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NEUTRON SOURCE BASED ON THE MULTIFUNCTIONAL ACCELERATOR COMPLEX OF THE NSC KIPT

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An overview of existing neutron sources in the world, which are used for fundamental and applied research in various fields of science and technology, was conducted. The possibility of creating a neutron source on the basis of a superconducting electron accelerator, which is the basis of the multi-functional accelerator complex of the National Science Center NSC KIPT, was considered. Based on the design parameters of the electron beam, the intensity of the neutron beam was estimated.

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INTRODUCTION

Along with the wide use in physical research of various sources of electrons, protons, and photons, neutron beams provide an opportunity to obtain a number of important information about the nature of phenomena that can be investigated thanks to the unique characteristics of the neutron.

While the number of protons in the nucleus of an atom determines the chemical properties of the atom, the physical properties of the nucleus depend on the number of neutrons in the nucleus. Only the nucleus of the lightest isotope of hydrogen does not contain neutrons, all other nuclei consist of protons and neutrons. In atomic nuclei, the neutron is the basis of the stability of the nucleus over time.

A free neutron has a mass of $1.674927471 \times 10^{-27}$ kg [1 - 6], which slightly exceeds the mass of a proton. The mean square radius of the neutron is close to 0.8 fm. A neutron has a magnetic moment and is a fermion with spin ½. A neutron has no electric charge [1, 3, 5].

A free neutron is an unstable particle whose main decay channel is into a proton, an electron, and an antineutrino

$$n^0 \rightarrow p^+ + e^- + \nu_e.$$

The beta decay time of neutrons according to the latest measurements is 877.75 s [7 - 9].

A neutron is a bound state of three quarks [1, 3, 5, 6].

Experimentally, the internal structure of the neutron was investigated by electron scattering on a deuteron by R. Hofstadter [10 - 12].

The interaction of neutrons with atoms is relatively weak, which allows neutrons to penetrate deeply enough into matter – this is their significant advantage compared to X-rays and γ-rays, as well as beams of charged particles.

1. SOURCES OF NEUTRONS

Free neutrons are formed as a result of nuclear-physical processes in nuclei and the interaction of nuclei with incident particles.

A) The most intense source of spontaneous fission neutrons is the ^{252}Cf isotope of californium [13 - 15].

Radionuclide ^{252}Cf decays by the mechanism of alpha decay (96.3%) and spontaneous fission (3.1%).

Neutron radiation ^{252}Cf consists mainly of spontaneous fission neutrons. One act of spontaneous fission is accompanied by the emission of 3.76 neutrons with an average energy of 2.3 MeV. The half-life of the isotope is 2.645 years.

The isotope can be obtained by long-term irradiation of uranium or plutonium with neutrons in powerful nuclear reactors specially built for the production of transuranium elements.

The main application of ^{252}Cf is the production of powerful and extremely compact neutron sources (Fig. 1).

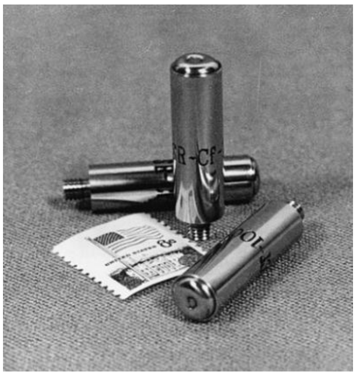

Fig. 1. A small container with californium that can be used as a compact source of neutrons [16]

Currently, the only producers of the isotope in the world are the High Flux Isotope Reactor HFIR at Oak Ridge National Laboratory (ORNL) and the High Flux Reactors at Dimitrovgrad in Russia [14].

The annual production of the isotope is about 500 mg [17].

1 g of the isotope can emit a powerful flow of neutrons – $2.3 \cdot 10^{12}$ n/s.

^{252}Cf sources are used in neutron activation analysis, in neutron radiography; in geological exploration and mineral extraction; in the steelmaking, chemical, oil refining, and coal mining industries; in the production of parts for nuclear energy and aerospace engineering, as well as in nuclear medicine for the treatment of malignant tumors.

B) Somewhat less intense are radionuclide sources of neutrons [18], built on the basis of excitation in certain chemical elements of nuclear reactions of the type (α, n) – absorption of an α-particle with the emission of a neutron, or (γ, n) – absorption of a γ-quantum with neutron emission. They are, as a rule, a homogeneous compressed mixture of an element emitting α-particles or γ-quanta and a target element in which a nuclear reaction is excited. Polonium, radium, plutonium, americium, curium are used as α-emitters, and antimony, yttrium, radium, and mesothorium are used as γ-emitters. Target elements for α-emitters are beryllium, boron, for γ-emitters – beryllium, deuterium. The mixture of elements is sealed in ampoules made of stainless steel. The most famous ampoule sources are radium-beryllium and polonium-beryllium.

