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Generation of a High-Yield Fast Neutron Flux on the Accelerator Based Neutron Source VITA

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***Abstract*—Radiation testing of perspective materials by fast neutron flux is an important task for large physical facilities such as the Large Hadron Collider or the International Thermonuclear Experimental Reactor. Such a source of fast neutrons is the accelerator based neutron source VITA, proposed, developed and actively used at the Budker Institute of Nuclear Physics. VITA consists of an original vacuum-insulated tandem accelerator for generating a powerful dc proton/deuteron beam with an energy up to 2.3 MeV and a current up to 10 mA, a solid lithium target for neutron flux generation in the exothermic (non-threshold) reaction ^{7}Li(d,n) up to $2 \cdot 10^{12}$ s^{-1} and a concentrator to focus the neutron flux in the direction of beam propagation. The paper describes the accelerator based neutron source VITA, its limitations and specifics related to the generation of a powerful fast neutron flux, the result of a long lasting experiment with fast neutron generation, further plans to increase the energy and current of the deuteron beam, to develop a compact fast neutron generator, and to increase the total fast neutron yield to $2 \cdot 10^{13}$ s^{-1}.**

Keywords—VITA, perspective materials, radiation testing, fast neutrons, dosimetry

I. INTRODUCTION

The accelerator based neutron source VITA has been proposed and developed at the Budker Institute of Nuclear Physics (BINP) and enables the generation of a stable neutron beam [1]. The neutron source has applications in various fields, such as: boron neutron capture therapy (BNCT) [2], [3], activation studies of materials, blistering studies of materials, fundamental studies of the physics issues, radiation testing of perspective materials and other applications [1]. Radiation testing of the perspective materials is providing by fast neutrons, which are generated in the process of exothermic (non-threshold) reaction *^{7}Li(d,n)*.

Neutrons are using for various applications. In the case of radiation testing of materials at least 10^{13}-10^{14} neutrons per cm^2 must be accumulated on the material to be tested, for which the neutron flux density must be at least 10^8-10^9 cm^{-2}s^{-1}. Neutrons are also used to perform nuclear doping of silicon, for this purpose 10^{14}-10^{18} neutrons must be accumulated per 1 cm^2 of material [4], nuclear reactors are used for this. Neutrons are also used for small angle scattering, diffractometry, spectrometry, reflectometry, mechanical stress studies, magnetic and crystalline structure studies of materials. For these purposes, the required neutron flux density is 10^5-10^6 cm^{-2}s^{-1} [5]. The VITA, as will be shown later, fulfills these conditions, and occupies a median position between total neutron yield (or flux density) and compactness and simplicity of operation and maintenance.

II. MATERIALS AND METHODS

A. VITA and Lithium Target

The VITA provides dc proton/deuteron beam with a wide range of beam energy and current. Accelerator neutron source VITA consists of the vacuum-insulated tandem accelerator for obtaining a high-power dc proton/deuteron beam, lithium target for generating neutrons and a set of beam shaping assemblies for obtaining neutrons with required energy – cold (D_2O moderator at cryogenic temperature), thermal (D_2O or plexiglass), epithermal (MgF_2 moderator), fast (concentrator without moderation) [1].

The scheme of the facility in the fast neutron generating mode is shown in Fig. 1. Negative ion beam (H^- or D^-) is accelerated in the high-voltage electrodes of vacuum-insulated tandem accelerator *1*, stripped in the argon stripping target to positive ion beam (p^+ or d^+) and accelerated again to the energy up to 2.3 MeV. The lithium target *3* is located in the vertical or horizontal tract, to transport ion beam to the position A the bending magnet *2* is not enabled; to transport ion beam to position B the bending magnet is enabled with a current, corresponding to the beam energy. When radiation tests of the materials by the fast neutrons are conducted, the target is located in the position B in the irradiation room, neutron concentrator *4* is located around the lithium target. Gamma *5* and neutron *6* dosimeters are located at the distance of 5 meters from the lithium target.

