Radiation Protection Dosimetry (2018), Vol. 180, No. 1–4, pp. 273–277
Advance Access publication 22 December 2017

doi:10.1093/rpd/ncx281

# INTENSE THERMAL NEUTRON FIELDS FROM A MEDICAL-TYPE LINAC: THE E_LIBANS PROJECT

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**The e_LiBANS project aims at producing intense thermal neutron fields for diverse interdisciplinary irradiation purposes. It makes use of a reconditioned medical electron LINAC, recently installed at the Physics Department and INFN in Torino, coupled to a dedicated photo-converter, developed within this collaboration, that uses (γ,n) reaction within high Z targets. Produced neutrons are then moderated to thermal energies and concentrated in an irradiation volume. To measure and to characterize in real time the intense field inside the cavity new thermal neutron detectors were designed with high radiation resistance, low noise and very high neutron-to-photon discrimination capability. This article offers an overview of the e_LiBANS project and describes the results of the benchmark experiment.**

## INTRODUCTION

The e_LiBANS project started in 2016 within the framework of the Istituto Nazionale Fisica Nazionale (INFN) technological research line, to develop, at its first stage, intense, homogenous and portable thermal neutron fields for interdisciplinary applications.

Its acronym stands for 'electron-LINAC Based Actively monitored Neutron Sources'.

The idea is to produce neutrons via photo-reaction and then to moderate them to the wanted energy in a dedicated assembly[1], that is the main subject of this article.

For the purpose, a reconditioned ELEKTA SL18 MV has been recently installed and commissioned in an existing bunker at the Physics Department of University of Torino.

The LINAC is coupled to a novel photo-converter, optimized through extensive Monte Carlo simulations, to achieve in the experimental cavity a pure thermal spectrum with a highly homogenous transverse profile.

In order to monitor on-line and to achieve highly accurate metrology of the generated neutron field, new devices have been developed within this project.

The field is complex, pulsed and mixed, and this makes e_LiBANS also very interesting and challenging for radiation detection.

In the following sections the most relevant features of the e_LiBANS project are discussed.

## THE LINAC

The accelerator ELEKTA SL18 MV was formerly operating in a hospital for clinical radiotherapy and has now been totally dedicated to research.

Its main characteristics are listed below and commented in the following:

(1) Primary electron energy tunable between 6 and 18 MeV.
(2) Electron or gamma output mode.
(3) Flattening filter option.
(4) Tunable rate, tunable field aperture.
(5) Typical electron rate on target: $I_e \sim 10^{14}\ s^{-1}$.

Option (2) refers to the fact that the mono-energetic primary electron beam can be converted into gammas by Bremsstrahlung onto an internal high-Z target. A rotating carousel allows five possible output configurations, to be chosen over a wide range of options. For the e_LiBANS applications, the following have been chosen so far:

(1) 18 MeV electrons with scattering foil.
(2) 18 MeV electrons without scattering foil.
(3) 15 MV gammas with flattening filter (effective electron energy on target: 12.3 MeV).
(4) 18 MV gammas with flattening filter (effective electron energy on target: 15.7 MeV).
(5) 18 MV gammas without flattening filter (effective electron energy on target: 15.7 MeV).

These choices allow to study the neutron production inside the cavity as a function of different LINAC working conditions as explained in the following sections.

## THE E_LIBANS PHOTO-CONVERTER DESIGN

The photo-converter simulation studies have been carried out mainly using MCNP6[2] that includes (γ,n) processes in high Z and low Z elements for photons up to 30 MeV. A complete simulation of the LINAC relevant parts has also been included. The photo-reaction model assumes that the dominant neutron emission mechanism is evaporation, with a Maxwellian neutron energy distribution and an isotropic angular distribution. A small (at percent level) prompt neutron emission component, is also considered. The photo-neutron production is simulated referring to the electron beam current, so that all the relevant outputs are given in terms of single source particle. The size of each run has been dimensioned in order to have a statistical uncertainty below 5%. To deal with the low Giant Dipole Resonance (GDR) photo-neutron production cross section (two orders of magnitude less than the total one), specific variance reduction techniques have been employed.

