CYSP: A new cylindrical directional neutron spectrometer. Conceptual design

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HIGHLIGHTS

- Conceptual optimization design of a new cylindrical neutron spectrometer (CYSP).
- CYSP scattered neutron contribution is negligible at least below 10 MeV.
- CYSP response matrix has been calculated within an overall uncertainty of 3%.

ABSTRACT

This communication describes in detail the design of a new cylindrical neutron spectrometer (CYSP) embedding 7 active thermal neutron detectors in a moderating structure made of polyethylene, borated plastic and lead. The device provides a strong directional response within the energy interval from thermal to hundreds of MeV, being nearly insensitive to neutrons coming from directions other than the cylinder axis with energies up to about 10 MeV. Therefore it will be especially suitable for applications where the neutron spectrum as a function of the emission angle needs to be measured. The Monte Carlo transport code MCNPX has been used to reach the final configuration for the spectrometer in terms of size, collimator, and arrangement of borated plastic and lead layers, number and position of the detectors. Moreover, MCNPX has been also used to calculate the response matrix of the instrument.

1. Introduction

Accurate determination of neutron spectra over the wide energy range that can be found in neutron producing facilities has been traditionally performed using the Bonner Sphere Spectrometer (BSS) (Thomas, 2010). This is a well-established technique that, nevertheless its demonstrated capability, has the main inconvenience of requiring successive exposures with the consequent long irradiation session and limiting the applicability to neutron field that does not change during the measurements.

Alternative devices based on multiple detectors within a single moderating structure have shown the possibility of measuring neutron spectra with a single exposure. In particular, previously published results obtained with a spherical spectrometer developed in the framework of projects NESCOFI (Italy) and FIS2012-39104 (Spain) showed the possibility to obtain spectral resolution by taking advantage of the different moderation of thermal neutron detectors located at selected positions within a polyethylene sphere (Gómez-Ros et al., 2010, 2012: Bedogni et al., 2014). Nearly isotropic response was obtained by averaging the response of the detectors placed at the same radial distance (Gómez-Ros et al., 2010).

But isotropic response is not always a desired feature and sometimes directional response can be required to determine neutron spectrum of radiation coming from a specific direction or to characterize angular and energy distributions of fluence. From

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the results previously obtained for the spherical spectrometer, a similar moderation can be expected to be achieved with thermal neutron detectors located along the main axis of a polyethylene cylinder, in case of a monodirectional beam incident along the axis of the cylinder. Accordingly, a cylindrical geometry based on the long counters geometry (Knoll, 2010) was initially considered, consisting on thermal neutron detectors arranged along the axis of a polyethylene cylinder. At it will be discussed in Section 3, the final design includes a collimator required to increase directionality by defining a small solid angle at the entrance. Moreover, other elements like additional layers of borated plastic to increase scattered neutron absorption, air channels for streaming and lead material to detect high energy neutrons needed to be included.

The purpose of this communication is to describe the conceptual design process for a new cylindrical neutron spectrometer (CYSP) with directional response, focusing on the optimization process that has permitted to obtain the definitive configuration for the instrument. This instrument can be used as a real-time spectrometric monitor in neutron producing facilities where information about the angular distribution is relevant, such as collimated neutron beams, neutron beams from targets and small scale accelerator based sources. First experimental results in the reference quasi mono-energetic neutron fields from 144 keV to 16.5 MeV at NPL (UK) have been described in a different paper (Bedogni et al., 2015). The response matrix described below in Section 4 (calculated and partially validated at NPL) shows spectrometric capability in the range from thermal to fast neutrons, practically eliminating the sensitivity to the scattered neutrons up to about 10 MeV coming from other directions. This new spectrometer has been developed within projects NEURAPID (Italy) and FIS2012-39104 (Spain).

2. Materials and methods

All the simulations have been performed with the MCNPX Monte Carlo code (Pelowitz, 2011), using the ENDF/B-VII cross section library (Chadwick et al., 2006) for neutrons with energies below 20 MeV and the room temperature cross section tables in polyethylene, S(α,β). Response functions for neutrons with energies above 20 MeV were calculated using the Bertini intra nuclear cascade model and the Dresner evaporation model (Pioch et al., 2010; Gómez-Ros et al., 2012). A cut-off in the number of histories has been applied to obtain statistical uncertainties lower than 3% in all the cases.

