LEMRAP Laboratory
2025 Annual report

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In collaboration with
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ENEA Frascati

1 BRIL (CMS, CSN 1)

1.1 Introduction

In collaboration with Torino University and INFN section

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.
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 developed "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 averaging the signals of all detectors located at the same radial position;
- 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

The Tetra-Ball (T-Ball) is an extended-energy-range single-sphere neutron spectrometer specifically designed for long-term neutron spectrum acquisition during the High-Luminosity LHC operation in the CMS cavern. Compared to its predecessor, the SP2 system [1], the T-Ball features a reduced number of thermal neutron sensors, from 31 to 21 Silicon Carbide (SiC) detectors coated with ^{6}LiF, enabled by a tetrahedral arrangement of the detectors within the moderator volume. The spherical polyethylene moderator has a diameter of 28 cm and incorporates a lead insert to enhance sensitivity to neutrons with energies exceeding 10 MeV. The influence of neutron field anisotropy on the spectrometric performance of the device was investigated by means of Monte Carlo simulations. Although the analysis does not encompass the full range of possible neutron

energy distributions and operational conditions, the obtained results indicate that the T-Ball provides satisfactory spectrometric capabilities and maintains a good degree of isotropy across most high-energy application scenarios.
A comparison between the spatial distributions of the thermal neutron detectors in the T-Ball and in the SP2 [1] configuration is reported in Fig. 1.

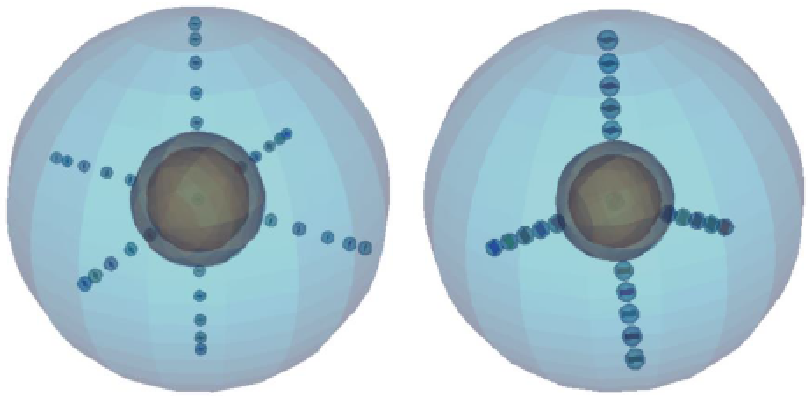

Figure 1: Arrangement of the internal thermal neutron detectors in the SP2 (left) and T-Ball (right) single-sphere neutron spectrometers.

The Tetra-ball response matrix is shown in Fig. 2.

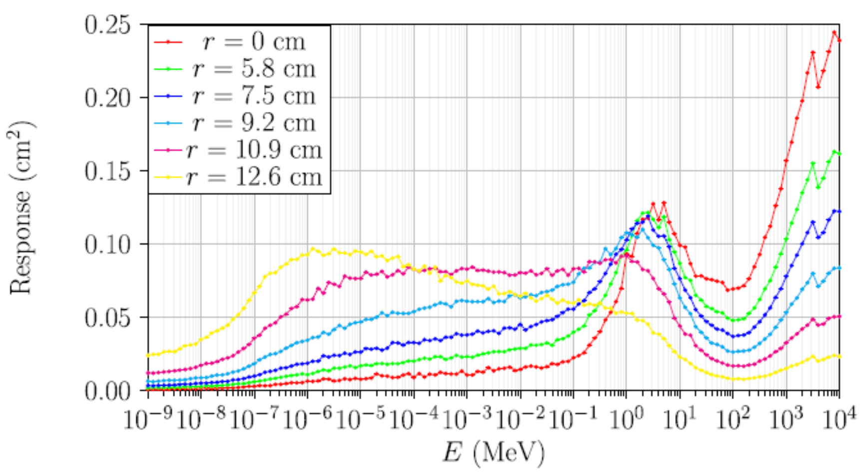

Figure 2: Response matrix of the T-Ball spectrometer, defined as the average count per unit fluence of the detectors at the same radial position, obtained under isotropic irradiation condition.

Figure 3 presents examples of neutron spectra (label "FRUIT") obtained by simulating the exposure ot the TetraBall in a CMS-like radiation environment, using two different "guess" spectra.

"MC" denotes the reference spectrum, which is well reproduced by the unfolding procedure [2].

