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LUE-40 LINAC BASED NEUTRON SOURCE FOR IRRADIATION TESTS OF HEP DETECTOR MATERIALS AND COMPONENTS

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A photoneutrons source based on the NSC KIPT LUE-40 electron linac was designed and constructed to study the effect of neutron and gamma radiation on the properties of materials used in high-energy physics (HEP) detectors. The source was used to irradiate the optical elements of the PLUME detector in LHCb experiment with the neutron fluency of 10^{14} cm^{-2}. Ways to increase the neutron yield, in particular, by installing an additional high Z metal shell are shown. At electron energy of 85 MeV, the neutron yield exceeds 10^{-2} neutron over one electron.

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INTRODUCTION

One of the biggest challenges in developing new or upgrading existing facilities for high energy physics research is creating detectors and interface electronics that will experience unprecedented absorbed doses and associated radiation damage. This requires the development of new radiation-resistant equipment based on their pilot and radiation tests. The intense particle fluxes from the collision create significant levels of neutron and gamma-dominated radiation load on the surrounding detector systems and measurement electronics. For example, in the LHC detectors, near the interaction point, at present, the integral levels of the absorbed dose are 10^6 Gy, and the total density of heavy particles, expressed in 1 MeV neutron equivalents, exceeds 10^{16} n·cm^{-2} [1]. The greatest radiation load is experienced by internal trackers, however, other elements also experience a significant effect of radiation. The new PLUME (Probe for LUminosity MEasurement) detector [2, 3], will play an important role in LHCb operation during Run 3. The detector is based on registering Cherenkov light produced in quartz material by particles coming from the collision region. The detector components will operate in the harsh radiation environment of up to 200 kGy gamma components and up to 10^{14} n/cm^2 neutron fluences. In view of the future increase in luminosity of the LHC and the radiation load on the equipment, work on new radiation-resistant materials development and components is carried out in many laboratories. Naturally, this activity requires a significant number of experiments to study the radiation effect on the properties of materials and components. Currently, there is a great need for facilities that can be used as neutron and gamma radiation sources to create radiation conditions that are adequate to the operating conditions of the materials and devices under study as a part of detector systems. Unfortunately, the small number of existing irradiated facilities cannot provide sufficient resources for the growing demand for full-fledged radiation research. Not the last role is played by the financial component of experimental research. The main goal of our work is to develop a universal irradiation facility on the base of linear accelerator of electrons LUE-40 for the needs of developing HEP projects and, in particular, the LHCb collaboration at CERN

1. ELECTRON LINAC

The electron linac LUE-40 [4] (Fig. 1) consists of an electron source, an injector based on a resonance system with non-propagating oscillations, and two accelerating sections of the Kharkiv-85 type [5]. The most important parameters of the beam at the accelerator output are given in Table 1. The accelerator has all the means for measuring all beam parameters (beam energy, current and energy spectrum, emittance, spatial distribution, beam position on the target). Average current at the linac output is limited by the existing radiation shielding. The main accelerator feature is the ability to change the beam energy in a wide range 35…95 MeV. The electron beam is emitted into the atmosphere through a thin titanium foil, behind which devices for generating radiation are installed.

Fig. 1. LUE-40 electron linac

Table 1

Parameter	Value
RF frequence, MHz	2797.15
Beam energy, MeV	35…95
Energy spread (70% of beam), %	< 3
Beam pulse current, mA	up to 70
Average beam current, μA	<6
Normalized emittance, mm·mrad	< 60
Beam pulse duration, μs	1.5
Repetition rate, Hz	50

2. NEUTRON SOURCE

The developed neutron source is based on a well-known principle, which is as follows. The electrons at the accelerator output bombard a high-Z metallic target. The resulting gamma bremsstrahlung interacts with the atoms of the same target, and as a result of the (γ,n) reaction, a neutron flux is generated. A significantly higher neutron yield $Y=N_n/N_e$ (the ratio the neutrons number to the incident electrons number) can be obtained from a combined target consisting of a gamma radiation source (tungsten or tantalum) and a neutron source (fissile materials or beryllium). The design of such converters is quite complex and requires the use of expensive and maintenance-intensive materials. In this regard, we decided to develop a single-component electron-neutron converter based on tungsten.

It is known that in order to obtain the maximum neutron yield, the target thickness must be at least 5-7 radiation lengths [6]. For tungsten, the radiation length is 0.35 cm and the corresponding thickness with the maximum neutron yield is 1.75…2.45 cm. On the other hand, as shown by calculations, the main ionization losses of electrons, and corresponding the target heating, occur at distances close to the extrapolated range. For tungsten (density 19.3 g/cm^3) at electron energy of 80 MeV, the extrapolated range is 0.94 cm. Therefore, we chose the W – target thickness, which intensively cools, equal to 1 cm. The target consists of 10 tungsten plates with a thickness of 1 mm and transverse dimension of 16×16 mm (Fig. 2). The distance between the plates is 1 mm. The plates are placed in cylindrical aluminum housing through which compressed air is passed.