The role of the photo-converter is to produce neutrons by (γ,n) reaction and to moderate them down to thermal energies, minimizing gamma and fast neutron contaminations. In particular, the gamma background is due both to primary unconverted photons (low energy) and to those coming from neutron capture processes in the moderator.

A prototype has been manufactured and its geometry is shown in Figure 1; it contains mainly 15 cm thick lead neutron target followed by heavy water moderator and surrounded by graphite reflector blocks. The entire apparatus is planned to be covered by a 1 cm thick lithiated polyethylene layer to shield the cavity (not present in Figure 1).

Photo-neutron cross-section on lead shows a maximum of 600 mbarn for $E_\gamma$ = 13.5 MeV. The convolution of this peak with the bremsstrahlung spectrum gives the theoretical expected amount of emitted neutrons, which have an energy spectrum characterized by a most probable energy around 1 MeV. They can then be thermalized mainly through elastic scattering in moderator materials. Heavy water has been chosen for its high moderation power combined with its low neutron capture cross section.

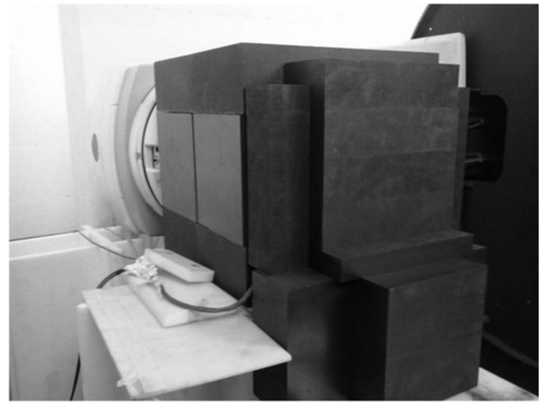

Figure 1. The photo-converter prototype '*in situ*' during April 2017 data taking.

The photo-converter and moderator assembly contains a 30 × 30 × 30 $cm^3$ experimental 'cavity' that can be closed by a block made of graphite and polyethylene. This block is mounted on a movable platform, that allows to easily access the cavity and place samples to be irradiated. The thermal neutron field inside the experimental volume is controlled and monitored online using novel neutron detectors developed for the e_LiBANS project and illustrated in the following section.

## DETECTION TECHNIQUES

The group has a well established experience in developing active thermal neutron detectors: the

Thermal Neutron Rate Detector (TNRD)[3], developed in a previous Neurapid project, is a well-known detector and it is used as reference point for this work. It has a minimal gamma sensitivity and a wide operating range of thermal neutron fluence rate[4].

The output of detector with its electronics is a DC level proportional to the rate. TNRD's substrate is made of silicon, and it may suffer radiation damage when exposed to thermal fluences higher than $10^{11}$ $cm^{-2}$. Large exposures affect the reticular structure of the silicon, thus, compromising the detector's response. As a consequence, TNRD is not suitable for long exposure in the E_LiBANS cavity where fluence rates >$10^7$ $cm^{-2}$ $s^{-1}$ will be reached.

Two possible solutions to this problem are being explored: first of all, substrates of silicon carbide (SiC) detectors with thin micron $^6$LiF deposit, due to the similar characteristics with silicon but more radiation resistant. This material, as it is well known, has a large energy gap between the bands and excellent thermal properties; for these reasons, SiC's have been studied in the past for in-core instruments for nuclear reactors. Their radiation hardness and small dimensions make them very interesting for this application.

The second technique under investigation is a couple of cubic centimeter sensitive volume ionization chambers with in-house $^{6}$LiF deposition. The working point has been determined by preliminary X-ray irradiation tests: with this technique a bias voltage of ~200 V is needed, while TNRD's and SiC's perfectly work unbiased. This last feature is clearly advantageous and makes SiC's very attractive for e_LiBANS application.

Results shown in the following refer to TNRD's measurements. SiC's and air chambers have been tried in the e_LiBANS cavity with positive response but their complete calibration is foreseen for summer 2017.

## PROTOTYPE RESULTS

During April 2017 an extensive measurement campaign has been carried out with the new LINAC at the Physics Department. The goals were to check the main feature of the e_LiBANS project on a prototype version of the photo-converter cavity optimized for thermal neutrons, to proof the concept, to verify the complete acquisition chain and to compare results with MCNP simulations. A final and optimized version of the thermal photo-converter is foreseen for December 2017.