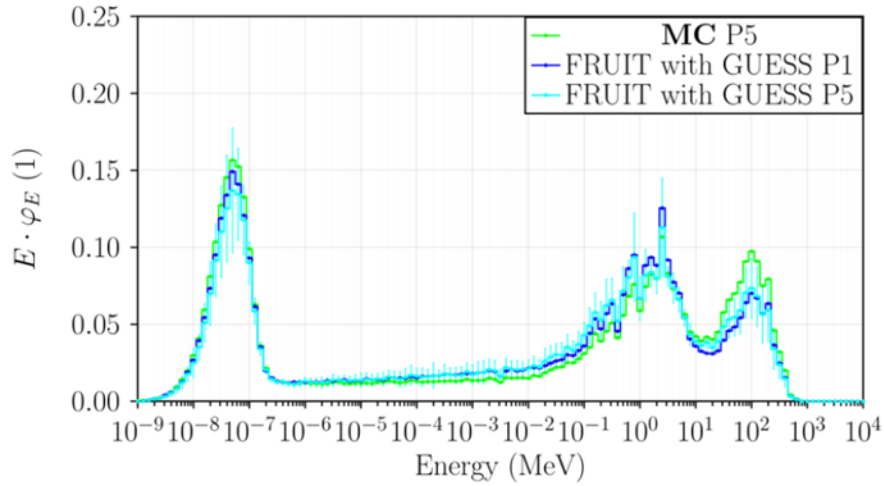

Figure 3: Neutron spectrum unfolding test in CMS-like radiation envirnment.

1.3 Experimental

The following activities wew conducted in 2025:

- The first Tetraball was assembled in Frascati in May 2025;
- Electronic testing was performed in Turin in June 2025. The DAQ system was elaborated by DIGITECH SRL (Peccioli, Italy) and the control / elaboration software by INFN Turin (See Fig. 4);
- Commissioning in CMS cavern during LHC Technical Stop (23-26 june 2025) in position BHTOP+, see Fig. 5.

For every TetraBall internal detector, the neutron counting rate is proportional to LHC luminosity (see Fig. 6).
Validation of the simulated energy and angular response of Tetraball spectrometer was carried out at the MONNET (JRC Geel) quasi mono-energetic fast neutron facility in November 2025.
Additional calibration with a continuous-spectrum (0.01 - 11 MeV) neutron source of $^{241}Americium{-}Boron$ was performed at ENEA C.R. Frascati in December 2025.
Data analysis is ongoing.

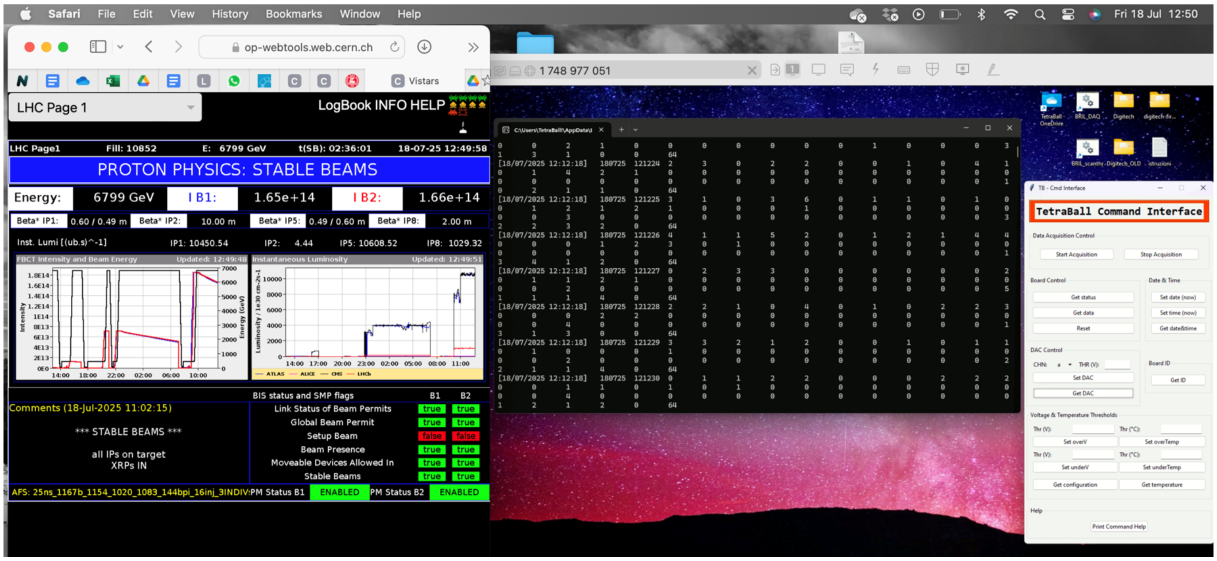

Figure 4: Tetraball software interface for data acquisition.

