LEMRAP Laboratory

2020 Annual report

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Torino University and INFN section

1. ANET experiment (2019 - 2021) - CSN 5

1.1 Introduction

ANET is a CSN 5 experiment including LNF, Torino (nat. resp.), Trieste and Pavia units and has the objective of prototyping an innovative design of compact collimator for slow neutron Imaging applications (neutron radiography, tomography and other non destructive neutron inspection techniques).
To achieve good geometric conditions (high collimating ratio L/D, small penumbra, reduced blurring and divergence) over reasonably fields of view (ten of cm), practical collimators are always very long (ten meters or more).
This requires:

- Large facilities
- Very intense primary neutron beams.
- Need for ^{4}He filling or operation under vacuum to prevent neutron attenuation in air.

ANET aims at prototyping and testing an innovative type of compact neutron collimator, able to reach the mentioned desired geometrical beam properties in **one meter or less**.

Neutron science will greatly benefit from such a device, as neutron imaging or scattering experiments will be feasible in small-medium scale labs, using neutron source much weaker than a reactor. In addition, shorter collimating structures would not require ^{4}He filling or operation under vacuum.

ANET compact collimator was designed as a complex, micro-structured body, using borated plastic to select particle directions and Aluminium as supporting structures. The design was submitted as an INFN patent (102020000010132 dated 06/05/2020).

1.2 Small-scale compact collimator

To verify the feasibility of such a design, ANET-LNF developed a small-scale compact collimator with 10 cm length, 2 cm x 2 cm field of view, L/D=40. See Figure 1.1.

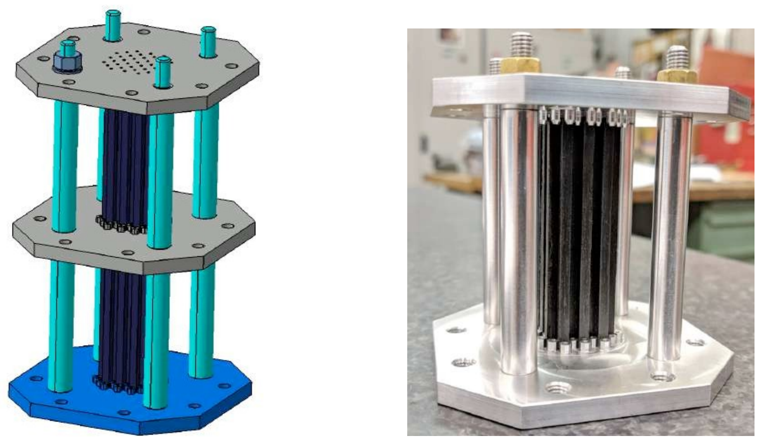


Figure 1.1. Small-scale compact collimator (10 cm length, field of view 2 cm x 2 cm, L/D=40).

The small-scale compact collimator was tested at the Helmholtz-Zentrum Berlin (HZB) neutron imaging facility, obtaining the pattern shown in Fig. 1.2 where the elementary collimating cells are visible.

