Development of gamma insensitive silicon carbide diagnostics to qualify intense thermal and epithermal neutron fields

O. Sans Planell, M. Costa, E. Durisi, A. Lega, E. Mafucci, L. Menzio, V. Monti, L. Visca, R. Bedogni, M. Treccani, A. Pola, D. Bortot, K. Alikaniotis, G. Giannini and J.M. Gomez-Ros.

Università degli Studi di Torino, via Pietro Giuria 1, 10125 Torino, Italy
INFN, Sezione di Torino, via Pietro Giuria 1, 10125 Torino, Italy
INFN, Laboratori Nazionali di Frascati, via Enrico Fermi 40, 00044 Frascati, Italy
Universitat Autonoma de Barcelona, Departament de Física, 08193 Bellaterra, Spain
Politecnico di Milano, Dipartimento di Energia, via La Masa 34, 20156 Milano, Italy
INFN, Sezione di Milano, via La Masa 34, 20156 Milano, Italy
Università degli Studi di Trieste, via Valerio 2, 34127 Trieste, Italy
INFN, Sezione di Trieste, via Valerio 2, 34127 Trieste, Italy
CIEMAT, Avenida Complutense 40, 28040 Madrid, Spain

E-mail: oriol.sansplanell@to.infn.it

ABSTRACT: The e_LiBANS project aims at creating accelerator based compact neutron facilities for diverse interdisciplinary applications. After the successful setting up and characterization of a thermal neutron source based on a medical electron LINAC, a similar assembly for epithermal neutrons has been developed. The project is based on an Elekta 18 MV LINAC coupled with a photoconverter-moderator system which deploys the $({\gamma},n)$ photonuclear reaction to convert a bremsstrahlung photon beam into a neutron field. This communication describes the development of novel diagnostics to qualify the thermal and epithermal neutron fields that have been produced. In particular, a proof of concept for the use of silicon carbide photodiodes as thermal neutron rate detector is presented.

KEYWORDS: Models and simulations; Neutron detectors (cold, thermal, fast neutrons); Neutron sources; Radiation-hard detectors

*Corresponding author.
1 Introduction

A worldwide interest exists to develop compact and cost-wise low energy neutron sources. The most common ones are based on proton or deuteron beams on different materials [1] with relevant technological and cost-effective investments. An alternative to such sources is the use of the \((\gamma, n)\) reaction, in which neutrons with a typical evaporation spectrum around 1–2 MeV are produced, by converting the high energy photons on a heavy material target. Exploiting a modified medical LINAC, the INFN e_LiBANS collaboration has successfully developed two converter-moderator assemblies, one for thermal neutrons and a second one for epithermal neutrons.

The e_LIBANS project started back in 2016 and ended in spring 2019. For an extensive description see [2]. It offers two fully functional facilities with a wide range of applications: from cell testing for medical research, to detector characterisation. Alongside the creation of the two photoconverters-moderators, some novel diagnostics have been built to properly measure the neutron fluence rates and the energy spectra. The root technology, upon which the new diagnostics are based, is the Thermal Neutron Rate Detector (TNRD) developed by the group under previous projects [3]. The “TNRD technology” is characterized by the differential readout of an assembly of two silicon detectors where a thin layer of \(^6\text{LiF}\) is deposited on one of the two detectors while the other operates “bare”. The \(^6\text{LiF}\) has an extremely high absorption cross section for thermal neutrons. When the \(^6\text{Li}\) nucleus absorbs a neutron, it undergoes the following nuclear reaction:

\[
 n + ^6\text{Li} \rightarrow \alpha + ^3\text{H} + 4.75 \text{ MeV}
\]  

(1.1)

The geometry of the detector assembly is optimized so that the intrinsically short-range products of the nuclear reaction leave their signal only in the deposited diode, while background photons can produce signals in both devices. A differential readout has been implemented, so that the photon signal tend to cancel out, leaving the neutron signal intact. This method makes the device virtually...
insensitive to photons and, thus, optimal to work in a mixed γ-n field. The detector has shown a linear response on a wide neutron fluence-rate range and it has also been proved to work well under pulsed fields, such as that of a LINAC. The radiation hardness of the silicon substrate of the TNRD has proved to withstand neutron fluences up to $5 \times 10^{11}$ cm$^{-2}$ [4], deeming it adequate for radioprotection purposes, although it has inspired a research for more radiation resistant devices. In this paper two new detectors are presented: the first deals with the implementation of the TNRD technology on a silicon carbide substrate to reach higher radiation hardness, while the second one aims at extending the “TNRD technology” to a fluence-meter device able to operate in intense epithermal neutron fields.