Fig. 2. Exterior of the target

In order to increase the neutron flux density on the samples, it is desirable to place them as close as possible to the converter, while avoiding their heating. Therefore, special attention was paid to the study thermal processes in the target. The Monte-Carlo code GEANT4 version 10.6e [7] was used to calculate the heat deposition power in each plate. Calculation data at beam current of 5 μA for different particle energies are shown in Fig. 3. The total thermal power in the target at energies of 45, 65, and 85 MeV is 128, 169, and 204 W, respectively. These data were used to calculate the temperature and the cooling system parameters. In particular, with a total termal power in the target of 180 W and an air velocity at the entrance of 18 m/s, the maximum temperature of the plates does not exceed of 23.5°C. Thus, in the presence of a compressor that will provide such air speed, the temperature of the converter will not pose a problem for irradiating the samples when they are installed directly on the converter housing. Based on calculated data, a reciprocating compressor was used to cool the converter, providing an air flow rate 27 m^3 per hour at a pressure of 0.5 bar. The performed calculations were verified experimentally. During the target irradiation at electron energy of 82 MeV and average beam current of 4.7 μA, temperature rise of the Al housing did not exceed of 37°C, which is a good result.

At GEANT4 simulations parameters of the incident electron beam (energy spectrum, spatial distribution) were consistent with the experimental data. The performed simulation shows that the neutron yield at an electron energy of 80 MeV is $5.8\cdot10^{-3}$ N_n/N_e. This, in particular, means that with an average electron beam current at the accelerator output of 5 μA ($N_e=3.125\cdot10^{13}$ s^{-1}), the total neutron flux N_n into the 4π angle will be of $1.81\cdot10^{11}$ s^{-1}.

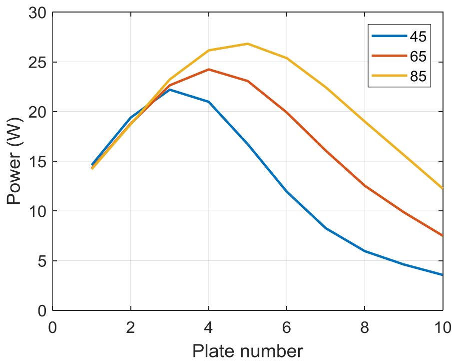

Fig. 3. Heat deposition power in the target

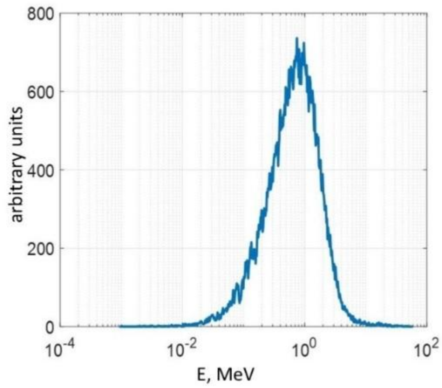

Fig. 4. Neutrons energy spectrum

The energy spectrum of neutrons (Fig. 4) with most probable energy of 0.7 MeV and an average of 2 MeV is typical for neutron sources based on the interaction of gamma radiation with the nucleus. The angular distribution of neutrons near the target, where the samples under study will be located, is not isotropic and essentially depends on the dimensions and configuration both the target and the structural elements surrounding it.

In 2021, optical elements of the new PLUME detector of the LHCb experiment were irradiated on the LUE-40 electron linac using this neutron source. In particular, various quartz radiators, quartz fibers and photomultipliers were irradiated with doses close to the operating conditions (neutron fluence up to 10^{14}n/cm^2 and absorbed dose (gamma + electrons) up to 1 MGy). The results were used in the selection materials and devices for PLUME detector [8].

At the same time, as shown by the performed calculations, the used source is not optimal in terms of the neutron yield. Neutron yield can be increased by placing additional high-Z metal elements (for instance lead) close to W target. These elements do not require intensive cooling. Therefore, we investigated a neutron source built according to this principle (Fig. 5).