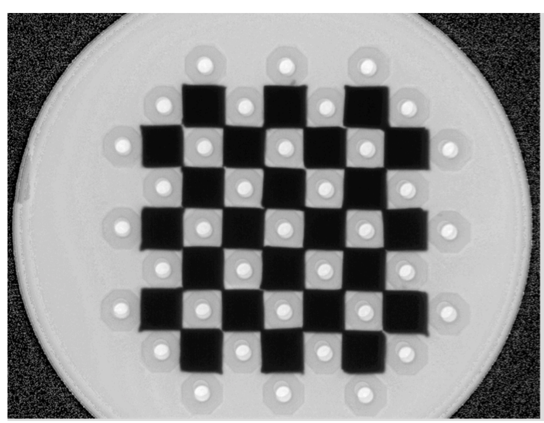


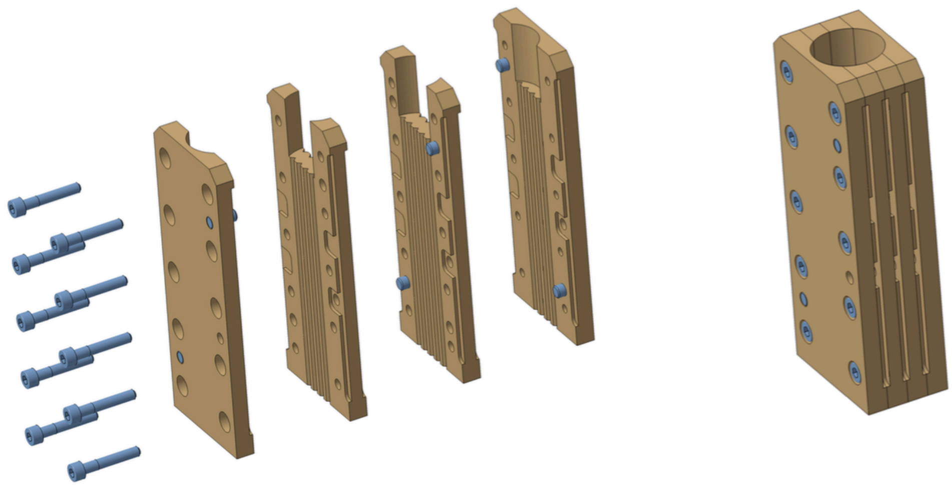
Figure 1.2. Neutron radiography of the Small-scale compact collimator (10 cm length, field of view 2 cm x 2 cm, L/D=40) taken at the Helmholtz-Zentrum Berlin (HZB) neutron imaging facility.

1.3 Real-scale compact collimator

After the new design for the compact collimator was experimentally verified on small-scale, a real-scale collimator with improved characteristics was designed, see Fig. 1.3. The characteristics of this collimator are: 40 cm length, field of view 4.75 cm x 4.75 cm, collimating ratio L/D = 160.

Figure 1.3. Real-scale collimator with 40 cm length, field of view 4.75 cm x 4.75 cm, collimating ratio L/D = 160. Top: mechanical drawings. Centre: supporting structures. Bottom: assembling the elementary collimating cells.

A specific technological process was developed to produce the elementary collimating cells (2.5 mm x 2.5 mm x 100 mm borated plastic rods). A brass casting mold was designed and manufactured at INFN-LNF SPCM Service, see Fig. 1.4.



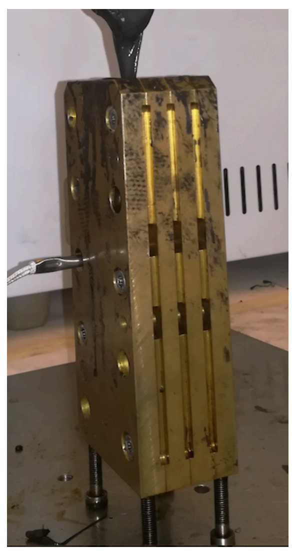


Figure 1.4. Brass casting mold for manufacturing the elementary collimating cells in borated plastic. Top: drawings. Bottom: manufacturing process.

The manufacturing process took place at DIGITECH SRL via Boccioni, 2 56037 Peccioli (PI)).

2. ENTER_BNCT experiment (2020 - 2022) - CSN 5

2.1 Introduction

Neutron Capture Therapy (NCT) is an alternative form of radiotherapy based on neutrons with energy in the keV - tens keV region (epithermal neutrons). The tumour cells are not directly killed by neutrons impinging the patient, but through a "sensitizer" agent in the form of a drug with the following main characteristics:

- Designed to ideally reach only malignant cells.
- Contains a high percentage of elements with high neutron interaction probability, or more precisely high neutron capture cross section
- This neutron absorbing material produces secondary ionising radiations as a result of the neutron capture, having the capability to kill the surrounding malignant cells. Neutron capture preferentially occurs in the thermal neutron domain.
- The secondary particles are preferably charged particles with energy in the order of MeV and range in the order of few to ten micrometers in tissue, so that the killing effect is limited to the labelled cell and the damage to surrounding healthy cells is limited.

Of the elements with highest thermal neutron capture cross-section, like 3-He, Cadmium, 10-Boron, 6-Lithium or Gadolinum, only Gadolinum and 10-Boron have been studied for NCT as they are practicably usable to mark pharmaceutical drugs. Gadolinium has higher cross section but the secondary particles, electrons and gammas, are weakly ionising if compared to the charged particles produced by neutron capture in 10-Boron. 10-B cross section is also very high (nearly 4000 barn) and produces highly ionising charged particles (alphas and tritons). Being 10-Boron the best candidate for NCT, this type of therapy is also called BNCT, Boron Neutron Capture Therapy.

