NESCOFI@BTF
NEutron Spectrometry in COmplex FIelds @ Beam Test Facility

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Politecnico di Milano and INFN-Milan
CIEMAT-Madrid, Spain

1 Introduction and motivation

NESCOFI@BTF started in 2011 with the aim of developing innovative neutron sensitive instruments for the spectrometric and dosimetric characterization of neutron fields, intentionally produced or present as parasitic effects, in particle accelerators used in industry, research and medical fields. Neutron spectra in these fields range from thermal (10^{-8} MeV) to tens or hundreds MeV, thus spanning over more than 10 decades in energy. Only the multi-sphere spectrometer (or Bonner Sphere spectrometer) is able to simultaneously determine all energy components over such a large energy interval. The main disadvantage of this spectrometer is the need to sequentially expose a considerable number (usually more than 10) of detector+moderator configurations, thus leading to time-consuming irradiation sessions. The idea behind NESCOFI is to provide real-time spectrometers able to simultaneously provide all energy components in a single irradiation. These could be employed for:

1. Monitoring the neutron fields in terms of energy-integrated neutron flux and spectral neutron flux in energy intervals of interest.

2. Active real-time control of possible deviations from nominal field properties and of possible modifications induced by materials introduced in the radiation field (samples, waste elements, materials to be tested).

The final users of the NESCOFI products will be a variety of facilities interested to monitor not only the intensity of a neutron beam, but also -and simultaneously- its energy and/or direction distribution (chip-irradiation, material science neutron beam-lines, reference neutron fields, research and cancer therapy facilities).

The basic idea behind the project is to exploit the moderation of neutrons in hydrogenated materials, as extensively done in Bonner Sphere spectrometers, but new designs and computational methods have been introduced. Particularly, instead of estimating the neutron energy distribution by exposing different detector+moderator configurations, this project aims at a single moderator embedding several "direct reading" thermal neutron detectors at different positions. The energy or angle distribution of the neutron field will be obtained using unfolding algorithms relying on the device response matrix and on the reading of the different detectors. This "unfolding" problem has a number of analogies with the spectrum reconstruction with Bonner Sphere spectrometers, for which a special code called FRUIT (FRascati Unfolding Interactive Tools) was developed at LNF. The NESCOFI project planned to be completed in three years (2011-2013), organized as follows:

2011

1. optimization (via Monte Carlo simulation) of the spectrometer geometry and development of a prototype working with passive detectors
2. establishment of a reference neutron field for testing purposes, namely the photo-neutron beam from the n@BTF facility at the LNF.

2012

Development of suitable "direct reading" (or active) thermal neutron detectors to be embedded in the final spectrometers

2013

Establishment and calibration of the final spectrometers

2 Achievements of the first year (2011)

See 2011 Annual report

3 Achievements of the second year (2012)

3.1 Cylindrical spectrometer (CYSP): final design and response matrix

The CYSP (cylindrical spectrometer) is the target instrument for workplaces where a directional spectrometry must be performed. Typical cases are the fast neutron irradiation beam-lines used at spallation facilities like ISIS, SNS and (in future) ESS. Key elements of the CYSP are:

- Length and diameter suited for the energy interval of interest (thermal up to GeV);
- A Cd-lined collimator to define the direction of interest;
- The distribution of the thermal neutron detectors (TNDs) along the cylindrical axis should be adequate to maximise the spectrometric performance with a reduced self-perturbation effects;
- A high-Z radiator to allow detecting neutron above 20 MeV, placed at the adequate depth.

An extensive simulation campaign was performed with the Monte Carlo code MCNPX. This allowed studying the variation of the CYSP response matrix as the mentioned parameters varied. Fig. 1 reports the sketch of one among the studied configurations.

