LEMRAP Laboratory
2024 Annual report

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1 BRIL (CMS, CSN 1)

1.1 Introduction

The Beam Radiation, Instrumentation, and Luminosity (BRIL) group operates a number of detectors for measuring the luminosity and monitoring beam conditions in CMS (Compact Muon Solenoid) at CERN. Having multiple detectors provides redundancy in case of problems with one, as well as a way to measure how their behaviour changes in different LHC beam conditions. These detectors are expected to play an important role in the upcoming Run 3 of the LHC. Within the BRIL collaboration, Frascati and Turin INFN sections are developing "Tetraball", a single moderator neutron spectrometer for the CMS cavern.
The main characteristics of this spectrometer are the following:

- It is sensitive to neutrons from thermal to GeV;
- Its response is nearly isotropic by combining radial positions;
- It is made up of a single polyethylene sphere containing pairs of radiation resistance SiC diode. One member of the pair is coated with ^{6}LiF to make the whole detector sensitive to neutrons while the other sensor is not coated, so is mainly sensitive to photons and charged particles;
- It is equipped with a lead shell to make the device sensitive to high-energy neutrons;
- It needs a single exposure and an unfolding process to get the spectrum while the traditional method of Bonner spheres requires multiple exposures.

1.2 Simulations

Tetra-Ball (T-Ball) is a new type of extended energy range single sphere neutron spectrometer suited for the long acquisition of neutron spectra in the High-Luminosity LHC period in the CMS Cavern. Compared to its predecessor, the SP2, it reduces the number of sensors from 31 to 21. This is achieved with a tetrahedric disposition of the sensors.
The polyethylene spherical moderator is 28 cm in diameter and includes a lead insert for the detection of neutrons above 10 MeV. The work performed describes the T-Ball design and calculates the response matrix considering four different irradiation geometries. The impact of anisotropy effects on the T-Ball spectrometric performance is investigated by simulation. Although the performed work does not cover the totality of the possible energy distributions and conditions of use, the results suggest that T-Ball could offer adequate spectrometric performance and a good isotropy in most operating scenarios in the high-energy field.

The spatial distribution of thermal neutron sensors in T-Ball in comparison to SP2 is shown in Fig. 1.

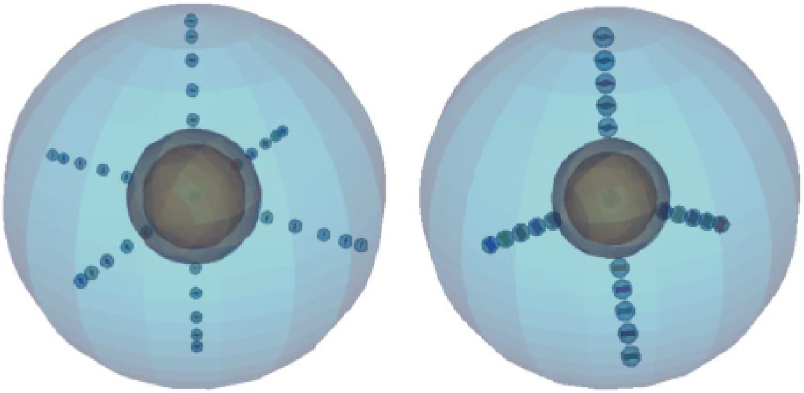

Figure 1: Disposition of the internal thermal neutron detectors in the SP2 (left) and T-Ball single moderator neutron spectrometers (right).

After having proved that the response of the device is isotropic through simulations, we can compute the set of response functions (for each radial position) when the neutron field is impinging the device isotropically. The set of response functions in this case are those shown in Fig.2 which are reminiscent of the classical response functions of standard Bonner Sphere Systems.

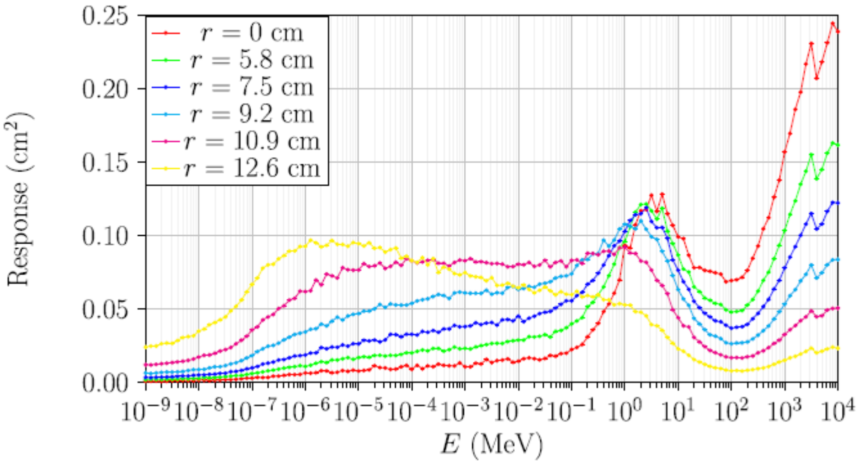

Figure 2: Response matrix of the T-Ball obtained under isotropic irradiation geometry. The response as a function of the radial position is obtained by averaging the readings of the detectors at the same radial position.

Fig. 3 shows an unfolded neutron spectrum in a MC-Unfolding test where the goodness of the isotropic response is under test. In that test, similar conditions of those found in CMS cavern are simulated. The neutron spectrum shown in Fig. 3 is therefore containing the same elements that will be find on the CMS cavern, that is to say, thermal, epithermal, fast and high energy neutrons.