It is worth mentioning how BNCT compares with radiotherapy with electrons/gammas and hadrons. Being definitively a charged-particle-based therapy, it is usually effective for tumours that resist to electrons and gammas. In this sense it is similar to hadron therapy. However, whilst hadron therapy is suited for tumours defined in space, BNCT operates a selection on a cell-by-cell basis. Thus it is suited for infiltrated tumours.

Current scientific challenges in BNCT are

- designing a drug that maximises the ratio between the Boron concentration in the tumour and that in the surrounding normal tissues (Boron uptake).
- maximising the thermal neutron fluence rate in the tumour location. As the human body is mainly water, it slows-down neutrons and tend to absorb them when they reach thermal energies. Thus a thermal neutron beam would be effective only for superficial tumours. By contrast, deep-seated tumours (up to about 6-8 cm) require epithermal neutrons: after being slowed-down in the surrounding tissues, they will reach the tumour with energy in the thermal domain. Neutron sources for BNCT are nuclear reactor or particle accelerators coupled with a neutron-producing target. Primary neutrons have MeV energies. A beam shaping assembly (BSA) is used to degrade the energy distribution of the primary neutrons to achieve the desired epithermal spectrum. BSAs are usually made of combinations of Teflon, Magnesium and Aluminum. The design of the therapeutic beam is done by very accurate Monte Carlo calculations. However, state-of-art techniques to experimentally verify the neutron spectrum are still limited, as they only measure energy-integrated quantities such as neutron activation in pure materials. Spectrometric techniques would be very desirable in BNCT, but are not currently implemented as neutron spectrometers are usually very complex and unsuited for routine scenarios. Also, very few neutron spectrometers simultaneously cover from thermal to MeV in energy. Bonner spheres fulfil this requirement, but they are cumbersome and do not work in real time. In addition, most existing neutron detectors do not operate in the very intense therapeutic fields encountered in BNCT.

2.2 ENTER_BNCT project

The ENTER_BNCT project aims to develop technical and measurement capabilities for the implementation of a centre for clinical BNCT (Boron Neutron Capture Therapy) based on a particle accelerator.

The project involves four INFN units: Pavia, Turin, LNL and LNF.

The main objectives of the project are:

- Developing a beryllium neutron target (LNL).
- Developing a Beam Shaping Assembly (made up of a new materials developed in previous project BEAT_PRO (Pavia).
- Design of the irradiation room and related tools (Pavia).
- Boron concentration measurements for clinical application (evaluations in the blood to determine irradiation time) and intra-cellular evaluation of boron distribution to calculate more precise dosimetry parameters (Pavia).
- Developing neutron measurements techniques for neutron beam quality assurance and patient dosimetry (LNF + Torino). The 2020 objective for LNF+Torino was the development of new neutron

spectrometer able to work as routine tool for beam control in BCNT, called NCT-WES (Neutron Capture Therapy – Wide Energy Spectrometer)

2.3 The NCT-WES neutron spectrometer

NCT-WES (Neutron Capture Therapy – Wide Energy Spectrometer) is a new type of real-time neutron spectrometer able to work as routine tool for beam control in BCNT.
NCT-WES is a single-moderator-type spectrometer based on a collimated cylindrical structure, see Figure 2.1.