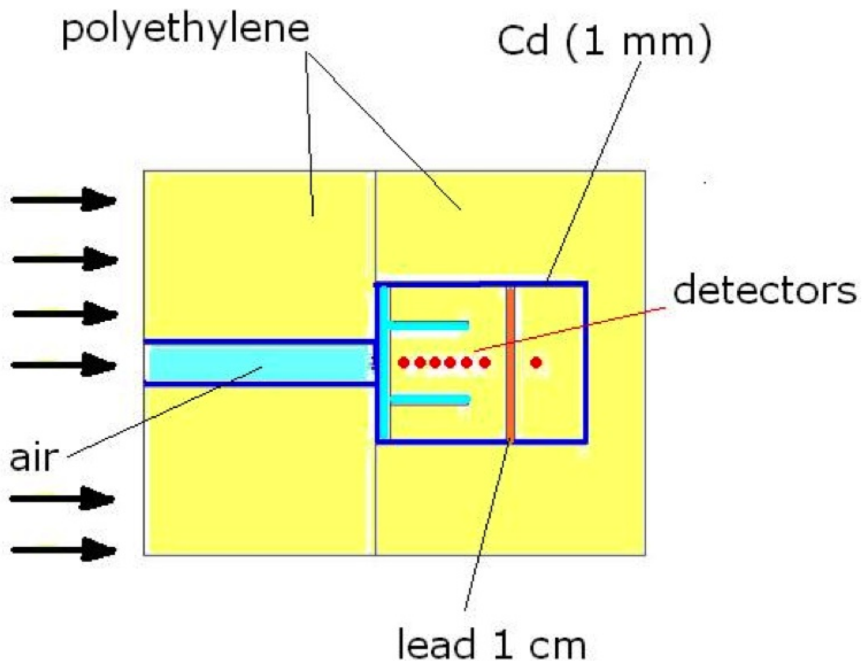

Fig. 1: The CYSP design.

Figure 2 shows a typical response matrix. The signal of every detector is reported, per unit incident fluence, as a function of the monochromatic neutron energy. Detector “0” is located on the CYSP front face and only detects thermal neutron present in the external field. Detectors “1” to “8” are located at increasing depth along the cylindrical axis. Detectors “6” to

"8" are "below lead", thus their response shows a "threshold" at approx 1 MeV. The detectors located near the lead filter (above and below) respond to high-E neutrons because secondary neutrons from (n,xn) reactions are also emitted at large angles. The spectrometric capability of the device is determined by the variation in the response observed when the position and the energy vary.

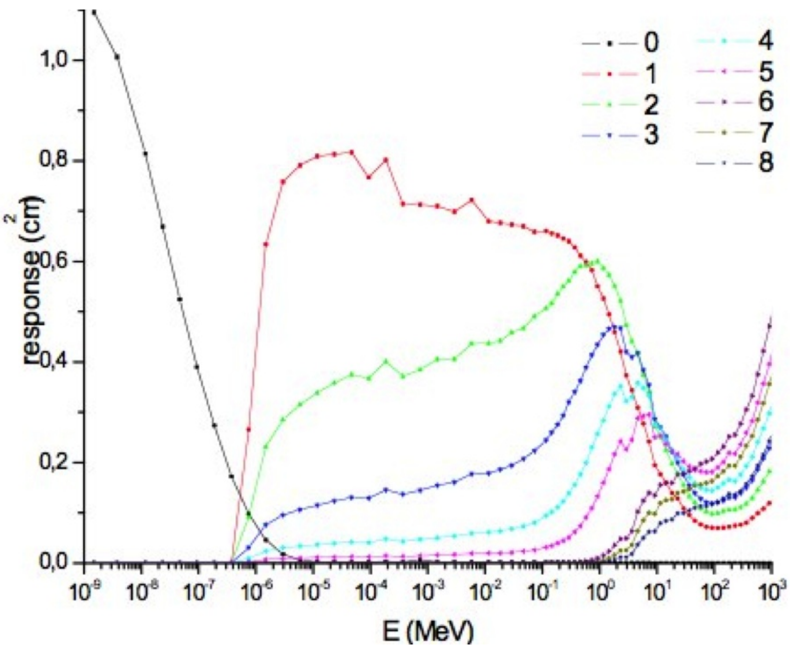

Fig. 2: Typical response matrix of the CYSP.

The directionality of the response was studied by simulating a realistic scenario where the CSYP is located in an irradiation room (see Fig. 3) where a neutron beam at different energies, emerging from a collimated source, reaches the CYSP front face. Two simulations have been launched for a given CYSP geometry:

- one with realistic walls, such to produce significant room scatter in any direction;
- another without walls, in order to have neutrons only in the desired measurement direction, i.e. the CYSP axis.

For every CYSP geometry the (wall absent / wall present) ratio was reported as a function of the detector position and of the irradiation energy (see Fig. 4 for $E = 10$ MeV).

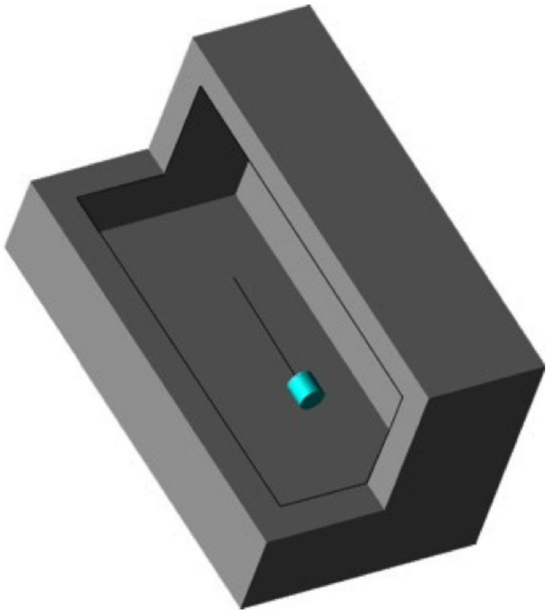

Fig. 3: Geometric set up for studying the directional response of the CYSP.