The thermal neutron detectors consisted of commercial 1 cm^2 windowless diodes made sensitive to thermal neutrons through a deposited layer of about 30 μm of ^6LiF on the sensitive face (Pola et al., 2014). The response of the neutrons detectors has been calculated as the number of neutron induced reactions, $N_{(n,x)}$, within the converter layer volume normalized per unit incident fluence, using the modified track-length scoring option for the fluence (F4 tally), i.e.:

$$N_{(n,x)} = \int dE \Phi_E V \rho_{at} \sigma_{(n,x)}$$

where $\sigma_{(n,x)}$ is the microscopic cross section for *(n,x)* reactions, *V* is the volume, ρ_{at} is the atomic density and Φ_E is the energy distribution of neutron fluence.

3. Instrument design

As it has been outlined in the introduction, this study was focused on the optimization process followed to design a neutron spectrometer based on thermal neutron detectors arranged along the axis of a moderating cylinder, looking for a collimated directional response in the energy range from thermal up to some hundreds of MeV. The conceptual model initially considered (Fig. 1a) consisted of eight thermal neutron detectors located on the axis of a high density polyethylene (HDPE) cylinder, thick enough to minimize lateral contributions from epithermal neutrons, with an inner layer of Shieldwerx SWX-238 borated flexible plastic to increase thermal neutron capture. In addition, a ring of air holes around the main axis was considered to enhance the neutron streaming towards the detectors located at deepest positions as well as a lead disk to increase the response for high-energy neutrons (Gómez-Ros et al., 2012).

An exhaustive set of different configurations have been evaluated, varying one by one the size of the cylinder, the position of the detectors and the configuration of the different elements in the instrument (collimator, borated plastic layers, lead disk, air holes). To determine the effectiveness to detect only incident neutrons from a given direction, a model of the device has been simulated within a room 6 m long, 3 m width and 3 m high, with walls of 50 cm concrete (Fig. 1b). An isotropically emitting point source is located 1 m high and 1 m from the end of the room. The instrument is located at the same height, 3 m from the source. The response of the detectors has been calculated with and without the room's

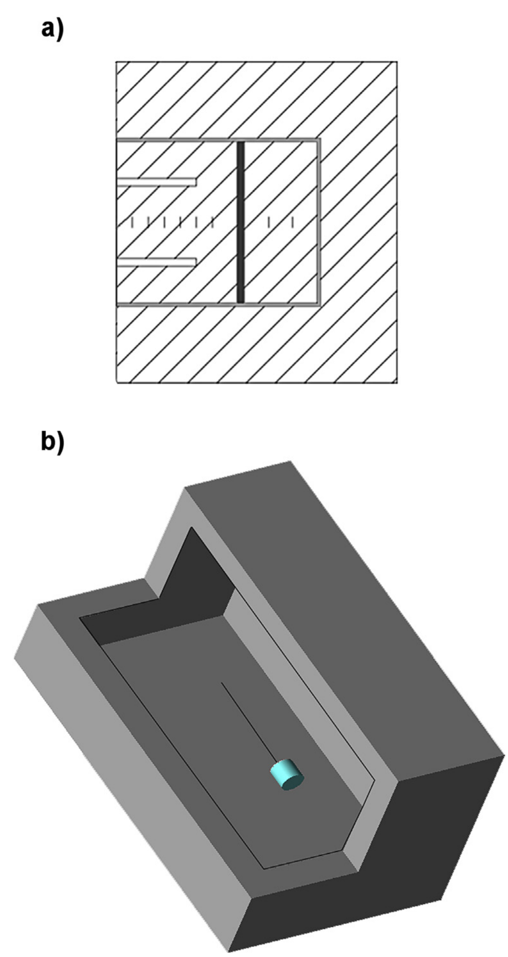

Fig. 1. a) Preliminary conceptual design of the CYSP spectrometer (polyethylene is shaded with diagonally striped pattern, borated plastic appears in light grey and lead in dark grey); b) Schematic view of the simulated irradiation geometry for the cylindrical spectrometer located within a room 3 × 3 × 6 m^3, with concrete walls 50 cm thickness (see the text for additional details). A neutron beam is directed towards the device along the axis of the cylinder.

walls in order to determine whether neutrons coming from undesired directions are adequately rejected.