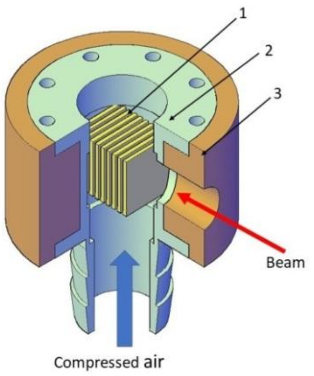

Fig. 5. Design of neutron source:
1 – 10 tungsten 16×16×1 mm plates;
2 – aluminum casing; 3 – lead sheath

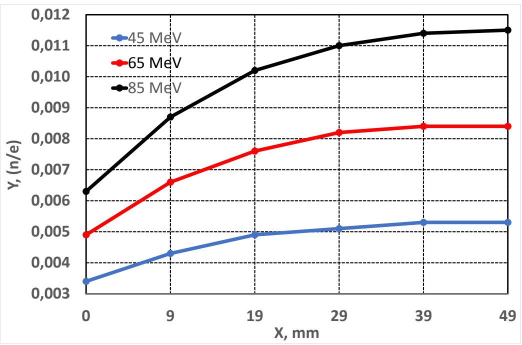

Fig. 6. Neutron yield vs shell thickness

As a result of GEANT simulation, the dependence of the neutron yield on the lead shell thickness was obtained for different incident electron energies (Fig. 6). It can be seen that the use of an additional shell makes it possible to significantly increase the neutron yield.

The neutrons spatial distribution near the electron-neutron converter, which has a complex geometry, is an important factor in choosing the irradiated samples location. The neutrons angular distribution at different values of electron energy was investigated. The simulation results at energies of 85 MeV are presented in Fig. 7. It can be seen that the neutron flux is more intense in the direction of electron beam propagation ($\theta=\pi/2$). Wherein inhomogeneity increases as the electron energy increases. This anisotropy is caused by the presence of the lead shell, since, as it was shown by GEANT simulation, in the neutron's distribution from 10 tungsten 16×16×1 mm tungsten plates, the anisotropy did not exceed of 25%.

To determine the neutron fluence in different directions, 10×10 mm detectors were installed in the GEANT model. Detectors were placed on a sphere with a radius of 75 mm (as shown in Fig. 8) and a radius of 44 mm. The sphere center is centered on the first plate surface. The detectors location is defined as follows. Detector number 1 corresponds to the direction along electron beam propagation (direction z +), detector number 2 in the opposite direction (direction z -). Other detecting surfaces correspond to the x and y coordinate axes: number 3 (x - direction), number 4 (y - direction), number 5 (x + direction) and number 6 (y + direction). The Table 2 presents the simulation results – the dependence of the neutron fluence η normalized to the total electrons number vs the electrons energy and detectors location. It can be seen that the maximum neutron flux occurs in the direction of electron beam propagation. At an average current of 5 μA and energy of 85 MeV at a distance of 44 mm, the neutron fluence power is $4.7\cdot10^9$s^{-1} ·cm^{-2}.

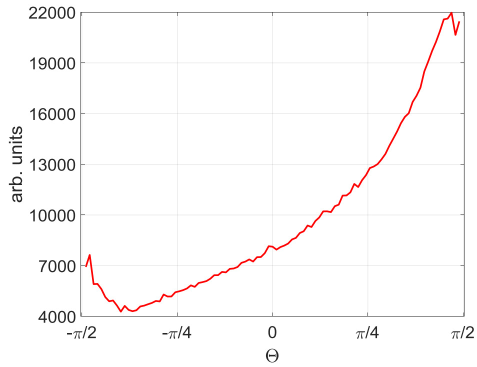

Fig. 7. Neutron number vs polar angle θ.
The lead sheath thickness is 29 mm

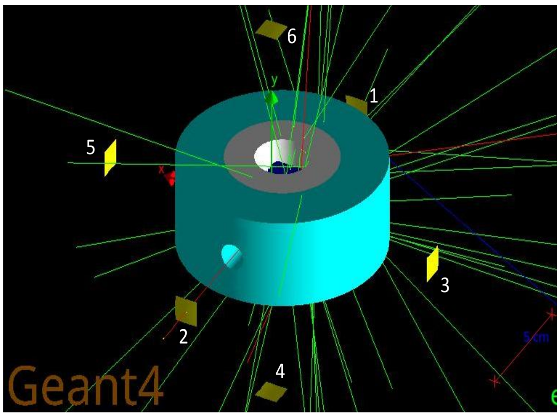

Fig. 8. The Geant 4 model. The numbers 1-6 indicate the detectors location

It is obvious that samples located near the target will be affected by both neutron and mixed electron-gamma radiation. In each specific case, according to the experimental conditions, it is necessary to carry out appropriate simulation. As an example, we will present simulation data and calculation of the absorbed dose power in polyethylene samples installed on a sphere with a radius of 44 mm (see Fig. 8). The beam current at an energy of 85 MeV is 5 μA. The simulation results are shown in Table 3.

