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EFFECTS OF THE BEAM FOOTPRINT ON THE NEUTRON YIELD IN SINQ

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ABSTRACT

Measurements of neutron fluxes performed at SINQ for different beam profiles have shown that there is a clear effect on the neutron yield, which is to some extent dependent on the size of the incoming beam. The effect is of about ±5% if the width of the distribution is decreased/increased by 10%, i.e. the neutron yield is increased with a narrower beam. This effect is clearly of interest since if correctly exploited it may lead to an increase of neutron production simply by changing the beam parameters. We have performed a study based on Monte Carlo calculations using MCNPX in order to understand this phenomenon. Calculations have been performed for the latest two solid targets used at SINQ, target 7 and target 8, which have different characteristics, the latter being optimized for neutron production giving a yield higher by about 35%. Particular care was taken in the correct modelling of the profile of the proton beam hitting the target. Moreover, calculations have been performed with and without the specimens inserted in the target for the STIP program. The results show that the neutron yield depends on the position of interaction of the particles in the target. The effect of neutron increase is higher for the non-optimized target 7. This effect could be exploited to optimize the neutron production in spallation targets.

1. Introduction

An investigation of the effects of the proton beam footprint on the neutron production has been performed at the PSI neutron spallation source SINQ with the solid target “Target 7” [1]. The experimental results of the neutron flux measurements have evidenced a significant flux increase when reducing the beam size. As shown in Fig. 1, the neutron flux increase in the SINQ facility is almost of 10% when varying both transverse dimensions of the proton beam (by changing the quadrupole settings) from a +10% to −10%, with respect to the reference conditions. In order to evaluate to which extent the beam footprint contributes to this effect, one has to take into account that by changing the beam width the fraction of beam intercepted by the last collimator KN33, located in front of the SINQ target, varies accordingly. This beam loss is measured by a halo monitor whose efficiency has been estimated to be around 25%. The uncertainty on this value has a direct impact on the influence of the beam footprint on the neutron production since lower efficiency would turn into smaller significance of the footprint effect.

The aim of this work is to understand this effect using numerical simulations. Neutron fluxes were calculated with the MCNPX Monte Carlo transport code, version 2.5.0, by using different kinds of sources and varying the beam size. Since these effects are relatively small, the approach adopted in this work was, first of all, to describe in the best possible way the proton source, including the beam divergence.

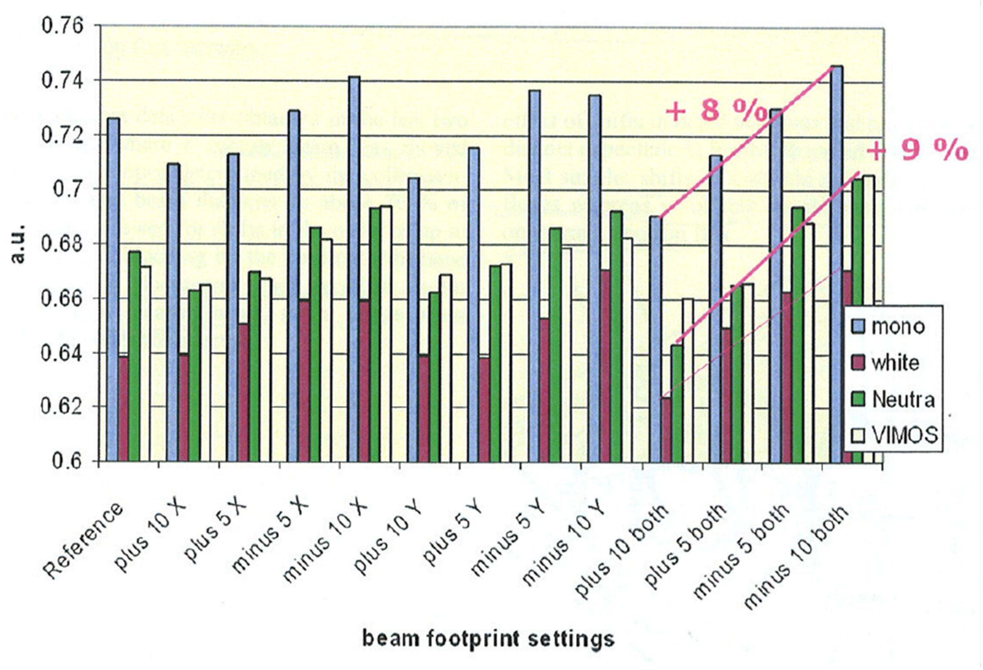

Figure 1. Experimental results of the beam size variation effect on the neutron flux [1].