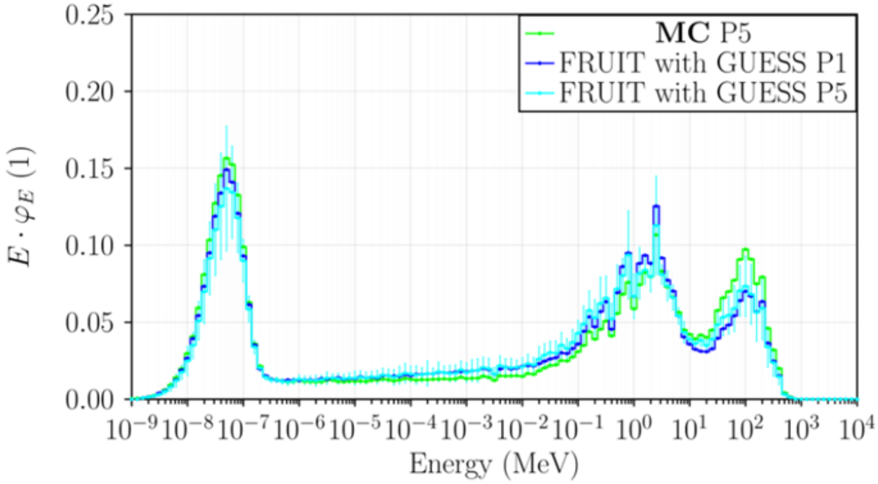

Figure 3: Unfolding test using the isotropic response matrix and changing the guess spectrum.

1.3 Experimental tests

The electronic boards for the project were designed by DIGITECH srl (Peccioli, Pisa) and tested by LEMRAP.
The electronic chain used for the experiment is made up of two different boards, shown in Fig. 4:

- a multi-channel analogue board, in order to correctly acquire the pulses produced in the interactions of the neutron field with the neutron spectrometer;
- a digital board and a microprocessor, in order to discriminate the pulses beyond a certain threshold (due to neutrons and not to photons or electronic noise) and to count them using a dedicated software.

The aim of this activity was to optimize the parameters of the analog board to extract a neutron pulse height distribution from the silicon carbide detector when exposed to neutrons.
In addition, a challenging work was performed in order to guarantee stability and efficiency for a 42-channels analog-digital system.

An example of Pulse Height Distribution (PHD) obtained with a Silicon Carbide detector covered with 6-Lithium Floride (see Fig.5) in the thermal neutron source HOTNES (Thermal Neutron Source in ENEA Frascati) is reported in Fig. 6.

During 2024, a set of experimental tests was performed in CMS cavern with different configurations in order to study the response of the system under variable experimental conditions (proton-proton, heavy ions collisions).
An example of experimental configurations (4 Bonner Spheres with 4 detector couples, one bare

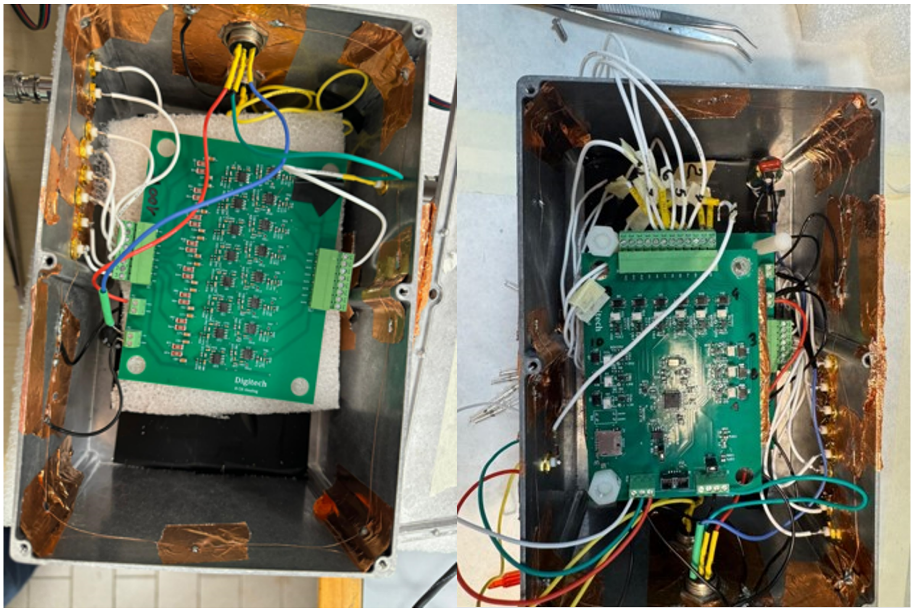

Figure 4: (Left) Analogue board equipped with pre-amplifier and amplifiers. (Right) Digital board with comparator and counting microprocessor.

Figure 5: SiC placed inside HOTNES.

and one covered with 6-Lithium Floride) installed by our research team in CMS experimental cavern is shown in Fig. 7.

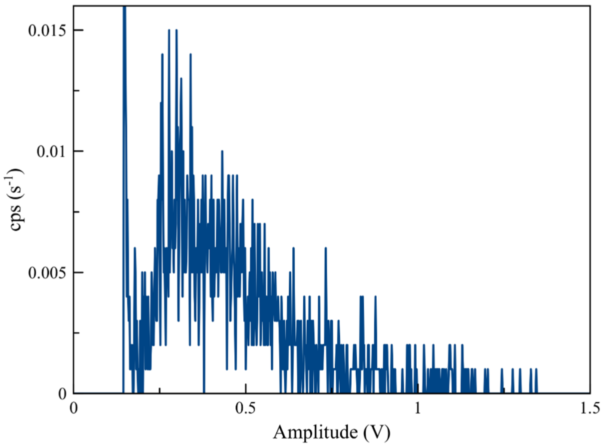

Figure 6: Spectrum of the 7.6 mm2 SiC obtained at HOTNES with the 3-channel DIGITECH board.