From the many evaluated configurations, Fig. 2 shows only those corresponding to the most significant changes. The relative response, calculated as the quotient of response removing the room walls divide by the response included the walls contribution, is shown in Fig. 3 for the designs illustrated in Fig. 2a–f and a monoenergetic neutron beam of 1 MeV. The relative response has been also calculated for designs 2e–2f and a 10 MeV neutron beam. In all the cases, the size of cylinder, collimator and air channels are summarized in Table 1.

Starting with one of the former designs (Fig. 2a) with a polyethylene cylinder radius 20 cm and height 35 cm, the corresponding response curve (squares in Fig. 3a) clearly shows a strong lateral contribution that increases for deep detectors. The modified designs illustrated in Fig. 2b and c include respectively a 15 cm and

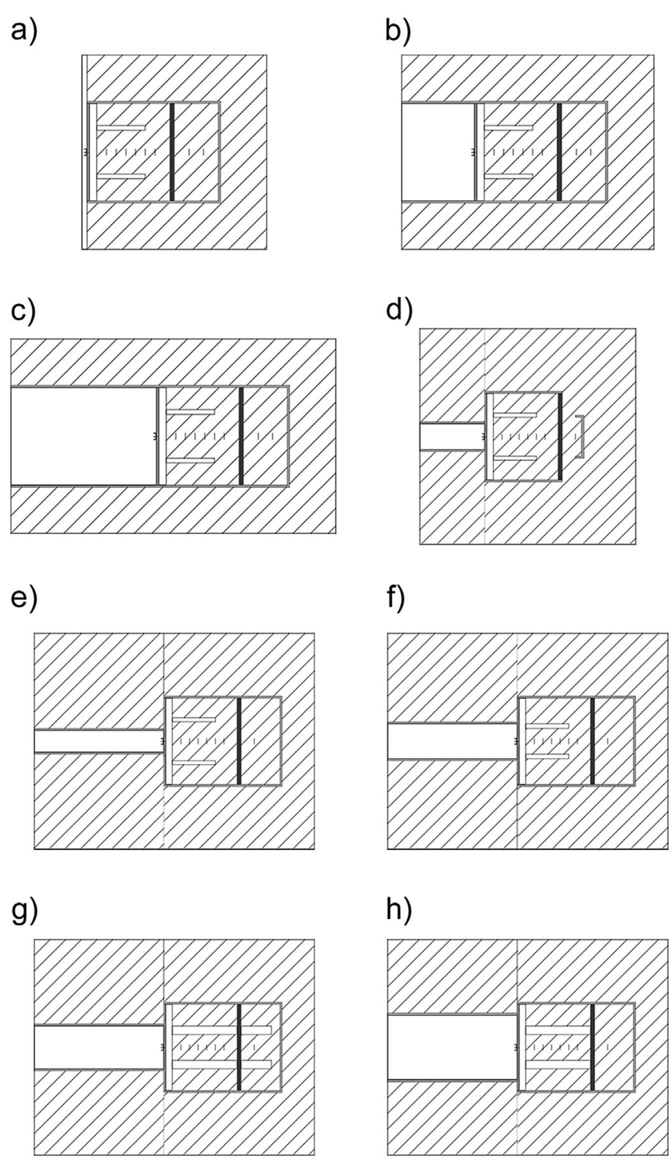

Fig. 2. Longitudinal section of some of the designs evaluated for the cylindrical spectrometer (labelled a–h), varying their geometrical parameters. In all the cases, a cylindrical layer of borated plastic (light grey) has been included to reduce thermal neutron. A lead disk (dark grey) increases the response to high energy neutrons. Polyethylene is represented as diagonally striped pattern. A more detailed representation of the final design is depicted in Fig. 5.