For the determination of the neutron energy spectra, a Bonner Sphere Spectrometer has been used, coupled to a TNRD as active detector. The TNRD-BSS spectrometer has been calibrated at the National Physical Laboratory (England) and at the ENEA-Frascati Neutron Generator (Italy [5]).

2 The e_LiBANS testing facilities

The e_LiBANS collaboration can rely on three different calibrated neutron facilities that have been setup by the group. Some details are given in the following sections.

2.1 The e-Linac based facility in Torino

The Torino facility exploits the bremsstrahlung gammas produced by the conversion of the electron beam, produced by an ELEKTA SL 18 MeV Linac, on a thin tungsten target [6]. The high energy gammas can then be used to produce neutrons through $(\gamma, n)$ reaction on a high-Z material as lead. Neutrons are produced with a typical evaporation spectrum peaked around 1–2 MeV. The thickness of the target can be tuned to maximise both the conversion process, and the absorption of the unconverted gammas. The processes are represented in figure 1.

![Figure 1](image)

*Figure 1. Schematic view of the different components of the e_LiBANS neutron source.*

After being extracted from the target, neutrons pass through a region in which they undergo moderation (i.e. reduction of their energy) to the desired range. Two different moderator assemblies were constructed in order to obtain homogeneous neutron fields with energy in the thermal and epithermal ranges, respectively.

In the thermal configuration (see figure 2), the producer block is surrounded by an external graphite structure, followed by a central core of deuterated water that thermalizes the neutrons. The minimal absorption cross section and the high scatter capabilities of those materials makes them
ideal for reflection and moderation. A coating made of borated rubber and polyethylene highly reduces the dose imparted to the exterior of the photo-converter. Embedded in the moderator can be found an experimental cavity of $30 \times 30 \times 20$ cm$^3$ volume in which it is possible to place samples and detectors. The overall structure has a volume slightly above 1 m$^3$ and it weights 1 Ton [6].

In the epithermal configuration, the lead target design is similar to that of the thermal structure, but the materials for the moderation vary: in order to keep the neutron energy confined in the epithermal range and to eliminate the thermal and fast components of the spectrum, a combination of aluminium and polytetrafluoroethylene (PTFE) is used as core, while a thin shield of borated rubber — 0.5 cm — and cadmium has been placed surrounding the internal walls of the cavity to eliminate the thermal component of the spectrum. All the structures have been optimised through extensive Monte Carlo simulation work with MCNP6 [7] as transport code. The cross section data library used to work out the calculations was the ENDF-B/VII.1 [8]. The configurations are graphically described on figure 2.

![Figure 2](image)

**Figure 2.** Left: the thermal neutron photoconverter-moderator geometry. Right: the epithermal neutron photoconverter-moderator geometry. The beam direction is also indicated in both figures.

The Torino neutron facilities underwent extensive characterization and calibration campaigns. Typical neutron fluence rates are of the order of $10^5 - 10^6$ cm$^{-2}$s$^{-1}$ in the thermal energy range and $10^4 - 10^5$ cm$^{-2}$s$^{-1}$ in the epithermal energy range. As far as the gamma background is concerned the gamma dose rate measured in the centre of the cavity results: $D_\gamma = 1.85 \pm 0.08 \mu$Gy s$^{-1}$. For more details see [6]

### 2.2 The HOTNES and EPINES facilities

Two more detector testing facilities are available in Frascati to the ANET collaboration, that have been built thanks to a collaboration between ENEA and INFN: the HOMogeneus Thermal NEutron Source (HOTNES [9]) and the EPIthermal NEutron Source (EPINES). Both of them exploit a Am-B neutron source and provide a uniform neutron field in a specific volume, with almost zero
gamma contamination, although with limited intensity with respect to the Torino e-Linac sources. An accurate characterisation of such field was carried out employing a calibrated set of Bonner Spheres [10]. Thanks to the large accessible volume in which is possible to place the detectors and the uniformity of the neutron field provided, these two sources are ideal for test and calibration of novel detectors. In HOTNES and EPINES it is possible to test, respectively, thermal and epithermal neutron detectors. The simulated geometries for both facilities are presented in figure 3.