2. Model and source definition

The SINQ facility has been operating since 1997. A spallation target is irradiated by a high current (more than 1 mA) proton beam of 575 MeV energy. The typical operation time of a spallation target is of 2 years [2]. Target 7 was irradiated in 2007-2008 and consisted of a bundle of rods arranged in layers of 9 or 10 rods each, for a total of 37 rows and 351 rods. Each rod consisted of a cylinder with radius of 0.54 cm and 13.6 cm length. There were different types of rods: *1)* the majority consisted of Pb rods inside zircaloy cladding, the volume of the cladding being filled to 90% with Pb; *2)* the lowest row of 9 rods consisted of $AlMg_3$ cylinders with D_2O circulating inside, for cooling purpose during operation; *3)* several rods filled with specimens for the STIP program [3] (mostly steel specimens) occupied some of the central positions. Calculations were repeated for the Target 8, irradiated in 2009, in order to compare the results obtained with the two different targets. This target was also based on a rod bundle structure, but it was surrounded by a cylindrical lead blanket to increase the neutron production. The material of the tubes was zircaloy. The targets were modelled with MCNPX and are shown in Fig. 2.

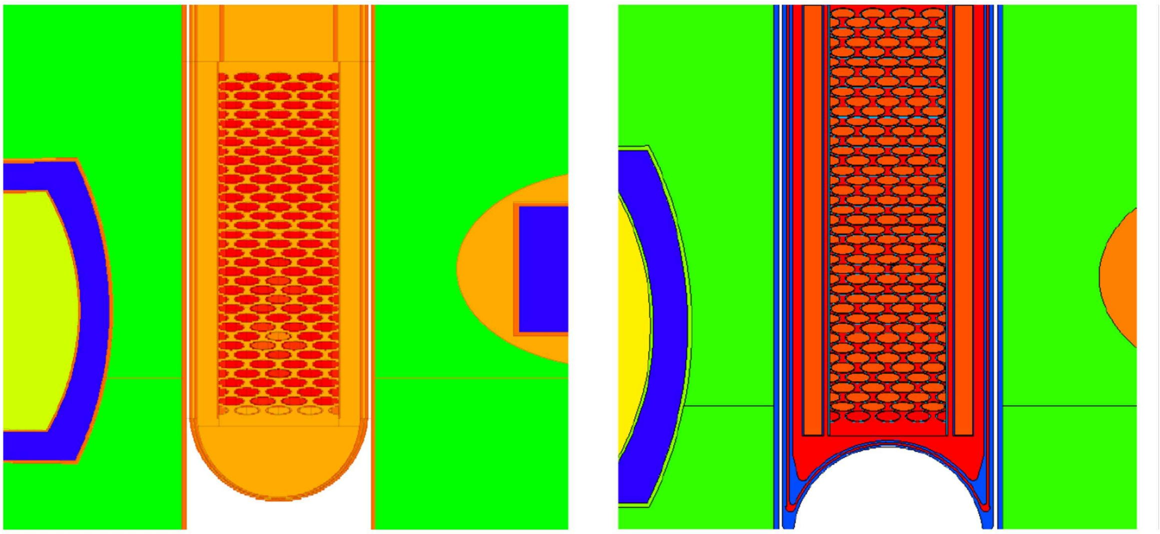

Figure 2. MCNPX model of target 7 (*left*) and target 8 (*right*).

The first tests were done with a series of ring-shaped sources of different diameter (Fig. 3). The goal of this test was to obtain information about the weight that the different neutron production regions in the target have on the total neutron flux production. The oval shape of the rings and their size were chosen according to the shadow projected by the collimators on the target. The dimensions of the seven rings are listed in Table I.

Table I: List of the outer axes sizes of the rings.

Ring ID	Major half axis (cm)	Minor half axis (cm)
1	2.5	0.5
2	3.5	1.5
3	4.5	2.5
4	5.5	3.5
5	6.5	4.5
6	7.5	5.5
7	8.5	6.5