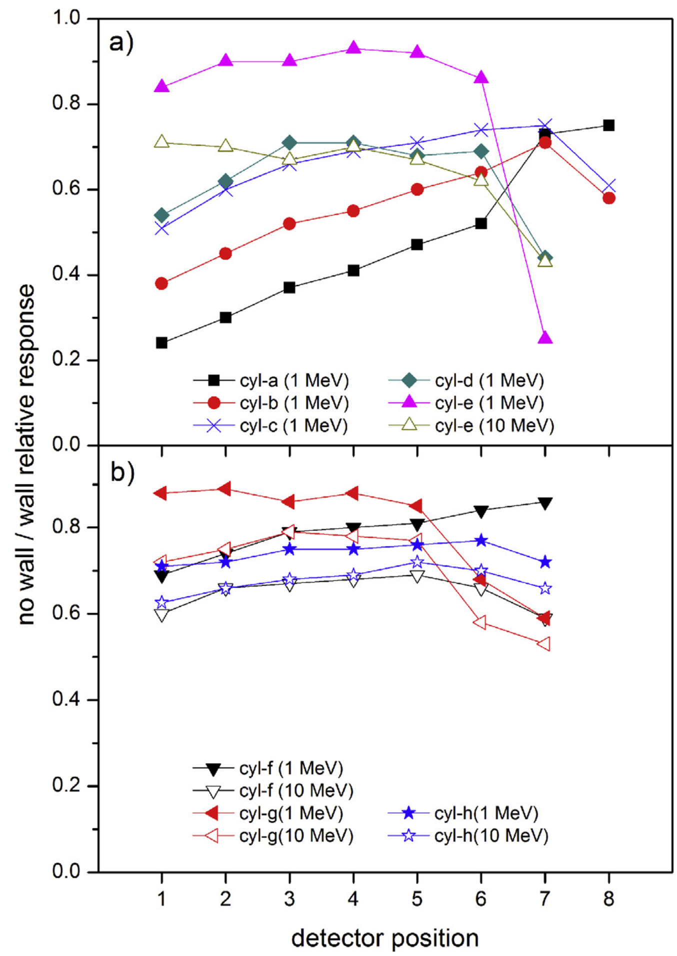

Fig. 3. Relative response of detector models a–h (Fig. 2a–h), in free space and within the room 3 × 3 × 6 m^3.

a 30 cm long, 20 cm diameter, collimator. Nevertheless, they are not enough to get a relative scattered contribution independent of the detector position, as it can be seen in Fig. 3a (circles for design 2b and crosses for design 2c). Therefore, a narrower mouth has been tried in models depicted in Fig. 2d–e (diamonds and up triangles in Fig. 3a) and the eighth detector has been removed, now resulting in a more convenient profile but with a very low sensitivity for the deepest detector at position 7.

A better relative response (less dependent on detector position) is obtained for model f (Fig. 2f and down triangles curves in Fig. 3b) either for 1 MeV and 10 MeV incident neutrons. Nevertheless, some dependence can still be noted and further changes on the design model has been studied. The new models are shown in Fig. 2g–h and the relative responses are plotted in Fig. 3b, compared with the results for model 2f. The model labelled cyl-h (Fig. 2h) provides the best performance so it was selected to build a first prototype.

4. Instrument assembly and response matrix

A detailed 3D view of the instrument designed according to the procedure discussed in the previous section is shown in Fig. 4. It is a cylinder 65 cm long by 50 cm long consisting of two main parts: the first one (the collimator) is 30 cm long with a 15 cm diameter mouth covered by a 5 mm layer of borated plastic. Then, seven detectors are located along the axis of the cylinders at distances 4, 6, 8, 10, 12, 14 and 21 cm from the end of the collimator. A lead disk

Table 1
Main geometric parameters (cm) of the models labelled a–h, shown in Fig. 2.