![Figure 3. Left: details of HOTNES. Right: schematics of EPINES.](image)

The work illustrated in this paper has profited of all the facilities previously described.

3 Novel diagnostics

3.1 Silicon Carbide neutron detectors

One of the main concerns about the silicon detectors used for the TNRDs resided in their limited radiation hardness. As stated in [4] their signal started to be compromised for neutron fluences above \(5 \times 10^{11}\) cm\(^{-2}\). In order to find more radiation hard substrates, the behaviour of some commercial silicon carbide (SiC) devices was inspected. This material constitutes a promising choice for high fluence thermal neutron fields, as its energy gap is about three times greater than silicon’s. Our choice focused on SGLux GmBh photodiodes [11], originally conceived for UV measurements. They are extremely low noise devices with dark current in the fA range. They can have active areas ranging from 1 mm\(^2\) to 7.6 mm\(^2\): this allows to scale the geometry of the device to the source fluence rate, in order to get manageable counting rates. Moreover the junction contact potential provides around 1 micrometer depletion layer thickness at zero external bias, that can be exploited to detect alphas and tritium from neutron conversions, making the device nearly insensitive to photons. In unbiased operative conditions the relative gamma to neutron sensitivity has been evaluated to be \(10^{-4}\). In the following, results with a 7.6 mm\(^2\) SG01XL device by SGLux GmBh are shown. Firstly we compared the response to thermal neutrons of a bare SiC detector with respect to one coated with a thin layer of \(^{6}\)LiF. Measurements have been taken at the e_LiBANS thermal facility in Torino. Results are shown in figure 4.
Figure 4. Comparison between the signal pulse heights measured by two SG01XL SiC detectors exposed to the e_LiBANS thermal neutron field. For clarity, the result with the bare detector is also replicated in the picture on the right.

The bare detector has about 1% counts of the $^6$LiF coated one. These few counts are due to the boron doping of the SiC junction and can be assumed to give a negligible contribution to the total signal. This also suggests the possibility to use a linear readout, instead of a differential one as it was applied for the TNRDs.

The linearity of $^6$LiF coated SG01XL SiC detectors has also been studied. Results are shown in figure 5, where the average of the signal amplitude, readout in current-mode, as a function of the Linac beam rate is shown. The maximum rate corresponds to a thermal neutron fluence rate of $2 \times 10^6$ cm$^{-2}$s$^{-1}$. The device linearity has been proved to be extremely good and its capability to cope with intense neutron rate has been demonstrated.

To check the $^6$LiF coated SG01XL SiC radiation hardness, we exposed the device to a total neutron fluence of $10^{13}$ cm$^{-2}$ at the ENEA Casaccia TRIGA reactor [12]. This fluence value was chosen as it would represent a three years exposure in the e_LiBANS thermal neutron facility at maximum rate. We then repeated the linearity test at the Linac facility, as previously described. The result is shown in figure 5.

Figure 5. Left: linearity test performed with the SiC detector under the thermal field in Turin, at rates ranging from 50 to 400 Monitor-Units(MU)/min. Right: the same measurement performed on an irradiated detector exposed to an integrated neutron fluence of $10^{13}$ cm$^{-2}$. 
As expected the charge collection efficiency got affected by the high radiation dose: a reduction of about a factor three is observed. Nonetheless the linearity of the response remains unchanged and the signal amplitude is still sufficient to operate the device. We observe a net improvement with respect to silicon based devices [3]. The response degradation suggests the need of a periodical calibration to adjust the detector response. More radiation campaigns on SGLux GmBh SiC devices is needed to come to a conclusive statement on their radiation hardness.