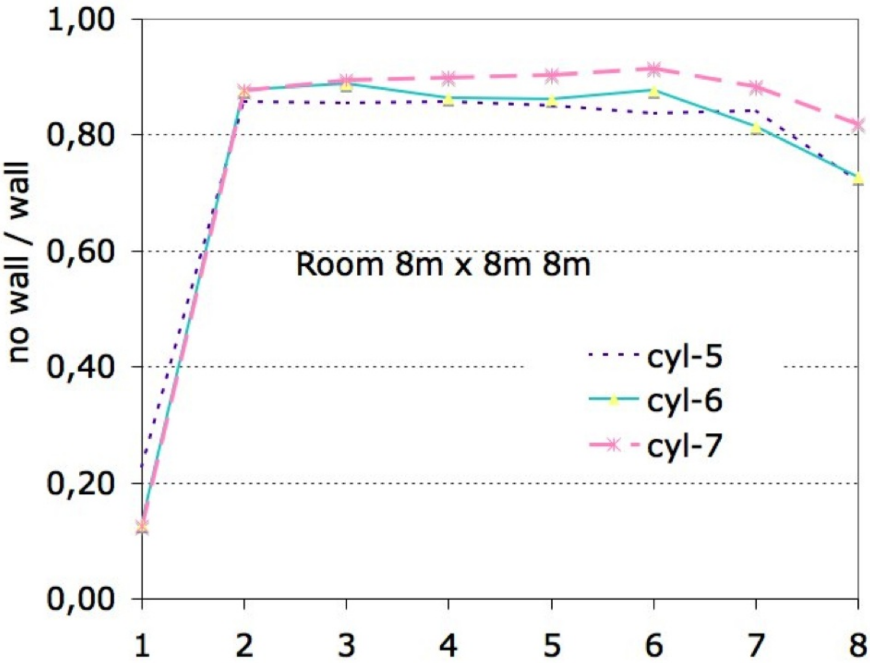

Fig. 4: Directional response study.

The simulation campaigns above described allowed reaching a compromise configuration (see Figure 5) showing good spectrometric capability and optimal directionality. The prototype is currently under construction.

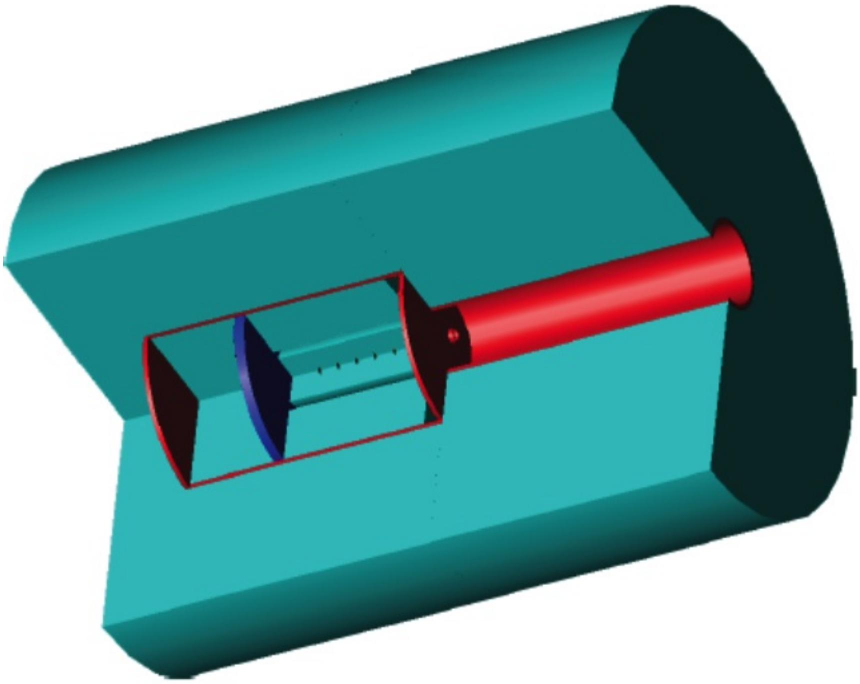

Fig. 5: Solid model of the CYSP.

3.2 Active detectors: state of art

Both CYSP and SP^2 spectrometers in their final versions will embed a number of active thermal neutron detectors (ATND), 31 in the SP^2 and 8 in the CYSP. The target dimension for the single ATND is approximately 1 cm^2 area and $1-2$ mm thickness. Several options have been analyzed, including diamond detectors, gas detectors and silicon-based semiconductors. A multi-criteria analysis was done, considering the cost, the sensitivity and the level of miniaturization as key parameters. The final choice was 1 cm^2 silicon-based elements made sensitive to thermal neutrons with an in-house physical-chemical process. Silicon detectors are cheap but are known to be prone to radiation damage. Thus the decision was to firstly produce spectrometers for low-medium flux range using silicon detectors (up to approx. 10^6 $cm^{-2}s^{-1}$ continuous for ten years in the measurement point).

