COLLIMATED NEUTRON BEAM FOR NEUTRON RADIOGRAPHY

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The obtaining of a collimated neutron beam on the tangential channel of the ACPR reactor from INR Pitesti that to satisfy the requests of a neutron radiography facility it is presented. The collimation of neutrons means the elimination from the neutron beam of those neutrons that have trajectories that are not inside the space defined by walls or successive apertures that are made of neutron absorbent materials. The assembly that assures the collimation of neutrons, named collimator, is optimized using MCNP 4B code based on Monte Carlo method for neutrons and gamma radiation.

Key words: neutron radiography, collimator for neutrons, collimation ratio, MCNP 4B code.

1. INTRODUCTION

A tangential channel of a nuclear reactor has some peculiarities regarding intensity and energetic spectrum of neutrons in comparison with a radial channel of a nuclear reactor or tubes used to extract neutrons from other neutron sources. On a tangential channel the neutron beam has a bigger cadmium ratio and a lower gamma contamination than on a radial channel and is more suited to be used for thermal neutron radiography.

For neutron radiography, different of other nuclear physics applications that use neutron beams, are necessary large neutron beams to obtain images of a large area of the investigated objects.

An ideal neutron beam should be parallel, monoenergetic, with big intensity, free of other contaminant radiation and uniform on its cross section. In practice it is intended to have experimental arrangements that to accomplish neutron beam parameters as closely as possible to ideal ones. For this purpose it is used a collimator. The neutrons pass through a collimator from the entrance aperture placed nearby neutron source to the exit window where are used for neutron radiography investigations. The inner space of a collimator is evacuated or filled with air, or better filled with helium. A characteristic parameter of a collimator that defines the degree of divergence of the neutron beam is the L/D ratio, where L is the length of the collimator and D is the diameter (or generally the opening) of the entrance aperture.

The place from where thermal neutrons start (the source of neutrons) is a moderator that contains neutrons moving in all directions. In order to have a neutron beam on a direction, nearby the moderator it is placed a collimator. The neutrons entering in the collimator must have the direction of the exit window to be useful otherwise they are captured by walls or apertures to avoid the scattering. The entrance aperture must be big enough to permit a larger number of neutrons to go inside the collimator but small enough to have a bigger L/D ratio. The L/D ratio depends also by the length of the collimator (or otherwise by the distance from entrance aperture to object plane if the object is put far away from collimator), a bigger L means a better resolution.

Because the moderator emits neutrons in all directions, their intensity is proportionally with $1/r^2$. To have a bigger intensity the object must be placed closer to neutron source but for a better geometrical resolution it must be placed farther. Bigger neutron intensity determines a better statistics, therefore a bigger contrast of the image that is able to differentiate between different materials. But for dimensional measurements it is necessary to have precise separation lines, therefore a big geometrical resolution. A compromise must be made between the two parameters, L and D.

A transmission method for neutron radiography it is involved because are detected the neutrons that pass through investigated object. If the neutrons come to investigated object more scattered, then the projection of a detail is larger in the plane of the detector and the geometrical resolution of the image is poorer.

There are known different types of collimators, more important are that named pin-hole, Soller and divergent collimators.

The pin-hole collimator has a simple construction. An aperture is placed at a distance from neutron source in order to establish a L/D ratio of the collimator. For a pin-hole collimator it is necessary a large neutron source that to have an equal neutron flux on its surface in order to expose uniformly the object to neutrons.

At Soller collimators appear on image the network of absorber walls that delimits inner minicollimators. This type of collimator requires a large uniform neutron source.

The most used is the divergent collimator because it permits the investigation of large objects, every point of the object being exposed to a neutron beam with approximately the same L/D (this means an intrinsic geometrical resolution uniform in the exit window of the collimator). A divergence collimator has the neutron source in its entrance aperture.

Based on dimensional constrains of the tangential channel of ACPR, previous experimental determinations of the thermal neutron flux and intensity ($8 \cdot 10^{11}$ n/cm^2/s near core and $1.12 \cdot 10^6$ n/cm^2/s at the exit of tangential beam tube, at 100 kW operating power of ACPR) and working methods involved, were established the parameters of the divergent thermal neutron beam. Some of them are:

- the thermal neutron beam intensity at least $5 \cdot 10^5$ n/cm^2/s;
- the collimation ratio, L/D, at least 90;
- the exit window, 250 mm in diameter;
- the n/γ ratio at least $1 \cdot 10^6$ n/cm^2/mrem (that determines used investigation methods);
- the divergent angle under 4^0;
- the cadmium ratio above 17.