One of the main feature of coupling a thermal neutron source with an e_LINAC is to check the final neutron fluence rate as a function of the primary beam current. The output of an accelerator for radiotherapy, as the one used for the e_LiBANS project, is quantify in terms of delivered dose to a patient in defined conditions. The dose rate is directly proportional to the primary beam current and it is measured in terms of monitor unit rate (MU/min) (100 MU = 1 Gy). In the following the neutron fluence rate will then be studied as a function the dose rate. A linear dependence is expected, because the number of neutron produced is directly proportional to the bremsstrahlung photon flux. Another interesting feature to be explored is the dependence of the thermal neutron fluence rate on the primary beam energy. The neutron production proceeds mainly through GDR that indeed is a threshold process: for example with lead or tungsten only photons above 7 MeV can trigger neutron emission, with a maximum probability around 13.5 MeV. An increase of neutron production is then expected by rising the energy endpoint of the bremsstrahlung spectrum. During the measuring campaign, two energies (12.3 and 15.7 MeV) and three different rates (100, 200, 400 MU/min) were implemented. Results are shown in Figures 2 and 3; data have been collected using TNRD's.

The results are consistent with the theoretical expectations and they show e_LiBANS source flexibility, to be tuned on the particular application.

Comparing the TNRD's results with MCNP simulations, a consistency at the 5% level, i.e. one sigma deviation, has been proved (Figure 3). This is an important result because it demonstrates that the geometries and the particle transport are well simulated. An independent measurement using the activation of calibrated golden foils confirms the TNRD's results.

Furthermore, the thermal neutron field on a cross plane of the cavity was tested and it turned out to be uniform at the level of 3%.

One of the goals of the e_LiBANS project is to obtain a pure thermal field. The neutron energy

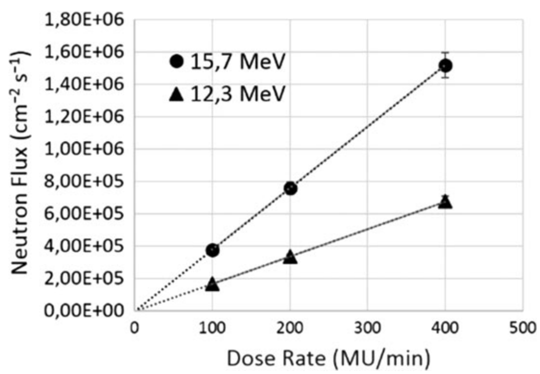


Figure 2. Thermal neutron fluence rate inside the e_LiBANS cavity measured as a function of the dose rate (see text for the definition of MU/min).

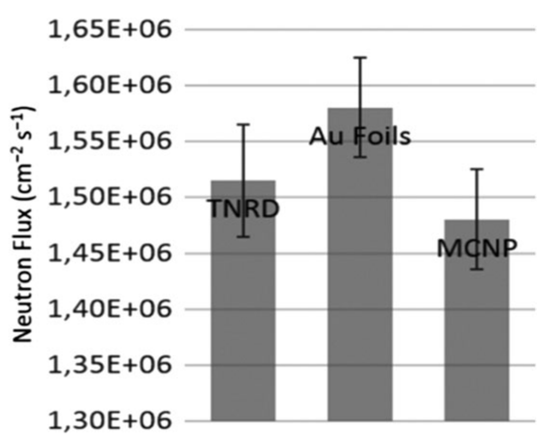


Figure 3. Comparison between TNRD's and golden foils measurements with respect to MCNP simulation results at $E = 15.7$ MeV and 400 MU/min LINAC dose rate.

spectrum in the experimental cavity was determined with a Bonner sphere system using a TNRD. Figure 4 shows the thermalized spectrum to unit fluence in lethargy representation. Two different unfolding codes (FRUIT and BUNTO) have been used and the results are shown together with the MCNP initial guess spectrum.

The measured thermal neutron spectrum is very clean. Only few percent of fast neutrons survive. The cadmium ratio extracted from the Au-foils measurement is 5,7 with a 3% uncertainty. This result is very encouraging and it is in agreement with the simulation output.

