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Linac-based thermal neutron source construction and characterization

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Summary. — Within the INFN E_LIBANS project, an intense thermal neutron source has been designed and set up at the University of Torino. It is based on an electron medical linac coupled to a photoconverter structure based on (γ,n) reaction in a lead target. The photoconverter materials and geometry have been optimized in order to have a pure and intense thermal neutron field in an irradiation cavity. This paper describes the results of the first benchmark experiments concerning the linearity of the thermal fluence rate with the linac current, the spatial uniformity of thermal neutron field and its highly thermal energetic spectrum. The achievements concerning different active neutrons diagnostics able to measure intense thermal neutron fluence rates are also reported.

1. – Introduction

Thermal neutron irradiation facilities are used in many fields, ranging from biomedical research to radiation protection, material science, electronics, aerospace. The most common sources are reactors or spallation sources based on proton and ion accelerators. Nevertheless neutron beams can be also produced in facilities based on electron accelerators through photoneutron processes on high-Z targets.

The design and construction of the thermal neutron irradiation facility is the aim of the INFN (CNS V) E_LIBANS (Electron Linac Based Actively monitored Neutron Source) project [1]. It includes both the neutron source and the detection system. At the Physics Department (University of Torino) a medical electron linac has been recently installed and a thermal photoneutron source has been set up with it. The linac is a commercial machine, commonly used in hospital for radiotherapy, producing an 18 MeV electron or X-Ray beam. A suitably designed structure, called photoconverter, has been manufactured and placed in front of the linac head, leading the bremsstrahlung X-ray beam of the linac to impinge a heavy material target. The resulting fast neutrons are thermalized by the moderator materials assembly surrounding the target. A pure thermal neutron field is obtained in an open or closed irradiation cavity, with transverse dimension of $30\times30\,\mathrm{cm}^2$ and expandable depth from 5 to 40 cm. Appropriate shields for unconverted photons and for fast neutrons are optimized to minimize the contaminations in the cavity.

The neutron field in the cavity has been measured with different active and passive detectors. Gold activation foils results were compared with measurements obtained with active thermal neutron rate detectors (TNRD) developed by INFN [2] and with different new active diagnostics based on silicon carbide or ionization chambers which are under development in the E_LIBANS project. Radiation resistant neutron detectors are in fact required to operate in intense sources for a long time.

The neutron energy spectrum has been evaluated with a Bonner Sphere System equipped with a TNRD detector. With the same device, a spatial uniformity characterization has been performed.

For the design and optimization of the source, a massive simulation study with the MCNP6 transport code [3] was employed.

In this paper the results of the first measurement campaign are shown as far as the neutron field spectrum, uniformity and intensity are concerned.

2. – E_LIBANS thermal neutrons facility

The E_LIBANS is based on three steps:

- inside the linac electrons are accelerated and converted into photons by bremsstrahlung;
- in the photoconverter neutrons are produced via (γ,n) reaction and then moderated;
- in the experimental cavity thermal neutrons are detected by permantent diagnostics and are available for sample irradiation.

2·1. *Linac.* – The linac used is a commercial radiotherapic linac Elekta SL18 Precise carefully disassembled from a hospital and re-installed at the Physics Department of Turin. It is now completely dedicated to research. Both an X-ray beam, generated via bremsstrahlung on a small target, and the primary accelerated electron beam can be obtained as output beam. For the purpose of the thermal neutron source the X-ray mode is used. In this modality, the machine has been set in order to work in three different preset configurations by varying the values of the acceleration energies and the filters presence along the beam path in the linac head. 15 MV or 18 MV X-ray beams are available and a special 18 MV configuration without flattening filters has been prepared to obtain a more intense flux. The removal of the flattening filters causes a peaked dose profile at the patient plane by increasing the amount of photons in the center of the beam spot.