Nonetheless, given their good response, linearity and gamma insensitivity, 16 $^{6}$LiF coated SG01XL SiC detectors were assembled into a $4 \times 4$ matrix (so called SiC-Matrix), as shown in figure 6, to build a beam monitor detector with a field of view of $10 \times 10\,\text{cm}^2$, with the capacity of being readout simultaneously in both impulse or current modes. The uniformity of the field inside the e_LiBANS thermal cavity was measured with the SiC-Matrix beam monitor. The individual SiC response is known within 5% error. The uniformity result is shown in figure 6 and it is in agreement with what has been previously quoted [6]

### 3.2 Epithermal Neutron Rate Detector

Basing its structure on the presented TNRD, an Epithermal Neutron Rate Detector (labeled EPI3), was built by placing a cube of high density polyethylene between two silicon photodiodes, one of which (Diode2) was coated with a thin layer of $^{6}$LiF, while the other (Diode1) remained bare without any coating, as shown in figure 7. The whole structure is enclosed in a box of borated rubber that has been dimensioned to absorb neutron in the thermal energy range. Those above the epithermal threshold (0.4 eV) penetrate the borated cup and get thermalized along their path in the polyethylene, before getting converted in the $^{6}$LiF silicon coating of Diode2. The differential readout of the diodes gets rid of the possible gamma contribution and provides a clean neutron signal. The result is an effective, compact and active device to measure epithermal neutron fluence.

![Figure 6. Left: matrix of Silicon Carbide photodiodes for the e_LiBANS project. Right: measurement performed with the matrix inside the e_LiBANS thermal cavity.](image)
The prototype discussed in this paper has dimensions $4.5 \times 3 \times 2 \text{cm}^3$. The EPI3 response function has been simulated using the MCNP6 code and the result is shown in figure 7 (right).

![Diagram of the EPI3 detector](image)

**Figure 7.** *Left:* the design of the epithermal neutron rate detector. *Right:* the response curve of the detector as a function of the energy.

The EPI3 detector has been calibrated at the EPINES facility by comparing its response to that extracted from the measurement with the calibrated Bonner Sphere Spectrometer described in [5]. The calibration factor obtained is: $(1.33 \pm 0.08) \times 10^{-4} \text{ V cm}^2 \text{s}^{-1}$.

Figure 8 shows the result of a measurement taken with the EPI3 detector placed inside the e_LiBANS epithermal cavity (figure 2) with the Linac operated at a rate of 400 Monitor Unit (MU)/min. Diode2 and Diode1 signals are shown independently. Diode1 signal amplitudes are mainly concentrated in the lower part of the spectrum below 1.5 V while Diode2 signal amplitudes extend to higher values up to 3 V. By properly setting a threshold a Region Of Interest (ROI) can be defined, in order to maximize the neutron signal and to minimize the background contribution.

![Graph showing Diode signals](image)

**Figure 8.** Measurement taken with the EPI3 detector at the epithermal facility in Turin. The two diode signals are shown separately.
To properly define the ROI, the following R factor has been computed as a function of the threshold voltage

$$ R = \frac{Diode_2 - Diode_1}{Diode_2} $$

(3.1)

![Figure 9. Left: dependence of the R ratio on the threshold voltage. Right: statistical error on the difference between the two diode signals as a function of the threshold voltage.]

The dependence of the R ratio on the threshold voltage is shown in figure 9. A threshold value of 1.1 V has been chosen corresponding to R = 0.91 ± 0.01, so that the statistical error caused by the subtraction of the two diode signals is minimized.

The EPI3 detector has then been used to measure the epithermal neutron fluence rate in the \( e\_\text{LiBANS} \) cavity operating the LINAC at 439 MU/min. The epithermal neutron fluence rate extracted from EPI3 measurement is \((2.98 \pm 0.23) \times 10^4 \text{cm}^{-2} \text{s}^{-1}\).

In order to check the EPI3 linearity the measurement has been repeated at different LINAC rates. The result is shown in figure 10.

![Figure 10. Counts measured by the EPI3 detector as a function of the e-LINAC rate.]