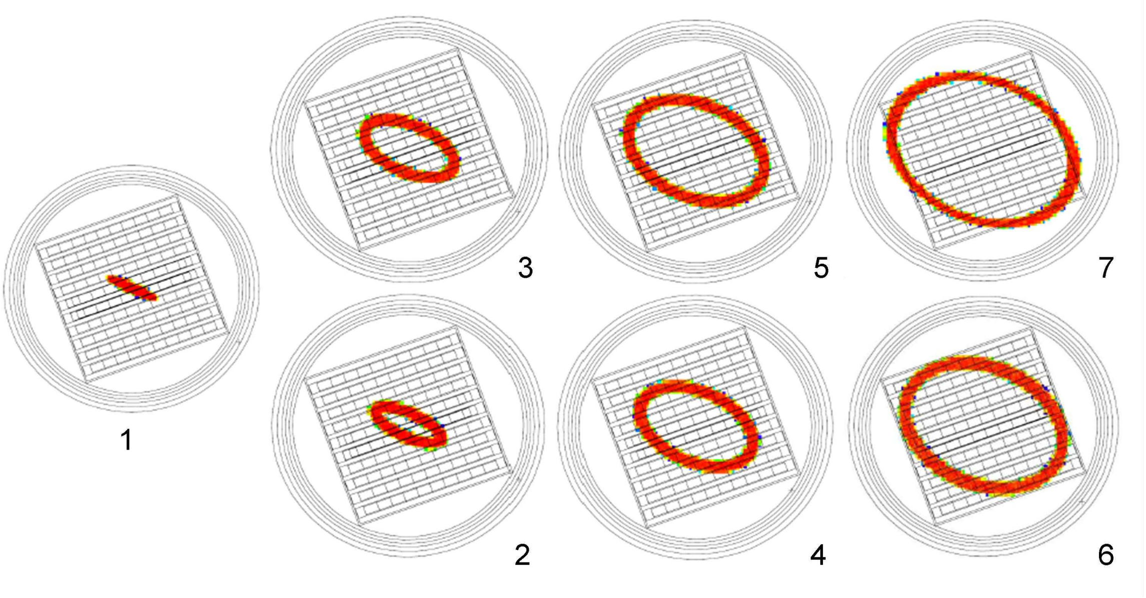

Figure 3. Shape of the ring-sources by the simulations giving different footprints on Target 7.

Following the tests with the ring sources, in order to reproduce reliably the irradiation conditions of the measurements a calculated source was used. The source was obtained from the simulation of the beam dynamics using TURTLE [4], according to five quadrupole settings used for the experiment, corresponding to five different footprints on the target: reference, +10% (in both *x* and *y*), +5%, -5% and -10%. The TURTLE data provided a table of 10^5 particles with their positions (*x*,*y*) in mm, their divergence (*x'*,*y'*) in mrad, and their momentum in MeV/c. The data were calculated at different reference planes, in particular at the exit of the collimator KN33, and at the target entrance (Fig. 4).

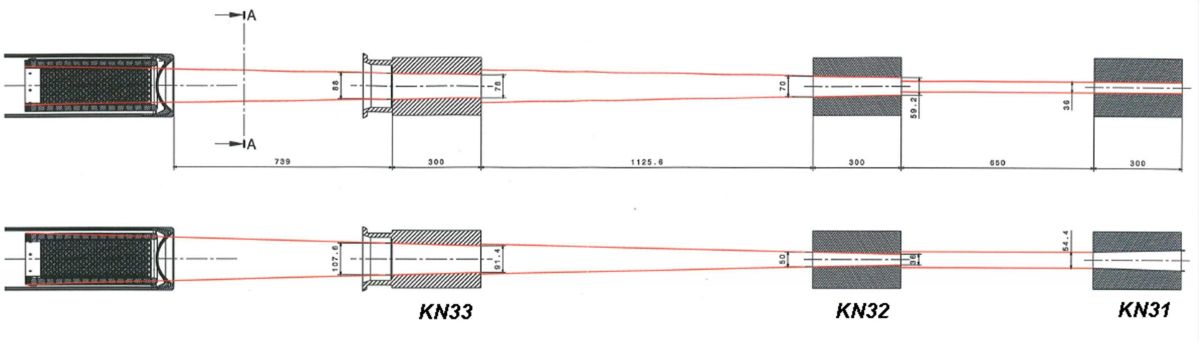

Figure 4. Geometrical configuration of the target and of the last three collimators.

The position and the divergence distributions at the target entrance were used to define a source in MCNPX reproducing the trajectory of each particle before hitting the target. Although the proton beam has a narrow energy distribution (due to interaction with the pion production target before arriving at SINQ) for simplicity we considered a monoenergetic beam of 575 MeV.

The resulting distribution of the proton beam colliding on the target in the reference case, as resulting from the developed source, is shown in Fig. 5. In the figure, to display the particle trajectories, all the volumes in the geometry have been put to void, hence there is no interaction of the proton beam with the target.

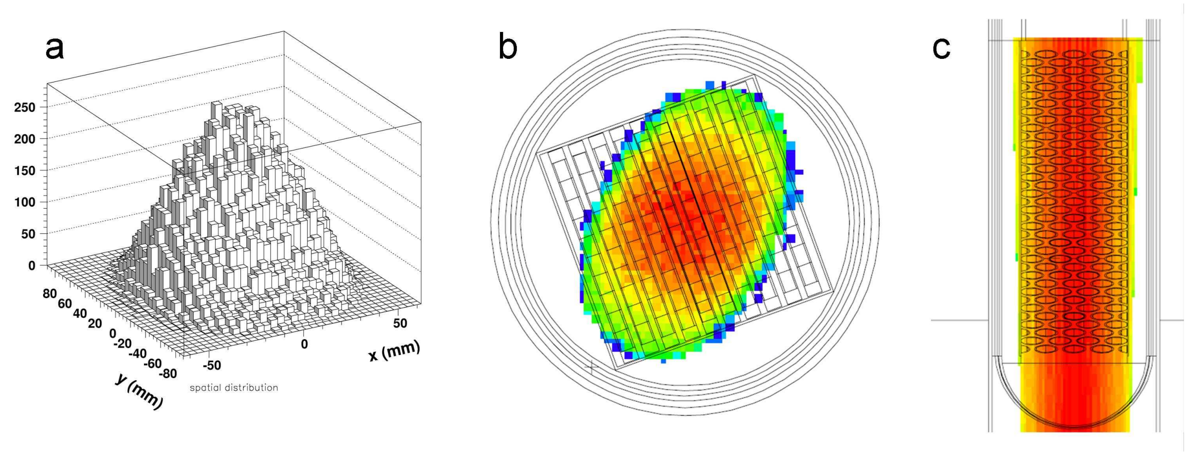

Figure 5. *a*: lego plot of the proton spatial distribution at the target entrance; *b*: view on the (*x*, *y*) plane. *c*: lateral view.