The bunched electron beam of the linac has the following parameters when used for X-ray production: peak current up to 35 mA, pulse duration 2.4 μs, frequency 50–200 Hz. An estimation for the number of electrons per second impinging on the tungsten linac target is about 1.05×10^{14} per second. This number has an important role in the normalization of the numerical simulation results because it allows to compare the estimation of fluence per source particle extracted by Monte Carlo with the flux measurements.

To maximise the number of photons arriving on the photoconverter a minimum collimation is done in the linac head for the forward direction.

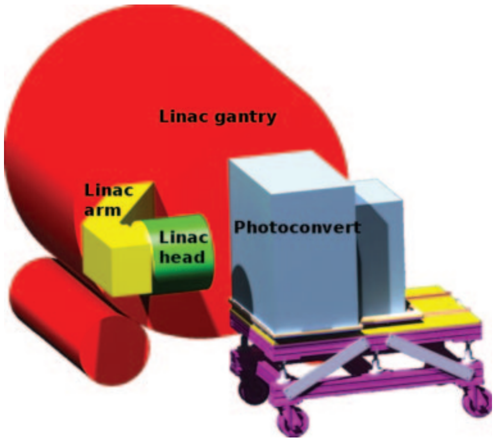

Fig. 1. – Illustration of E_LIBANS thermal neutron source: linac plus photoconverter.

For radiation protection issues a rotation of 90 degrees is always applied to the linac gantry so that the beam path runs parallel to the bunker floor and is dumped in a properly shielded wall. Figure 1 illustrates the source setup.

2·2. *Photoconverter*. – The manufactured structure used as photoconverter is projected in order to maximise the production of neutrons by photonuclear processes. These reactions consist in the absorption of a photon by a nucleus of the target material that is brought to an excited state. Afterwards the excited nucleus decays in the fundamental state by boiling off a neutron, according to the mechanism of the Giant Dipole Resonance. The neutron can be made free only if the energy of the absorbed photon is greater than the binding energy of the nucleons in the nucleus, so that the (γ,n) reaction has a threshold energy which is lower for high-Z nuclei with respect to light nuclei. Furthermore, cross sections present higher values for heavy materials. For these reasons, lead has been chosen as target material for the photoconverter. It also presents a very low neutron absorption cross section, that helps in minimizing the neutron losses by capture, and a high shielding power for the unconverted photons of the primary beam. Neutrons are produced by the (γ,n) reaction as fast neutrons with an energy distribution peaked around 1 MeV. For their slowing down, heavy water and graphite are chosen as moderator material because of their low absorption cross section and high inelastic scattering probability. The entire apparatus is covered by a 1.5 cm thick slab of borated rubber and polyethylene to shield the external environment. A scheme of the photoconverter geometry is drawn in fig. 2. The overall dimension of the structure is about 1 cubic meter and its weight is 1.5 tons. An MCNP6 simulation study has lead to choose the optimal configuration. The source was simulated starting from the electron beam so that the linac head was included. The quantities of interest for this study were the average neutron flux in the experimental cavity and the percentage of its thermal component, the spatial uniformity of the neutron field and neutrons to photons ratio. The number of histories has been dimensioned in order to have statistical uncertainties below 5%. To deal with the low photonuclear processes cross section with respect to the total one (about two orders of magnitude) specific variance reduction techniques have been employed.

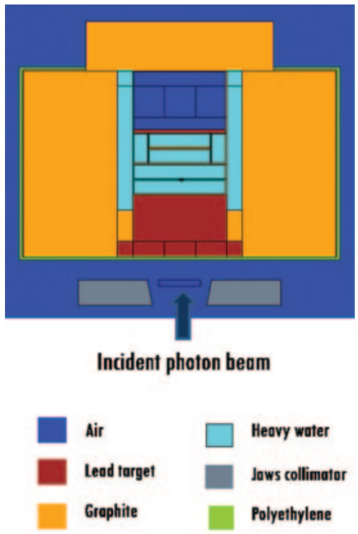

Fig. 2. – Geometry scheme of the photocoverter.

