PROJECT OF A NEUTRON SOURCE BASED ON THE SUB-CRITICAL ASSEMBLY DRIVEN BY ELECTRON LINEAR ACCELERATOR*

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Abstract

Today accelerator driven subcritical assembly is candidate for the next generation of energy-generating nuclear facility, which could provide safe energy production, burning of trans uranium elements and transmutation of the radionuclides. Use of the electron beam with particle energy up to 150-200 MeV secures several advantages. Electron linear accelerators are much cheaper compare to hadron accelerators. Homogeneous irradiation of the assembly with neutrons could be provided. NSC KIPT together with ANL develops the project of a neutron source based on the sub-critical assembly driven by electron linear accelerator. Energy of electrons is 100-200 MeV. The target and assembly design is optimized to maximize the neutron source intensity with subcriticality of 0.98. Accelerator on average beam power of 100 kW, with repetition rate up to 300 Hz and pulse duration of 3,2 μs is under development. Transportation line should provide beam transfer with minimal losses of electrons and should form homogeneous distribution of the particle density at the target. Maximal value of a neutron flux is F_m=2.4×10^{13} n/(cm^{2}s), and power of energy release in the result of nuclei fission is P_m≈ 100 kW.

INTRODUCTION

National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT, Kharkov, Ukraine) together with Argonne National Laboratory (ANL, USA) develops the conceptual project of a neutron source based on the sub-critical assembly driven by electron linear accelerator. The main functions of the subcritical assembly are to support of the nuclear industry and medical researches. Reactor physics and material researchs will be carried out at the facility. The goal of the development is to create in Ukraine the experimental basis for neutron research based on safe intensive sources of neutrons. The main facility components are an electron linear accelerator, a system for electron beam transportation from linear accelerator to the target, neutron production target, subcritical assembly, biological shield, neutron channels and auxiliary supporting systems.

Neutron source is a hybrid facility, which is composed from high-current electron accelerator and subcritical assembly. Photonuclear reactions, induced by hard electromagnetic radiation emerging at retarding of the beam of relativistic electrons in the target from heavy element, are used to generate primary neutrons. Two options of the target are under consideration: tungsten and natural uranium. Energy of electrons in driven beam is 100-200 MeV. The sectioned construction of a neutron-generating target has been selected based on depositing of energy and thermo-hydraulic calculations.

The core of the sub-critical assembly on thermal neutrons is made of fuel elements based on the enriched uranium with level of enrichment of 20% uranium isotope-235. Water is a neutron moderator and coolant. Graphite is used as neutron reflector. The target and subcritical assembly is designed to obtain neutron flux as high as possible with subcriticality of 0.98. Thus, possibility of chain reaction occurrence is excluded in the facilities of such a type. Maximal magnitude of neutron flux F_m, one of the main characteristics of the source, depends on beam parameters of the accelerated particles, efficiency of neutron yield from the neutron-generating target and characteristics of the sub-critical assembly. Magnitude of neutron flux is regulated by beam current and neutron field in the source disappears after shutting down the driving beam.

In the described facility the maximal meaning of middle plane of a neutron flux averaged by time using uranium target and nominal power of electron beam makes F_m=2.4×10^{13} n/(cm^{2}s), and power of energy release in the result of nuclei fission of U^{235} makes P_m≈ 250 kW. Considerable proportion of fast neutrons as well as of neutrons of intermediate energies is in energy spectra together with thermal neutrons.

This pater is the first publication inended to describe the main parameters and status of the facility.

The start of the described project can be marked as 2006. At the moment the conceptual design project of the neutron source are desigen and egieniering development of the facility systems are began.

SUB-CRITICAL ASSEMBLY BUILDING

The arrangement of the neutron source based on the accelerator-driven sub-critical assembly is shown in Fig. 1. The linear accelerator is located in the building of the former linear electron accelerator LUE-2000 (1). The electron beam is transported from the accelerator through the transport channel (2) to the sub-critical assembly (3). The sub-critical assembly is to be installed in the experiment room 24x36 m of a new building adjacent to the accelerator building. The sub-critical assembly building contains all the sub-critical assembly elements, neutron channels, neutron stations, and auxiliary systems. The three-storied part of the sub-critical assembly building (5) will host the control room, express laboratories, and all support systems.

The radial dimension of the heavy-concrete biological shielding with a density of 4.6 g/cm^3 is 1.8 m. The

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biological shielding contains neutron channels (4), which can be used for various purposes. The neutron channels have a biological shielding of heavy-concrete and steel key blocks, which contain vacuum neutron channels and neutron guides. The channels take neutrons to research stations, which have a biological shielding of their own. Each channel ends in an absorber of unused neutrons with an appropriate biological shielding. Some neutron stations have in-built neutron stoppers.

