STATUS OF THE EXISTING ACCELERATORS AND NEW ACCELERATOR PROJECTS

NSC KIPT NEUTRON SOURCE STATUS

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The state of development and construction of ADS research facility in NSC KIPT is given. The facility presents a neutron source based on a subcritical uranium assembly driven by a linear electron accelerator with energy of 100 MeV and beam power 100 kW.

PACS: 29.25.Dz

INTRODUCTION

In accordance with the agreement between the governments of Ukraine and USA the ADS research nuclear facility is under construction in the National Scientific Center “Kharkov Institute of Physics and Technology” (NSC KIPT) together with Argonne National Laboratory (ANL). The facility is a neutron source (NS) which is based on a subcritical uranium assembly driven by a linear electron accelerator [1].

Development of the design documentation of NS buildings and engineering design of the technological systems and equipment were fulfilled by organizations and companies from Ukraine, Russia, China, USA and Germany.

Neutron production principle and NS conceptual design project and the main characteristics of the technological systems were considered in article [1].

Intensive neutron flux production in the facility is based on the multiplication of external source neutrons in a fissionable material media. The media geometry and the fission material mass are chosen so that the effective neutron multiplication factor k_{eff} does not exceed 0.98 ($k_{eff} \leq 0.98$) at any initial event. Thus the multiplying media is a subcritical assembly (SA).

This requirement guarantees the facility nuclear safety and eliminates the possibility of critical mass formation. Consequently, the self-sustained chain fission reaction does not arise. The neutron flux value Φ (n/cm^2·s) in NS is regulated with the external source intensity Q_0(n/s) and the total neutron production in time unit is $Q_0/(1-k_{eff})$.

A photonuclear source was taken as a driver of the SA. In the driver neutrons are emitted when a heavy metal target (*W*, *U*) is exposed by the high-energy gamma rays. When the energy of γ-quanta is higher than a threshold of photonuclear reactions ((γ, n), (γ, 2n), (γ, 3n), (γ, f), etc.) the neutron emission occurs. The electromagnetic bremsstrahlung radiation is used. It is generated when the electron beam with energy of 100 MeV and average current of 1 мA is bombarding the neutron producing target. The neutron yield from uranium target of optimum geometry makes about 5% per one incident electron. From a tungsten target the neutron yield is 2 times lower [1].

For production of high energy electron beams the linear resonance accelerator has been developed by Institute of High Energy Physics (IHEP), Beijing, China. All equipment and systems needed for the linac exploitation were manufactured, tested and transported to NSC KIPT.

It is known [2] that an accelerator of relativistic protons with energy $E \geq 1$ GeV is more effective for neutron production then electron one. In this case due to proton collisions with heavy element nuclei (*spallation*) the energy inputs for producing of one neutron is approximately in 30 times less than for electron interactions with a heavy metal target [3].

Table 1

Parameter	Value
Electron energy, MeV	100
Beam average power, kW	100
Neutron production target	Uranium, tungsten
Neutron yield, n/s	$3.01 \cdot 10^{14}$ (U-target) $1.88 \cdot 10^{14}$ (W-target)
k_{eff}	Less then 0.98
Core fuel	19.7% enriched uranium
Neutron reflector	Two-region: beryllium, graphite
Moderator, coolant	Demineralized water (H_2O)
Core neutron flux, n/cm^2·s	$1.95 \cdot 10^{13}$ (U-target) $1.14 \cdot 10^{13}$ (W-target)
Fission energy release, kW	192 (U-target) 131 (W-target)

However in this project a linear electron accelarator was chosen as a driver of subcritical assembly [8]. The reason was a very high cost and complication of proton ADS facility (Accelerator Driven Systems) and the short terms of NS construction and putting it into operation [4, 5].

The general parameters of the constructed neutron source are presented in Table 1 [1].

The core of SA is assembled from the fuel assemblies (FA)) of VVR-M2 type, which are produced by the TVEL corporation (Russia). The fuel assemblies contain a low enriched uranium (19.7% ^{235}U), that as a fine-dispersed powder of uranium dioxide UO_2 is homogeneously distributed in a matrix of SAV-1 aluminum alloy. The FA design, their specification and arrangement in the NS core are considered in [1].