4 Conclusions

The thermal and epithermal accelerator based neutron sources developed at the Physics Department of the University of Torino, together with the HOTNES and EPINES sources in Frascati, offer small
scale, easily accessible irradiation facilities in which it is possible to test and to calibrate novel diagnostics.

This paper shows the results that have been obtained for the following novel active devices:

1. **Silicon Carbide neutron detector.**

Starting from a commercial silicon carbide substrate, a thermal neutron fluence meter has been produced. Its sensitive area can be properly scaled with neutron field intensity. This novel device has proved to be gamma insensitive and able to operate in pulsed fields, with a linear response to the thermal neutron fluence rate. Concerning its radiation hardness it has proved to be still operable and linear after being exposed to an integrated neutron fluence of $10^{13}\text{cm}^{-2}$, although with reduced efficiency. Based on $4 \times 4 \text{SiC}$ devices a beam monitor detector has been assembled covering a field of view of $10 \times 10 \text{cm}^2$ and its use has been demonstrated by mapping the transverse field inside the e_LiBANS cavity.

2. **Epithermal Neutron Rate Detector.**

Following the original design of the TNRD, though optimised for the epithermal range, a compact, linear, gamma insensitive, epithermal neutron fluence meter, able to operate in a pulsed neutron field, has been produced. Its reduced dimensions make it suitable to be used for carefully mapping epithermal neutron fields. The epithermal neutron rate at the e_LiBANS facility measured with this device turned out to be $(2.98 \pm 0.23) \times 10^4 \text{cm}^{-2}\text{s}^{-1}$, in agreement with the expected value from the MCNP6 simulations.

**Acknowledgments**

This project has been supported by Compagnia di San Paolo grant “OPEN ACCESS LABS” (2015), Fondazione CRT grant n.2015.AI1430.U1925, INFN CSN 5, MIUR Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337). The authors are also grateful to Azienda Sanitaria Ospedaliera San Luigi Gonzaga — Orbassano, Ospedale S. Giovanni Antica Sede — Torino and to the Elekta S.p.A. for the technical support in the LINAC commissioning and maintenance.

**References**

[1] J.M. Carpenter, *The development of compact neutron sources*, Nature Rev. Phys. 1 (2019) 177.

[2] V. Monti, *Design and characterization of the Torino Linac based thermal neutron source developed within the e_LiBANS project*, Ph.D. thesis, University of Torino, Torino, Italy (2018).

[3] R. Bedogni et al., *A new active thermal neutron detector*, Radiat. Protect. Dos. 161 (2013) 241.

[4] R. Bedogni et al., *Experimental characterization of semiconductor-based thermal neutron detectors*, Nucl. Instrum. Meth. A 780 (2015) 51.

[5] R. Bedogni et al., *An active Bonner sphere spectrometer for intense neutron fields*, Nucl. Instrum. Meth. A 940 (2019) 302.

[6] V. Monti et al., *The e_LiBANS facility: a new compact thermal neutron source based on a medical electron LINAC*, Nucl. Instrum. Meth. A 953 (2020) 163154 [arXiv:1909.00762].
[7] T. Goorley et al., *Initial MCNP6 release overview*, LA-UR-11-07082, Los Alamos National Laboratory, U.S.A. (2012) [Nucl. Technol. 180 (2012) 298].

[8] M. Chadwick et al., *ENDF/b-VII.1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data*, Nucl. Data Sheets 112 (2011) 2887.

[9] R. Bedogni, A. Pietropaolo and J. Gomez-Ros, *The thermal neutron facility HOTNES: theoretical design*, Appl. Radiat. Isotop. 127 (2017) 68.

[10] R. Bedogni et al., *Experimental characterization of HOTNES: a new thermal neutron facility with large homogeneity area*, Nucl. Instrum. Meth. A 843 (2017) 18.

[11] SG01XL-B5 UVB-only SiC based UV photodiode $A = 7.6 \text{ mm}^2$, https://download.sglux.de/photodiodes/SG01XL-B5.pdf.

[12] D. Chiesa et al., *Characterization of TRIGA RC-1 neutron irradiation facilities for radiation damage testing*, Eur. Phys. J. Plus 135 (2020) 349 [arXiv:1911.09374].