Energy spectra of α-neutron sources are non-continuous, from thermal to 6...8 MeV, γ-neutron sources are approximately monoenergetic, tens or hundreds of kiloelectron volts. The neutron yield of γ-neutron sources is 1-2 orders of magnitude lower than that of α-neutron sources, and is accompanied by strong γ-radiation.

The field of application of radionuclide sources coincides with the field of use of the ^{252}Cf isotope.

C) In scientific research and industry [18, 19] widely used neutron sources that use nuclear reactions between hydrogen isotopes deuterium and tritium:

$$D+D > {}^{4}He+n+3.3\ MeV;\ D+T > {}^{4}He+n+14.6\ MeV.$$

In such sources, deuterons are accelerated to an energy of 100...500 keV in an electrostatic field and interact with targets saturated with deuterium or tritium.

The main parts of a neutron generator are an ion source, an accelerator tube, a target, a vacuum system, and a high voltage source.

Depending on the tasks, various implementations of the accelerator design are possible. Thus, for nuclear-geophysical methods of research, unsoldered tubes that do not require a special vacuum system are often used in wells and many laboratory generators. They contain an ion source, an accelerating gap and a target, as well as a deuterium repository [19]. The yield of neutrons in such tubes reaches $10^8...10^9\ s^{-1}$.

The accelerator of a portable neutron generator for the treatment of oncological diseases [20] (Fig. 2) requires a special deuterium source, a pumping system and target cooling. A reaction is used in the neutron source

$$^{2}H + {}^{9}Be \rightarrow {}^{10}B + n.$$

The average energy of neutrons in this process is about 2.5 MeV. The neutron output of such a generator is about 10^9 n/s.

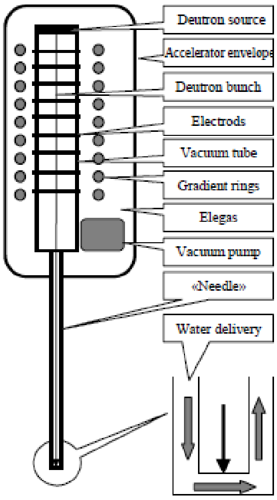

Fig. 2. Scheme of the accelerator [20]

For the industrial production of the medical isotope ^{99m}Tc [21, 22], an installation was developed and manufactured, the general view of which is presented in Fig. 3.

The source of neutrons in this production is a deuteron accelerator and a tritium target. In such an accelerator-target system, it was possible to achieve the highest neutron flux – $4.6\cdot10^{13}$ n/s. The cut diagram of the installation is shown in Fig. 3.

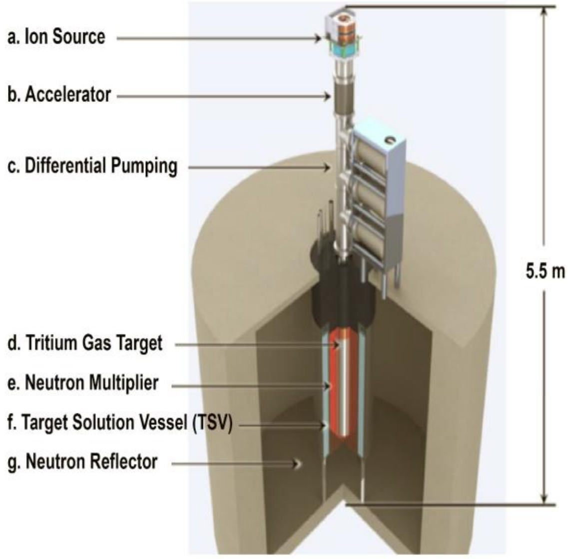

Fig. 3. Scheme for obtaining the ^{99m}Tc isotope [21]

The appearance of the deuteron accelerator is shown in Fig. 4.

Fig. 4. Deuteron accelerator [21]

An important advantage of neutron generators over isotope sources is the possibility of their operation in the pulse mode, control of neutron output and a relatively narrow range of their energies.

D) For the production of neutrons, the most intensive and one of the most effective processes is nuclear fission in nuclear reactors, as well as spallation sources.