The measuring campaign carried out with the photo-converter prototype here presented has been a confirmation that intense and clean thermal neutron fields can be produced by coupling the e_LINAC with an appropriate photo-converter and moderator structure. The neutron fluence rate depends on the energy and the current of the primary electron beam. The facility at the Physics Department (University of Torino) shows that the neutron fluence rate can be varied over more than an order of magnitude.

To measure the thermal neutron field intensity and spectrum, time stability and spatial uniformity, new active detectors are under development. They will allow to perform an online monitor of the field in the experimental cavity with a 3% accuracy. This is in itself a relevant results and it opens up the use of such detectors also for other applications.

## OUTLOOK

The e_LiBaNS prototype campaign has proved the good agreement between data and simulations. This was indeed not trivial due to the necessity of simulating not only the photo-converter but also the LINAC and the surrounding bunker. Two parallel improvements are now open, depending on the way one wants to operate the LINAC. As said in the previous sections, the machine can be operated either in 'gamma mode' or in 'electron mode'. These two modes are geometrically different: while the first is a cone-like emission of photons that intercept the photo-converter target on a plane, the second is a pencil beam that can be used to create a 'point-like' neutron source inside the photo-converter, being the radiation length in lead only 0.5 cm. Moreover, while bremsstrahlung emission tends to be collinear in the energy range of interest (10–20 MeV), neutron production is isotropic. For this reason the photo-converter coupled to the LINAC operated in e-mode can have the experimental cavity at 90° with respect to the primary beam direction. This can reduce the contribution of unconverted gammas in the cavity even more.

Figure 5 shows the optimized unit lethargy spectrum for the gamma mode photo-converter. A photon component is present, due both to unconverted photons and to neutron capture reaction. In order to quantify the relevance of such a component the gamma dose normalized to the thermal neutron fluence, $D_\gamma/\phi_{th}$, is quoted. This quantity together with the fast neutron dose normalized to the thermal neutron fluence, $D_f/\phi_{th}$, defines the quality of the thermal neutron field.

Tables 1–3 show fluence rates for neutrons and photons. Tables 1 and 2 refer to the gamma-mode photo-converter with electron energy on target 15.7 and 18 MeV, respectively, while Table 3 refers to electron-mode photo-converter with electron energy 18 MeV. The values are normalized to the same beam current.

The thermal neutron fluence rates range between $5 \times 10^6$ and $8 \times 10^7\,cm^{-2}\,s^{-1}$ and they account for ~80–85% of the total neutron fluence rates. They clearly depend on the beam energy but also on the

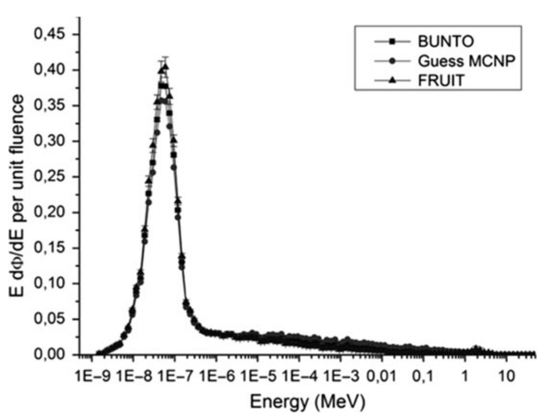


Figure 4. Unit lethargy spectrum in the e_LiBANS photo-converter cavity obtained by a Bonner Sphere Spectrometer with inside a TNRD.

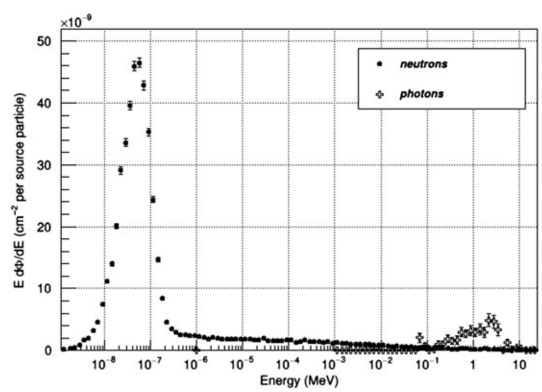


Figure 5. Unit lethargy spectrum in the e_LiBANS 'gamma-mode' optimized photo-converter cavity (MCNP6 simulation). A photon component is visible in the MeV range.