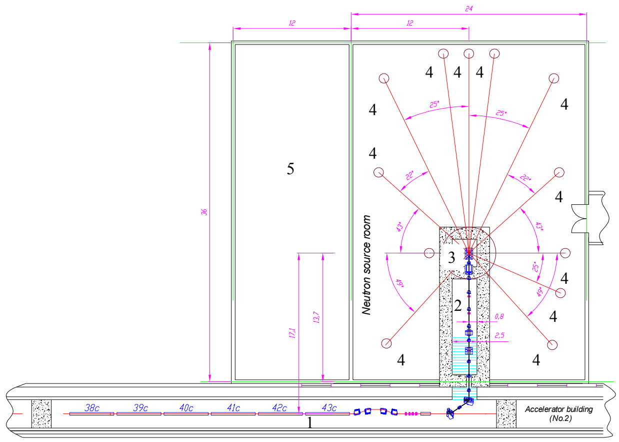

Figure 1. Layout of the Neutron Source Location: 1 – linear accelerator; 2 – electron beam transport channel; 3 – sub-critical assembly; 4 – neutron channels; 5 – express laboratories building.

LINEAR ELECTRON ACCELERATOR

The use of linear electron accelerator (LEA) as a sub-critical assembly driver imposes a number of requirements. The accelerator output energy of electrons must be in the range of 100-200 MeV. It ensures a sufficient neutron yield, and on the other hand the volume of the neutron target will be sufficient to decrease the energy deposition density and thermomechanical target stress. The existing accelerating structures, sources of high-frequency power and injector systems allow getting an average current at such accelerator output in the required electron energy range approximating 1 mA. Thus, the average power in the beam reaches 100 kW. To minimize losses during beam transport to the target, the energy distribution must not exceed 1%.

The LEA will be installed in the bunker of the LU-2000 linear accelerator complex available at NSC KIPT. Such location of the complex will not require any significant capital construction efforts and will allow utilization of the available engineering infrastructure of the LU-2000 accelerator. New equipment will be installed after dismantling of the existing equipment and renovation of the premises. The main elements of the accelerator complex include an electron injector and five S-range accelerator sections. Section 1 is placed in a short solenoid. The accelerator sections are followed by a beam energy compression system (ECS) consisting of a magnetic debuncher and a compensator section. The system of RF power supply for the accelerator sections and the injector is based on using six SLAC-5045 klystrons.

Considering an average electron beam power of 100 kW at 100-200 MeV energy, the selected klystron type and beam parameters have prompted the accelerator system consisting of five accelerator sections in which the electron beam with 1 A pulse current, 3 μs pulse duration, and 300 Hz repetition rate should achieve the energy of ~ 130 MeV.

There has been selected a uniform regular S-range structure on a progressive wave with 2π/3 type oscillations 4.3 m long. The time required to fill the accelerator structures with HF power is 0.4 μs. The accelerator sections have the following parameters: shunt resistance 46.3 MΩ/m; attenuation 0.0558 1/m; group velocity 0.0327 sec; Q factor 14300. The analyses also considered other accelerator section options for beam current pulse frequency 450 and 600 Hz and a corresponding shorter duration of the pulse current. The results of beam parameter analysis at the exit of LEA and ECS are provided in Table 1.

Table 1: Parameters of the Electron Beam at the Exit of The Linear Accelerator with Energy Compressing System

I_{out}, A	W_{out}, MeV	d, mm	Δ_{rms}, mm mrad	Δφ°	ΔW/W %
0.85	132.8				
70% particles		1.6	21	16	0.098
95% particles		3.8	21	41	1

TRANSPORTATION CHANNEL

The electron beam transportation channel from the electron linear accelerator to the target should meet the following requirements: transportation of the high current electron beam from the driving linear accelerator to the subcritical assembly with minimal particle losses, electron beam size at the subcritical assembly should be of about ±33 mm in both transversal directions with small value of the beam divergence, electron beam density distribution at the target should be uniform.

The detail description of the transportation channel is given in [1]. The layout of the transportation channel is shown in Fig. 2. After accelerator electron beam is bended with bending angle 90° (two bending magnets, 45° bend in each magnet). The first magnet is aligned with 45° angle to the horizontal plane, the second magnet is aligned in the same plane. Next, the beam is turned on 22.5° angle with two 11.25° bending magnets in vertical plane and turns in horizontal position. In the last turn the reference trajectory of the beam is bended with angle 90° in vertical plane by two 45° bending magnets and is aimed to the target straight from vertical direction.

The beam sizes at sections 1-3 are not bigger than 1 mm. Such focusing provides beam transportation to the section 4 without particle losses. In section 4 quadrupoles and octupoles of nonlinear objective for the beam density shape transformation are set. Increasing of beam sizes in sections 5, 6 can be explained by the requirements to the beam sizes at the target. Aperture of the channel at the sections 1-4 is ±20 mm and at section 5, 6 is ±70 mm. The total beam length is 27.542 m.