The world's most famous neutron centers work using these processes [23, 24]:

Asia and Australia

J-Parc (Japan)

KENS (Tsukuba, Japan)

JAERI (Japan)

KUR-RI (Kyoto, Japan)
ISSP (Tokyo, Japan)
KAERI (Hanaro, Korea)
OPAL at ANSTO (at Lucas Heights, Australia)
Europe
ILL (Grenoble, France)
ISIS (Oxford, UK)
GKSS (Geestach, Germany)
BENSC (HZB, Berlin, Germany)
FRM II at Garching (T.U. Munich, Germany)
TUDelft (Delft, The Netherlands)
SINQ (at PSI Zürich, Switzerland)
BNC (Budapest, Hungary)
FLNP (Dubna, Russia)
PNPI (Gatchina, Russia)
JEEP-II (Kjeller, Norway)
North and South America
SNS and HFIR at Oak Ridge (USA)
LANSCE (Los Alamos, USA)
NIST (USA)
McMaster University (Canada)
Chalk River (Canada).

In the thirties of the twentieth century, it was established that the uranium nucleus, after absorbing a neutron, underwent fission, as a result of which an average of 2.416 free neutrons were released. These neutrons have an average energy of about 2 MeV. During the decay of the uranium nucleus, energy of about 202.5 MeV is also released. This phenomenon became the basis for the creation of an intensive source of free neutrons – a nuclear reactor. The most intensive neutron flows are obtained in specially designed research reactors. In the most powerful reactors, the highly enriched isotope of uranium ^{235}U is usually used as fuel.

The research neutron source FRM II Heinz Maier-Leibnitz Zentrum (MLZ) in Garching, Germany [25] is one of the most powerful neutron sources in the world. Its thermal capacity is 20 MW. It produces a flux of more than 10^{14} n/(cm^2·s) on the surface of the active zone, which are used for scientific research, industry and medicine.

The FRM II fuel cell [26] (Fig. 5) is a cylinder with a length of about 1.3 m, a diameter of 24 cm and a total weight of 53 kg. It contains approximately 8 kg of uranium ^{235}U enriched to 93%. The fuel used is U_3Si_2 dispersed in an Al matrix. After 60 days of operation in the nominal mode, the spent heat-emitting element is unloaded, and then placed under water for a minimum of 6.5 years.

Fig. 5. Reactor fuel element [26]

The location of the fuel element in the reactor is shown in Fig. 6.

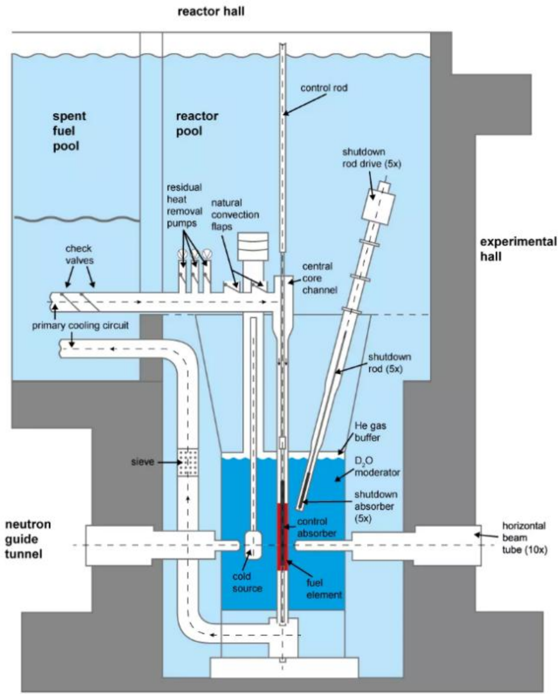

Fig. 6. Section of the reactor [27]

The Institut Laue-Langevin (ILL) reactor in Grenoble, France [28 - 30] produces the world's most intense continuous flux of neutrons in the core: $1.5·10^{15}$ n/(s·cm^2), with a thermal power of 58.3 MW.

The fuel cell in the reactor is small in size and uses enriched uranium (93% ^{235}U).

The reactor operates 24/7 continuously for a 50-day period, with a subsequent shutdown to replace the heat-emitting element. There are usually 4 cycles in a year, which provides 200 days to work with neutrons. The reactor supplies neutrons to 40 installations that can use the beams at the same time.

ILL belongs to three founders – France, Germany and Great Britain. These three associated countries contributed about 78 million euros in 2022 to ensure the work of the institute. This amount has significantly increased from the contributions paid by the participating countries of scientific research: Austria, Belgium, the Czech Republic, Denmark, Italy, Poland, Slovakia, Slovenia, Spain, Sweden and Switzerland. The total budget of the ILL in 2022 was about 108 million euros.

The view of the reactor from the location of the neutron exit channels is shown in Fig. 7. The saturation of the active zone with equipment is clearly visible, which is a characteristic feature of research reactors.

ILL uses its facilities and experience to make the beams available for visiting by the maximum number of scientists. It has a user community of about 2.000 researchers from 40 countries who come to work at the reactor every year. 850 experiments are performed annually, the results of which are published in almost 600 scientific articles.