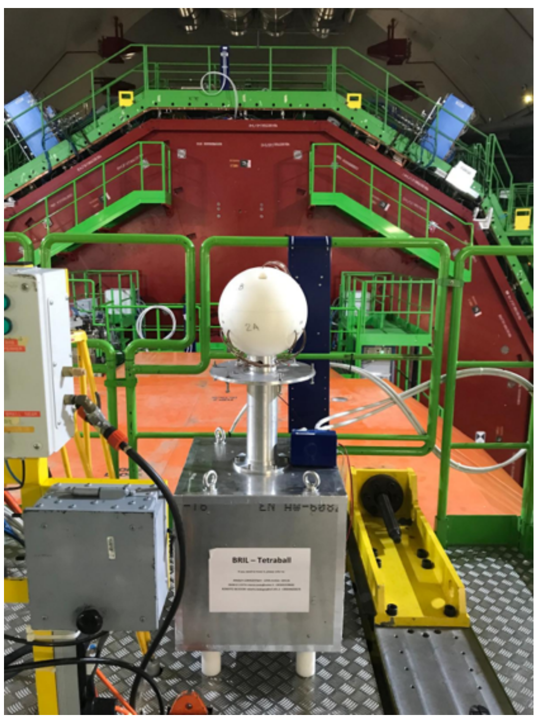

Figure 5: First Tetraball spectrometer installed in CMS cavern during LHC Technical Stop (23-26 june 2025).

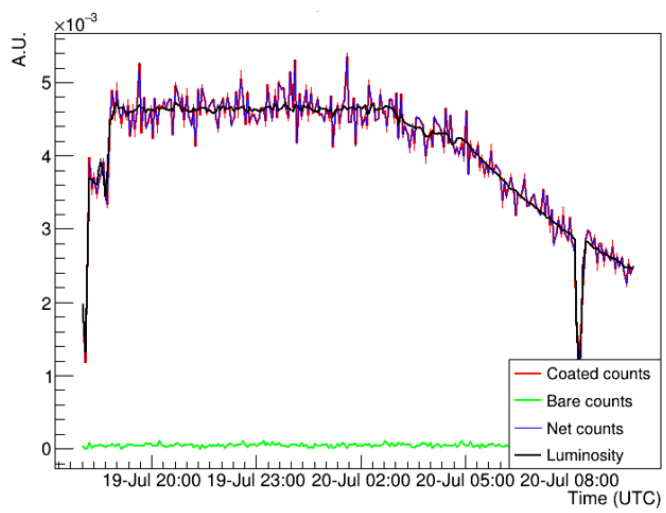

Figure 6: Counting rate proportionality to LHC luminosity. All values are normalized to unit area.

2 DOIN LAST MILE

In collaboration with:

- *DIGITECH SRL (Peccioli, Italy);*
- *ENEA C.R. Frascati.*

DOIN is a novel multi-sensor type of active neutron personal dosemeter designed and prototyped at LEMRAP. Owing to a patented design, DOIN achieves IEC-compliant energy and directional response, and an improved sensitivity (factor more than 2) with respect to existing commercial devices of the same class. DOIN was designed to provide either the neutron or the gamma ambient dose equivalents, Hp(10).
Activities performed in 2025 are listed below:

- Mechanical, electronic and three-dimensional design of the prototype;
- Monte Carlo (MCNP) simulations of the response function and energy-identification curve (See curve in Fig. 7). According to the design, the reading of the internal thermal neutron detectors are combined to obtain the energy identification index "q". When used in unknown field, the direct measurement of q allows selecting the most appropriate calibration factor;
- Assembly, mechanical and electronic testing of the first prototype;
- Production of a mini-series of prototypes to be distributed to external users for field testing (See Fig. 8 - left). The calibration of these devices took place at the ENEA C.R. Frascati using a continuous-spectrum $^{241}Am-B$ source, see 8 - right.