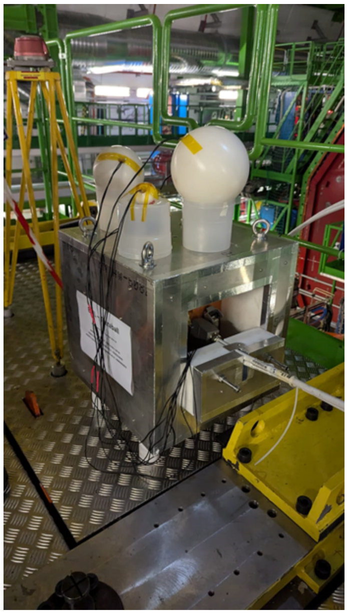

Figure 7: Experimental set-up in CMS cavern with 4 Bonner Spheres, each one containing a couple of SiCs (one bare and one covered with 6-Lithium Floride).

First experimental results show that the count rate of covered detectors is proportional to the instantaneous luminosity (see Fig. 8).

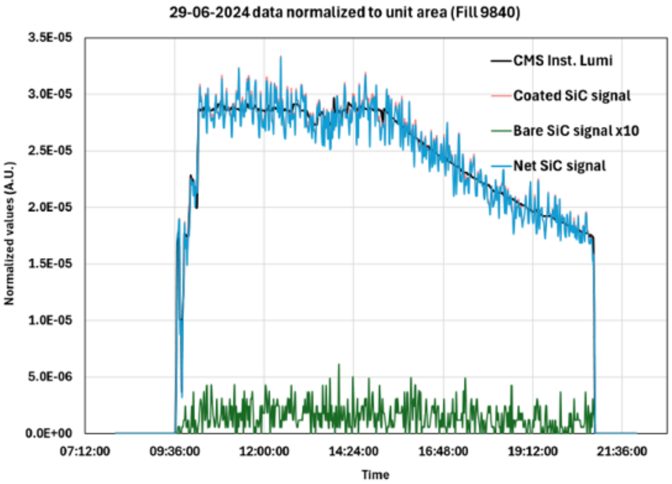

Figure 8: Neutron count rate of a covered silicon carbide as a function of instantaneous luminosity.

2 SAMADHA (CSN 5)

The SAMADHA project aims to investigate and study the neutron dose due to secondary neutrons produced by the interaction of cosmic particles with Oxygen and Nitrogen in atmosphere reaching the Earth below the SAA (*South Atlantic Anomaly*), a region in the planet with the lowest geomagnetic field where few or no data are available. This dose account for about one half of the effective dose received by humans at high-altitudes (i.e. commercial flights $5000 \div 7000$ m). Ambient dosimetry campaigns will be performed in high altitude sites in the SAA area, to study the relation between dose rate and space weather/atmospheric phenomena particularly at the high-altitude Chacaltaya Lab (5240 m) Bolivia. Neutron spectrometry using a new spectrometer designed specifically for the measurement of cosmic neutrons will be done to provide an accurate neutron dose assessment and obtain information on the factors affecting the dose contributions such as environmental conditions.

The SAMADHA research group consists of multidisciplinary experts from dosimetry, cosmic ray physics, solar physics, space weather atmospheric physics, with experience in instrumentation and data analysis. INFN-LNF LEMRAP is one of the 5 collaborating groups and is responsible for:

- Design and construction of a Bonner sphere neutron spectrometer for measurements at high elevation;
- Ancillary systems for unattended operations;
- Monitor and data acquisition software;
- Data analysis and simulations.

The Bonner sphere spectrometer was completely built, characterised and calibrated in reference secondary standard field of ^{241}Am-Be (Politecnico di Milano), their diameter are:

- 80 mm;
- 100 mm;

- 120 mm;
- 150 mm;
- 170 mm;
- 200 mm;
- 200 with lead-bullets insert (apparent density of bullets $\rho \simeq 6.758$ g/cm^3);
- 200 with iron-bullets insert (apparent density of bullets $\rho \simeq 4.8094$ g/cm^3).

The internal metal parts in lead or iron (steel) are needed to increase the response above 10 MeV.

Figure 9: Bonner spheres of the SAMADHA spectrometer installed in Chacaltaya laboratory (left). The Chacaltaya laboaratory in Bolivia (right).

After manufacturing, the spheres where mechanically characterised in terms of actual sizes and density of all parts, and a very realistic MC (*Monte Carlo*) modelling of their response was performed.
The response functions for the SAMADHA spheres were simulated using the MCNP6 code for an extended neutron incidence energy range (from 1 meV to 5 GeV) to cover thermal to cosmic neutron energies.
Three experimental / maintenance campaigns in Chacaltaya Laboratory were conducted:
March 2023: Installation of the system.
November 2023 and November 2024: Replacement of discharging detectors / damaged boards.
The typical energy distribution of the neutron fluence at Chacaltaya site is reported in Fig. 10.

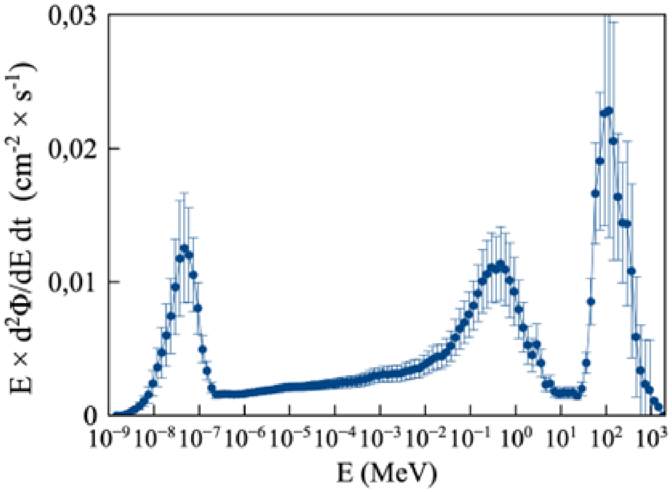

Figure 10: Energy distribution of the neutron fluence rate in Chacalataya: one week of acquisition in april 2024.