3. Target 7 calculations

Neutron flux calculations were performed for the NEUTRA beam line and for the cold neutrons of the D_2 moderator (Fig. 6).

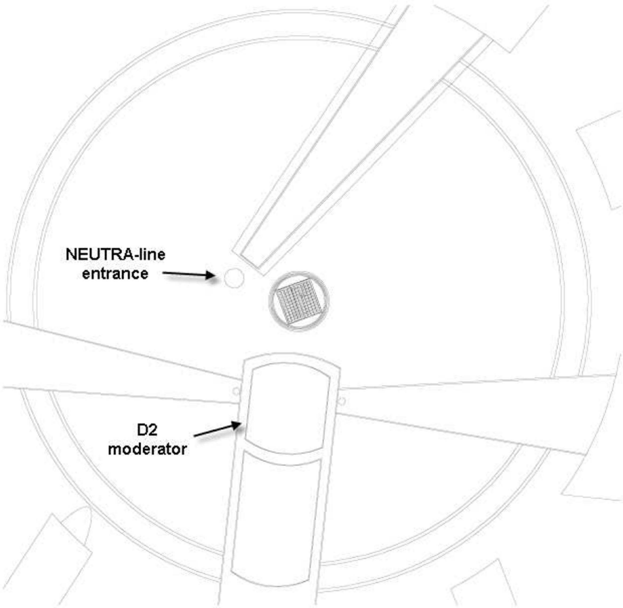

Figure 6. View of the SINQ facility on the (*x*, *y*) plane, showing the target and the surrounding heavy water tank. The indicated volumes are the entrances of the beam lines used for the measurements and calculations.

The following physical quantities were calculated:

- neutron flux at the NEUTRA beam line entrance and exit;
- neutron flux in the D_2 moderator and at the exit of the ICON beam line;

The possible factors which can influence the neutron production when varying the proton beam width and produce the observed effect could be several:

- target geometry factors, i.e. scattered protons escaping the target before releasing all the energy, or fraction of protons never hitting the target because of the beam focusing;
- target material factors, such as the presence of the STIP samples concentrated at the center of the target;
- view factor, or probability of a neutron to reach a region outside the target depending on the production position. According to this hypothesis, a theoretical point source placed at the center of the target would give more neutrons at a beam line entrance than a more extended target (Fig. 7). Clearly this effect is expected to be partially washed out by the moderator process in the heavy water tank.
- losses in the collimator;

Additionally, beam movement and consequent enlargement of the footprint during the measurements could play a significant role.

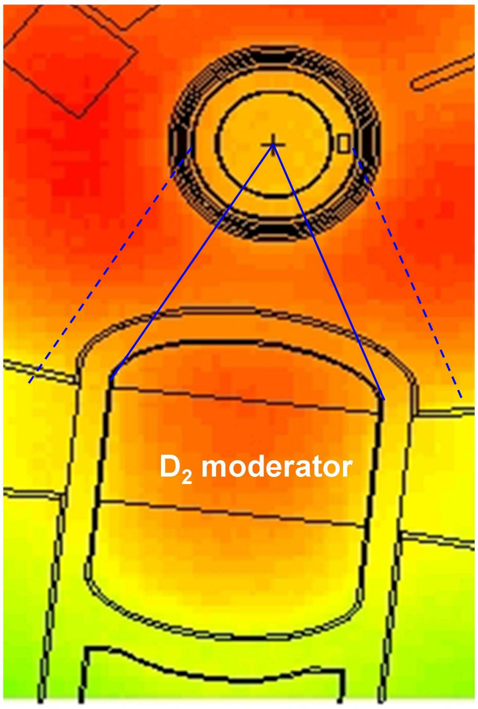

Figure 7. The view factor: a point source of neutrons (full blue lines) could in theory "view" the D_2 moderator more than an extended source (dashed lines).

3.1 Results with the ring source

The aim of using this source is to achieve qualitative information about the contribution to the total neutron flux due to protons colliding on different points in the target. The values of the calculated fluxes at NEUTRA and in the D_2 moderator as a function of the "ring ID" are shown in Fig. 8.

The results demonstrate that the neutron fluxes depend on the ring ID and on the presence or not of the STIP samples in the target. For the rings placed near the borders of the target the flux is lower: the reduction is almost 20% when passing from ring 5 to ring 6. The presence of the STIP samples (mainly steel) produces a decrease in the contribution to the neutron flux for the inner rings. Comparing the curves with and without STIP samples, we note that for some points (especially the first ring) the flux decrease is very large. However, most of the protons in the actual beam profile come from rings 3,4 and 5, for which the decrease is only of about 10%. From these graphs it is clear that the fluxes at the entrance and exit of the neutron beam lines are very well correlated. This allows us to take into account only the fluxes at the beam-lines entrance, which are calculated with higher statistical significance.