The developed NS is a hybrid nuclear facility, the systematic analysis of which features and practical applications were started at the end of XX century [6]. In the world the accepted terminology for these facilities is the ADS or ADSCS installations (Accelerator Driven SubCritical Systems).

The technological equipment of these installations conceptually consists of two parts functioning of which is based on the different physical principles. The electro-physical part includes a charged particle accelerator and a channel to transport the beam on a target for production of the primary neutrons. The nuclear-physical part consists of the neutron production target and SA for multiplying the primary neutrons and equipment for usage of the produced neutrons in scientific researches and applications.

Since NS is the nuclear facility all stages of its life-cycle including: technical proposal, selection of construction site, design project development, engineering design, construction license issue, construction, equipment mounting, commissioning, facility operation and decommissioning are regulated with the Ukraine Nuclear Legislation and the official normative documents.

Unfortunately, the countries which suppose to construct the ADSCS facility is only developing the proper normative base. The normative acts in force are related to the zero power subcritical stands or nuclear reactors (*power, research*) in which the self-sustaining fission reaction is controlled by the mechanically moved neutron absorbers.

The average power of the uranium fission in NS is about 200 kW. Thus, a nuclear fuel cycle, which occurs in a power or research reactor, is fully realized in the given facility. It includes: the storage of non-irradiated nuclear fuel, loading of FA in the core, process of *"nuclear burning"* stimulated by the initial photo-neutrons, the FA rearrangement to compensate the SA reactivity decreasing due to uranium fission, the SA cooling, unloading of FA to a cooling water pool to decrease the residual radiation, waste FA transportation for burial.

To include the hybrid nuclear installation (NS) in the Ukrainian nuclear legislation the national Regulator (Ukrainian Nuclear Regulation Inspection) developed and accepted the normative document that determines the requirements to ADSCS-installation, including all stages of its life cycle starting from technical proposal up to the facility decommissioning [7]. The basic requirements of this normative document are nuclear and radiation safety of a facility taking into account possible design accidents related to the equipment failures, facility staff errors, fire, natural and anthropogenic phenomena (earthquake, flood, hurricane, shock wave). In addition the facility design project should foresee the hypothetical accidents (airplane falling, terroristic act and others) and the measures to eliminate their consequences.

In this paper the main characteristics and final engineering and technological solutions of some systems and equipment of the KIPT are briefly considered The systems and equipment allocation and construction progress are considered also.

1. ELECTRON LINAC AND BEAM TRANSPORTATION CHANNEL

As a rule a linear accelerator (*linac*) is the most complicated and power-consuming system of ADSCS facilities of middle 0.1…1 MW and higher fission power.

The main design project parameterss of the linac are given in Table 2 [1, 8]. The integration of the linac and the beam transportation channel with the subcritical assembly is shown in Fig. 1.

Table 2

Parameter	Value
Electron energy, MeV	100
Average beam current, mA	1
RF frequency, MHz	2856
Repetition rate, Hz	625
Pulse duration, μs	2.7
Pulse current, A	0.6…0.8
Energy spread, %	~1
Normalized emittance, m·rad	$5 \cdot 10^{-7}$
Pulse/average klystron power	30 MW/50 kW
Accelerating wave type	2π/3
Accelerating section length, m	1,38
Number of accelerating sections	10
Total accelerator length, m	24.5

The neutron source is allocated in a separate building, consisting of experimental hall, engineer-laboratory additional building and annex for the linac.

The linac systems are allocated in the annex and partially in the experimental hall. The plane *A-A* (see Fig. 1) is the interface between these buildings. In the annex first floor there is a linac klystron gallery 1. The main technology equipment of the linac is arranged in the gallery: 6 klystron amplifiers for RF power supply of accelerating sections, cabinets with the power supply sources for magnetic elements of accelerating channel and the beam transportation channel to the target (focusing solenoids, quadrupole lenses, magnetic correctors, bending dipoles etc.). Cabinets with beam diagnostics devices, power supply sources, control racks of vacuum system etc. are there also.