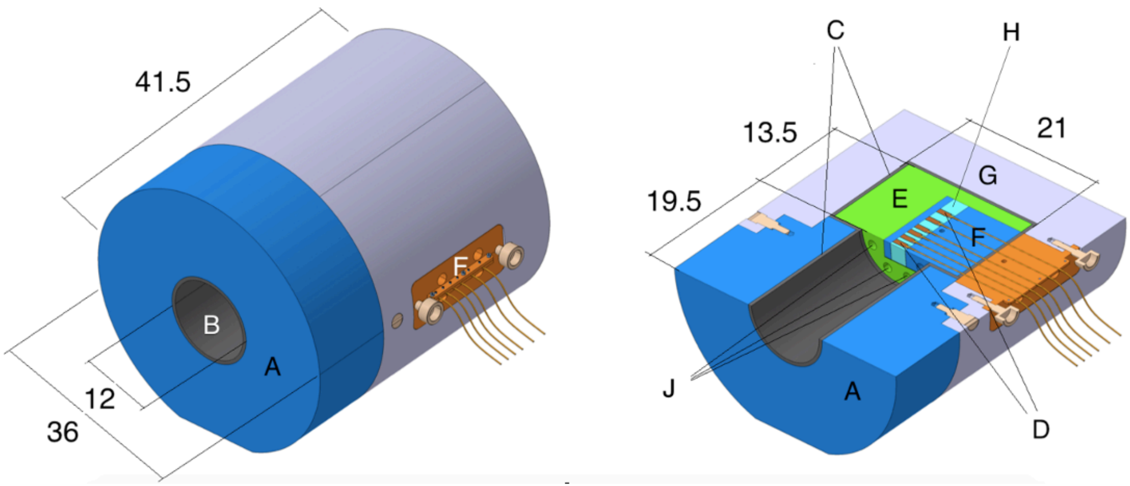


Figure 2.1: Schematics of the NCT-WES spectrometer. Quotes are in cm.

NCT-WES appears as a HDPE (high-density polyethylene) cylinder with diameter 36 cm and total length 41.5 cm. The dimensions of the cylinder as well as the location of detectors have been chosen to maximize the "spectrometric capability" of the device in the epithermal domain, i.e. the degree of differentiation between the response functions associated to different detector positions. The collimator (label A in Fig. 1) is 19.5 cm in length and its collimating aperture (label B), 12 cm in diameter, is internally lined with 0.5 cm of borated plastic SWX-238 from Shieldwerx (label C). Six thermal neutron detectors (D), located along the cylindrical axis, are contained in the HDPE capsule (label E, 20 cm in diameter, 13.5 cm in length). In order to facilitate maintenance, they are embedded in an extractable HDPE drawer (label F + label H). An external shield made of 0.5 cm of SWX-238 (label C) plus 7.5 cm of HDPE (label G) protects the capsule against neutrons arising from undesired directions. The centre of the shallowest detector is located at 0.72 cm depth from the end of the collimator. Detectors spacing (centre to centre) is 1.3 cm from the 1st to the 4th, and 2 cm from the 4th to the 6th. The detectors are parallelepipeds with external dimensions 0.32 cm x 1.5 cm x 1.3 cm and are connected through a 2 mm diameter coaxial cable. Their response is discussed in Section 3. It should be noted that NCT-WES can be adapted to allocate internal detectors with different size by simply replacing the polyethylene piece labelled H.
Label J refers to eight cylindrical air cavities, 1.3 cm in diameter, designed to enhance the response of deeper detectors relying on neutron streaming. The centres of these cavities are equally spaced on a circumference with radius 4.25 cm centred on the NCT-WES cylindrical axis.
The assembled NCT-WES is shown in Fig. 2.2.

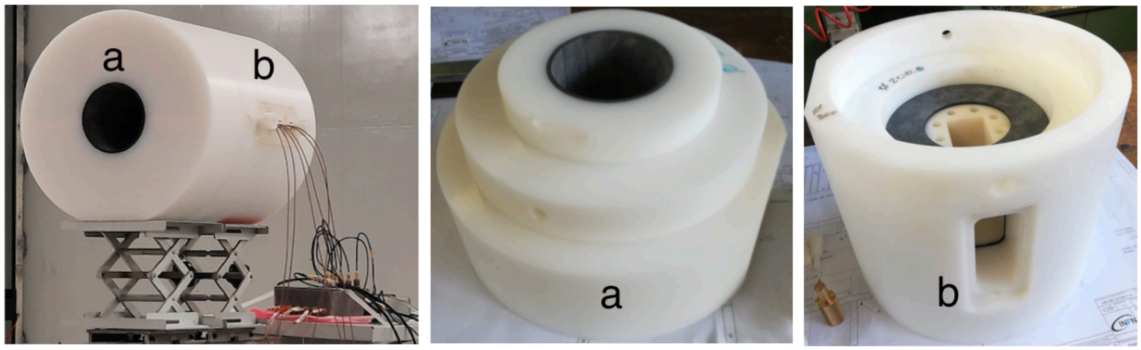


Figure 2.2. NCT-WES. On the left, the assembled prototype with the detector drawer inserted. At the centre, the part (a) including the collimator. On the right, the part (b) including the sensitive the capsule and its lateral protection. Air penetrations are visible. The drawer is extracted.

A Monte Carlo model was done to obtain the response matrix, obtaining the result in Figure 2.3.