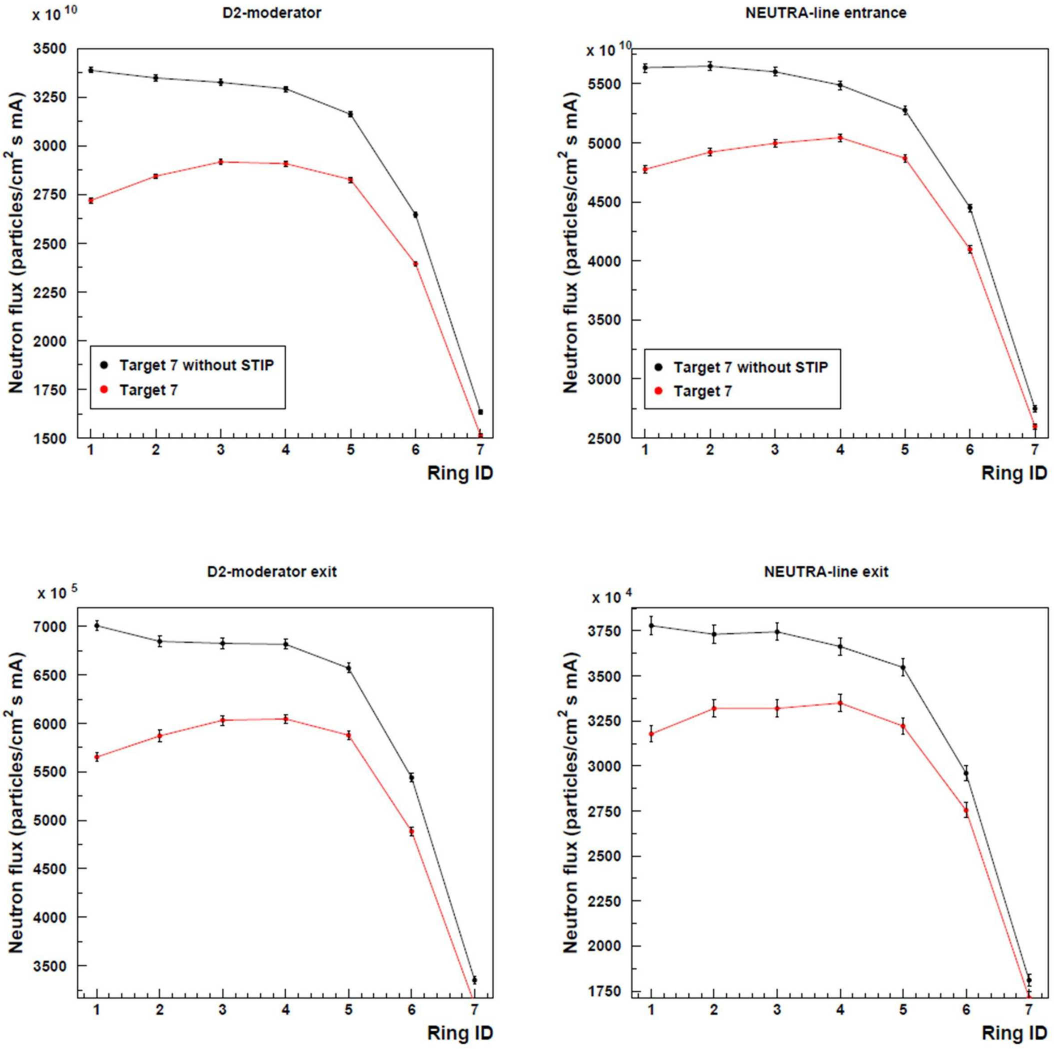

Figure 8. Calculated fluxes in the *D_2* moderator and at the NEUTRA line using the ring sources.

3.2 Results with the calculated source

The main objective of this work was to reproduce the experimental results by calculations. For this study the calculated source previously described was used. One of the physical factors which can influence the neutron production when varying the beam size is the beam divergence. In order to split the contribution due to this factor and obtain more information about the observed effect, a preliminary study was performed neglecting the beam divergence.

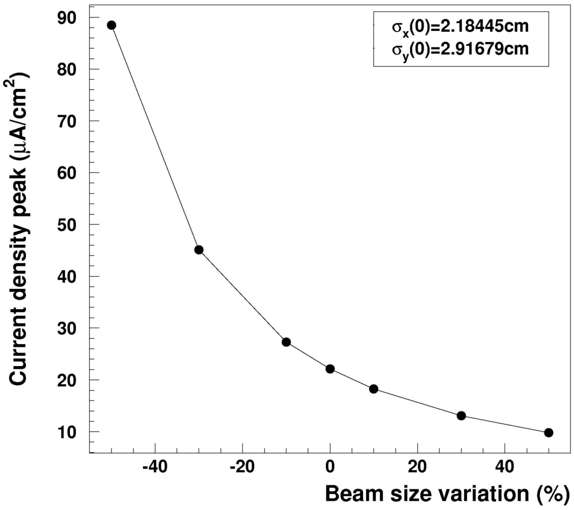

Figure 9. Peak current density at the target window as a function of the beam size variation.