To obtain a thermal neutron beam with such parameters were used:

- a graphite illuminator placed on channel nearby reactor core to scatter neutrons towards exit of the channel;
- a mobile monocrystaline bismuth filter for the attenuation of the gamma radiation and scattering of fast neutrons that will allow performing direct neutron radiography investigations and also γ radiography investigations;
- a set of successive apertures from boral, indium and lead for the formation of the divergent collimator.

The position and dimensions of these components were optimized by calculus made with MCNP 4B code based on Monte Carlo method both for thermal neutrons and both for gamma radiation.

2. CALCULUS WITH WIMS 4D AND MCNP 4B CODES

The tangential beam port has an overall length of 5644 mm (Figure 1) and has two sections. First with the length of about 2984 mm and the diameter of 219 x 6.5 mm, and second with the length of about 2660 mm and the diameter of 273 x 6.5 mm. The distance between the center of the reactor and the beam port axis is 575 mm. The beam port exceeds with 508 mm, to the axis of the pool, the perpendicular right line on its own axis that passes through the center of the core. The beam port contains a mobile lead shutter with the thickness of 381 mm and 406 mm in diameter placed at 1015 mm from beam port exit. Between the edge of the core and the tangential beam port is a distance of 157.8 mm. The space between core and beam port is filled with regular demineralised water. A better transmission of the neutrons from core to channel will be assured placing aluminum in free locations of the reactor grid. In this way the reduction of the initial thermal neutron flux of the channel through divergent collimator construction is compensated.

The optimization of the transmission of neutrons to channel and the optimization of the dimensions and positions of the collimator components is done using WIMS D4 and MCNP 4B codes.

To establish the spectrum of the neutron flux at the edge of the ACPR reactor, the transport program WIMS D4 was involved. Because of cylindrical shape of the reactor, it is suitable to be modeled by WIMS program. The model consists of cylindrical rings that cover the central hole, ACPR fuel, water etc. The neutron flux calculated for 69 broad groups in a thin volume at the edge of the core has been collapsed in 3 or 23 groups. Their weights, after the renormalization to unit and upper boundaries for energy groups were used in the inputs of the MCNP program.

The WIMS D4 code was used to study the effect of the replacement of the water between core and beam port with an aluminum block, aluminum pins placed in grid's holes or air in aluminum box. The replacement of the water leads to an improvement of the transfer of the neutrons towards beam port. The results of the calculations are shown in Table 1. It can be seen that the increase of the thermal neutron flux is maximum using a box filled with air. To disturb not other experiments for irradiation tests, a bell box is put in place from where the water is pushed out and replaced by air.

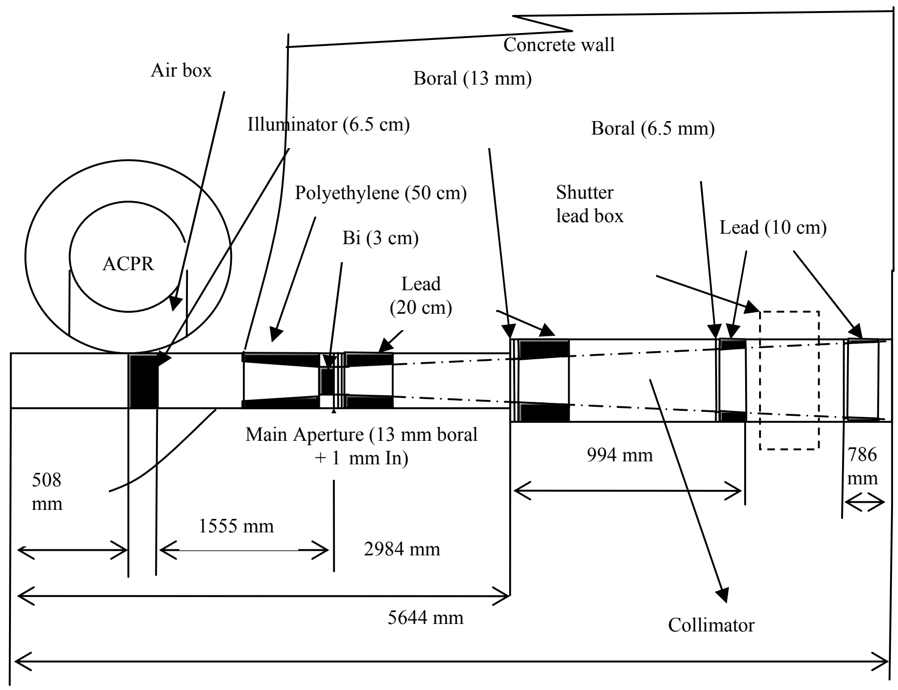

Fig. 1. Sketch of the collimator of the neutron radiography facility at the tangential beam port of the ACPR.