2˙3. *Diagnostics*. – In the aim of the E_LIBANS project a permanent diagnostic system will be installed in the experimental cavity to provide the on-line monitoring of the thermal neutron flux during irradiations. Different active detectors are under development to fulfil the radiation hardness requirement. As reference for the characterization measurements an active neutron detector, TNRD, developed in the NESCOFI@BTF INFN project [2, 4] has been employed. It is an easy to use device based on a silicon diode made sensitive to thermal neutrons through the deposition of a thin slab of lithium fluoride enriched in ^{6}Li. A special process of evaporation under controlled conditions allows to precisely deposit multiple detectors at the same time. The detector output is a voltage level proportional to the neutron flux. A calibration of the device was performed both at the radial thermal column of the ENEA Casaccia TRIGA reactor [5], which can provide a neutron fluence rate of the order of $10^6\,\text{cm}^{-2}\,\text{s}^{-1}$ comparable to the one of the E_LIBANS source, and at the INFN-HOTNES facility, a radioisotope thermal neutron source with a well known thermal neutron flux [6]. A TNRD detector has also been used inside a set of suitably designed polyethilene Bonner Spheres for the spectrum measurements.

Since the silicon suffers radiation damage when exposed to a thermal fluence higher than $10^{11}\,\text{cm}^{-2}$ and the detector response can be compromised, new devices suitable to be used in the E_LIBANS field are under study and have been tested in the experimental cavity. Two possible solutions to this problem are being explored. The first one is substrates of silicon carbide (SiC) detectors with thin micron ^{6}LiF deposit, which show similar characteristics with silicon but higher radiation resistance together with small dimensions fitting the application requirement. The second technique under investigation is a couple of air ion chambers with parallelepypedal sensitive volume of about $5\,\text{cm}^3$ with in-house ^{6}LiF deposition. These chambers work in pairs: one is coated with ^{6}LiF, whilst the other (uncoated) is used to subtract the residual photon signal.

Measurements presented in this paper have been mainly performed with the TNRD detectors. The absolute value of thermal fluence rate in the middle of the cavity has been also measured with gold activation foils, read with a germanium scintillator.

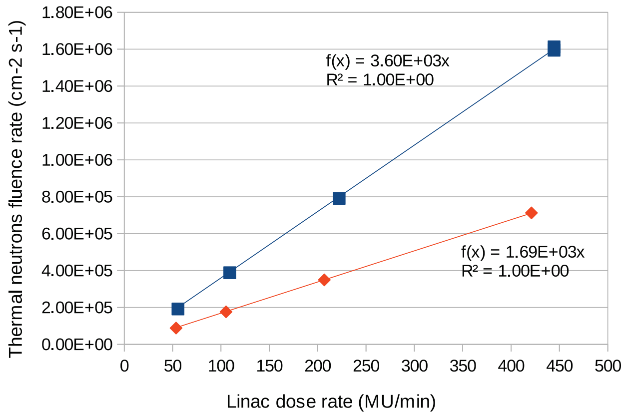

Fig. 3. – Thermal neutron flunce rate in the middle of the photoconverter cavity at different linac dose rate for 18 MeV electron beam (blue squared points) and for 15 MeV (red rhombi).

3. – Results and discussion

In fall 2017 a measurements campaign for the first characterization of the cavity has been realized. The major results are shown below.

3˙1. *Linearity*. – First of all the linearity of the thermal neutron flux with the linac dose rate has been verified. The dose rate corresponds to the primary electron beam rate and it is expressed in terms of monitor units per minute (MU/min), where MU indicates a measure of the machine output corresponding to the amount of radiation needed to deliver a fixed dose in standard phantom (1 MU = 1 cGy delivered by photons in standard conditions, SSD 100 cm, field $10 \times 10\,\text{cm}^2$, at build up in water phantom). In fig. 3 the thermal fluence rate is plotted *vs.* linac dose rate for two different energies, 15 MV and 18 MV. A TNRD detector placed in the middle of the closed cavity was used to measure the fluxes.