**Table 1. MCNP6 values for the optimized photo-converter 15.7 MV (gamma-mode).**

| | Fluence rate ($cm^{-2}\,s^{-1}$) | Percentage of total neutron flux (%) |
|---|---|---|
| Thermal neutron | $(5.28 \pm 0.02) \times 10^6$ | 82.5 |
| Epithermal neutron | $(9.74 \pm 0.04) \times 10^5$ | 15.2 |
| Fast neutron | $(1.46 \pm 0.01) \times 10^5$ | 2.3 |
| Photon | $8.22 \times 10^5$ | |

**Table 2. MCNP6 values for the optimized photo-converter 18 MV (gamma-mode).**

| | Fluence rate ($cm^{-2}\,s^{-1}$) | Percentage of total neutron flux (%) |
|---|---|---|
| Thermal neutron | $(9.6 \pm 0.1) \times 10^6$ | 83.3 |
| Epithermal neutron | $(1.69 \pm 0.02) \times 10^6$ | 14.6 |
| Fast neutron | $(2.43 \pm 0.07) \times 10^5$ | 2.1 |
| Photon | $1.05 \times 10^6$ | |

**Table 3. MCNP6 values for the optimized photo-converter 18 MeV (electron-mode).**

| | Fluence rate ($cm^{-2}\,s^{-1}$) | Percentage of total neutron flux (%) |
|---|---|---|
| Thermal neutron | $(8.5 \pm 0.1) \times 10^7$ | 85.0 |
| Epithermal neutron | $(1.36 \pm 0.02) \times 10^7$ | 13.6 |
| Fast neutron | $(1.40 \pm 0.07) \times 10^6$ | 1.4 |
| Photon | $7.7 \times 10^6$ | |

operating mode. Fast neutron component accounts for ~2% of the total in gamma-mode while it is only 1.4% in electron-mode. Gamma to neutron ratio is ~1/10. The quality of the field is not dependent on the energy but it turns to be slightly better in the electron-mode ($D_\gamma/\phi_{th} = 6 \times 10^{-13}$ Gy cm$^2$, $D_f/\phi_{th} = 8 \times 10^{-14}$ Gy cm$^2$) than in the gamma-mode ($D_\gamma/\phi_{th} = 7 \times 10^{-13}$ Gy cm$^2$, $D_f/\phi_{th} = 2 \times 10^{-13}$ Gy cm$^2$) at the same energy.

## CONCLUSIONS

The e_LiBANS project aims at producing intense thermal neutron field with low contamination of fast neutron and photons. Neutrons are produced via GDR reaction by coupling a suitable photo-converter and moderator apparatus to an electron LINAC with energy above the GDR threshold. This article reports about the novel facility that has been setup at the Physics Department (University of Torino) where an ELEKTA SL18 MV has been recently installed and commissioned. In April 2017 a measuring campaign with a photo-converter–moderator prototype has been done. Data were collected using active detectors developed inside this collaboration. The results show a good linearity response with the beam rate and a general agreement at 5% level with the MCNP simulations. Cross-check with Au-foils technique was also consistent. The same detectors within a Bonner sphere system were used to extract the neutron energy spectrum inside the cavity: a clean thermal neutron spectrum has been measured.

The results open up for the next foreseen steps in the project, to finalize an optimized photo-converter with a cavity $30 \times 30$ cm$^2$ in transverse plane, and a longitudinal extension that can vary between 10 and 30 cm. Expected fluence rates range between $5 \times 10^6$ and $8 \times 10^7$ cm$^{-2}$ s$^{-1}$ with $D_\gamma/\phi_{th}$ and $D_f/\phi_{th}$ of the order of $10^{-13}$ Gy cm$^2$. Final results are expected for December 2017.

## FUNDING

The e_LiBANS project is funded by the Istiituto Nazionale Fisica Nucleare. The LINAC ELEKTA SL18 has been funded by the University of Turin and the Istituto Nazionale Fisica Nucleare, with contributions from Compagnia di San Paolo and Fondazione CRT.

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