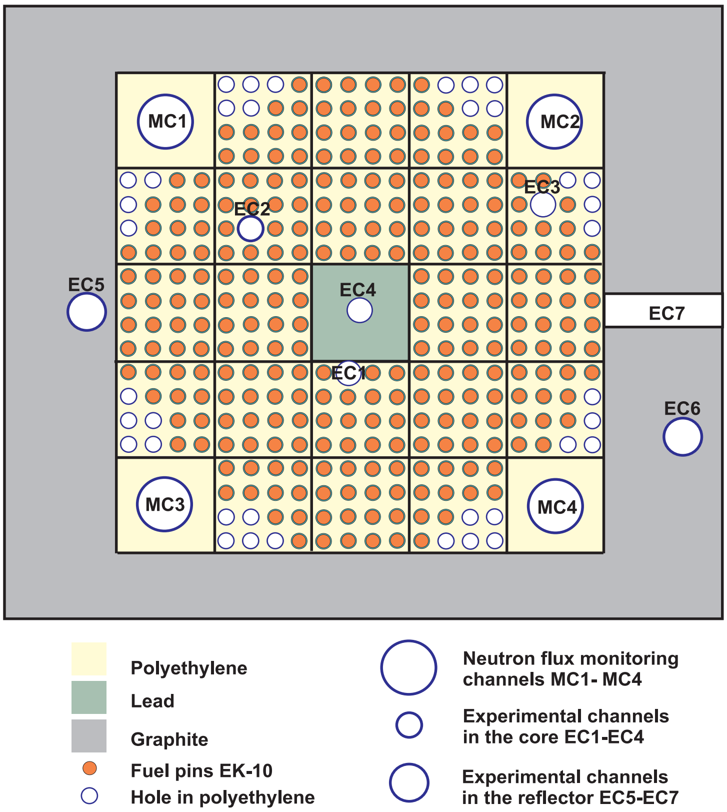

FIG. 2. X-Y cross sectional view of the YALINA-T subcritical assembly. E1-E3 are the experimental channels inside the core; M1-M4 – measurement channels for neutron flux monitoring; E4 – channel in Pb – target,
E5-E7 – experimental channels in reflector.

thermal one - of 108 polyethylene subassemblies. Central part of the booster zone, containing highly enriched (90%) metallic uranium fuel and Pb target is encased into a separate stainless steel frame. The absorber zone is located at the outer boundary of the booster zone. It consists of inner layer of rods with metallic natural uranium inserted into stainless steel casing tubes (outer diameter 9 mm, wall thickness 0.7 mm) fixed in lead blocks, as in the previous cases, and of an outer layer of rods filled by boron carbide powder, B_4C. Boron carbide rods are located in the same lattice as the uranium fuel pins in the booster zone with pin pitch 16.00 mm. The density of the boron carbide powder is approximately 1.38 g/cm^3.

This absorber zone enables fast neutrons to penetrate into the thermal zone, outside the absorber and fast zones, and prevents thermal neutrons from entering the booster zone from the thermal zone. The result is a fast neutron coupling of the fast and the thermal zones. The absorbing rods with B_4C are fastened rigidly and may not be taken out accidentally, to prevent undesired reactivity insertions.

The thermal zone surrounds the booster zone and the absorber zone. It consists of 108 closely packed polyethylene subassemblies each having 16 holes (D=11.7 mm) for fuel pins of EK-10 type location according to square lattice with pin pitch 20 mm. Each subassembly, having total length 576 mm, consists of twelve blocks (in length), each with side dimensions 79.2×79.2×48 mm. The blocks are made of polyethylene undergone to high pressure treatment with density 0.923 g/cm^3. The fuel pin pitch of 20 mm is optimal for multiplying medium with polyethylene moderator and fuel pins of EK-10-type. The pin tube is filled by UO_2 of 10% enrichment with addition of Mg. The length of the fuel part is 500 mm and the average content of ^{235}U in the pins is 7.73 g. There are three experimental channels in the thermal zone: EC5T, EC6T and EC7T.