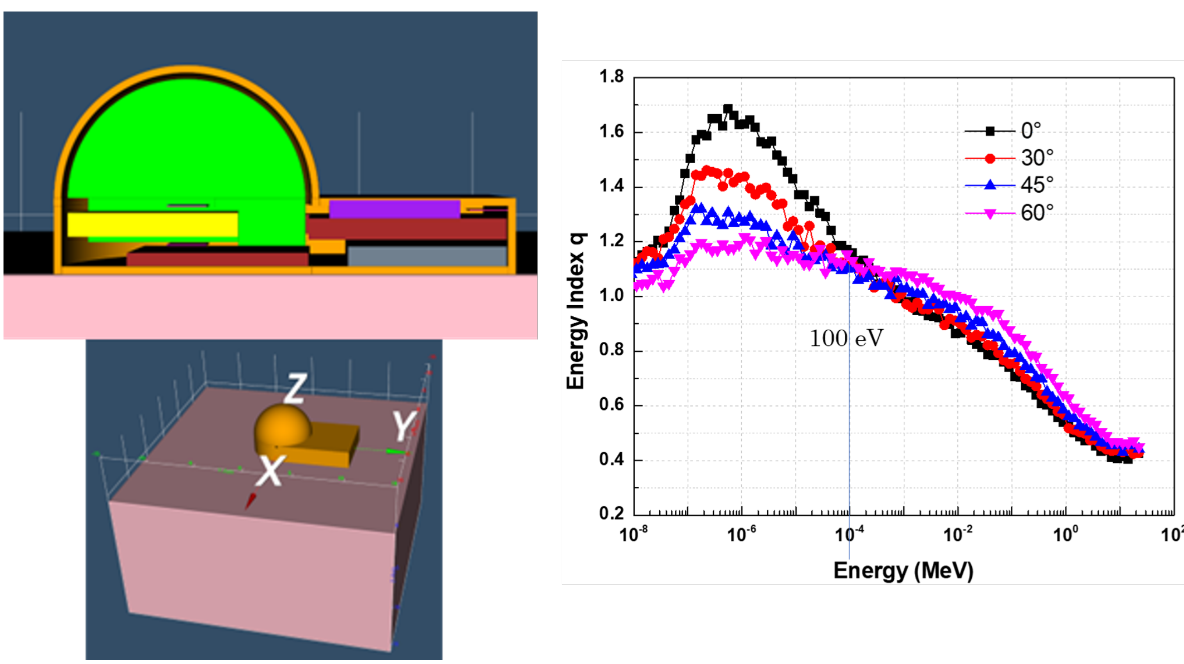

Figure 7: (left) Geometry for the MCNP calculations (dosemeter attached to a standard ISO phantom representing the human body), and (right) DOIN's energy identification curve.

Figure 8: (left) DOIN mini-series of dosemeters assembled, and (right) dosimetric tests at ENEA C.R. Frascati.

DOIN's simulated response was experimentally validated at the MONNET quasi mono-energetic fast neutron facility (JRC Geel). According to the experiment, based on monoenergetic energies of 0.144, 0.565, 1.2 and 5 MeV, the overall uncertainty of the simulation model is below 4% (See Fig. 10).

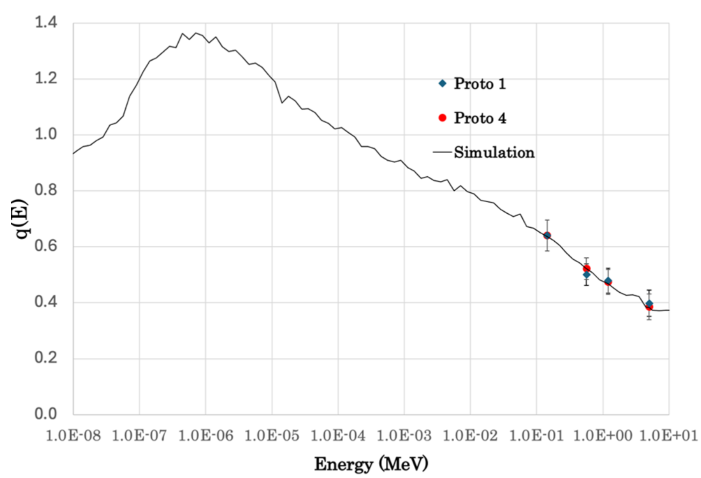

Figure 9: Validation of the energy identification curve.

Dosemeters were sent for field testing at the following external nuclear centres:

- Clinica Universitaria de Navarra (Madrid, Spain) operating a proton therapy;
- 2.5 MeV and 14 MeV fusion research facility FNG (ENEA Frascati);
- Aerospace Dosimetry Laboratory of the Instituto de Estudos Avançados (IEAv Brazil) using a MP320 Thermo 14 MeV fusion generator;
- National Research Council Canada and Bruce Power in Canada (nuclear industry, CANDU reactors);
- Rotunda Scientific Technologies LLC (Mainsfield, Ohio) (nuclear industry).

3 EYEDOS

Contract with Engineering Italy Solutions S.r.l. (Rende, CS) for Call 2 - R&D Projects for MPMI and Midcap (PR ERDF TOSCANA 2021 - 2027, ACTION 1.1.4)

The aim of EYEDOS is developing an active personal dosemeter for the eye lens dose in radiological practices, mainly interventional radiology and cardiology.

From the study of literature and the consultation with experts in the field, the following project goals were identified:

- The use of appropriately filtered silicon sensors (ISO 15382) to respond in terms of Hp(3) as a function of energy and angle;
- The linearity of the response should be verified up to at least 100 mSv/h;
- The dosimeter should therefore be placed on the head, close to the eyes;
- Although a position close to the eye on the most exposed side is the most recommended, this side is not known a priori, and a fixed position on the right or left could disadvantage some operators. Since, at least at this stage, a dosimeter usable by all operators must be designed, the central position between the eyes is considered the best solution.