3 Compact neutron sensors for particle therapy applications

3.1 Radiation hard silicon carbide thermal neutron detectors for quality assurance in BNCT

Quality Assurance in BNCT dosimetry includes the determination of spatial distributions of thermal neutrons in a water phantom. Activation foils are typically adopted as thermal neutron detectors, making measurements time consuming and requiring considerable manpower. This process would be greatly simplified if an active thermal neutron sensor existed which could scan the volume of a water phantom, as done in conventional radiotherapy with electron LINACs. To this aim, an experiment was organised using rad-hard Silicon Carbide Schottky diodes with active area 1 mm^2, sensitized to thermal neutrons with a 30 μm ^6LiF coating. To operate in water, they were made waterproof through a customised 3D printed plastic holder. A suitable neutron field was produced by degrading the 14 MeV beam from the ENEA Frascati Neutron Generator with an assembly formed by a copper-lead shielding followed by a water phantom. The thermal neutron fluence achieved in the water phantom was in the order of $2-3\ 10^5 cm^{-2}s^{-1}$. The spatial distribution of thermal neutrons in water was measured using both the Silicon Carbide Schottky diodes and the gold activation foils. The experiment was fully simulated with MCNP.
In this experiment, a couple of radiation hard Silicon Carbide (SiC) diodes were used. One of them was coated with ^6LiF. The response to thermal neutrons is considered as the difference between the response of the SiC coated with 6LiF and the one bare. In Fig. 11 the configuration of the SiCs in the measurement points is shown. The cylindrical part is used to protect the sensors and the induced electronic signals from water.

In this experiment, thermal neutrons induced the Pulse Height Distribution (PHD) shown in Fig. 12.

In Fig. 13 the irradiation set-up when gold foils were used is shown. Different 3D plastic adaptors were used so the positions at time of using SiC sensors or gold foils were reproducible to an acceptable uncertainty in the positioning.

Depth and lateral response profiles of radiation detectors are of interest for the medical

Figure 11: SiC+LiF and SiC-bare pair coaxially cabled and encapsulated in the 3D-printed, waterproof holder. Right: X-ray image of the detector complex.

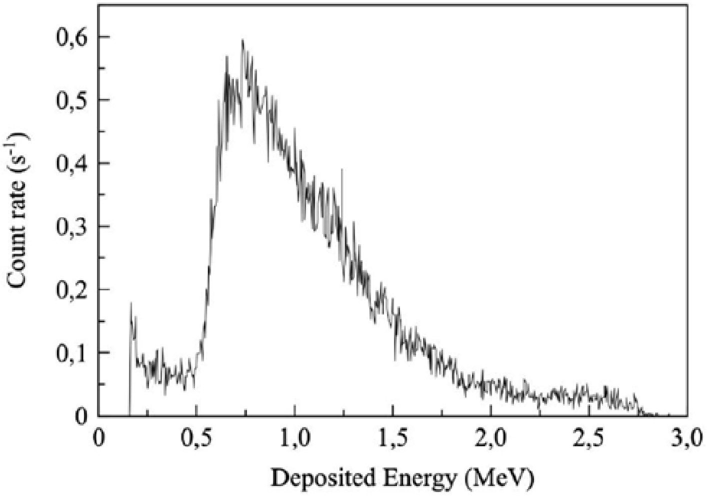

Figure 12: Typical PHD for the SiC+LiF detector.

physics community and they were obtained in this work.
In Fig. 14 it is shown the depth profile from SiC+6LiF diodes experimentally measured, and simulated. In Fig. 15 it is shown the lateral profile from SiC+LiF diodes experimentally measured, and simulated.

Figs. 14 and 15 show agreement in the relative responses exhibited by the suggested SiC sensors, the traditional detectors used in Quality Assurance in BNCT dosimetry, i.e., gold foils and their respective Monte Carlo simulations on the response.

3.2 Compact neutron sensors for better determination of neutron doses in hadron therapy

In hadron therapy, neutrons are the most important component for peripheral dose, as they irradiate the whole patient. They can extend in energy from thermal up to hundreds MeV neutrons. Neutrons from MeV to tens of MeV range are particularly important as their radiation weighting factor is as high as 20. The secondary neutron field in hadron therapy has been studied in the

Figure 13: From left to right: FNG target, copper-lead energy degrader and water tank phantom embedding the 3D-printed activation foil holder.

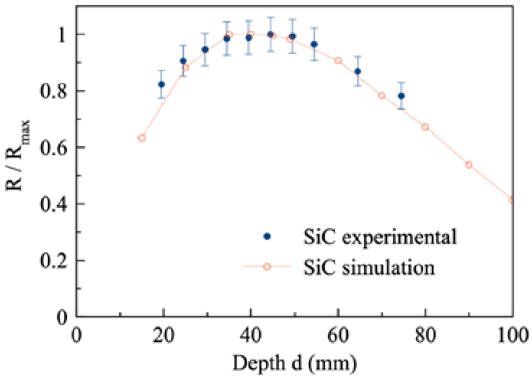

Figure 14: Depth profile from SiC+LiF diodes experimentally measured, and simulated.

areas around the patient but not ”in” the patient.

By contrast, in-phantom measurements would be needed to infer peripheral doses. Very few measurements of this type were done, all of them based on passive detectors such as nuclear-track and thermo-luminescence sensors. Passive detectors require time-consuming post-processing and are not suited for implementation on a large scale.