Finally, the thermal zone is surrounded radially by a graphite reflector of thickness around

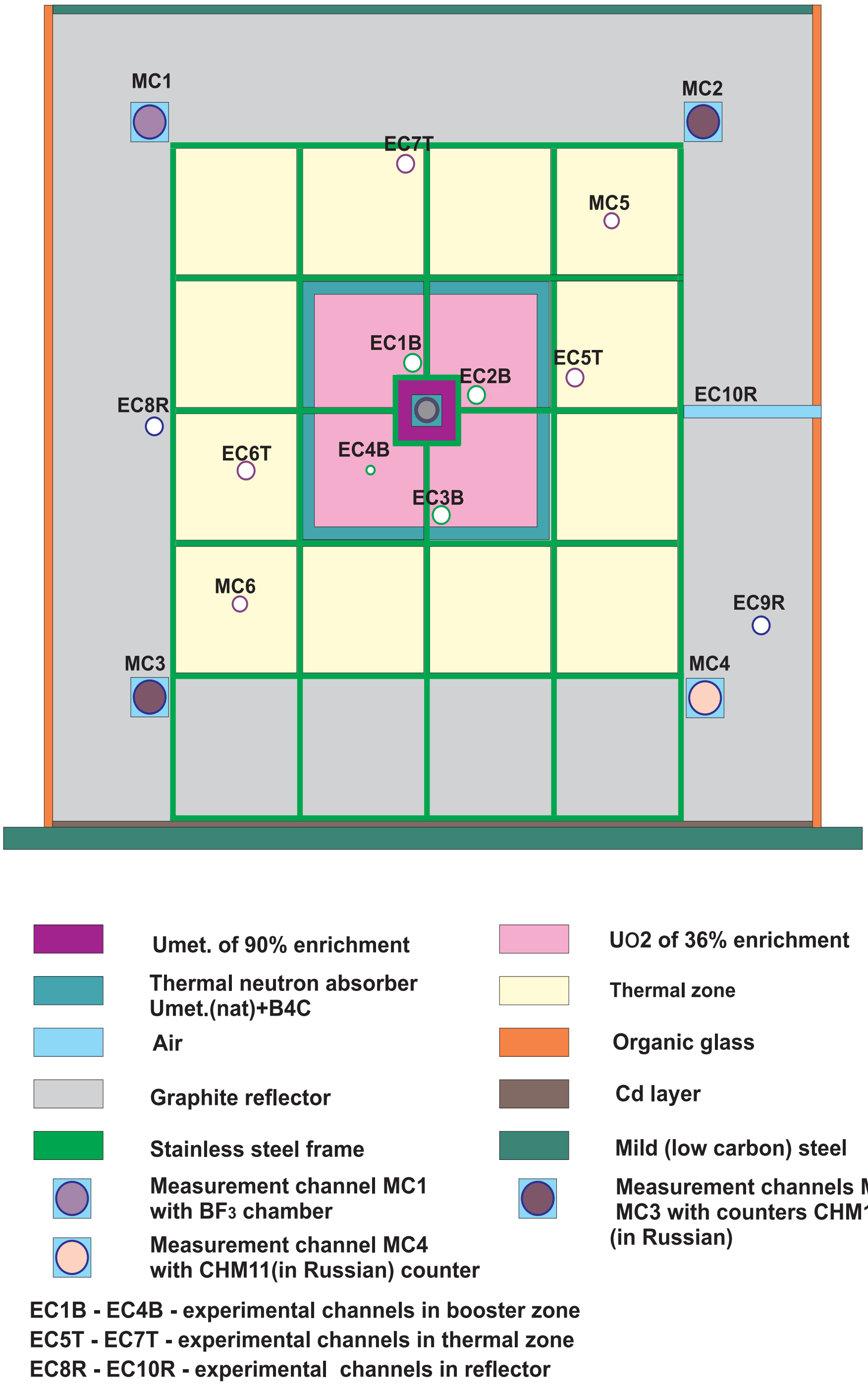

FIG. 3: X-Y cross-sectional view of YALINA-B assembly.

25 cm. In the reflector, the experimental channels EC8R, EC9R and EC10R can be found. Axially, the core is limited by borated polyethylene.

4. Neutron generator NG-12-1

Neutron generator is linear accelerator of deuterium ions produced at duoplasmatron and accelerated to energy E_d = 250 keV. Accelerator magnet system separates D^+ ions only that by means of electromagnetic lenses are directed towards the $Ti^3H_{1.5—1.8}$or $TiD_{1.5—1.8}$ targets where in reactions $d(T,n)^4He$ and $d(D,n)^3He$ neutrons are generated with energies E_n = 13-15

MeV and $E_n = 2.5$-3.0 MeV, respectively. At present highly effective water-cooled targets with diameters 230 and 45 mm are used in experimental program.

Energy distribution of neutrons in the sub-critical systems is main parameter that defines most of ADS-technology characteristics and first of all transmutation of minor-actinides and long-lived fission fragments. Figs. 4 and 5 show neutron spectrum in experimental channels of YALINA-T and YALINA-B calculated by MCNP code [7]. Obviously YALINA-B assembly can be used for larger range of research in comparison of YALINA-T.