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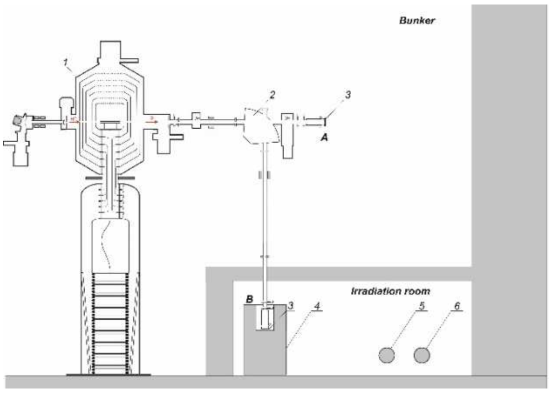

Fig. 1. Scheme of the VITA in the fast neutron generating mode. 1 – vacuum-insulated tandem accelerator, 2 – bending magnet, 3 – lithium target, 4 – neutron concentrator, 5 – gamma dosimeter, 6 – neutron dosimeter, A and B – sites of the lithium target.

B. Neutron Generating Reactions

Radiation resistance tests require neutrons with an energy of more than 1 MeV, which are obtained in the following exothermic reactions:

$$d + d \rightarrow {}^{3}He + n + 3.265\ MeV,$$

$$T + d \rightarrow {}^{4}He + n + 17.588\ MeV,$$

$$^{7}Li + d \rightarrow {}^{8}Be + n + 15.028\ MeV,$$

$$^{7}Li + d \rightarrow 2\,{}^{4}He + n + 15.122\ MeV,$$

$$^{9}Be + d \rightarrow {}^{10}B + n + 4.362\ MeV.$$

Fig. 2 presents neutron yields obtained in these and other reactions in thick targets [6]. Reaction *Li*(*d, n*) has the highest neutron yield when the energy of deuterons exceeds 0.8 MeV. Indeed, at a beam energy of 2 MeV neutron yields in *Be*(*d, n*) and *Li*(*p, n*) reactions are 6×10^{11} and 1.1×10^{11} mC^{-1} respectively, while in the *Li(d,n)* reaction is 13.5×10^{11} mC^{-1} [7], [8].

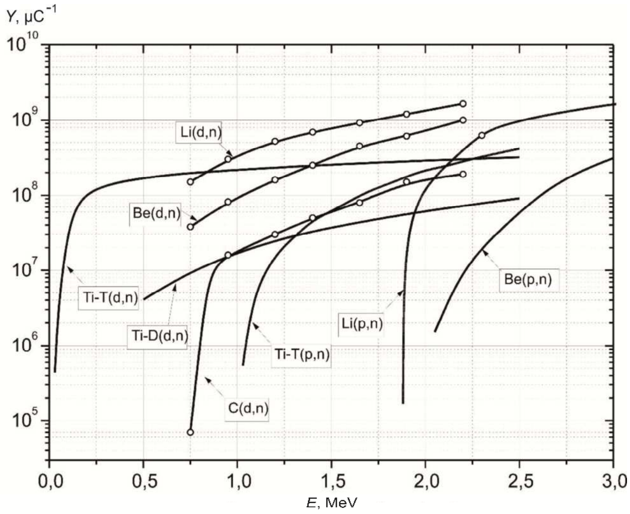

Fig. 2. Neutron yield of reactions in thick targets.

The important part of radiation tests of materials is possibility to detect and measure/simulate/estimate quantity and distribution of the neutrons. The VITA is equipped with neutron detector with GS-20 lithium glass for measuring of the neutron flux; set of activation foils; two HPGe-detectors for measuring spectrum and flux of the γ-rays; α-spectrometers for measuring elemental composition by spectroscopy of ion scattering; γ-dosimeters for measuring of the radiation fields during and after irradiation.

III. EXPERIMENTAL SETUP AND RESULTS

Earlier it was shown that VITA can be used as fast neutrons generator with total neutron yield 1.4×10^{12} s^{-1} [8] and this yield is sufficient for providing radiation testing of materials, fast neutron therapy [9] and other applications. During the first fast neutrons generation the radiation dose was so huge, even in the control room, so we had to stop the experiment after 10 seconds.