Preliminary experimental tests carried out during 2025 show the following results:

- In a laboratory environment at INFN and ENEA (see Fig. 10), using well-characterized X-ray fields comparable to those of the ISO Narrow series, the EYEDOS dosimeter demonstrated good performance in terms of linearity, response range, and energy and angular dependence. In particular, it is capable of responding linearly in terms of dose equivalent rate from approximately 1 μSv/h (minimum detectable level) up to 300 - 600 mSv/h, depending on the X-ray beam quality;
- Testing of the EYEDOS dosimeter in a quasi-operational scenario at the Cisanello Hospital (AOUP) made it possible to explore exposure conditions typical of the clinical environment, both in terms of irradiation geometry (simulating the position of the first operator and other operators), field quality and intensity (60, 80, 100 kV, tube currents 0.5 to 5 mA). The X-ray unit was set to produce the combinations of kV and mA used in clinical practice. These resulted into ambient dose rate values at the measurement positions ranging from 120 μSv/h to 25 mSv/h.
  In all these scenarios, the EYEDOS dosimeter was able to correctly estimate the dose equivalent, with maximum deviations ranging from -4% to +28% (position of the first operator, near the X-ray unit)and from -9% to +16% (position of other operators far from the X-ray unit).
  This result is very encouraging, since the accuracy criterion specified by IEC 61526 allows for a wider tolerance interval, from -29% to +67%.

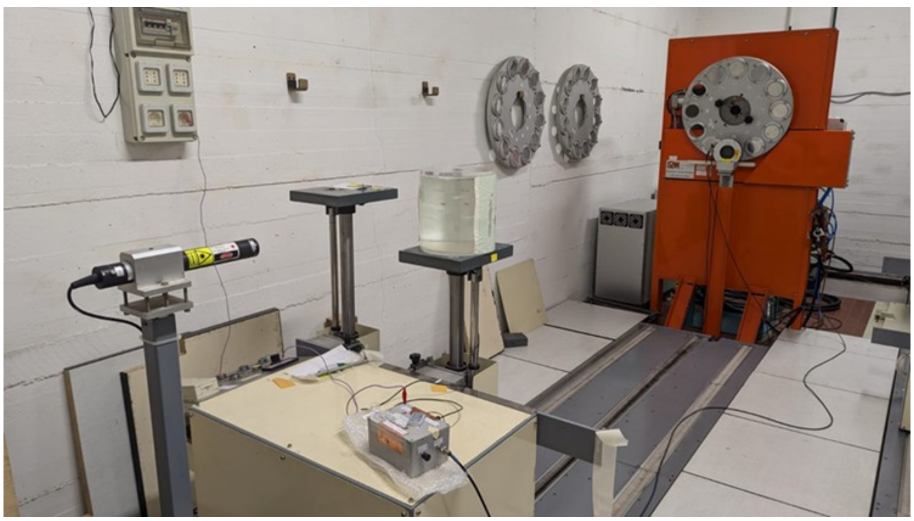

Figure 10: ENEA Bologna - X-ray calibration facility.

4 EYERAD (INFN_E)

In collaboration with INFN Sections/Laboratories of Milan, Bicocca, Ferrara, Napoli, LNGS, Bari, and LNS

EyeRAD is an initiative aimed at monitoring the air particulate to detect artificial radionuclides potentially emitted during nuclear and radiological accidents. The national distribution of the various structures of the institution allows for good coverage of the Italian territory.
EyeRAD is configured as support for national institutional monitoring networks, with a view to a synergic effort for the radiological protection of the population. In its initial configuration, EyeRAD includes eight INFN "pilot structures" engaged in periodic sampling of atmospheric particulate and in associated training activities.
LEMRAP commissioned a 3" Sodium Iodide gamma spectrometer in a 10-cm thick low background shielded structure, see Fig. 11.