The linac is allocated at the annex second floor in a tunnel 2 (see Fig. 1). The tunnel walls are the biological shielding from ionizing radiation and radioactive aerosols produced during the linac operation. Above the tunnel, in the third floor (unshown) the equipment of NS special ventilation is set. This system cleans air of the klystron gallery, the linac tunnel and the experimental hall. It includes the aerosol filters and equipment for control of air activity thrown out to the atmosphere.

The linac accelerating channel is built using the standard technology. It includes the injection part (triode gun with the electron energy of 100 keV and the pulse current up to 2 A, pre-buncher, buncher and the first accelerating section to 12 MeV) and 9 sections of the main part. The accelerating sections are the diaphragmatic waveguides in which a travelling 2π/3 wave are excited.

Beam focusing in the injection part is provided with solenoids, producing the longitudinal magnetic field. In the main part of linac 5 elelctro-magnet quadrupole triplets located after every two accelerating sections are used for beam focusing.

The beam diagnostics system includes the beam current transformers, beam position and profile monitors, detectors of particle losses. The electron beam energy, energy spread and transverse beam profile and emittance are measured also.

The linac vacuum system includes: diode and triode ion pumps, turbomolecular and mechanical ones. Operation residual gas pressure in the accelerating sections and the transportation channel is $0.5 \cdot 10^{-5}$ Pa and $1.5 \cdot 10^{-5}$ Pa correspondently.

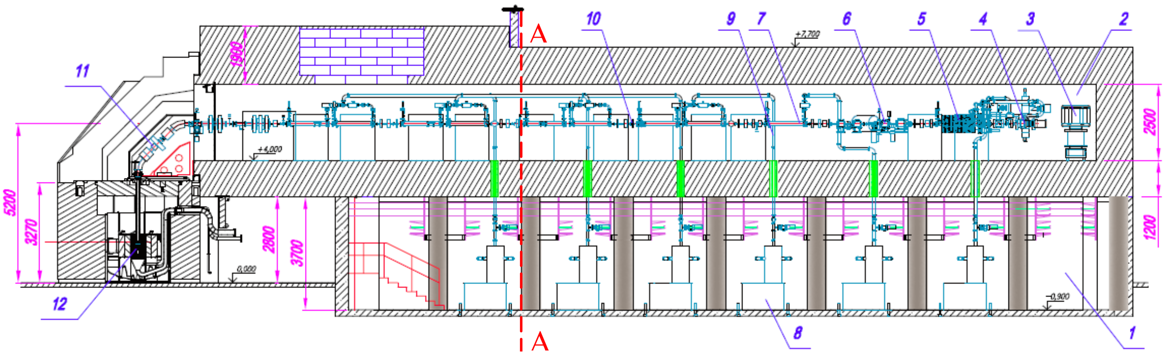

Fig. 1. Layout of linac and subcritical assembly: 1 – klystron gallery;2 – accelerator tunnel; 3 – electron gun power supply; 4 – linac injecion part; 5 – the first accelerating section, 6 – chicane; 7 – accelerating section; 8 – klystron; 9 – wave guide; 10 – quadrupole triplet; 11 – beam transportation channel; 12 – subcritical assembly

Very important operation parameters of the linac with beam power of 100 kW are the electric energy efficiency that is the ratio of the beam power to the linac power supply, and the *radiation purity* of accelerating sections and the beam transportation channel.

The radiation purity depends on electron energy and the beam current losses on the elements of accelerating sections and the transportation channel. The generated bremmstrahlung radiation creates the radiation background and γ-rays, with energy higher than a threshold of photonuclear reactions of construction materials and causes their activation. As a result the biological shielding cost increases and the maintenance of equipment becomes more complicated.