On the contrary, the availability of miniaturised active neutron sensors with accurate dose equivalent response would certainly encourage a large number of hadron therapy centres to perform peripheral dose measurements. A detector suited for peripheral neutron field measurements in hadron therapy should fulfil the following requirements: compactness, to minimally perturb the field; real-time capability; radiation resistance; insensitivity to the associated photon field and to charged particles, sufficient energy discrimination capability to provide accurate dosimetric results. Indeed, the radiation weighting factor for neutrons is energy-dependent.

An assembly of 3 Silicon detectors with different neutron converters was prepared, one neutron converter was ^{6}LiF so that detector configuration would give a signal to the thermal part of a complex neutron field. Another neutron converter was polyethylene which is rich in hydrogen so

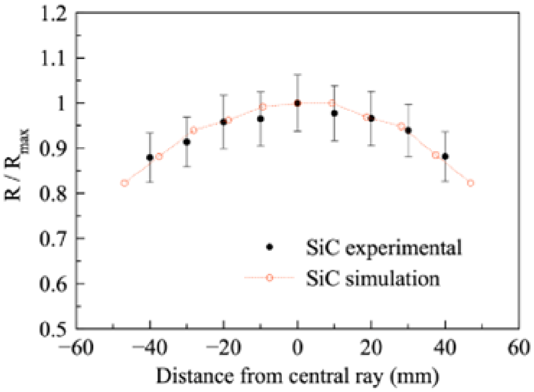

Figure 15: Lateral profile from SiC+LiF diodes experimentally measured, and simulated.

fast neutrons can be detected through the recoil protons generated in polyethylene. Fig. 16 shows an assembly of the 3 silicon detectors.

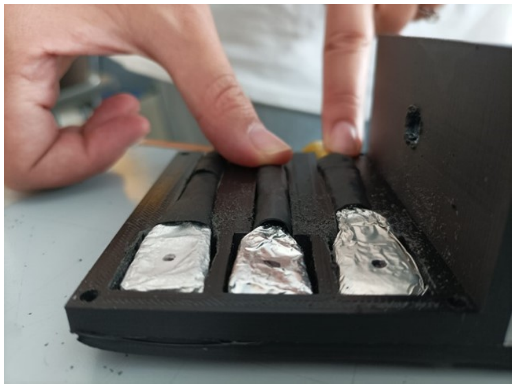

Figure 16: Assembly of the 3 silicon detectors. The configurations are the following: Si Bare, Si+6LiF and Si+Polyethylene.

The assembly as well as the associated nuclear electronics was irradiated in the 14 MeV fusion neutrons available at the Frascati Neutron Generator of ENEA Frascati. The assembly was placed at 90° in respect to the direction of the accelerated deuterium impinging on the tritium target and at a distance of 60 cm. The induced Pulse Height Distributions (PHDs) in each configuration is shown in Fig. 17. The “Difference PHD” is the difference between the responses of the configuration of Si+Polyethylene and the configuration of Si (bare Si).

The “Difference PHD” is the response that is proportional to the fast neutrons of a complex neutron field.
With this kind of assembly, a determination of the thermal neutron fluence and fast neutron fluence could be performed in particle accelerators where complex neutron fields exist.

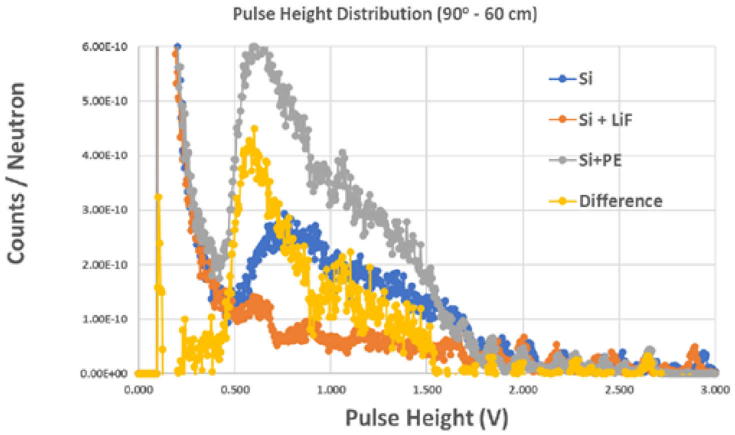

Figure 17: Figure PHDs for each configuration (Si, Si+LiF, Si+Polyethylene(PE)) as well as the difference PHD obtained with the configuration of PE and the bare configuration. Positioning 90º at 60 cm.

4 NEUCOL (CNTT)

A multi-cell slow neutron collimator has been patented (Italian patent 102020000010132 ”collimatore” licensed on 16-5-2022), capable of improving the spatial resolution and divergence of neutron imaging systems. The prototype (see Fig. 18) has been used for neutron tomography in an operational environment (current TRL =7).

As the collimator is made of a borated PLA (polylactic acid) composite, its long-term exposure

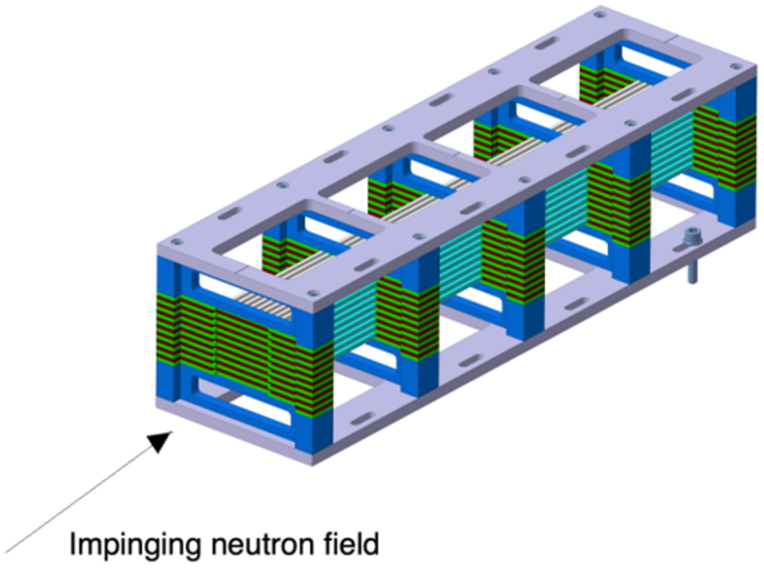

Figure 18: 3D model of the compact neutron collimator.