3.3 Spectrometric chain

For every detector a spectrometric chain (charge preamplifier + amplifier) is needed. Because many detectors must be simultaneously acquired, dedicated 8-detector boards were developed. This choice is a factor 50 less expensive than purchasing commercial systems. The electronic performance of the NESCOFI board was evaluated and compared with that of common commercial systems (ORTEC and SILENA). No significant differences were observed (See Fig. 6)

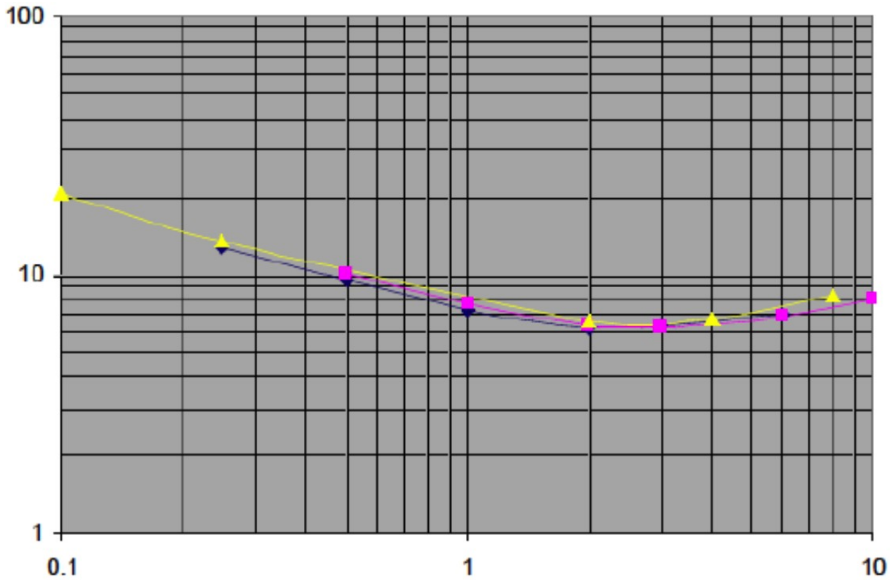

Fig. 6: NOISE FWHM in keV as a function of the shaping time (us): the NESCOFI board (yellow) compared with ORTEC (pink) and SILENA (blue) systems. Vbias=12.2 V, test pulse amplitude = 2.5 mV, injection capacitor = 4.91 pF.

3.4 Thermal neutron sensitisation

Silicon detectors are made sensitive to thermal neutrons with the deposition of an adequate converter. Two types of converters, called C1 and C2, have been evaluated. The sensitivity of the final detector can be tuned over more than a factor 10 by varying the deposit thickness and mixture. The sensitization process is reproducible within 8% (in terms of variability of the response of a batch of detectors deposited with the same nominal converter thickness). The deposition process is quality assured by exposing the final detector to a standardized thermal neutron field obtained with a 1 Ci $^{241}\mathrm{Am}-\mathrm{Be}$ source and a moderating assembly (see Fig. 7). The reference spectrum is shown in figure 8. This test also serves as calibration procedure.

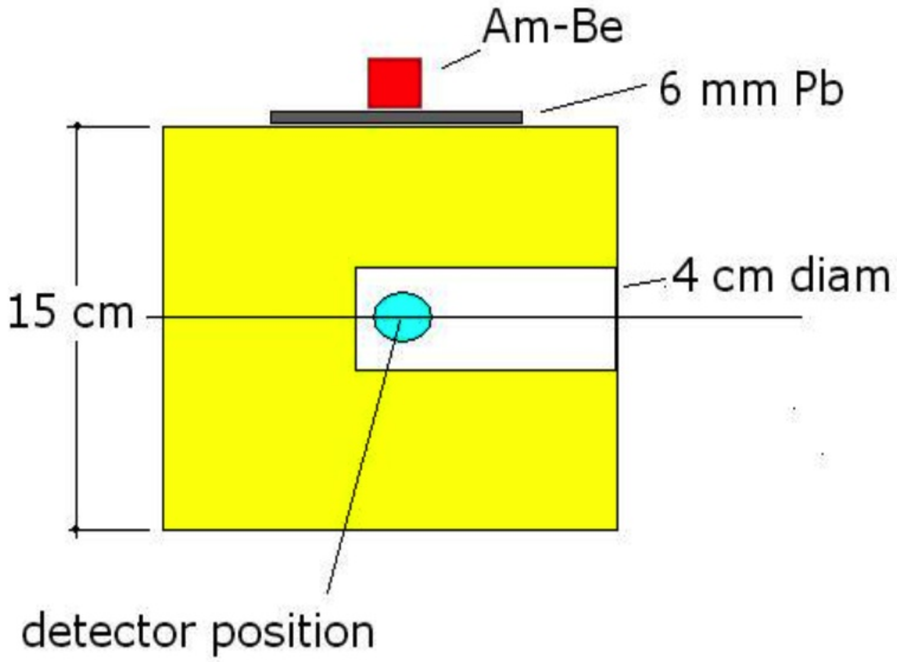

Fig. 7: Assembly for detector testing and calibration.