Table 2

R, mm	E_{e-}, MeV	$\eta_1 = \frac{\mathbf{N}_{\text{n 1 side}}}{N_e}$	$\eta_2 = \frac{\mathbf{N}_{\text{n 2 side}}}{N_e}$	$\eta_3 = \frac{\mathbf{N}_{\text{n 3 side}}}{N_e}$	$\eta_4 = \frac{\mathbf{N}_{\text{n 4 side}}}{N_e}$	$\eta_5 = \frac{\mathbf{N}_{\text{n 5 side}}}{N_e}$	$\eta_6 = \frac{\mathbf{N}_{\text{n 6 side}}}{N_e}$
75	45	$1.2 \cdot 10^{-5}$	$4.6 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$	$6.9 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$	$7.4 \cdot 10^{-6}$
	65	$2.54 \cdot 10^{-5}$	$7.7 \cdot 10^{-6}$	$7.7 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$7.47 \cdot 10^{-6}$	$1.15 \cdot 10^{-5}$
	85	$3.67 \cdot 10^{-5}$	$9.9 \cdot 10^{-6}$	$1.05 \cdot 10^{-5}$	$1.78 \cdot 10^{-5}$	$1.15 \cdot 10^{-5}$	$1.58 \cdot 10^{-5}$
44	45	$4.98 \cdot 10^{-5}$	$2.02 \cdot 10^{-5}$	$1.43 \cdot 10^{-5}$	$2.02 \cdot 10^{-5}$	$1.53 \cdot 10^{-5}$	$1.89 \cdot 10^{-5}$
	65	$1.05 \cdot 10^{-4}$	$2.77 \cdot 10^{-5}$	$2.23 \cdot 10^{-5}$	$3.31 \cdot 10^{-5}$	$2.16 \cdot 10^{-5}$	$3.47 \cdot 10^{-5}$
	85	$1.5 \cdot 10^{-4}$	$3.47 \cdot 10^{-5}$	$2.52 \cdot 10^{-5}$	$3.36 \cdot 10^{-5}$	$2.73 \cdot 10^{-5}$	$3.78 \cdot 10^{-5}$

Table 3

Absorbed dose rate, Gy·s^{-1}

1	2	3	4	5	6
$2.9 \cdot 10^{2}$	$1.1 \cdot 10^{4}$	1.3	87	1.0	88

It can be seen that the distribution of gamma radiation is significantly inhomogeneous. Obviously this is caused by the presence of a lead sheath. This feature can be used if simultaneous irradiation of samples with neutrons and gamma radiation is required. Note that elements in high-energy detectors are subjected to combined irradiation. Thus, we can create radiation conditions close to the operating conditions in real detectors.

The efficiency of experimental studies based on the samples irradiation depends on the electron beam intensity at the accelerator output. At present, the average beam current at the accelerator output does not exceed 5 μA. There are several ways to increase current. The most effective is to increase the pulse duration, which will improve the energy spectrum. However, this requires upgrading the high-voltage klystron modulator. Another way is to increase the pulsed current. Studies of the self-consistent particle dynamics have shown that the spectrum deteriorates somewhat in this case, which, however, does not play a significant role for samples irradiation. We plan to strengthen radiation shielding and to increase the average beam current by at least 50%.

CONCLUSIONS

The developed neutron source on the basis of the electron linac LUE-40 allows conducting experiments to study the effect of neutron and gamma radiation on the properties of materials and components used in high-energy physics detectors. In particular, it already was used to determine the elements radiation resistance of luminometer PLUME at the LHCb experiment. An improved version of the source makes it possible to obtain the neutron 4π flux of $3.6 \cdot 10^{11}$ s^{-1} at electron energy of 85 MeV and an electron beam intensity $3.12 \cdot 10^{13}$ s^{-1}. The design of the source makes it possible to irradiate samples simultaneously with both neutrons and mixed electron-gamma radiation, which corresponds to the real conditions of their operation in HEP detectors.

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ДЖЕРЕЛО НЕЙТРОНІВ НА ОСНОВІ ЛІНІЙНОГО ПРИСКОРЮВАЧА ЛУЕ-40 ДЛЯ РАДІАЦІЙНИХ ВИПРОБУВАНЬ МАТЕРІАЛІВ ТА КОМПОНЕНТІВ ДЕТЕКТОРІВ ФІЗИКИ ВИСОКИХ ЕНЕРГІЙ

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Для вивчення впливу нейтронного та гамма-випромінювання на властивості матеріалів, що використовуються у фізичних детекторах високих енергій, розроблено та створено джерело фотонейтронів на базі електронного лінійного прискорювача ННЦ ХФТІ ЛУЕ-40. Джерело використовувалося для опромінення оптичних елементів детектора PLUME в експерименті LHCb з густиною потоку нейтронів 10^{14} см$^{-2}$. Показано шляхи збільшення виходу нейтронів, зокрема встановленням додаткової оболонки, виготовленої з важкого металу. При енергії електронів 85 МеВ вихід нейтронів перевищує 10^{-2} нейтронів на один електрон.