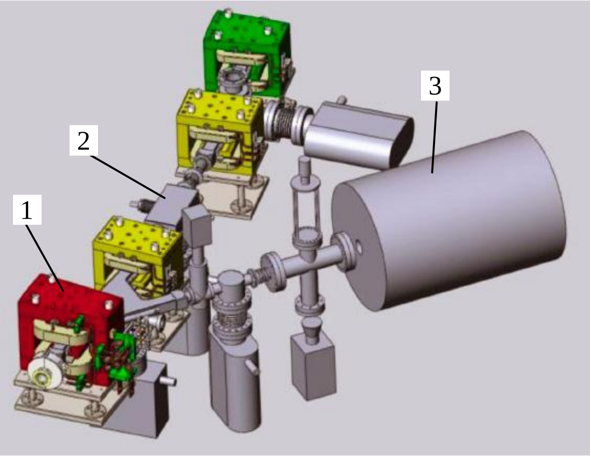

Fig. 2. Chicane: 1 – magnet dipole; 2 – collimator; 3 – beam dump

To decrease the beam current losses in the main part of the linac and the transportation channel, a chicane (*energy filter*) was installed after the first accelerating section (E_1=12 MeV) for the beam spectrum cleaning from the low energy electrons. The chicane 3D-model is shown in Fig. 2. The chicane includes four magnetic dipoles 1 with the beam bending angles of 10° and a water cooled collimator 2.

The first chicane dipole 1 and a beam dump 3 are used also to control the electron energy spectrum at the linac tuning. At this operation mode the bending angle of the first dipole magnet is 45°.

The beam dynamics numerical simulations show that the electron beam losses in the linac main part are no more then 1 kW if the chicane is used. Along accelerating sections the electron current losses decreases with energy growth as E_i^{-1}, where E_i is the *i*-section output energy.

The special design was needed for the output part of the transportation channel 11 (see Fig. 1) which is used for the beam input in the neutron production target. It consists of 2 magnetic dipoles with the bending angles of 45°, a quadrupole lens, a beam scanner and diagnostics elements [1].

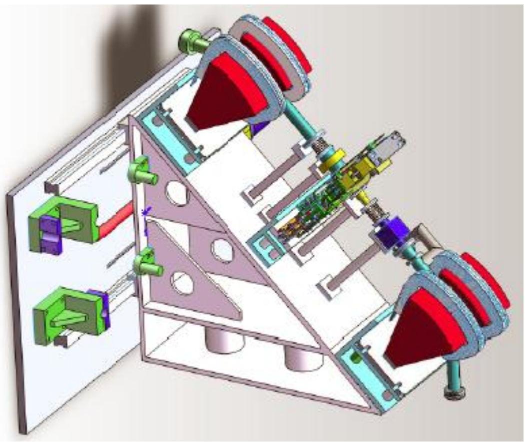

Fig. 3. The output part of the transportation channel

The 3D-model of this device which is the *accelerator-target* interface is presented in Fig. 3. The complicated construction of this device was related to the procedure of the target replacement. For the extraction of the activated target from the SA core it is needed to displace the device as a whole by the electromechanics drives with the remote control.

The output part of the transportation channel is mounted on a separate moved platform and after the target replacement must be returned at the initial position with a high accuracy.

The horizontal part of the transportation channel after the last accelerating section includes 5 quadrupole lenses, the beam diagnostic devices, vacuum pumps and fast-acting emergency valves blocking the linac volume when the vacuum window of neuron producing target is damaged.

The total electricity consumption of all linac systems is about 2.1 MW.

2. SUBCRITICAL ASSEMBLY AND NEUTRON PRODUCTION TARGET

The conceptual design of the subcritical assembly and the neutron production target are considered in the article [1]. In the final design documentation some changes related to the number of the fuel assemblies for the initial loading of the core was made.

The initial loading for the uranium target is 37 fuel assemblies and the calculated SA reactivity is k_{eff}=0.976. When the target is extracted from the core the reactivity does not change. Thus the neutron absorption by the uranium target is negligible.

The tungsten target with mass of 2.8 kg has a strong absorption of neutrons. It is needed to load 42 FA to have k_{eff}=0.979. Before the tungsten target is extracted from the core it is necessary to unload 5 fuel assemblies. Otherwise the multiplication factor k_{eff} may approach the critical value that is the severe violation of the nuclear safety requirements.

The initial decision to compensate the reactivity growth was to insert two neutron absorbers in the core before the tungsten target extraction. The absorbers are made of the boron carbide B_4C with the density of 1.38 g/cm^3. They have a cylindrical shape with diameter of 10 mm and length of 500 mm. The absorbers are inserted in the zone of beryllium reflector [1]. In this case the most activated fuel assemblies are not discharged from the core.