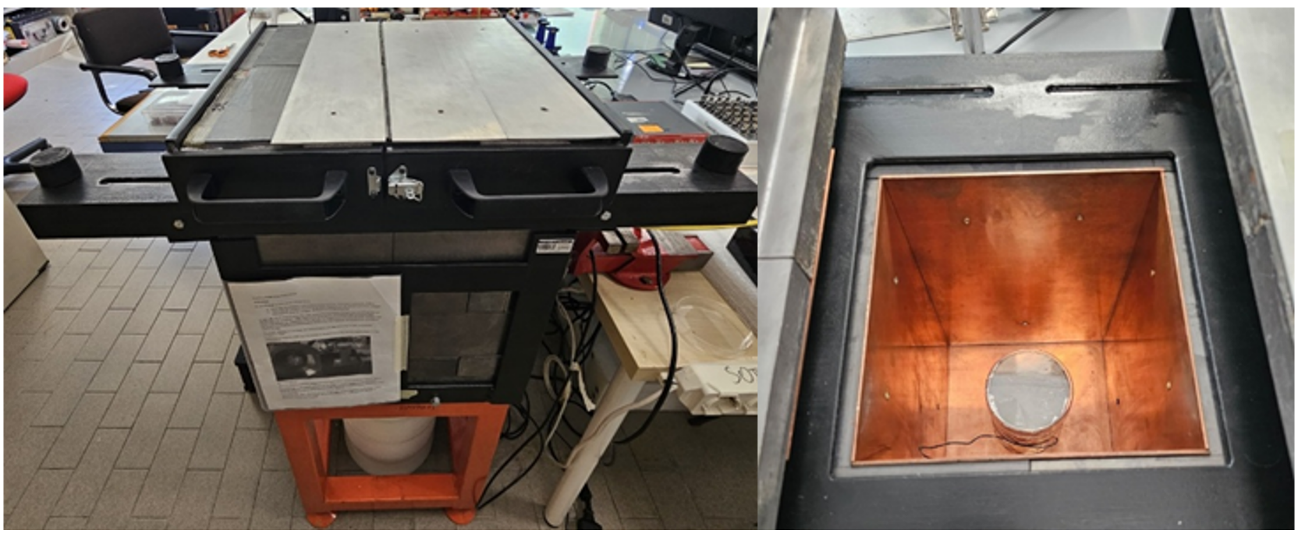

Figure 11: 3" Sodium Iodide gamma spectrometer in a 10-cm thick low background shielded structure.

The atmospheric particulate is sampled in paper filter with the air sampling system shown in Fig. 14. After a typical sampling time of 23 h at 1000 lpm, the filter was gamma-counted after 2, 5, 24, 48 and 72 h from the extraction, obtaining the spectra reported in Fig. 13.

Similar results were obtained by aspirating until 10 Ml. On December 9th, a collaboration meeting was held at the INFN presidency premises to discuss the data and further improve the results. Actions are taking place at this moment to observe the presence of ^{7}Be.

Figure 12: Air sampling system at INFN-LNF-LEMRAP.

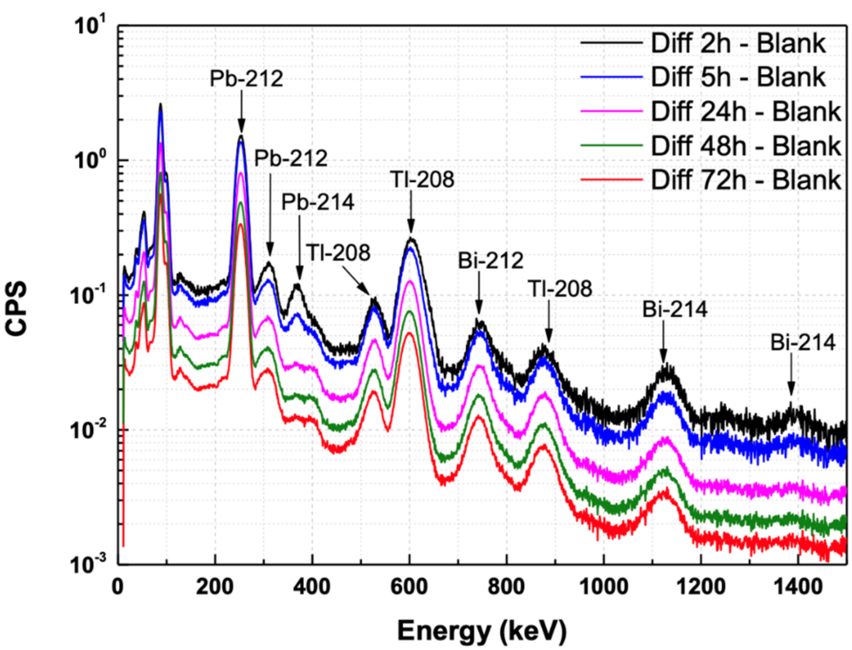

Figure 13: Net spectra measured on the EYERAD filter at 2-, 5-, 24-, 48-and 72-hour times.

5 EUROFUSION

In collaboration with ENEA C.R. Frascati

In the framework of EUROFUSION (https://euro-fusion.org/eurofusion/) a shielding benchmark experiment was organized at the 14 MeV neutron source of FNG (the ENEA Frascati Neutron Generator).
The aim of the experiment was measuring the attenuation curve of thermal and fast neutrons within a concrete mock-up made of 13 blocks with size 50x50x4 cm^3. The concrete has a specific composition to meet the requirements of the DEMO facility.
The detector used is made up of a couple of 7.6 mm^2 Silicon carbide detectors, one bare and one coated with Lithium floride.

- Thermal neutrons are regarded to be proportional to the signal of LiF-SiC − bare SiC;
- Fast neutrons are regarded to be proportional to the signal of bare SiC. The depleted region is in the order of 5 μm.