After this, the irradiation room was prepared (position B of the lithium target in the Fig. 1). Walls of this room are made of concrete with boron carbide, door made of borated polyethylene, these materials are effective moderators and absorbers of neutrons. Inside the room, around the lithium target a concentrator was made. The concentrator is made of lead and wood, since lead is a reflector of neutrons and wood is not activated by neutrons. Model of the lithium target assembly and photo of the concentrator are shown in Fig. 3. Lithium target consists of copper disc with diameter of 144 mm and 3 mm thickness. On this disc the lithium is evaporated by thermal heating method in vacuum chamber of lithium evaporating system of BINP.

Fig. 3. Model of the lithium target assembly (left) and photo of the concentrator (right).

Since preparations were finished, the fast neutrons irradiation experiment have been resumed. There were different experimental groups that irradiated following devices:
– coils of optical cables developed at the Saclay Nuclear Research Center (France) for high-luminosity operation of the CERN Large Hadron Collider (LHC);
– semiconductor photomultipliers and direct current converters for the ATLAS detector of the CERN LHC;
– diamond neutron detector for the International Thermonuclear Experimental Reactor (ITER, Cadarache, France);
– plates made of B_4C for ITER (Cadarache, France);
– neodymium magnets for the hybrid focusing system of the DARIA in Institute for Theoretical and Experimental Physics (ITEP, Moscow) [10];
– natural and synthetic diamonds for the Nikolaev Institute of the Inorganic Chemistry (Novosibirsk)
– gas sensors based on titanyl phthalocyanines for Novosibirsk State University laboratory;

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– semiconductor devices of the Novosibirsk Semiconductor Devices Factory.

When the neutrons are generated by the proton beam, the energy of the beam is varied up to 2.3 MeV and current up to 10 mA. In case of the deuteron beam, these values smaller. The energy of the beam is limited by the power supply of bending magnet down to 1.5 MeV. The current of the beam is limited by the ion-optical system of the H$^-$ source down to 1.5 mA. These currents and energies provide the generation of fast neutrons with a total yield of 10^{12} s^{-1}.

Before delivering a powerful deuteron beam (with ~ MeV energy and ~mA current) a calibration of neutron flux was conducted, since γ-detectors cannot properly work in the radiation fields, dose rate of which exceeds 0.1 Sv/h. Using the UDMN-100 γ-dosimeter, it was established, that at the energy of the proton beam 1.011 MeV and current 0.5 μA the dose rate of the generated neutrons is 0.044 Sv/h. Distance from lithium target to sensitive area of detector was 120 mm. It was also measured, that increasing the energy of the deuteron beam from 1.0 to 1.5 MeV doubled the neutron dose rate. Since the amount of generated neutrons is proportional to the beam current, finally, at the deuteron beam energy 1.5 MeV and current 1.5 mA the neutron dose rate at the distance of 120 mm from the lithium target is $0.044\times2\times3\times10^3 \approx 250$ Sv/h. The dose rate in the control room with these parameters was ≈40 μSv/h, that is not safe even for radiation group A personnel. The experiment was paused for a construction of a temporary wall, made of concrete blocks, containing boron carbide. The photo of the wall is shown at the Fig. 4.

Fig. 4. Photo of the temporary wall.

After these preparations the neutron dose rate in the control room became ~4 μSv/h, this level is acceptable for radiation group A personnel.

After the experiment restart, the facility was worked on average 11 hours per day (8 hours in neutron generating mode), 5 days a week, from 25th April to 25th May of 2022 year. During this time it was only 1 unexpected stop, when we had to substitute malfunctioned forevacuum pump by a working one. In the Fig. 5 the neutron yield (in arbitrary units) normalized on deuteron current as a function of time (sec) in 2nd and 23th irradiation day, measured by neutron detector with lithium glass GS-20 (The Saing-Gobain Crystals, USA) is shown.