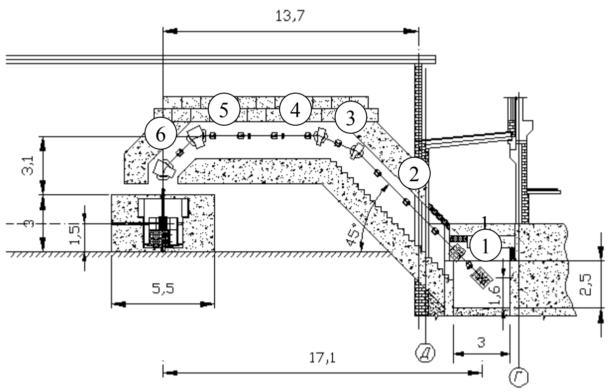

Figure 2. Layout of the transportation channel from the linear accelerator to the sub-critical assembly. Vertical plane.

In the transportation channel two octupole magnets, that are set in place 1 and 2 (Fig. 2), are used [2]. In the point 1 the octupole effects distribution function in horizontal direction. Octupole magnet in the point 2 transforms beam distribution in vertical direction. Initially, it was assumed, that electron beam at the entrance of the transportation channel has Gaussian beam density distribution functions in both horizontal and vertical directions with the same RMS sizes (1 mm and 1 mrad). One can see from the Fig. 3 that use of octupole magnets allows to realize pseudo-uniform distribution of particle density at the target.

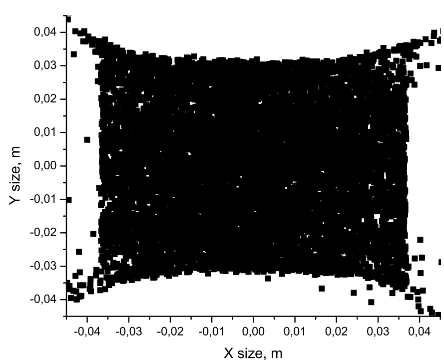

Figure 3. Transversal coordinate distribution of the driving electron beam at the target of the neutron source.

TARGET AND SUBCRITICAL ASSEMBLY

Natural uranium and tungsten are considered as materials for the neutron generating target. Uranium and tungsten produce the highest neutron yield for electron energy in the range of 50-200 MeV. A single-section WWR-M2 fuel assembly has been selected as reference design of the sub-critical fuel assembly.

The sub-critical assembly is disposed in the redan filled with water. All components of the active zone of the sub-critical assembly are set up in the bottom grid plate, which has orifices for arrangement of fuel elements and rods of graphite reflector. Unusable orifices can be covered with taps to form water flux one needs. All assembling activity concerning fuel elements and reflector will be made with handling machine. Active zone pool circled with reactor tank. Height of the water reflector above active zone is set by the pool height and can not be bigger to excide increasing of multiplication factor of neutrons higher then 0.98. Cooling water of the subcritical assembly is entered the bottom of the active zone tank, cools fuel elements and reflector and through orifice in the very bottom of the outer tank exit trough the tubes to the cooling system of the sub-critical assembly. Neutron target is disposed in the center of the subcritical assembly. The main parameters of the designed sub-critical assembly are provided in Table 2.

Table 2. Parameters of the Sub-Critical Assembly

N.	Parameter	Value
1	Electron beam power, kW	~ 100
2	Electron beam energy, MeV	100 ÷ 200
3	Neutron yield from the target (U/W), n/sec	$3.28\cdot10^{14}$/1.91·10^{14}
4	Target material	U238 / W
5	Fuel U^{235} enrichment, w/o	≤ 20
6	Neutron flux density, n/cm^2 sec	~ $2.4\cdot10^{13}$
7	Total neutron flux density in the reflector region, n/cm^2 sec	~ $2\cdot10^{13}$
8	Maximum fast neutron flux density in the fuel region with E > 0.1 MeV, n/cm^2 sec	~$1.3\cdot10^{13}$
9	Moderator	H_2O
10	Reflector material and, g/cm^3	Carbon, 2.3
11	Total power deposition in the fuel element region, kW	~ 230
12	Max power deposition in the reflector, kW	~ 20
13	Maximum power deposition in the sub-critical assembly, kW	~350

The subcritical assembly is configured in such way to provide maximum flexibility of its operation as with square as well with round target and with various types of fuel elements and reflector to provide variation of neutron flux spectrum.

CONCLUSION

A conceptual design of the "Neutron source based on the sub-critical assembly driven by the electron accelerator" which meets its primary functions has been developed. Implementation of the design will allow carrying out research with modern nuclear systems and provide ample opportunities for research using neutron beams.

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