As expected the higher energy of the primary beam induces a more abundant neutron production because of the larger amount of bremsstrahlung photons with energy above the (γ,n) threshold (7 MeV in lead). The peak of the GDR cross section in lead is indeed around 13.4 MeV. The ratio between the thermal neutron flux in the middle of the cavity at 15 MeV and at 18 MeV is 0.47.

3˙2. *Energy spectrum*. – The energy spectrum of the neutrons in the cavity was measured with a set of ten Bonner Spheres with diameter from 6 cm to 20 cm, equipped with a TNRD detector inside them. The spheres were placed with their center in the middle of the closed cavity. The result obtained with a 18 MeV electron beam is shown in fig. 4. The values are expressed per unitary fluence in lethargy representation.

Measured data were analyzed with the FRUIT unfolding code [7,8], which can operate either with a parametrized spectrum or by iteratively altering a starting guess spectrum used as pre-information. The second approach was used for this work and the spectrum predicted by MCNP6 simulation was inserted as a guess (squared dots in the plot).

Since the measurement apparatus was calibrated it was possible to estimate with the unfolding the absolute value of neutron flux in the photoconverter cavity. Best estimation was $2.12 \times 10^6\,\text{cm}^{-2}\,\text{s}^{-1}$ (3%) at 400 MU/min, 18 MeV. The thermal fraction

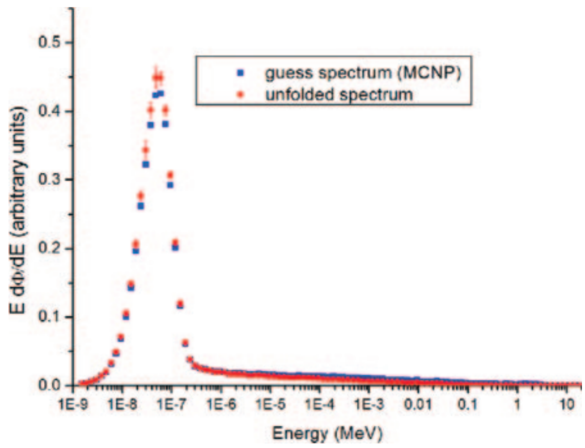

Fig. 4. – Neutron energy spectrum in the photoconverter cavity. Red points are the unfolded data and squared blue points the MCNP6 guess.

of this total fluence rate is 82.4% resulting in thermal fluence rate in Westcott convention of $1.55 \times 10^6\,\mathrm{cm^{-2}\,s^{-1}}$ in the same conditions. Fast component is strongly suppressed and its weight is less than 2%.

3·3. *Gold foils*. – An absolute value of the thermal neutron flux in the cavity has been also measured with the gold foils technique. Four gold foils have been exposed in the middle of the cavity and irradiated at 18 MeV in flattening filter free configuration. To isolate the thermal component from the non thermal background, two of the Au sheets were inserted in a cadmium cover. After an irradiation of about 1300 s the activation of the foils was measured with a Germanium detector. The value found for the thermal neutron flux is registered in table I compared with the TNRD and BSS values in the same position and linac conditions.

3·4. *Spatial Uniformity*. – The uniformity of the thermal flux inside the cavity has been checked by means of the TNRD. Moving the device in 9 different positions in the cross plane of the cavity at a medium depth a uniformity within the 6% was found. The results are plotted in fig. 5 together with a scheme of the measurements points. These values were collected in a configuration with open cavity, being this the more critical situation as far as uniformity is concerned. In fig. 6 the profile of the thermal flux along the beam axis is reported. Also in this case measurements were done moving the TNRD at different depth in the closed cavity. The presence of the cover makes the profile almost flat, with a gradient of 5% over 15 cm.