The detectors are moved in various positions within the block, starting from unshielded (0 block in front, 13 blocks behind) to the position where all blocks are in front. The experimental set-up is shown in Fig. 14.

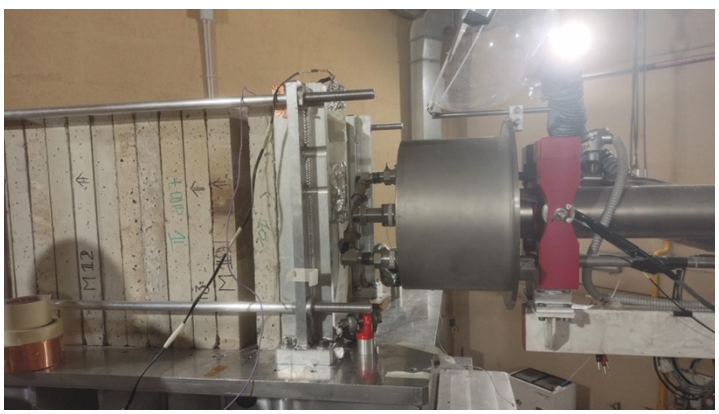

Figure 14: Experimental set-up for EUROFUSION measurements with two silicon carbide detectors.

Transmitted neutron fraction as a function of shielding thickness (in cm) for both thermal and fast neutrons is reported in Fig. 15.
Conclusions may be summarised as follows:

- Thermal neutrons reach a buildup at 20 cm and then slowly decay.
- After an equilibrium layer of about 10 cm, fast neutrons decay with a constant- spectrum mono-exponential with TVL = 19.9 cm. It must be pointed out that the square distance law is combined to an attenuation law.

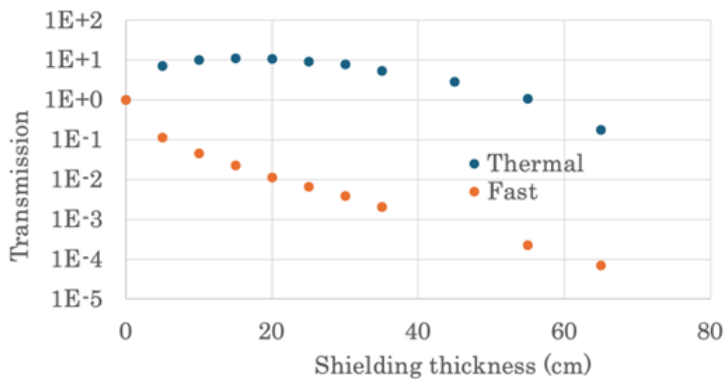

Figure 15: Transmission curve for thermal and fast neutrons.

6 External activity (conto terzi)

6.1 Contract with Helsinki University on the characterization of the neutron fields produced by (p,n) reaction of a solid target (May 2025)

A tunable-energy neutron beam produced with up to 1 mA / 5 MeV protons on a solid LiF target is available at the Physics Department of the Helsinki University for neutron metrology and research applications. The neutron spectra produced in the forward direction from 1960, 2040, and 2310 keV protons were measured using the NCT-WES single-moderator directional spectrometer (RIF). NCT-WES (Neutron Capture Therapy Wide Energy Spectrometer) is a recently developed single-moderator neutron spectrometer with a sharply directional response. Compared to the traditional Bonner spheres, NCT-WES is a very convenient instrument to characterise neutron facilities, as it determines the whole spectrum in a single exposure, and is considerably less sensitive to room-scatter. The data acquired in the Helsinki University (p,n) beam were unfolded using the FRUIT unfolding code, starting from guess spectra obtained with GEANT4 or MCNP6 transport codes.
The unfolding analysis showed that both codes produced plausible spectra, MCNP6 being more accurate for the 1960 and 2040 keV irradiations, and GEANT4 for 2310 keV.
The comparison between the spectra obtained from MCNP simulation and unfolded experimental data for 1960 keV proton energy beam is reported as an example in Fig. 16.

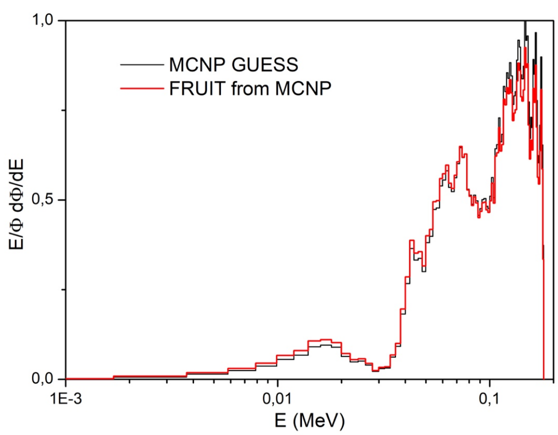

Figure 16: 1960 keV proton beam: MCNP6 simulation and unfolded spectrum obtained form NCT-WES experimental data, using MCNP6 as guess. The spectra are normalised to the unit fluence and are in equi-lethargy representation.