First, we considered the reference profile and rescaled the widths to +50%, +30%, +10%, −10%, −30%, −50% of the reference width. The use of a cookie cutter has been necessary to reproduce the presence of the collimators. The peak current density on the target window varies accordingly (Fig. 9). The results of the neutron fluxes in the D_2 moderator are shown in Fig. 10. The trend is the following: for very narrow beam widths (-50 % and -30 % of the reference beam) the neutron flux is lower, due to the presence of the STIP samples. The maximum flux is obtained for a beam size of -10 %, and then it decreases giving a total effect of 6%. The calculations were repeated using the calculated beam profile with the following conditions: reference, -10%, -5%, +5%, +10%, and taking into account the calculated divergence. Results are shown in Fig. 11. The effect of the divergence is negligible.

Finally we introduced an additional *ad hoc* effect consisting in the wobbling of beam during irradiation, an effect which was observed in a qualitative way during operation of MEGAPIE [5]. Since we do not have yet a precise information on the beam movement, we first made a simple test considering the beam distribution calculated at z=0 (center of the D_2 moderator) shifted down by 25 cm, that is, just below the window. In practice this corresponds to a beam wobbling of a few mm. The results shown in Fig. 12 give an effect of about 4%, indicating that the beam movement is probably an important effect, and will therefore be investigated further.

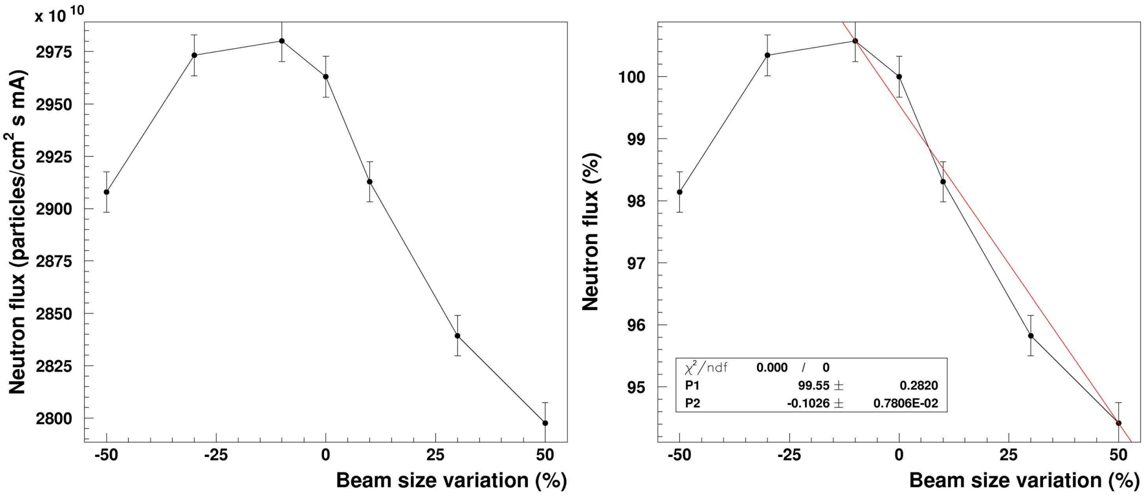

Figure 10. Target 7 results: calculated fluxes in the D_2 moderator as a function of the beam width, using the calculated source without divergence.

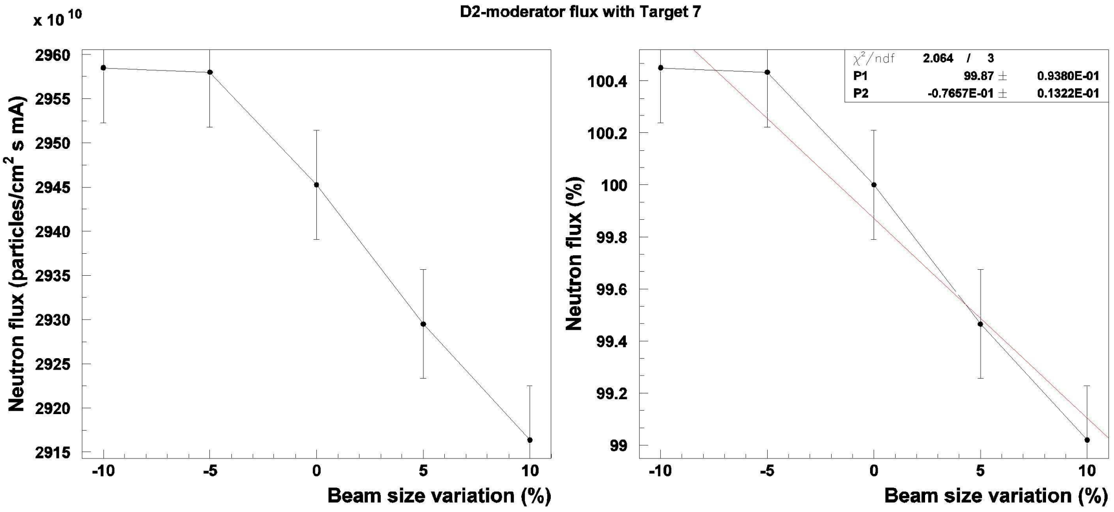

Figure 11. Target 7 results: calculated fluxes in the D_2 moderator as a function of the beam width, using the calculated source with divergence.