Built in 1965, the HIFR reactor in Oak Ridge [31] operates at a capacity of 85 MW and is the most powerful neutron source reactor in the United States. The density of the neutron tray in the active zone of the reactor reaches $2.5·10^{15}$ n/(cm^2·s).

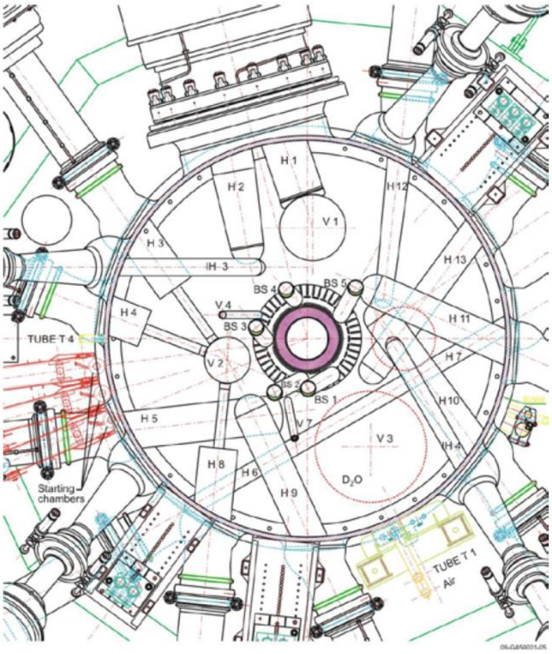

Fig. 7. View of the reactor from above [30]

The main task of HFIR during its construction in 1965 was the production of isotopes of transuranic elements. Channels built later (Fig. 8) provided support for basic research programs related to neutron scattering by polymers, colloids, magnetic materials, alloys, superconductors, and biological materials. More than 500 scientists conduct their research at this reactor every year.

In general, there are about 200 research reactors operating in the world [24], which conduct research using neutron beams.

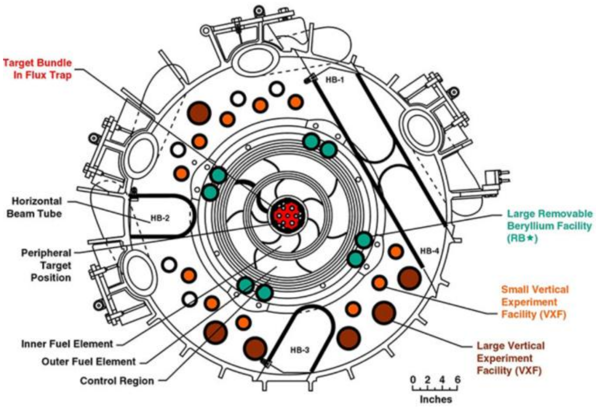

Fig. 8. The active zone of the HFIR reactor [31]

E) The world's most powerful neutron sources are based on the Spallation phenomenon.

In a Spallation Neutron Source, high-energy protons collide with a heavy metal target (such as lead, tungsten, mercury, or uranium). Under the influence of this impact, approximately 20 to 30 neutrons per proton are evaporated from the target's nucleus. The scheme of this process is presented in Fig. 9.

As of 2022, the most powerful neutron source in the world is the Spallation Neutron Source in Oak Ridge, Tennessee [32, 34]. The general view of the SNS is presented in Fig. 10.

Construction of the neutron center cost $1.4 billion and was completed in 2006.

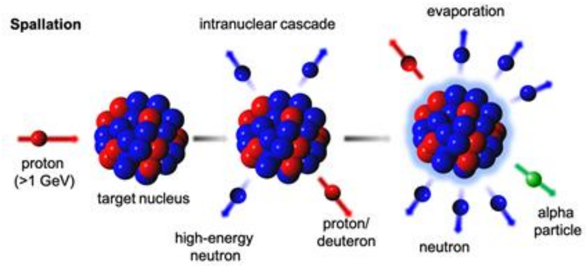

Fig. 9. Interaction of a proton with a nucleus [33]

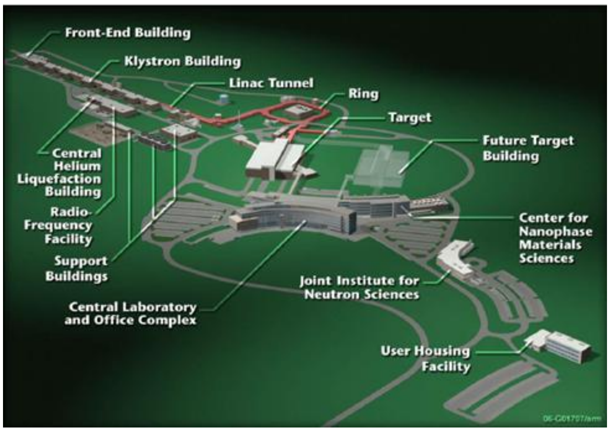

Fig. 10. Spallation Neutron Source in Oak Ridge

The basis of the neutron source is created by a linear accelerator that accelerates hydrogen ions from 2.5 MeV to 1 GeV with a frequency of 60 pulses per second and a length of 1 ms [35, 36]. Up to an energy of 200 MeV, two types of accelerator structures are used, which work at room temperature. Further acceleration is achieved using superconducting niobium resonators. These resonators are cooled by liquid helium to an operating temperature of 2 K.