to intense radiation fields is expected produce alterations in the polymeric structure resulting in macroscopic damages such as the radiation-induced embrittlement.
As the borated PLA used for this project is a new material, especially developed for the patented collimator, this NEUCOL project aimed at investigating these aspects through numerical methods and has carried out experimental activities in order to qualify the prototype (final TRL =8) by studying the embrittlement of the absorbing elements after severe irradiation simulating prolonged use over time (see Fig. 19).

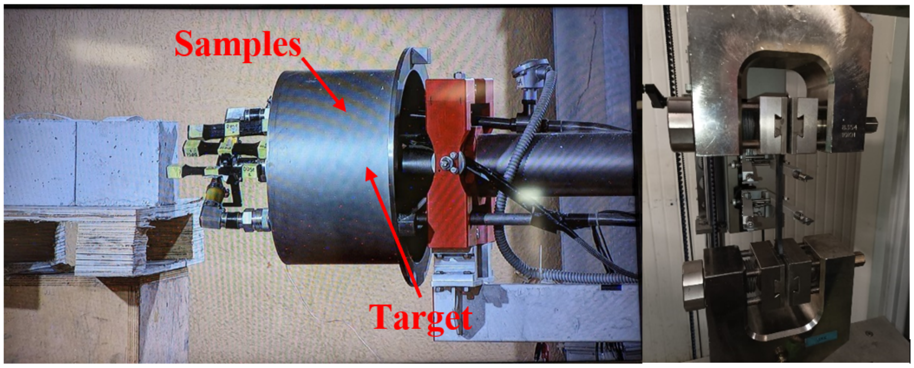

Figure 19: Borated plastic samples being irradiated (left) and mechanically tested (right).

The NEUCOL project has successfully evaluated the degradation and embrittlement of the neutron absorbent elements that compose the multi-cell slow neutron collimator (PCT Patent n. PCT/IB2021/053856 Collimator), currently on TRL = 7 stage, caused by the incident mixed field radiation commonly found in neutron imaging facilities. This was accomplished through extensive computational calculations and dedicated experimental campaigns. Samples were manufactured and a dedicated gamma sensor was acquired, tunned and calibrated for this project. Using the PGAA technique the amount of boron in the manufactured samples was determined and the manufacturing process exhibited an overall accuracy of 4%.
These samples were irradiated to the three main components of the mixed field radiation to simulate long-term usage and tested their mechanical properties after irradiation. The data show that the neutron absorbent elements can withstand a decade of usage without showing relevant mechanical damage.

5 EYERAD (INFN_E)

EyeRAD is an initiative aimed at observing environmental radioactivity, in particular aimed at detecting artificial radionuclides emitted following occasional anomalous events. The strengths of EyeRAD are the highly sensitive instrumentation present in the various structures and, above all, the high level of expertise in nuclear measurements and in solving complex conceptual and technical problems offered by its staff. Furthermore, the national distribution of the various structures of the institution allows for good coverage of the Italian territory for the planned sampling.
EyeRAD is configured as support for national institutional monitoring networks, with a view to a synergic effort aimed at safeguarding the population's exposure, in particular in the event of anomalous or accidental events. In its initial configuration, EyeRAD includes eight INFN "pilot structures" engaged in periodic sampling of atmospheric particulate matter and a structure

available to support training activities.
As far as the activities for LEMRAP at INFN-LNF concerns, an AirFlow HVS-TSP aspirator from AMS Analitica was installed near the laboratory for the sampling of artificial radionuclides. The noise levels of the system were tested to not disturb other laboratories, see Fig. 20.

Figure 20: Position and noise level testing of the system.

In order to have the best working conditions and for remote control access, the aspirator's firmware was updated as shown in Fig. 21.

AMS ANALITICA

Finish.
Update OK!

developed by ER Elettronica www.er-elettronica.i

Figure 21: Update of the system's firmware.

The system is now operative and is continuously sampling, an example of a test filter samples before and after aspiration is shown in Fig. 22.

More test filters are being sampled and studied for the detection of artificial radionuclides in the environment using a recently acquired and calibrated X-ray/gamma sensitive LaBr3(Ce) scintillator.