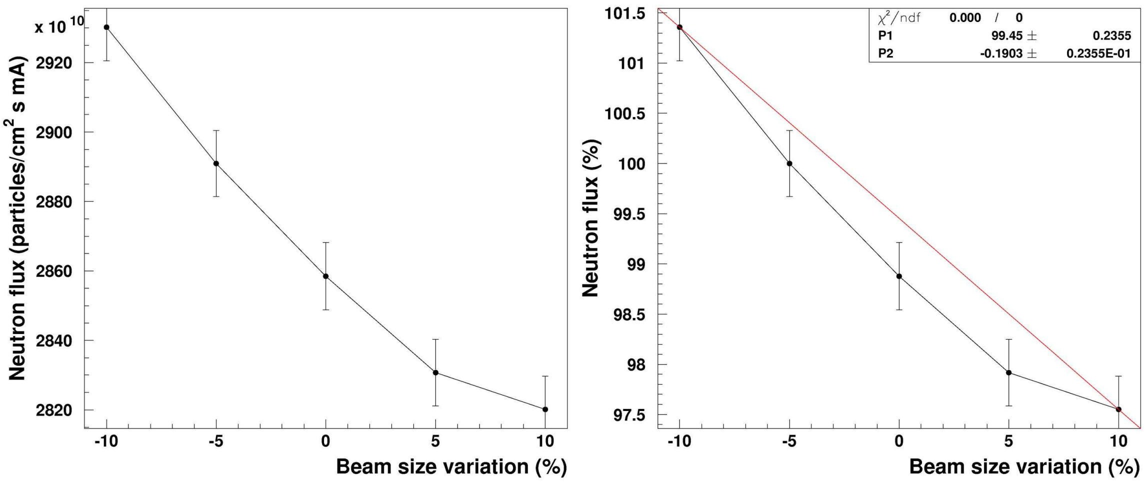

Figure 12. Target 7 results: calculated fluxes in the D_2 moderator as a function of the beam width, using the calculated source with divergence and beam movement.

4. Target 8 calculations

Some experimental measurements with Target 8 were also carried out. The results gave roughly an effect of 4-5 %, about half of what had been found with Target 7. Most of the calculations performed with the Target 7 were repeated also for the Target 8. The physical factors which can produce an effect when varying the beam size are the same as for the previous case, excluding the effect of the STIP samples which were not present in Target 8. However the improved design of this target, in particular the presence of the blanket which collects many of the protons escaping the main core of the target, seems to reduce the effect of about one half.

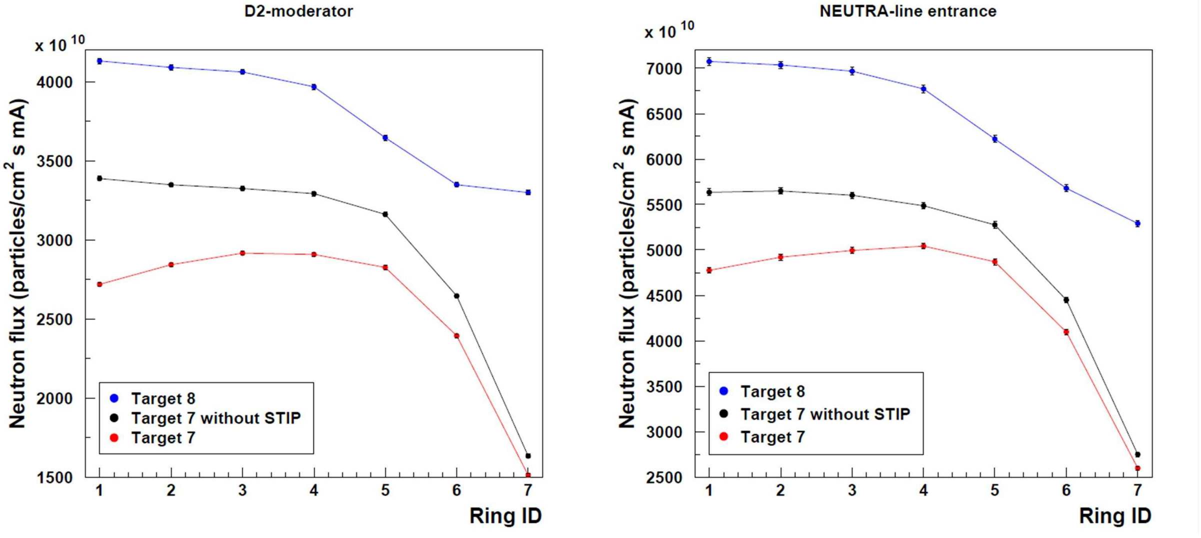

Figure 13. Target 7 and 8 results: calculated fluxes in the D_2 moderator and at the NEUTRA line entrance with Target 8 using the ring sources.