However the Regulator decided that this procedure of the tungsten target replacement is not sufficiently safe and demanded to decrease k_{eff} to 0.96 and consequently the number of FA became equal to 38. The argumentation was a human factor, possible failures of the loading machine and other initial events.

Consequently, in the case of tungsten target the neutron flux is approximately 4 times less than for the uranium one taking into account k_{eff}=0.96 and the photoneutron yield from the tungsten.

Thus, the enriched uranium mass in SA for the initial fuel loading does not exceed of 8.04 kg.

The neutron absorbers from the boron carbide are used for SA setting in the deep subcriticality mode (k_{eff}<0.95) when the facilities is stopped for a long time. That is the regulatory requirement of the nuclear safety normative documents.

In Fig. 4 the 3D-model of the subcritical assembly with the neutron production target is presented. All elements of SA are installed in a tank 2 of 2 m diameter and 2.2 m height. The tank is fabricated of SAV-1 aluminum alloy with the wall thickness of 10 mm. The tank is surrounded with a biological shielding 1 from a heavy concrete of 4.8 g/cm^3 density. Shelves 3 are used for storage of FA, the neutron absorbers and the beryllium reflector blocks.

The FAs, the absorbers and the beryllium blocks are loaded into SA using a remote-controlled fuel loading machine 8, equipped with a video camera.

The replacement of the irradiated target 7 and then its transportation into a special water storage pool for the radiation cooling is carried out by a separate device, installed at a transportation bridge crane that is not shown in Fig. 4.

The neutron reflector 4 of the NBG-18 reactor graphite and density of 1.85 g/cm^2 has a cladding from an aluminium alloy. The reflector external diameter is 1240 mm, and the height is 710 mm, and mass is 1802 kg. It is set on a plate, which is a bedplate for the core, the beryllium reflector blocks and the target. The central part of the plate has the holes forming a hexagonal grate for mounting of the core fuel assemblies and the beryllium reflector blocks.

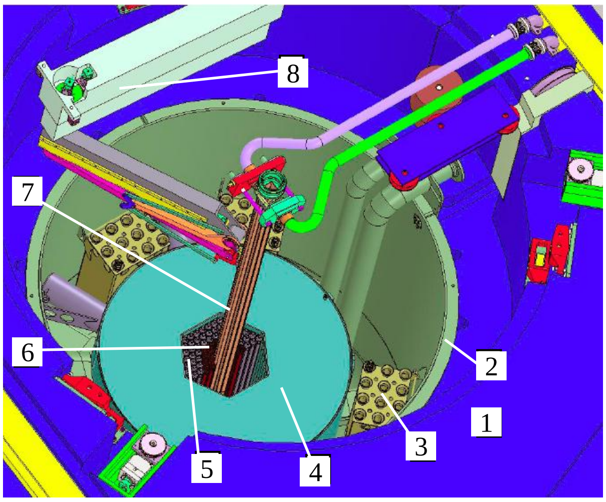

Fig. 4. 3D Subcritical assembly model: 1 – radiation shielding; 2 – SA tank; 3 – fuel shelves; 4 – graphite reflector; 5 – beryllium reflector; 6 – core; 7 – target; 8 – fuel loading machine

The SA tank is cooled with demineralized flowing water. The water is also the neutron moderator. The water layer thickness above the core is 50 cm. The SA cooling system has two loops. The first loop is closed. It includes the ion-exchange filters for the coolant cleaning from the activated corrosion products and the uranium fission products which contaminate the water if the fuel assembly cladding is damaged.

The system of special ventilation removes the activated gas-vapor mixture which arises over the SA water surface into the exhausting chimney. Besides it produces additional air exhausting off the linac tunnel and the subcritical assembly that eliminates the flow of the activated gases into the workrooms.

In Fig. 5 the general view of the neutron production target (a) and its fragment (b) are presented. The fragment (b) explains the construction of the target part which emits the photoneutrons directly. The construction is given for the uranium target. The conceptual design of the target is considered in the paper [1].

The target housing is a square section pipe of an aluminium alloy with internal size 66×66 mm and the wall thickness of 2 mm. The water cooling pipes are installed along the housing. The total length is 2620 mm. The target, Fig. 5, consists of a few parts: a vacuum electron guide 1 with the length of 2210 mm, a vacuum window 2 of 2 mm thickness, a set of neutron emitted plates 3 which are separated with gaps of 1.75 mm width for the flowing cooling water, a helium chamber 4 of 237 mm length and a fixing finger 5 to center the target in the bedplate.