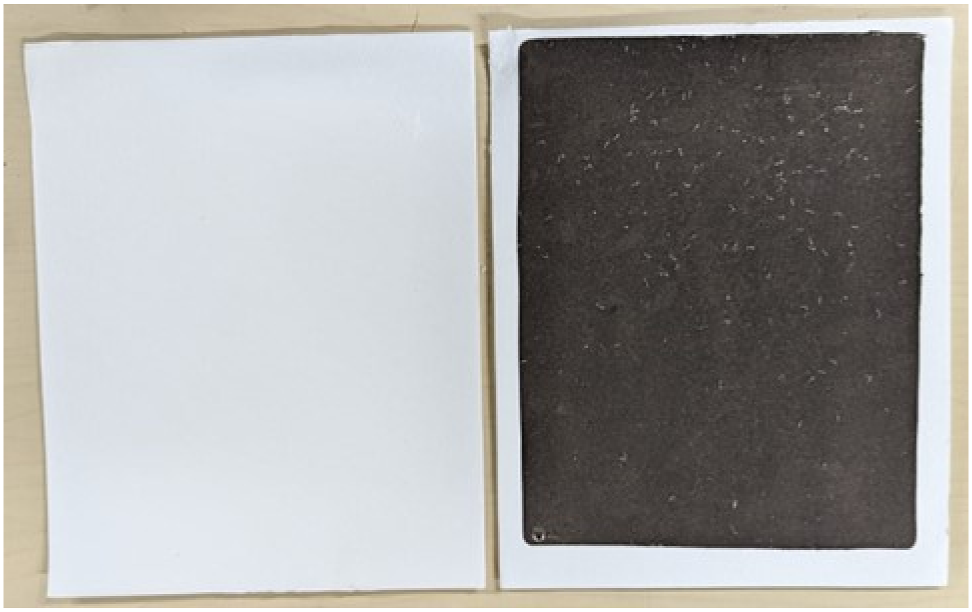

Figure 22: Test filter samples before and after aspiration.

6 EUROFUSION

In collaboration with ENEA Frascati (Fast Neutron Generator), the LEMRAP group is participating to EUROFUSION (https://euro-fusion.org/eurofusion/) experiments aimed at verifying the attenuation properties of multi-material layered neutron shields. Tungsten mixed with an efficient neutron moderator (such as water or polyethylene) might represent an optimal shielding material for fusion experiments, especially in regions where space constraints make difficult reaching the required neutron/gamma attenuation.

This is the case of DEMO (https://euro-fusion.org/programme/demo), where the first wall of the plasma chamber and the bio-shield will be composed of tungsten. Owing on the inelastic scattering above the MeV, Tungsten has good shielding properties with low neutron activation. Also, the high melting temperature and high heat refractoriness, make tungsten the best choice as first plasma wall facing component.

Thin neutron activation foils of different materials are the classical method to characterize the neutron field inside a mock-up shielding assembly.

This method is widely accepted, reliable and based on well-known activation cross sections. However, since the activation foils must be counted one by one, this method is time consuming and requires considerable manpower. These measurements would be greatly simplified if an active neutron sensor was available to scan the volume of the mock-up shielding assembly.

The experiment here presented relies on two Silicon Carbide (SiC) solid state detector simultaneously acquired:

- A fast neutron sensor relying on a bare Silicon Carbide, hereafter named “bare-SiC”. Fast neutrons are detected through the reaction $^{28}Si(n,\alpha)^{25}Mg$ with threshold energy 2.1 MeV;
- A thermal neutron sensor relying on a Silicon Carbide covered by a 30 μm thick ^{6}LiF layer, hereafter named “SiC+LiF”.

The SiC diodes have been chosen because of their high radiation hardness. Based on previous

simulations with MCNP5 and the JEFF-3.3 nuclear data library, a prototypal shielding assembly, made of layered tungsten and Perspex sheets, was built at ENEA Frascati.
An irradiation experiment with 14.7 MeV neutrons from the Frascati Neutron Generator (FNG) was performed, aimed at validating the use of rad-hard Silicon carbide sensors for mapping the thermal and fast neutron field within the assembly.
The dimensions of the mock-up are $48 \cdot 42 \cdot 39.4\ cm^3$ (See Fig. 23).

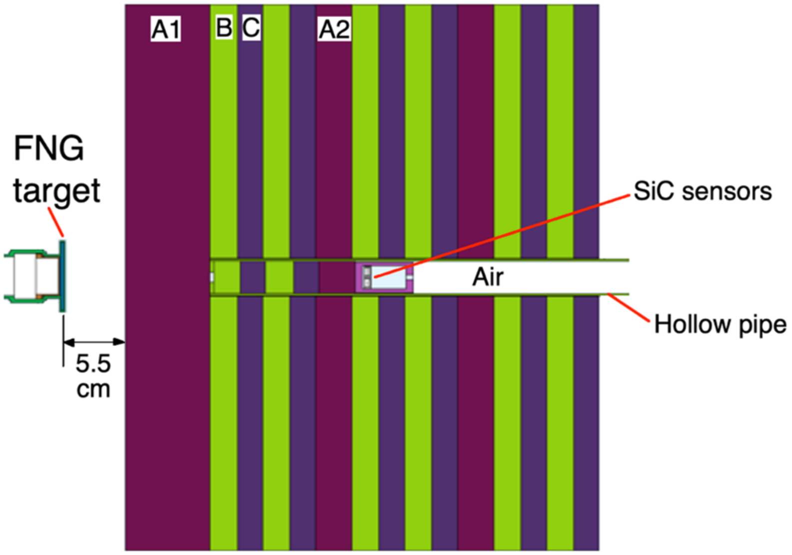

Figure 23: Representation of mock-up layers. A1 = Tungsten densimet-180 (7 cm thick); B = steel SS-316L (2.4 cm thick); C = Perspex (2 cm thick); A2 = Tungsten densimet-180 (3 cm thick).

The measurements took place at FNG in D-T mode at an emission rate of about $0.5 - 1.0 10^{10} s^{-1}$. The average neutron energy on the front face of the mock-up was 14.7 MeV. Main results are presented in Figgs. 24 and 25.

Fig. 24 generally exhibits an exponentially decreasing trend, due to the combination of inelastic scattering in W and radiative capture in H. This is superimposed to "local maxima" immediately after the W layers, due to (n,2n) neutron multiplication in W. in the oscillating trend of $\Phi_{thermal}$ feature an almost oscillating behavior, with the maxima occurring a densimet-180 layer.

In Fig. 25, the results for the fast neutron fluence are shown. This exponentially decreases inside the mock-up, due to the combination of inelastic scattering in W and elastic scattering in H.