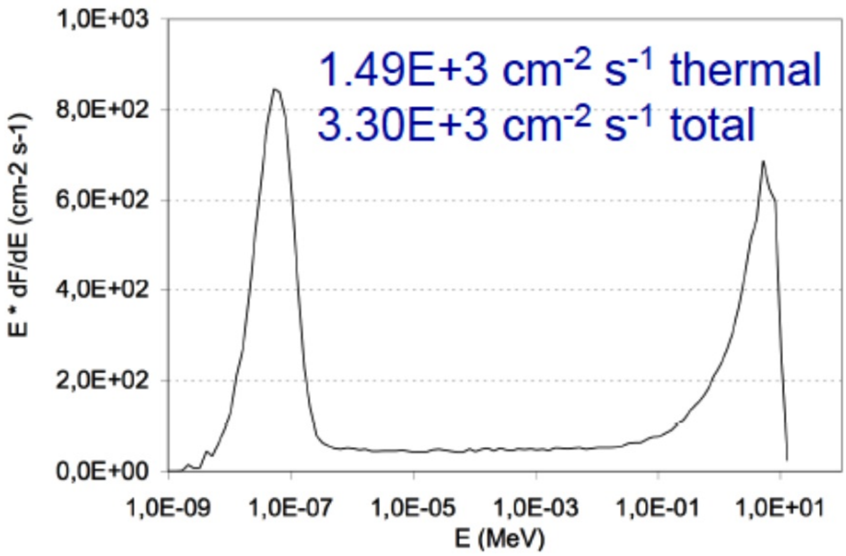

Fig. 8: Neutron spectrum and integrated flux at the reference point of the calibration field.

3.5 Performance of converter C1

To assess the performance of converter C1, a set of detectors were covered with different thicknesses and exposed to the same thermal neutron fluence using the test facility described in 3.4. The typical spectrum of energy deposited in silicon is reported in Figure 9. The label “bare” denotes the uncovered detector. The signal due to thermal neutrons is obtained by subtracting the “bare” spectrum from the “covered” spectrum. Unfortunately the thermal neutron peak (at approx. 80 mV) basically coincides with the maximum of the continuous energy distribution of the secondary electrons, thus requiring exposing a pair of detectors (bare and covered) to accurately determine the thermal neutron component. In other words, the ATND produced with converter C1 is sensitive to photons. Due to this disadvantage, further studies were undertaken to design another converter (C2) with considerably lower photon sensitivity (see 3.6).

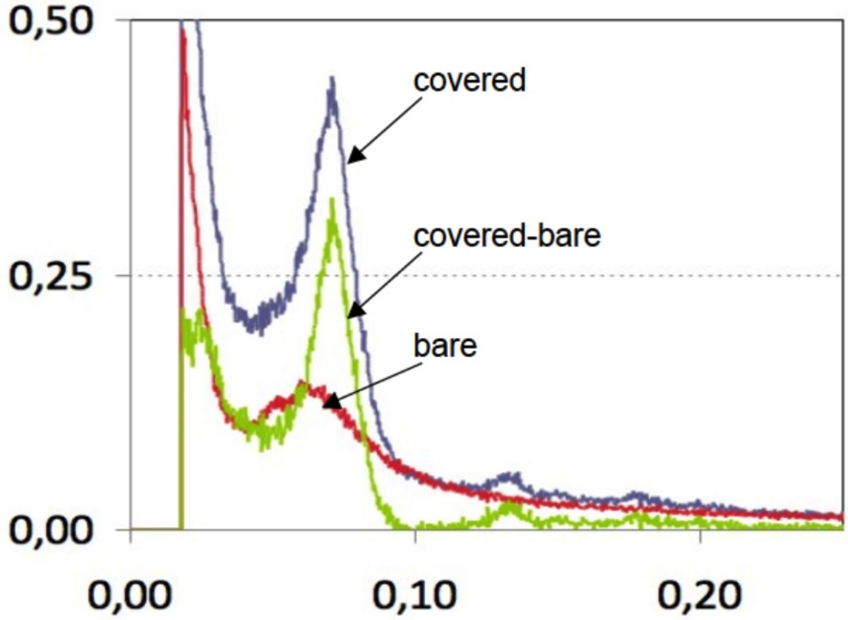

Fig. 9: Typical spectrum of energy deposited in silicon using converter C1. The label “bare” denotes the uncovered detector. X axis is pulse height (V) and Y axis is number of pulses (a.u.).