Model	Cylinder		Collimator		Air channels	
	Total length	External diameter	Length	Mouth diameter	Length	Diameter
a	35	40	–	–	10	1
b	50	40	15	20	10	1
c	65	40	30	20	10	1
d	50	50	15	6	10	1
e	65	50	30	5	10	1
f	65	50	30	8	10	1
g	65	50	30	10	23	2
h	65	50	30	15	15	2

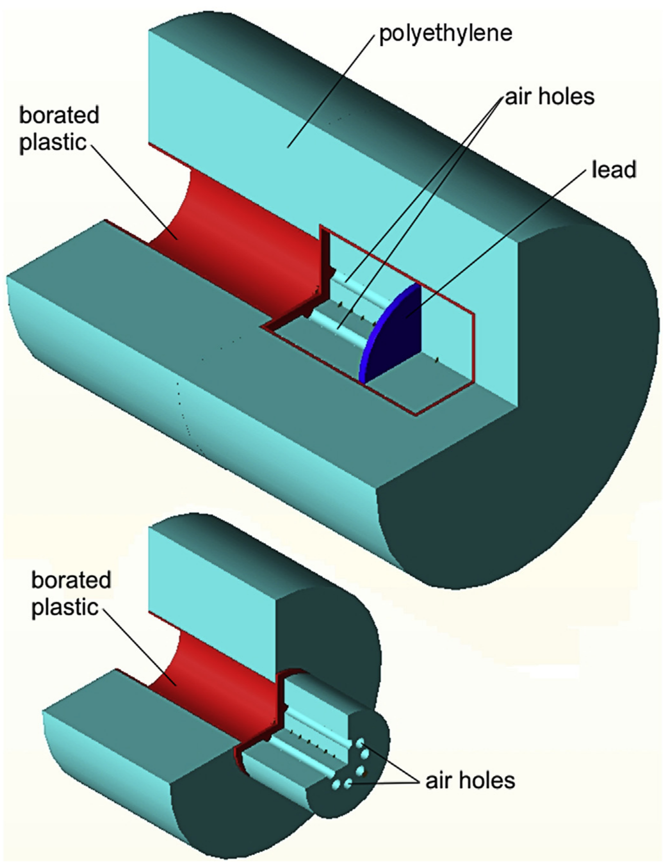

Fig. 4. Detailed 3D view of the final design (model h) for the cylindrical spectrometer.

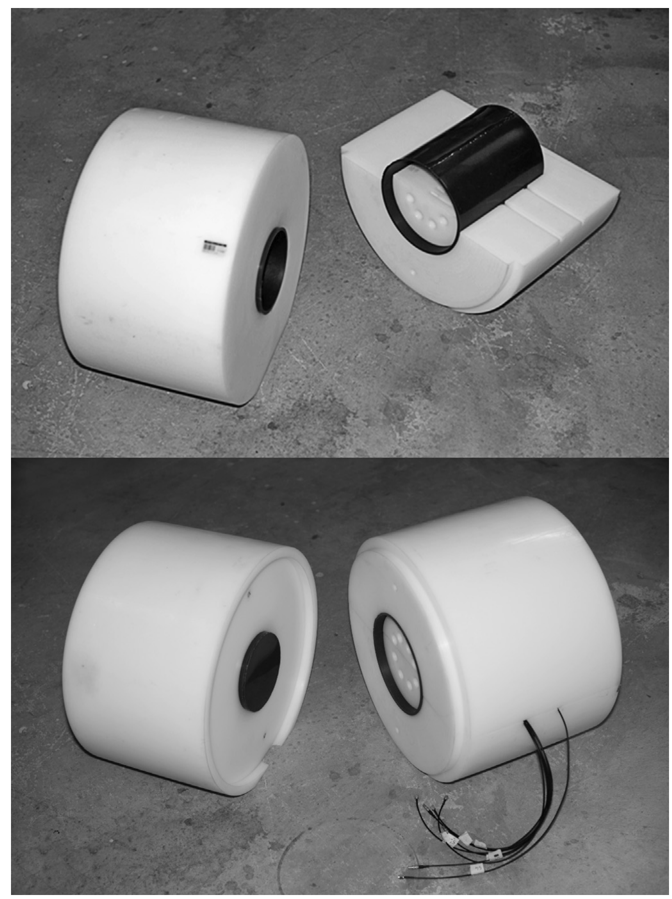

Fig. 5. First built prototype, showing the borated plastic layers, air channels and holes for detectors and cables. The instrument can be easily disassembled to change the detectors or to modify their distribution in the inner polyethylene cylinder.