7 External activity (conto terzi)

Contract TTA-24LNF-018 between INFN-LNF and Institut de Radioprotection et de Sureté Nucleaire (IRSN, France) "Neutron spectrometry for the Van Gogh irradiator neutron sources, Am-Be and Cf-252, located in the Cadarache center (Bouches du Rhône)".

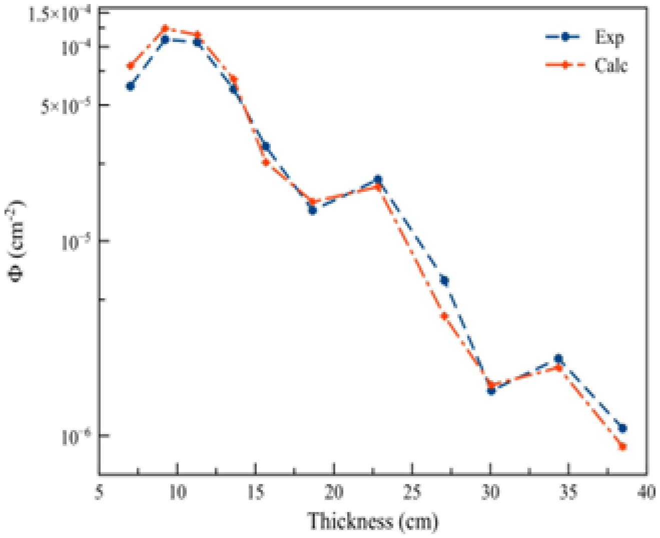

Figure 24: Experimental (SiC+LiF detector) and simulated (FLUKA) thermal neutron fluence per emitted neutron inside the mock-up as a function of the detector position. Uncertainties are smaller than graphical symbols. Dashed line are only eye-guide.

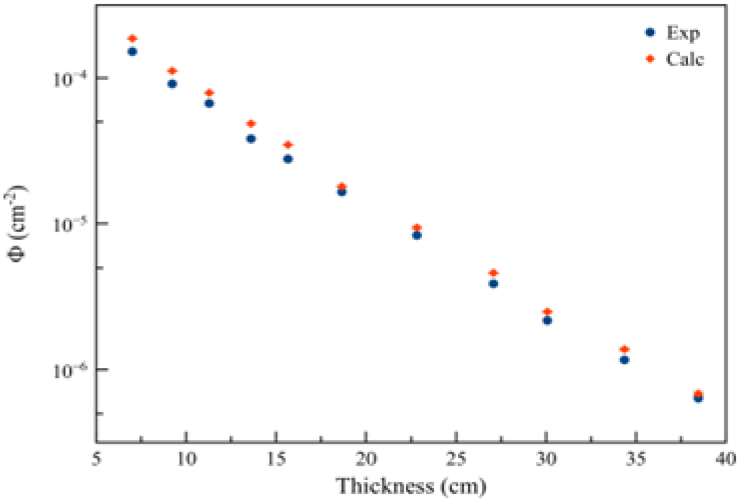

Figure 25: Experimental (SiC detector, exploiting the $28Si(n,\alpha)^{25}Mg$ with threshold energy 2.1 MeV) and simulated (FLUKA) fast neutron fluence per emitted neutron inside the mock-up as a function of the detector position. Uncertainties are smaller than graphical symbols.

8 List of Conference Talks by LNF Authors in Year 2024

- 9 - 13 december 2024 Geneva, Switzerland. CMS Upgrade Week held at CERN. A. I. Castro-Campoy et al., The first TB Carrot (arm) assembled and tested at LNF.
- 9 October 2024 Teddington (UK) Neutron Users Club NUC 2024 at the National Physics Laboratory NPL.

A. I. Castro Campoy et al., A simple PGAA system for boron determination in the tens of milligram range. R, Bedogni et al., The evolution of Bonner Spheres into single moderator neutron spectrometers.

- 7-9 October 2024, Roma, Università La Sapienza, CMS Italia meeting. Roberto Bedogni et al., Invited talk "Tetraball".
- CMS Upgrade Week held on CERN From 16th to 20th September 2024. Poster. Caballero-Pacheco, M.A. on behalf of CMS-BRIL collaboration. Tetra-Ball: a novel neutron spectrometer for the BRIL upgrade project.
- 24 – 28 june 2024 Krakow, Poland. ICNCT20. 20th International Congress on Neutron Capture Therapy.
- R. Bedogni, L. Russo, A. Calamida, A.I. Castro Campoy, M.A. Caballero-Pacheco, D. Dashdondog, E. Mafucci, V. Monti, M. Costa, A. Pietropaolo, M. Bunce, D. Thomas, P. Toroi, J. Huikari. Benchmarking the NCT-WES neutron spectrometer with monoenergetic neutrons and radionuclide neutron sources.
- M. A. Caballero-Pacheco, R. Bedogni, L. Russo, A.I. Castro Campoy, D. Dashdondog, A. Pietropaolo, A. Calamida. Use of semiconductor-based thermal neutron detectors for quality assurance in NCT facilities.

- 28 – 31 May 2024 SATIF-16 16th workshop on Shielding aspects of Accelerators, Targets and Irradiation Facilities - National Laboratories of Frascati, Italian National Institute for Nuclear Physics (INFN).
- R. Bedogni et al., From Bonner Spheres to real-time single-moderator neutron spectrometers.
- M. A. Caballero Pacheco et al., The Tetra-Ball single moderator neutron spectrometer.
- A. Pietropaolo et al., A new neutron monitor with extended energy range.
- A. Calamida et al., DOIN: a novel electronic personal dosemeter for neutrons.
- L. Russo, et al., Measuring high photon dose rates with semiconductor dosimeters.
- D. Dashdondog et al., The HOTNES thermal neutron facility.
- A. I. Castro Campoy et al., Prompt gamma activation analysis of borated concrete at the radionuclide-based HOTNES facility.

9 Publications

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