Table 1

Relative units of the thermal flux in the graphite illuminator for some materials between core and tangential beam port

Water	Aluminum pins	Aluminum block	Air
4.92	14.3	16	19.5

In order to assure a maximum thermal neutron beam at the exit of the collimator and a suitable established collimation ratio were performed Monte Carlo calculation based on MCNP code. Two models were prepared for Monte Carlo calculations.

The first model aimed to establish the thickness and position of the graphite illuminator for the maximum increase of the thermal neutron beam at the exit of the collimator. This model contains the source of neutrons offered by WIMS code for 3 and 23 groups, the box with air and the illuminator placed on beam port. The relative values obtained in a plane at 100 cm from illuminator, for different thicknesses of the illuminator are shown in Figure 2. The illuminator is placed near centerline. If the illuminator is placed in a centered position the thermal neutron flux is a little improved, but epithermal and fast neutrons increase more and it is not desirable. The maximum neutron beam is obtained for 6.5 cm and 7 cm illuminator thicknesses.

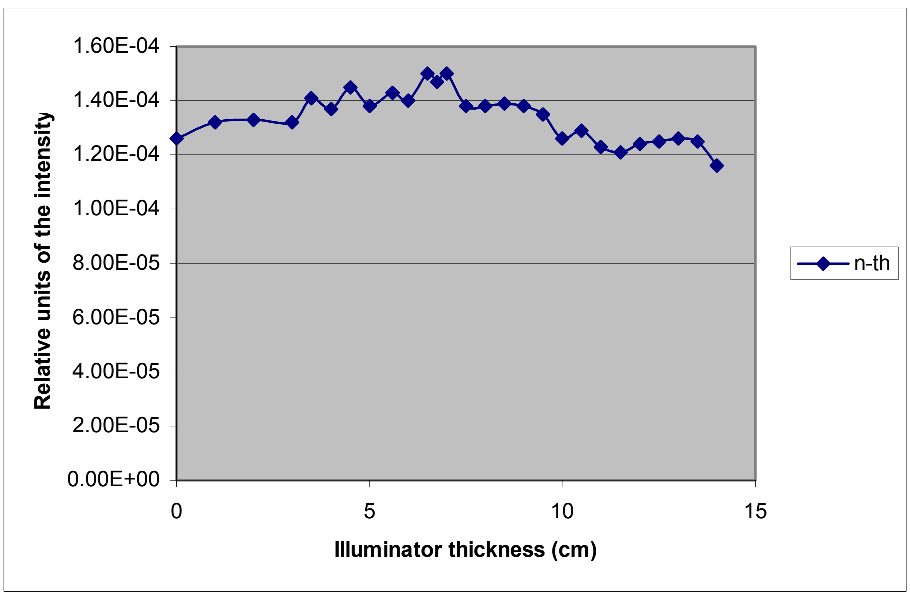

Fig. 2. Neutron beam intensity.

The second model targeted to establish the position and thickness of the single-crystal Bi filter, to obtain the maximum thermal neutron beam at the exit of the collimator. This model is based on the geometry of the collimator shown in Figure 1 and the source of neutrons is placed on the face of the illuminator. We consider the maximization of neutron flux below 1.E-06 MeV. On the geometry of the second model calculations were done for gamma radiation also.

Based on previous flux measurements and the results estimated from first MCNP model, it was established a value of 4.5 cm for the diameter of the collimator main aperture. Preliminary results obtained with the second model established a value of 3 cm for the thickness of the Bi single-crystal.

The main aperture will be built by 13 mm of boral, 1 mm indium and 200 mm lead.