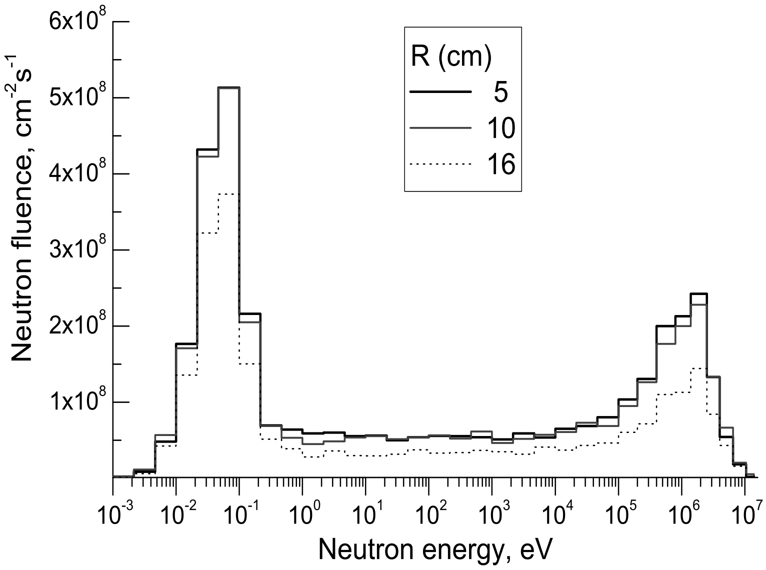

FIG. 4: Energy distribution of neutrons flux in the sub-critical assembly Yalina-T.

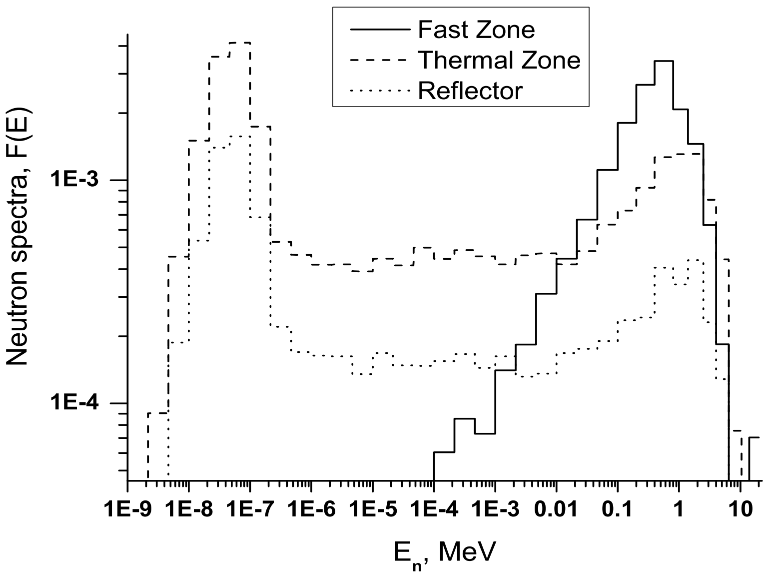

FIG. 5: Energy distribution of neutrons flux in the sub-critical assembly Yalina-B.

One of the main aspects of ADS-technology is transmutation of MA and LLFP. In this connection YALINA facility due to high neutron flux density in the core, possibility of core sub-criticality level variation ($0.90 \leq k_{eff} \leq 0.98$), application of various neutron sources and configurations "external neutron source–core" gives a unique opportunity for investigation of the peculiarities of MA and LLFP transmutation in ADS with thermal neutron spectrum that is of special interest for testing computer codes and evaluated nuclear data libraries. At present the theoretical and experimental investigations of ADS neutronics have been performed in the framework of international cooperation under the auspices of the IAEA and ISTC including:

1 - validation of methods of sub-criticality level monitoring,
2 - experimental study of sub-critical systems kinetics,
3 - measurements of spatial distribution of neutron flux density,
5 - time behavior of neutron flux depending upon neutron pulse parameters,
6 - measurement of long-lived fission products and minor-actinides transmutation rates.

5. Conclusion

A principal possibility of low energy accelerators and neutron generators application for investigations in the field of physics of multiplying system, driven by high energy ($E_p \sim 0.6 - 2.0$ GeV) particles accelerators was proved. A distinctive feature of the created facility is possibility to vary core configuration for carrying out the experiments by sub-criticality levels up to $k_{eff} \leq 0.98$, application of different neutron external sources [^{252}Cf; D(D,n)^{3}He; D(T,n)^{4}He] with its' various positions relative to the core center.

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