Characteristics of converter C1 are:

- Different detector thicknesses are easy to fabricate and well controllable;

- Optimal sensitivity obtained: 0.02 counts per unit thermal fluence (cm^2);

- Fabrication reproducibility 8%;

- Radiation damage: absent for integrated thermal neutron fluence up to 510^{10} $cm^{-2}s^{-1}$ (measured at the NPL thermal pile).

- A double exposure (bare and covered) is needed to determine the thermal neutron component of the field.

ATNDs obtained with converter C1 have been arranged in a "CYSP-like" assembly (see Figure 10) to perform simultaneous acquisition with the NESCOFI-developed 8-channel boards. Irradiation tests with reference monochromatic neutron beams of 0.565 MeV and 5 MeV were performed at NPL (Teddington, UK).

Fig. 10: On the left: moderating cylinder embedding seven ATNDs simultaneously acquired. On the right: shadow-cone used for room-scatter subtraction purposes at the NPL reference monochromatic neutron beam facility.

The spectrometric capability of such a moderating assembly is demonstrated by Figure 11, where the count profile (count rate in ATND as a function of the position along the cylindrical axis) is shown for both irradiation energies. Detector positions varies from 1 to 7, where 1 is the shallowest position and 7 the deepest one (See Figure 12).

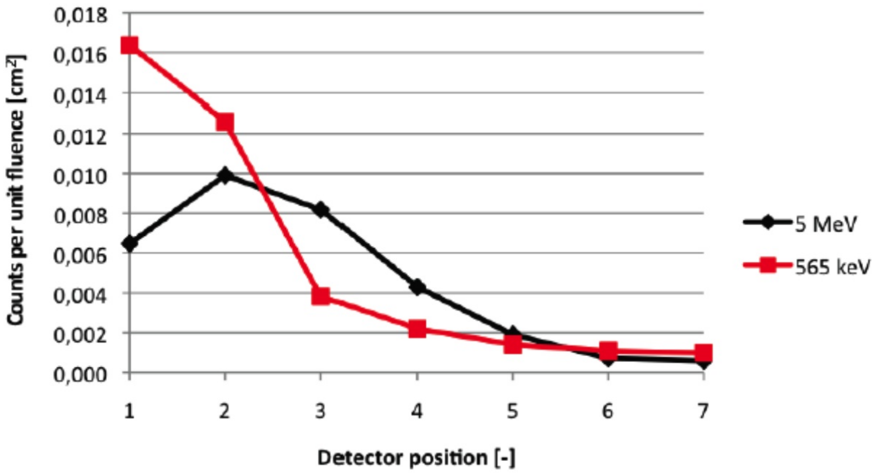

Fig. 11: Count profile (count rate in ATND as a function of the position along the cylindrical axis) for 0.565 and 5 MeV monochromatic beams.

Fig. 12: Cross section of the testing cylinder (50 cm length, 40 cm diameter). Position 1 is the shallowest one, whilst position 7 is the deepest one.

3.6 Performance of converter C2

Converter C2 was developed with the special aim of reducing the photon sensitivity without compromising the thermal neutron sensitivity. Different thicknesses were fabricated and tested in the facility described in 3.4. The results in terms of thermal neutron sensitivity as a function of the thickness are reported in Table 1, where RT denotes the so called "reference thickness".

Thickness (in unit of RT)	Response (cm^2)
0.17	0.003
0.25	0.007
0.32	0.013
0.50	0.016
0.87	0.017
1.00	0.026

Table 1: Thermal neutron sensitivity as a function of the thickness of converter C2.

As shown in Figure 13, the use of converter C2 does not require to expose a double detector because the photon-induced signal falls well below the spectral region of interest for thermal neutrons.