The accelerated beam flies through the foil, which removes electrons from the negatively charged hydrogen ions, forming protons (H+), and enters the magnetic ring. $1.5 \cdot 10^{14}$ protons circulating in the ring are released in a time of 0.7 μs into a liquid mercury target, where neutrons are generated (Fig. 11). These neutrons are directed into the channels attached to the instrument stations. There, neutrons of different energies are used in various experiments with materials. SNS can support 24 instruments that can run 80 experiments simultaneously.

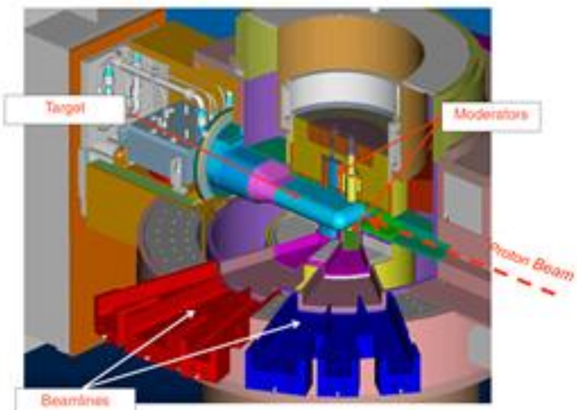

Fig. 11. Interaction of the beam with the target [34]

With a more intense, brighter neutron source and world-class instrumentation, SNS provides the community with unprecedented research opportunities. SNS enables measurements with greater sensitivity, higher speed, higher resolution, and in more complex sample environments than was possible with existing neutron facilities.

The average value of the neutron flux density obtained at proton accelerators is lower than at reactors, but when accumulators are used to reduce the pulse duration, the value of the neutron flux is high, which is especially important when using the flight technique in experiments.

The spectra of neutrons produced in reactors and proton accelerators also differ.

On Fig. 12 shows the normalized energy spectra of neutrons, which were obtained as a result of using the process of nuclear fission in reactors and the process of interaction of protons with an energy of 1 GeV on a Pb target [37].

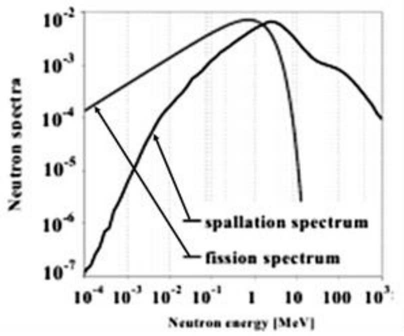

Fig. 12. Neutron spectra of various sources [37]

G) Photonuclear reactions of the type (γ, n) and (γ, 2n) are another possibility of obtaining neutrons. The intersection of these reactions has a so-called giant resonance for heavy nuclei at an energy of γ-quanta of about 15 MeV. Since the yield of bremsstrahlung γ quanta is proportional to the charge of the nucleus and the energy of the primary electrons, in order to obtain the largest number of neutrons, it is necessary to use accelerators with an energy of more than 30 MeV [38].

One of the most intense sources of neutrons built on these principles is nELBE [39, 40], which is created on the basis of the ELBE superconducting accelerator. This neutron source is designed to measure reactions caused by fast neutrons, which are relevant for future nuclear transmutation facilities and nuclear waste management. Experiments use neutrons in the energy range from 10 keV to 10 MeV. The average intensity of the neutron beam in the target for electrons with energy Ee = 40 MeV and beam current Ie = 1 mA is $2.7 \cdot 10^{13}$ n/s [40]. Due to the short pulse of electrons – 5 ps, the characteristics of the neutron beam of this source are not inferior to similar parameters of the beam of the most intense pulsed neutron sources [39, 40].

As it was already emphasized above, the spectra of neutrons from different sources have their own characteristics. Currently, in the practice of experiments, the classification of neutrons by energy [25, 30], presented in Fig. 13, is accepted.

Neutrons can also be classified by de Broglie wavelength and speed. For neutron imaging, thermal and cold neutrons are more promising due to simple registration methods. The fact that thermal energy neutrons have wavelengths comparable to interatomic distances in matter makes them an indispensable tool for condensed matter research. Methods of transforming the neutron spectrum in various neutron centers can be found in [23].