To optimize the position of the aperture and Bi filter, MCNP calculation were done for different positions of the filter. The results are shown in Figure 3. Supplementary, it was used the condition to have a uniform intensity of the neutron beam in the exit window of the collimator. This was precisely established with AutoCAD program that drawn the extreme lines of the neutron beam. In this way every point in the exit window is seen by the same area from the surface of the illuminator. In these conditions it was established the maximum distance between illuminator and aperture to be 152.5 cm, although the maximum of the neutron beam is obtained for the distance of 190-200 mm. The calculations for the distance of 152.5 cm, the main aperture of 4.5 cm and 3 cm of Bi indicates a decrease of the gamma radiation of 65.19 times, and for neutrons of 16.15 times (the Bi filter itself decreases the beam intensities 8.22 and 2.22 times, respectively). The calculations with MCNP code were done with polycrystalline Bi. In the real case, for single-crystal Bi with cross-section 3 times smaller at room temperature [1], it is expected a reduction of the beam intensity with 41% instead of 2.22 times reduction.

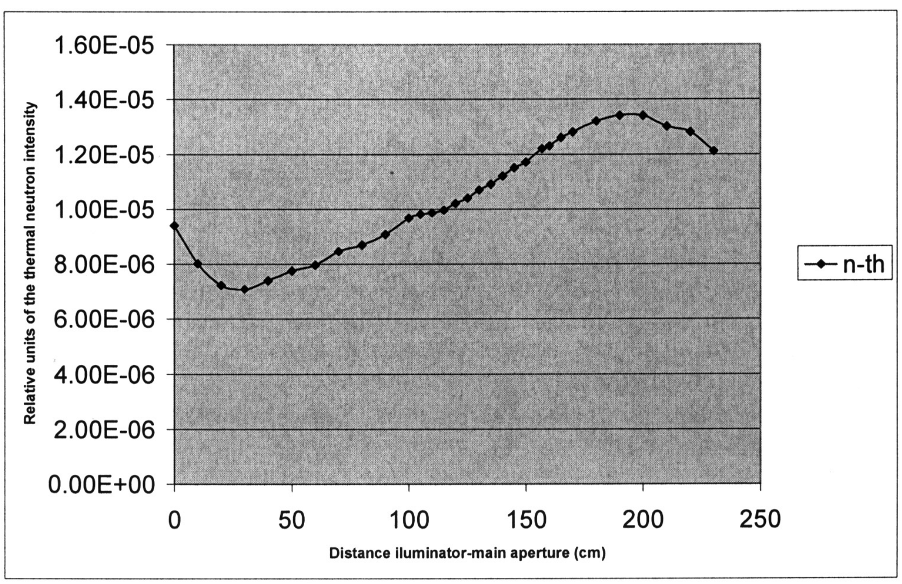

Fig. 3. Intensity of the thermal neutron beam at the exit of the collimator.

The minimum distance between illuminator and main aperture is considered to be 125 cm. For this distance the intensity of neutron beam decreases with 17%, but the resolution increases. The lead ring (20 cm) should be positioned at less 125 cm were is the edge of the concrete wall of the pool, otherwise the direct gamma radiation from reactor core cannot be properly stopped.

The secondary apertures are positioned to avoid any trajectory of the neutron directly from illuminator to reach the wall of the beam tube. The secondary apertures are boral plates and lead rings.

To increase the neutron beam for the direct method and to perform gamma radiographs it is designed to remove vertically the Bi filter with the help of a steel cable. The Bi filter is inside of a box, which contains lead ballast to fall back on position when cable is released.

3. CONCLUSIONS

The collimation of the neutrons on the tangential beam port of the ACPR reactor is done, in fact, with a pin-hole collimator with an aperture of 45 mm placed at the distance of 125-152.5 cm from the surface of the illuminator that has a thickness of 6.5 cm and the diameter of 18 cm. The estimated beam intensity for thermal neutrons with bismuth filter is $3.96\cdot10^5$ – $4.65\cdot10^5$ n/cm^2/s and $4.85\cdot10^5$ – $5.70\cdot10^5$ n/cm^2 /s without Bi filter.

The estimated values for gamma debit doses (for 152.5 cm illuminator-main aperture distance) are 1.75 rem/h without bismuth and 213 mrem/h with bismuth. The estimated n/gamma ratio is $1.03\cdot10^6$ n/cm^2/mrem and $8.44\cdot10^6$ n/cm^2 /mrem, respectively.

The divergent angle of the collimator is 3^o- 3.3^o and the collimation ratio 100-92.8 for the domain of distances 125-152.5 cm between illuminator and main aperture.

These values of beam intensity, n/gamma ratio and collimation ratio are in concordance with that from other facilities built at TRIGA reactors and offer the base to use with good results the direct and the transfer methods for neutron radiography.

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