1 cm thick is located at 17 cm. The small cylindrical volume containing the cavities to allocate the detectors, the air channels and the lead disk are also surrounded by a 5 mm layer of borated plastic.

A first prototype has been fabricated using recently developed thermal neutron pulse detectors (TNPDs) (Pola et al., 2014; Bedogni et al., 2015) (Fig. 5). The response matrix has been calculated according to the procedure described in Section 2 for 68 log-equidistant energies from 10^{-9} to 10^{3} MeV assuming two irradiation geometries: a) plane parallel mononergetic beam along the axis of the cylinder and b) lateral irradiation. As it is shown in Fig. 6a, displaying the calculated response matrix for incidence along the axis (direct response), the response to neutrons with energies from thermal up to around 10 MeV decreases as the detector depth increases. For energies above 10 MeV, the lead shell converter increases the response of detectors located at deeper positions (12, 14 and mainly 21 cm) through the *(n,xn)* reactions that allows to extend the energy response up to hundreds of MeV. Fig. 6b shows a slight contribution for energies above 10 MeV that is practically negligible compared with the direct response.

The response matrix has been partially validated with the monochromatic reference neutron fields of 0.144, 0.565, 2.0, 3.5, 5.0 and 16.5 MeV and the ^{252}Cf source (fluence averaged energy 2.13 MeV) available at NPL. The theoretically calculated response matrix agrees with the experimentally measured response within an overall 3% uncertainty (Bedogni et al., 2015). These results seems to indicate the design of the instrument is able to eliminate the response to scattered neutrons up to about 10 MeV.

5. Conclusions

A new neutron spectrometer called CYSP (Cylindrical Spectrometer) has been designed to provide an extended energy

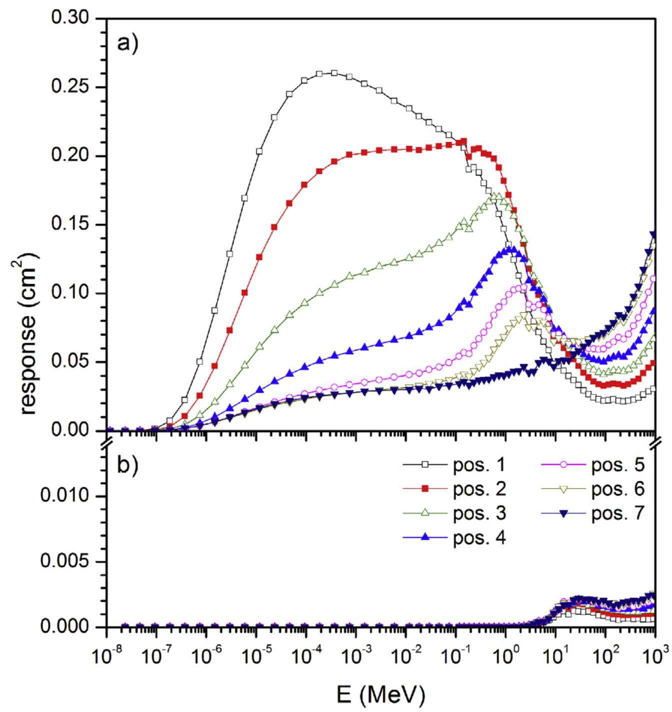

Fig. 6. a) Energy response functions of the seven thermal neutron detectors in the cylindrical spectrometer to monoenergetic neutrons: a) plane parallel mononergetic beam along the axis of the cylinder and b) lateral irradiation.

response, in the range from thermal to hundreds of MeV, to directional neutron irradiation. As it has been shown, the instrument is practically insensitive to scattered contributions. This makes it especially advantageous for characterizing direct neutron spectra even when scattered neutrons (from soil or walls) may contribute significantly to the radiation field. A first prototype for the instrument has been manufactured and the corresponding response matrix has been simulated and partially validated to reference neutron fields from 144 keV to 16.5 MeV obtaining a 3% as overall uncertainty.

Acknowledgements

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