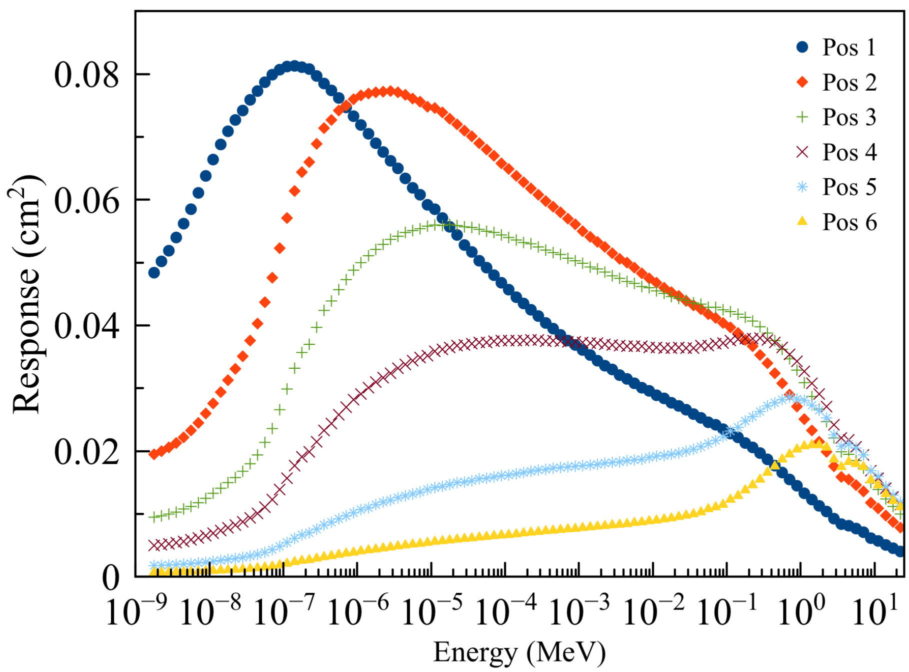


Figure 3. NCT-WES response matrix. The response is the expected number of measurable pulses in the TNPD, per unit incident fluence, as a function of the energy and the detector position.

An experimental measure was done to validate the Monte Carlo Model using a ^{241}Am-Be source available at the Polytechnic University of Milan as reported in Figure 2.4.

Figure 2.4. NCT-WES exposed in front of the ^{241}Am-Be source with the shadow-cone interposed.

The experimental and simulated count rate obtained in the internal NCT-WES are reported in Figure 2.5.

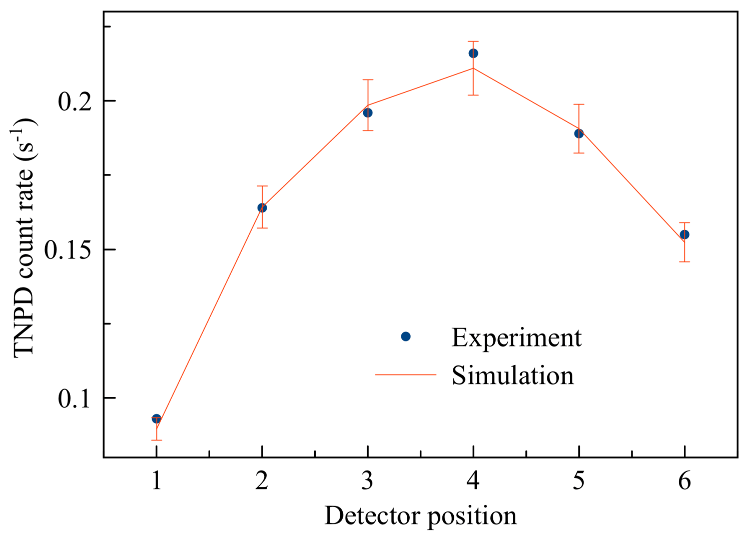


Figure 2.5. Experimental and simulated count rates in the NCT-WES internal detectors exposed to the un-collided field (total field - shadow-cone) from the ^{241}Am-Be radiation. Only the uncertainties on the simulated profile (< 5%) are reported. Line is only eye-guide.

The experiment/simulation ratio, averaged over the six detector positions, is 1.01 (variability ±2%, 1 s.d.), confirming the very high degree of accuracy of the model used to simulate the spectrometer and the measurement set-up.

Publications

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