The results obtained with the ring sources using Target 8 are shown together with the graphs Target 7 results in Fig. 13. As expected, the absolute flux obtained is higher than in the previous case; moreover, the total flux decrease with the bigger ring is much smaller because of the presence of the blanket, due of the fact that the protons in the larger rings hit the blanket and not the water, as in the previous target.

Looking at Fig. 13, it is interesting to note the trend of the flux values for the first four rings, for which presumably the protons fully deposit their energy inside the target. For Target 8 and Target 7 without STIP samples, the neutron flux is slightly decreasing. On the contrary, the flux is slightly increasing for Target 7 with the STIP samples, due to the lower neutron production and the larger absorption induced by the steel. Based on the trend of the calculated fluxes for the first four rods, one would expect a positive effect (flux increase) by narrowing the beam for Target 8, and a negative effect (flux decrease) for Target 7. In reality the measured effect as reported in Figure 1 was obtained with Target 7 including the STIP samples, while with Target 8 (without STIP samples) the effect was of one half. Although these are only qualitative considerations, this seems to indicate that the view factor is only a second order effect and that the experimental flux increase is mainly due to other reasons, such as less beam losses in the water, protons at the rim hitting water in Target 7 and blanket in Target 8, and beam movement.

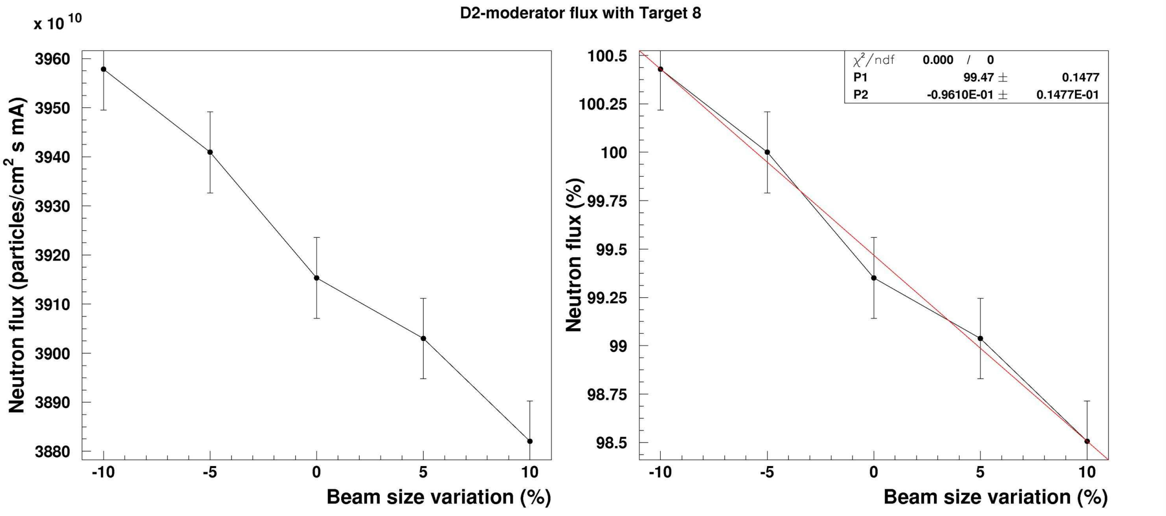

Figure 14. Target 8 results: calculated fluxes in the D_2 moderator as a function of the beam width, using the calculated source with divergence and beam movement.

The calculated beam profile was used with the following conditions: reference, -10%, -5%, +5%, +10%, and taking into account the calculated divergence and movement. Results are shown in Fig. 14. In agreement with the experimental measurements, the effect observed is lower than with Target 7, of about 2% from -10% width to +10% width.

5. Conclusions and outlook

In this study we have simulated the effect of the beam footprint on the neutron flux, by modelling the two solid targets, target 7 and target 8, for which measurements were made.

From the TURTLE calculations it was found that with the larger beam ("+10% both"), there was a loss in the collimator of 3% of the protons. Therefore the loss in the collimator is a factor to be taken into account. Adding the uncertainty in the experimental measurements, at the present status of this investigation, we think that we have understood at least qualitatively the observed flux increase, and different contributions have been identified: beam footprint effects seem to be of about 2 %; the beam divergence seems to give a negligible effect; on the contrary, beam movements seem to contribute significantly to the effect. Adding the losses in the collimator, we can therefore reproduce almost quantitatively the experimental effect. Further investigations will be carried out. In particular, the actual beam wobbling will be experimentally measured, and a proton source incorporating such movements, resulting in an enlarged footprint, will be calculated with TURTLE.

The correct modelling of the targets and of the beam profile was essential to understand such effects. One could exploit the effect narrowing the beam at the cost of higher current density, which is still acceptable for small variations. This effect could for instance compensate for the losses in the neutron yield due to inserting the STIP samples.

6. References

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