Neutrons	Energy range	Wavelength [Å]	Velocity [m/s]
ultra cold	≤ 300 neV	≥ 500	≤ 8
very cold	300 neV - 0.12 meV	52.2 – 26.1	7.5 – 152
cold	0.12 meV - 12 meV	26.1 – 2.6	152 – 1515
thermal	12 meV - 100 meV	2.6 - 0.9	1515 - 4374
epithermal	100 meV - 1eV	0.9 - 0.28	4374 - 13.8 10^3
intermediate	1eV - 0.8MeV		
fast	› 0.8MeV		

Fig. 13. Classification of neutrons by energy

2. SOURCES OF NEUTRONS IN NSC KIPT

Research with neutrons has been carried out at the National Science Center KIPT since the institute was established. The sources of neutrons were mostly various nuclear processes that occur during the interaction of accelerator beams with nuclei. You can learn more about these works from the review published in the monograph [41].

In recent years, several projects of neutron sources based on various physical principles have been developed and implemented [20, 41 - 43].

A subcritical assembly controlled by an electron accelerator was built, the main task of which is to create a prototype of a safe nuclear power plant of the future [43]. This installation can also be used as a source of neutrons to perform some tasks (see the program in works [42, 43]). The active zone of the installation is presented in Fig. 14. According to preliminary calculations [41, 42, 44], the maximum average intensity of the neutron flux in the center of the active zone of the installation will reach $(1.14...4) \cdot 10^{13}$ n/(s·cm^2) at a beam power of 100 kW and an electron energy of 100 MeV.

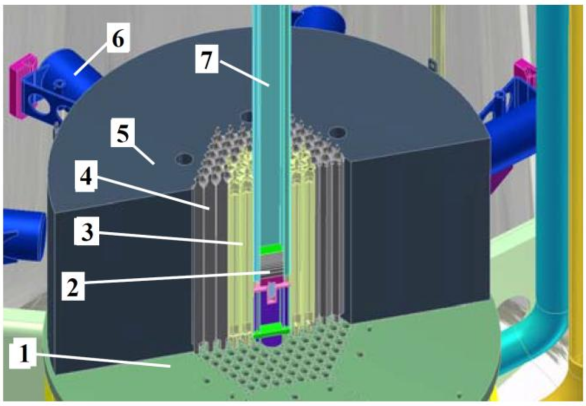

Fig. 14. 3D model of the active zone:
1 – support plate; 2 – source of neutrons; 3 – fuel cell of the active zone; 4 – beryllium reflector blocks; 5 – graphite reflector; 6 – neutron channel; 7 – electron beam vacuum chamber

The beginning of the neutron channels is located at a distance greater than 60 cm from the center of the active zone (see Fig. 14 [42]). As can be seen from the distribution of the neutron flux density in the subcritical assembly (Fig. 15), at such a distance the flux density will be about $1 \cdot 10^{12}$ n/(s·cm^2).

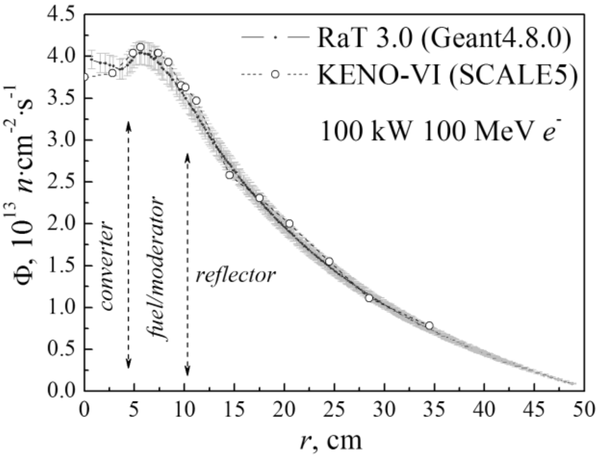

Fig. 15. Radial distribution of the neutron flux density in a subcritical assembly in the plane at the level of the converter [44]

Let's consider what neutron fluxes can be obtained when using a linear electron accelerator, which is the basis of the conceptual design of a multifunctional accelerator complex, which is being developed at the National Science Center KIPT [45, 46].

The superconducting injector of the complex in the high-charge mode will accelerate bunches of electrons with a charge of 1 ns, 15 ps long and a frequency of about 500 kHz. The average current at the injector output in this mode will not exceed 0.5 mA. After acceleration in a linear accelerator, the electron energy will reach 200 MeV.