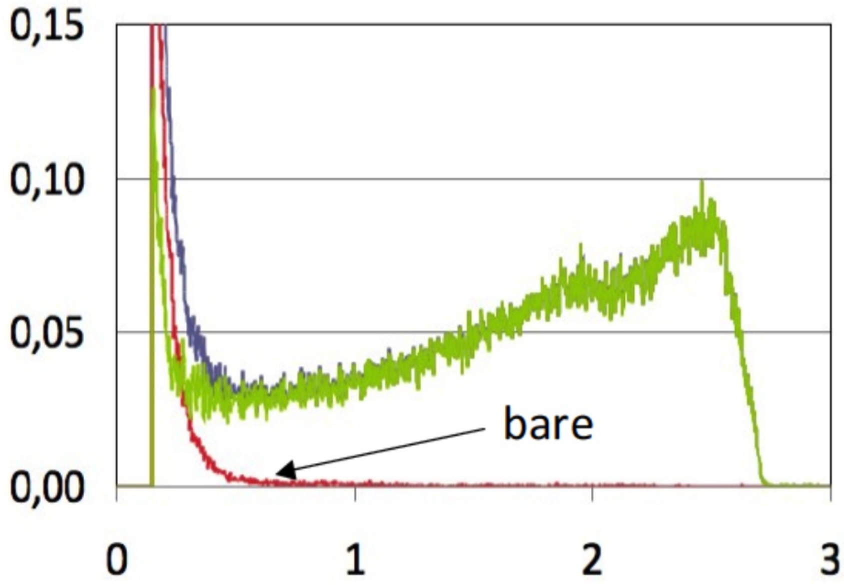

Fig. 13: Typical spectrum of energy deposited in silicon using converter C2. The label “bare” denotes the uncovered detector. The Blue spectrum is the “covered” detector. The green spectrum is the “covered” - “bare” spectrum. X axis is pulse height (V) and Y axis is number of pulses (a.u.).

Characteristics of converter C2 are:

- Different detector thicknesses are easy to fabricate and well controllable;

- Optimal sensitivity obtained: 0.026 counts per unit thermal fluence (cm^2);
- Fabrication reproducibility < 10%;
- Radiation damage observed for integrated thermal neutron fluence $3 \cdot 10^{12}\ cm^{-2}$ (measured at TRIGA reactor, ENEA Casaccia).
- A single exposure is sufficient to determine the thermal neutron component of the field.

3.7 Testing new detectors a standard Bonner spheres spectrometer

The ATNDs obtained with converters C1 and C2 were further tested against a well-established detector, the ^{6}LiI(Eu) scintillator, at the center of a set of Bonner spheres. The test was performed at TSL Uppsala, where a wide neutron spectrum is produced by bombarding a Be target with 30 MeV protons. Figure 14 reports the count profile obtained for the three configurations (LiI(Eu), C1 and C2). This profile is defined as the count rate per unit proton current as a function of the sphere diameter. Ideally, the ratio LiI(Eu)/C1 and LiI(Eu)/C2 should remain constant as the sphere diameter varies. Actually this was experimentally confirmed within ± 5%.

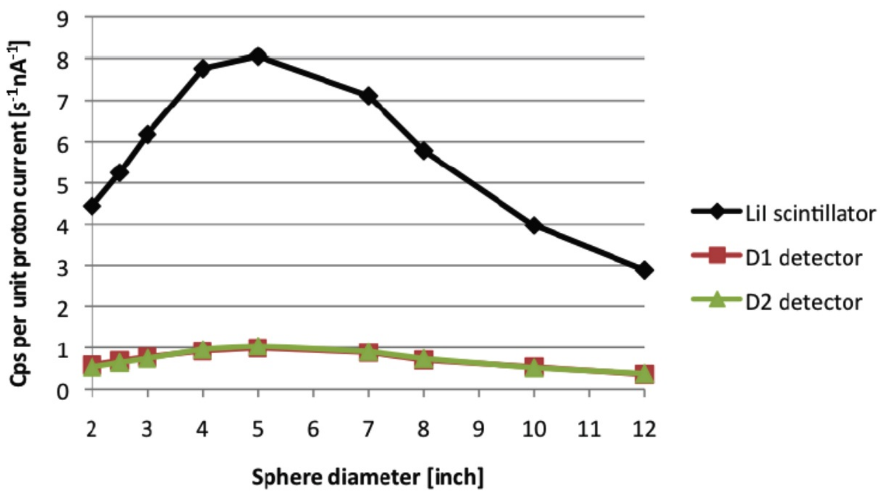

Fig. 14: Count profile obtained for the three configurations (LiI(Eu), C1 and C2) in the TSL experiment.

3.8 Testing new detectors in the medical field

Thermal neutron fluence measurements using converter C2 were performed inside an anthropomorphic phantom undergoing a 15 MV radiotherapy treatment at the Ospedale S. Camillo (Roma) (Figure 15). The thermal fluence at selected points representing special organs were known via Monte Carlo simulations and previous measurements with passive techniques (TLD pairs).