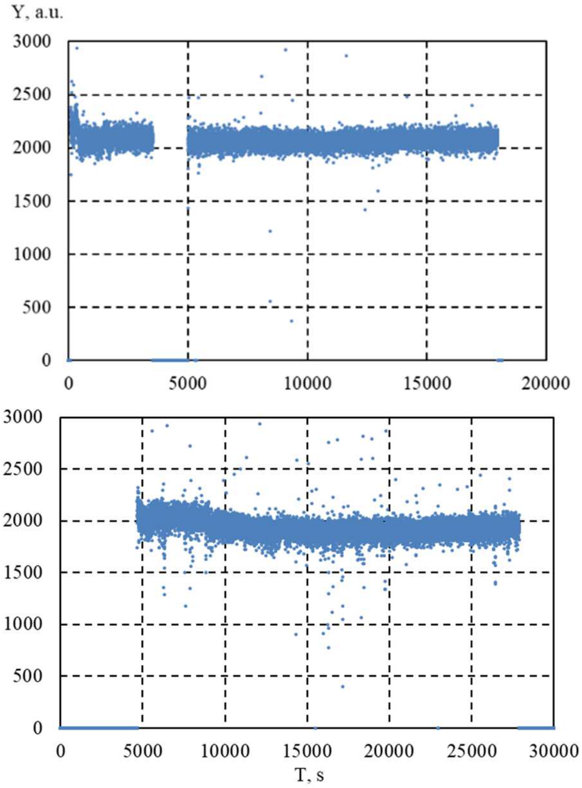

Fig. 5. Neutron yield (arb. unit) normalized on deuteron current as a function of time (sec) in 2nd and 23th irradiation day, measured by neutron detector with lithium glass GS-20 (The Saint-Gobain Crystals, USA).

The total integral current on the surface of the lithium target was 122 mA×h, the maximum neutron flux density per sample unit reached 2.9×10^{14} cm^{-2}. After the accumulated deuteron current integral of 122 mA×h, there were no any degradation of the neutron yield – nor energy degradation, nor degradation of the lithium neutron generating target.

IV. FUTURE PLANS

Now the modernization of the accelerator based neutron source VITA is under progress. Surface plasma ion source will be replaced by a volume one, which is developed and now is being created in the BINP. This source can inject beam with higher current, smaller emittance and it has not any bends, which allow extracting full-current deuteron beam up to 10 mA. Also there will be installed a new power supply for the bending magnet, it will allow to transport deuteron beam with energy up to 2.3 MeV and current up to 10 mA. With this parameters of the beam stronger neutron shielding will be needed. We already built a new wall, which is 2.5 times thicker than that one, which is shown on Fig. 4.

In addition, the development of compact source of fast neutrons is under progress. Main difference and, as it believed, advantage of this source is that the power supply to the electrodes is located inside the column on which these electrodes are located and no feedthrough insulator is used. A symmetrical cascaded voltage multiplier [11], [12] will be used as the power supply. The input of the cascade multiplier will be supplied by a transformer-type inverter (ac voltage of 24 kV with a frequency of 75 kHz). Twelve multiplier sections will be used, which, taking into account voltage sags due to beam loading and parasitic parameters, will give an output voltage of 450 kV. Since the accelerator on this compact neutron source will also be tandem type, the deuteron beam energy will be approximately of 900 keV. This energy with a beam current of a few mA will be sufficient to generate a powerful flux of fast neutrons.

Now on the accelerator based neutron source VITA the solid lithium target is used. This target can be operated with beam power densities up to 8 kW/cm^2. A rotating lithium target is now being developed that can operate at extreme parameters with power densities up to 50 kW/cm^2. This will make VITA the brightest neutron source with a total neutron yield of ~2×10^{13}s^{-1}. High brightness is provided by the fact that the beam size on the target is 5 mm and the thickness of the target is 3 mm. The neutron concentration in the vacuum volume located close to the target reaches 10^4 cm^{-3}. This will allow to provide direct studies of neutron structure using lepton or hadron beams or even construct an n-n collider.

V. CONCLUSION

Accelerator based neutron source VITA as generator of fast neutrons is a reliable facility. Nowadays the total yield of generated fast neutrons is 10^{12} s^{-1}. Research has shown that VITA as a fast neutron generator can operate for at least a month at 5 days a week, 8 hours of neutron generation per day.

The compact fast neutrons source now is under developing. It will generate ~10^{12} fast neutrons per second. This is sufficient for providing investigations on radiation testing of perspective materials for big physical facilities, such as CERN, ITER etc.

The accelerator based neutron source VITA is currently undergoing modernization, which will allow transporting a powerful (up to 50 kW/cm^2) deuteron beam to a rotating lithium target. Such a flux makes VITA the brightest neutron source with neutron concentration 10^4 cm^{-3} and allow to provide direct studies of neutron structure using lepton or hadron beams or even construct an n-n collider.

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