As follows from the works [38, 41, 44], one electron with an energy of 200 MeV in a uranium target generates ~0.14 neutrons. The total average flow of neutrons at the output of the neutron channel will be $4.4 \cdot 10^{14}$ s^{-1}. The pulse flow will reach $6 \cdot 10^{19}$ n/s. Such beam parameters, as demonstrated in works [39, 40], allow, due to the short pulse of electrons and the small size of the target, to obtain neutron fluxes on short flight bases that are not inferior to installations with proton accelerators.

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REFERENCES

1. P.A. Zyla et al. Review of Particle Physics (Particle Data Group) // *Prog. Theor. Exp. Phys*. 2020, 083C01. https://pdg.lbl.gov/2020/listings/contents_listings.html.
2. K.A. Olive et al. (Particle Data Group) Review of particle physics // *Chinese Physics*. 2014, C38, 090001.
3. G.L. Greene et al. New determination of the deuteron binding energy and the neutron mass // *Physical Review Letters.* 1986, v. 56 (8), p. 819-822. doi:10.1103/PhysRevLett.56.819.
4. E.G. Kessler et al. The deuteron binding energy and the neutron mass // *Physics Letters A*. 1999, v. 255, issues 4-6, p. 221-229. https://doi.org/10.1016/S0375-9601(99)00078-X.
5. Neutron, https://en.wikipedia.org/wiki/Neutron.
6. V.V. Fedorov. *Neutron physics. Educational manual.* St. Petersburg: “PIYAF”, 2004, 334 p.
7. F.M. Gonzalez et al. (UCNτ Collaboration) Improved Neutron Lifetime Measurement with UCNτ // *Phys. Rev. Lett.* 2021, v. 127, p. 162501, https://doi.org/10.1103/PhysRevLett.127.162501.
8. F. Shannon. Hoogerheide Measuring the Neutron Lifetime with Record-Breaking Precision // *Physics.* 2021, v. 14, p. 142. DOI: 10.1103/Physics.14.142.
9. L.J. Broussard et al. Experimental Search for Neutron to Mirror Neutron Oscillations as an Explanation of the Neutron Lifetime Anomaly // *Phys. Rev. Lett.* 2022, v. 128, 212503 p.
10. Robert Hofstadter. Electron Scattering and Nuclear Structure // *Reviews of Modern Physics*. 1956, v. 28, issue 3, p. 214-253. DOI:10.1103/RevModPhys.28.214.
11. Christoph Schweiger. The electron-scattering method and its applications to the structure of nuclei and nucleons. https://www.nobelprize.org/prizes/physics/1961/hofstadter/lecture/.
12. R. Hofstadter, F. Bumiller, M.R. Yearian. Electromagnetic structure of the proton and neutron // *Reviews of Modern Physics.* 1958, v. 30, p. 482-497. DOI: 10.1103/Revmodphys.30.482.
13. I.N. Bekman. *Radiochemistry*: Course of lectures. *14. Chemistry of Radioactive Elements: americium, curium, berkelium, californium, einsteinium, fermium, mendelium, nobelium and lawrenceium*. Moscow, 2006.
14. Periodic Table of Elements: LANL, Californium. https://periodic.lanl.gov/98.shtml.
15. Richard G. Haire. *Chapter 11. The Chemistry of the Actinide and Transactinide Element* / Third Edition, L.R. Morss, J. Fuger, and N.M. Edelstein, Eds, Springer Publishers, 2006.
16. Californium. https://en.wikipedia.org/wiki/Californium.
17. I.W. Osborne-Lee and C.W. Alexander. *Californium-252: a remarkable versatile radioisotope*. United States. 1995. Web. doi:10.2172/205871. https://doi.org/10.2172/205871.
18. Yu.V. Stogov. *Fundamentals of Neutron Physics*. Moscow, 2008.
19. S.A. Vyzhva, I.I. Onyshchuk, O.P. Chernyaev. *Nuclear geophysics: a textbook.* Kyiv: “Kyiv University Publishing and Printing Center”, 2012, 608 p.
20. A.Ph. Stoyanov, A.N. Dovbnya, V.A. Tsymbal. About the possibility of using the field of the portable neutron generator for treatment of oncological diseases // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”*. 2017, № 6, p. 172-174.
21. Argonne Demo of SHINE Process Produces Commercial-Grade Medical Isotopes. https://www.shinefusion.com/blog/argonne-demo-of-shine-process-produces-commercial-grade-medical-isotopes
22. *Environmental Impact Statement for the Construction Permit for the SHINE Medical Radioisotope*