Table I. – *Thermal neutron flux at 18 MeV, flattening filter free conditions, measured with the Gold Foils, the TNRD and the BSS+TNRD system.*

Device	Φ_{th} @650 MU/min ($\mathrm{cm^{-2}\,s^{-1}}$)	Uncertainty
Au foils	$1.98\ 10^6$	3%
TNRD	$1.80\ 10^6$	2%
BSS	$2.13\ 10^6$	5%

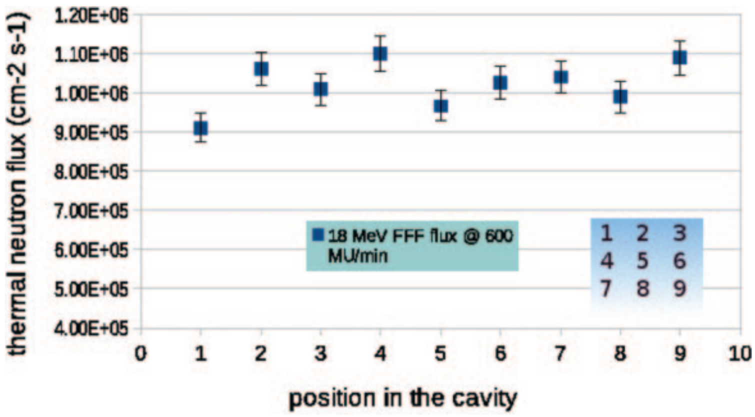

Fig. 5. – Uniformity in the cross plane of the cavity. The box in the bottom right of the figure shows the positions in which the detector has been placed. It represents the cross section of the cavity from a frontal view.

4. – Conclusions

With the installation of a medical electron linac at the Physics Department of Turin University the INFN E_LIBANS project has reached the first goal to set up an intense thermal neutron source with low fast neutron and gamma contamination. A thermal neutron field in a closed irradiation cavity is obtained by coupling the linac to a manufactured photoconverter. The results of the first characterization of the source are discussed in the paper. Data were collected using novel active neutron detectors developed inside the collaboration together with standard passive devices. The measure of the neutron energy spectrum with a Bonner Sphere System allowed us to confirm the high level of thermalisation reached in the cavity and the small amount of residual fast

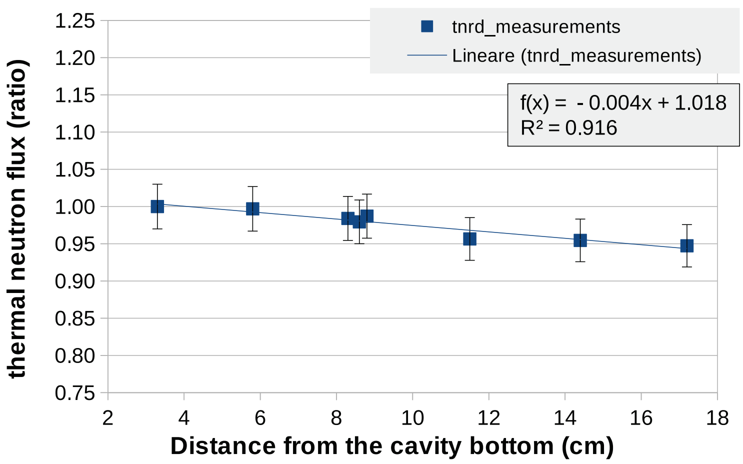

Fig. 6. – Uniformity along the beam axis of the cavity. Distance calculated from the bottom surface.

neutrons (<2%). The agreement of different measurement techniques establishes the thermal fluence rate in the middle of the cavity around $2 \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ when the linac is working at 650 MU/min in flattening filter free configuration. The thermal flux in the cavity is found to be highly linear with the linac dose rate, making the neutron source easily tunable in intensity. An enhancement of the primary electron mean energy would bring an effective advantage in the neutron field intensity.

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