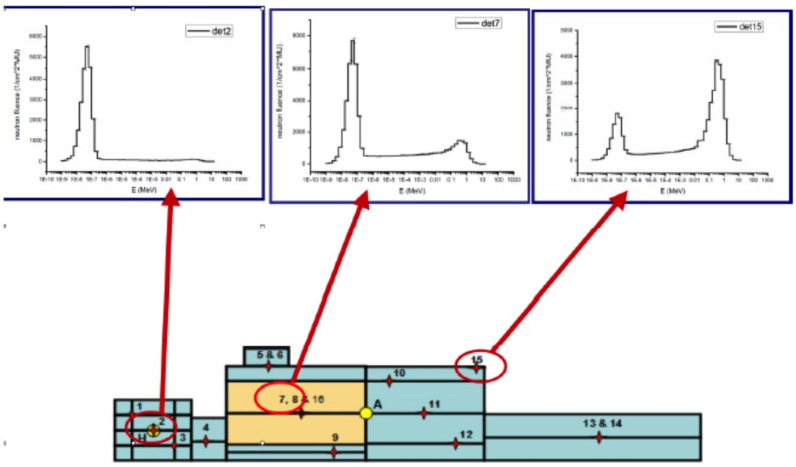

Fig. 15: Sketch of the phantom and location of the measurement positions. Neutron spectra in given positions are reported.

The test consisted in exposing the ATND (C2 converter) in the positions representing lung, abdomen and skin. A head treatment (10 Gy at isocenter) was delivered. Table 2 reports the thermal fluence measured with the ATND as compared with the TLD results. Uncertainties are 10 %.

Organ	ATND fluence ($x10^4$ cm^{-2}MU^{-1})	TLD fluence ($x10^4$ cm^{-2}MU^{-1})
lung	2.0	2.3
abdomen	0.1	0.1
skin	0.9	0.7

4 Publications 2012

R. Bedogni, K. Amgarou, C. Domingo, S. Russo, G.A.P. Cirrone, M. Pelliccioni, A. Esposito, A. Pola, M.V. Introini. Experimental characterization of the neutron spectra generated by a 62 AMeV carbon beam on a PMMA phantom by means of extended range Bonner sphere spectrometers. NIM A 681 (2012) 110-115.

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F. Sànchez-Doblado; C. Domingo; F. Gòmez; B. Sànchez-Nieto; J.L. Muñiz; M.J. Garcìa-Fusté; M.R. Expòsito, R. Barquero; G. Hartmann; J.A. Terròn; J. Pena; R. Méndez; F. Gutiérrez; F.X. Guerre; J. Rosellò; L. Nùñez; L.Brualla-Gonzàlez; F. Manchado; A. Lorente; E. Gallego; R. Capote; D. Planes; J.I. Lagares; X. Gonzàlez-Soto; F. Sansaloni; R. Colmenares; K. Amgarou; E. Morales; R. Bedogni; J.P. Cano; F. Fernàndez.Estimation of neutron-equivalent dose in organs of patients undergoing radiotherapy by the use of a novel online digital detector. Phys. Med. Biol.57,pp. 6167-6191.2012.

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L. Quintieri; R. Bedogni; B. Buonomo; A. Esposito; M. De Giorgi; G. Mazzitelli; P. Valente; J. M. Gomez-Ros. Photoneutron source by high energy electrons on high Z target: comparison between Monte Carlo codes and experimental data.Fusion Science and Technology.61,pp. 314 - 321.2012.

5 Collaboration and external funds

EU FP7 Erinda Program: 2.5 k€(instrument shipment) + 35 beam hours at TSL for project PAC 3/9 - 2012
CIEMAT Madrid 35,000 equiv-hours CPU time on EULER cluster
CRISP (INFN-LNF): 12 k€(neutron converters, trips exp. campaigns)
Politecnico di Milano 6 k€(trips at experimental campaigns) + support for electronics design and testing
Ospedale San Camillo: usage of 15 MV electron LINAC

LNF support: Beam-time (one week) at n@BTF
2 man per month at mechanical workshop
Guest-house: 30 man per night
Experiments for detector fabrication and characterization performed at FISMEL laboratories.

6 Project meetings

16 May 2012: NESCOFI@BTF 2012 Mid-Year Meeting & International Review Panel Meeting. INFN-LNF.

7 International Review Panel

Prof. Carles Domingo, Profesor Titular of the Universitat Autonoma de Barcelona, UAB Head of the Neutron Measurement group of the UAB `carles.domingo@uab.cat`

Prof. Francisco Sanchez Doblado, Profesor Catedratico of the Universidad de Sevilla, Head of the Physiology Department. `paco@us.es`

8 website

`http://www.lnf.infn.it/acceleratori/public/nescofi/`

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Angelone M, Batistoni P, Bedogni R, Chiti M, Gentile A, Esposito A, Pillon M, Villari R. Mixed n-gamma fields dosimetry at low doses by means of different solid state dosimeters. RADIAT MEAS, 46-12, (2011).

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J. M. Gomez-Ros, R. Bedogni, M. Moraleda, A. Esposito, A. Pola, M.V. Introini, G. Mazzitelli, L. Quintieri, B. Buonomo. Designing an extended energy range single-sphere multi-detector neutron spectrometer. Nucl. Instr. Meth. A 677 (2012) 4-9.