Production Facility: Final Report, NUREG-2183, October 2015.
23. Neutronsources.org https://neutronsources.org/about/.
24. Where are the neutron facilities? https://www.iucr.org/resources/commissions/neutron-scattering/where-neutrons.
25. Neutron Source. https://www.frm2.tum.de/en/frm2/home/; https://www.frm2.tum.de/en/frm2/the-neutron-source/.
26. Life cycle of a fuel element. https://www.frm2.tum.de/en/frm2/the-neutron-source/life-cycle-of-a-fuel-element/.
27. Installations in the pool. https://www.frm2.tum.de/en/frm2/the-neutron-source/reactor/installations-in-the-pool/.
28. The Institut Laue Langevin. The European Neutron Source. https://www.ill.eu/fileadmin/user_upload/ILL/1_About_ILL/Documentation/ILL-General-brochure/Brochure-ILL-GB.pdf.
29. Annual Report 2022, Institut Laue-Langevin. https://www.ill.eu/fileadmin/user_upload/ILL/1_About_ILL/Documentation/Annual_report/AR-22/Annual_Report_2022.pdf.
30. A. Bergeron, B. Dionne, Y. Calzavara. *Neutronics Conversion Analyses of the Laue-Langevin Institute (ILL) High Flux Reactor (RHF),* ANL/GTRI/TM-14/15, 9/30/2014, https://publications.anl.gov/anlpubs/2015/11/122482.pdf.
31. High Flux Isotope Reactor. https://neutrons.ornl.gov/hfir.
32. https://www.ornl.gov/project/sns.
33. Spallation. https://elena-neutron.iff.kfa-juelich.de/neutron-facilities/.
34. N. Fomin et al. Fundamental Neutron Physics Beamline at the Spallation Neutron Source at ORNL // *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 11 February 2015, v. 773, p. 45-51.
35. S. Henderson et al. *The Spallation Neutron Source Beam Commissioning and Initial Operations*, ORNL/TM-2015/321, July 2015.
36. Robert L. Kustom. AN Overview of the spallation neutron source project // *XX International Linac Conference*, Monterey, California, TU101, 2000, p. 321-325.
37. Antonin Krasa. *Spallation Reaction Physics:* Manuscript for the lecture / Neutron Sources for ADS for students of the Faculty of Nuclear Sciences and Physical Engineering at Czech Technical University in Prague. May 2010, 62 p.
38. V.G. Nedorezov, Y.N. Ranyuk. *Photofission of nuclei by giant resonance.* Kyiv: “Naukova dumka”, 1989, 192 p.
39. R. Beyer et al. Characterization of the neutron beam at nELBE // *Nuclear Instruments and Methods in Physics Research*. 2013, A723, p. 151-162.
40. nELBE: Neutron time-of-flight experiments at ELBE. https://www.hzdr.de/db/Cms?pNid=317.
41. I.S. Guk, A.N. Dovbnya, S.G. Kononenko, F.A. Peev, J.I.M. Botman. *Basic accelerator facility of the NSC KIPT in nuclear physics and high energy physics, physical justification*. Kharkiv: NSC KIPT, 2014, 225 p.
42. M.I. Ayzatskiy et al. NSC KIPT Neutron Source // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”*. 2012, № 3, p. 3-9.
43. A neutron source based on a subcritical assembly controlled by a linear electron accelerator. https://www.kipt.kharkov.ua/kipt_sites/NeutronSource/neut_source.html.
44. M.I. Bratchenko, V.V. Hann, I.S. Hook, A.N. Dovbnya, S.V. Dyuldya, S.G. Kononenko, F.A. Peev, A.S. Tarasenko, M. van der Wiel, J.I.M. Botman. Superconducting electron accelerator for controlling subcritical assembly // *Nuclear physics and energy*. 2007, № 2 (20), p. 79-88.
45. M.F. Shulga, G.D. Kovalenko, I.S. Hook, P.I. Hladkykh, F.A. Peyev. *Multifunctional accelerator complex of NSC KIPT “MAC NSC KIPT” project*. NSC KIPT, Kharkiv, 2023, 92 p.
46. M.F. Shul'ga, G.D. Kovalenko, I.S. Guk, P.I. Gladkikh, F.A. Peev. Conceptual project of the NSC KIPT nuclear physics complex for basic and applied research in the field of nuclear physics, high energy physics and interaction of radiation with substance // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”* 2022, № 5, p. 55-59.

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ДЖЕРЕЛО НЕЙТРОНІВ НА ОСНОВІ БАГАТОФУНКЦІОНАЛЬНОГО ПРИСКОРЮВАЛЬНОГО КОМПЛЕКСУ ННЦ ХФТІ

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Проведено огляд існуючих у світі джерел нейтронів, які використовуються для проведення фундаментальних та прикладних досліджень у різних областях науки та технологій. Розглянуто можливість створення на основі надпровідного прискорювача електронів, який є основою багатофункціонального прискорювального комплексу ННЦ ХФТІ, джерела нейтронів. На основі проектних параметрів електронного пучка зроблена оцінка інтенсивності пучка нейтронів.