6.2 Contract with PSI on the characterization of the reference neutron fields of the PSI Secondary Standard Calibration Laboratory (October 2025)

The reference neutron fields produced by radionuclide neutron sources of $^{241}Am - Be$, ^{252}Cf and ^{252}Cf moderated with heavy water were measured using the NCT-WES single-moderator directional spectrometer to investigate the dependence of the neutron emission from the source encapsulation and amount of active material.

7 List of Conference Talks by LEMRAP authors in 2025

- 9-13 June 2025, Mexico City, 21th International Conference on Solid State Dosimetry.
  R. Bedogni, M.A. Caballero-Pacheco, A.I. Castro Campoy, F. Frigi, L. Russo, A. Pietropaolo et al., The evolution of Bonner Spheres into single moderator neutron spectrometers - Oral Presentation.
  R. Bedogni, M.A. Caballero-Pacheco, A.I. Castro Campoy, F. Frigi, L. Russo, A. Pietropaolo et al., Rad-hard silicon carbide thermal neutron detectors for quality assurance in BNCT - Oral Presentation.

- 16 – 19 june 2025 National Laboratories of Frascati, Italian National Institute for Nuclear Physics (INFN), High Precision X-ray Measurements (HPXM) 2025. A.I. Castro Campoy, R. Bedogni, L. Russo, M. A. Caballero Pacheco et al., The INFN Frascati facility for X-Ray dosimetry - Oral Presentation.
  L. Russo, R. Bedogni, A.I. Castro Campoy, M. A. Caballero Pacheco et al., Development of a direct-reading dosimeter for eye-lens dose estimation in medical radiology - Oral Presentation.

- 16-18 september 2025, Cagliari, CMS Italia meeting.
  M.A. Caballero-Pacheco et al., First results with the novel CMS TetraBall Neutron spectrometer - Oral Presentation.

- 29 - 31 october 2025 Padova (Italy). XXXIX Congresso Nazionale di Radioprotezione – AIRP.
  Russo L., Bedogni R., Castro Campoy A.I. et al., Un nuovo monitor portatile per neutroni ad intervallo energetico esteso - Oral Presentation.

- 26 november 2025 Teddington (UK) Neutron Users Club NUC 2025 at the National Physics Laboratory NPL.
  Russo L., Bedogni R., Castro Campoy A.I. et al., New developments in active ambient and personal neutron dosimetry at INFN Frascati - Oral Presentation.

8 Publications

- Caballero-Pacheco, M.A., Bedogni, R., Castro Campoy A. I., Russo, L. et al. Tetra-Ball: design of a new type of extended energy range single-sphere neutron spectrometer.
  Eur. Phys. J. Plus 140, 180 (2025).
  https://doi.org/10.1140/epjp/s13360-024-05949-8

- Bedogni, R., Caballero-Pacheco M.A., Castro Campoy A. I., Russo L. et al., Rad-hard silicon carbide thermal neutron detectors for quality assurance in BNCT.
  Eur. Phys. J. Plus 140, 247 (2025).
  https://doi.org/10.1140/epjp/s13360-025-06149-8

- Russo L., Bedogni, R., Caballero-Pacheco M.A., Castro Campoy A. I., et al., A new neutron area monitor with extended energy range.
  Eur. Phys. J. Plus 140, 403 (2025).
  https://doi.org/10.1140/epjp/s13360-025-06348-3

- Bedogni R., Russo L., Castro Campoy A. I.,Caballero-Pacheco, M.A. et al., Neutron spectrometry in radionuclide-based reference neutron fields at the ASNR Cadarache CEZANE facility using the NCT-WES single-moderator directional spectrometer.
  Eur. Phys. J. Plus 140, 809 (2025).
  https://doi.org/10.1140/epjp/s13360-025-06716-z

- Calamida, A., Castro Campoy A. I., Russo, L., Bedogni R., Caballero Pacheco, M.A. et al., Fast and thermal neutron measurements inside a fusion-oriented shielding mock-up.
  Eur. Phys. J. Plus 140, 819 (2025).
  https://doi.org/10.1140/epjp/s13360-025-06715-0

References

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   First test of SP2: A novel active neutron spectrometer condensing the functionality of Bonner spheres in a single moderator,
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2. R. Bedogni, C. Domingo, A. Esposito, F. Fernández,
   FRUIT: An operational tool for multisphere neutron spectrometry in workplaces,
   NIM A 580 (2007) 1301-1309.
   https://doi.org/10.1016/j.nima.2007.07.033.