The numeral simulation results of the SA neutron field using the *MCNPX* 2.6 statistical code have shown that the efficiency of the photoneutron use may be increased up to 20% and the neutron flux will be increased, respectively, if under the target to set a chamber filled with helium. The chamber displaces the certain volume of water which is the effective neutron absorber. As a result an additional part of photoneutrons goes into the core and produces the fission neutrons.

The main technological difficulties to fabricate the target are related to the producing of the photoneutron emitting plates. Since the target plates are in the intensive fields of γ-radiation and the neutrons with a wide energy spectrum the target material changes its physical-mechanical properties due to the radiation damages.

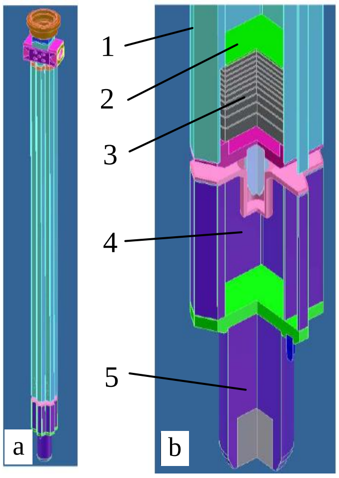

Fig. 5. Neutron production target: a – general view; b – fragment;1 – electron guide; 2 – vacuum window; 3 – emitting plates; 4 – helium chamber; 5 – fixing finger

In particular, the ^{235}U nuclei (0.71%) are fissionable (n, f) with the neutrons of any energies and the hard γ-quanta with the energy higher then the reaction threshold (γ, f). The ^{238}U isotope is fissionable with the fast neutrons and the hard γ-radiation. The fission products including gaseous are accumulated in the target and degrade the material structure.

The result of radiation damages is the target mechanical degradation and decreasing of its operation lifetime.

For the final target version the pure tungsten and natural uranium were replaced with alloys of tungsten-iron-nickel (1.5% Fe, 3% Ni) and uranium-molybdenum (7% Mo).

To decrease the chemical corrosion and the penetration of radioactive products in the cooling water the target plates were covered with a protective layer. The uranium plates were covered with an aluminium alloy of 1.0 mm thickness which was coated by the thermal-diffusion method. The tungsten plates were covered with a tantalum layer of 0.25 mm thickness which was coated on the surface using the *CVD* - method *(Chemical Vapor Deposition)* using the tantalum halogenide ($TaCl_5$) vapor phase technology [9].

CONCLUSIONS

The project of buildings and the design of the technological equipment and systems of the NSC KIPT Neutron Source were developed. The State Expertise has been made to estimate the project compliance to the national nuclear legislation, the sanitary legislation and the environmental protection. The positive conclusion was obtained. The Ukraine Cabinet Council approved the project of the subcritical nuclear facility. The State license on the facility construction and commissioning was obtained.

Now the facility buildings are mainly constructed. They include the experimental hall building with the engineer-laboratory building and the linac annex, the cooling towers, the pumping and compressor stations, the water demineralization installation and others.

The main part of NS equipment was manufactured and delivered to the NSC KIPT. The mounting of the technological equipment and systems was begun.

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Article received 17.10.2013

СТАТУС ИСТОЧНИКА НЕЙТРОНОВ ННЦ ХФТИ

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Представлено состояние разработки и строительства в ННЦ ХФТИ исследовательской ядерной установки – источника нейтронов, основанного на подкритической урановой сборке, управляемого линейным ускорителем электронов с энергией 100 МэВ и средней мощностью пучка 100 кВт.

СТАТУС ДЖЕРЕЛА НЕЙТРОНІВ ННЦ ХФТІ

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Надано стан розробки та будівництва в ННЦ ХФТІ дослідницької ядерної установки – джерела нейтронів, заснованого на підкритичній урановій збірці, що керується лінійним прискорювачем електронів з енергією 100 МеВ та середньою потужністю пучка 100 кВт.