A Neutron Booster for the SINQ Neutron Source Using Thin Fissile Layers

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Abstract. The use in the SINQ facility of fissile material in the form of thin fissile layers of ^{235}U has been studied using the Monte Carlo transport code MCNPX for two purposes: 1) creation of a local booster to increase the flux in some neutron lines, and 2) creation of a global booster using thin layers placed around the spallation target. The following quantities have been calculated: neutron fluxes, flux gains with respect to the MEGAPIE and solid spallation targets, power deposition in the fissile layers, and criticality factor *k*. In the case of the local booster, an additional fast neutron irradiation facility could be placed, exploiting the *fast neutron island* concept also based on thin fissile layers. For the local booster, the best configuration studied gives an increase of the flux at the exit of the SINQ target block at the sector 80 of a factor of 3.2, with a power deposited of about 1 MW. Fast neutron fluxes inside the irradiation facility higher than 3×10^{14} n/cm^2/s/mA can be obtained, which would allow reaching the target value of 10^{15} n/ cm^2/s with a 3 mA proton current. For the global booster, calculations have been performed with fissile layers thicknesses ranging from 0.13 mm to 0.5 mm, corresponding to amounts of ^{235}U from 1 to 4 Kg. Calculations were done for the MEGAPIE target and for the solid target used in 2007 and 2008. Excellent increases in the target performance have been reached with both targets. With a liquid metal target such as MEGAPIE, a fissile layer of 0.5 mm would bring a boost in the flux of a factor of 2.6. With the solid target, thanks to the additional moderation of the heavy water coolant, the gain factor is higher, up to 3.6. The main limitation for the operation of such a device comes from the cooling of the fissile layers. The cooling system will have to dissipate power levels of the order of 1 MW or higher.

1. Introduction

Materials science and fundamental physics studies based on low-energy neutrons require continuous improvements of the intensity of the neutrons sources, to allow for measurements that would not otherwise be possible. Neutron sources can be classified according to the time shape of the delivered neutrons, which can be continuous or pulsed. Pulsed neutron sources such as ISIS, LANSCE, SNS and the planned ESS are based on high-current proton beams impinging on targets surrounded by appropriately designed moderators. Continuous sources are typically research reactors, of which the most important, in terms of neutron flux delivered, is the ILL in Grenoble, which is capable of delivering a peak thermal neutron flux of more than 10^{15} n/cm^2/s.

Among continuous sources, one notable exception is given by the SINQ facility, where neutrons are generated from spallation reactions induced by a continuous beam of 575 MeV protons. For this reason, despite being a spallation neutron source, from the point of view of its scientific applications SINQ must be compared with a research reactor.

The peak thermal flux available at SINQ is about one order of magnitude lower than ILL. The performance of SINQ depends on the spallation target used. With a solid Pb rod target, which is used routinely in the facility, the peak thermal flux is of about 5×10^{13} n/cm^2/s/mA. With the MEGAPIE target, the peak was of about 9×10^{13} n/cm^2/s/mA. With a proton current currently achievable at the target of about 1.7 mA, this leads to a maximum value (with a liquid metal target) of about 1.5×10^{14} n/ cm^2/s.

The MEGAPIE target was optimized from the neutronic point of view, and its neutronic performance is likely to be close to the maximum achievable value at SINQ, using either a solid or liquid target and a non-fissionable heavy metal spallation material. The quest for a more performing facility must therefore follow a different path. One obvious improvement would be to increase the current of the proton beam on target. With a beam power of 10 MW the performance of SINQ would equal ILL, but this would require, for a proton energy of 575 MeV, a beam current of 17 mA, about 10 times what is currently delivered to SINQ. The use of such a high power is a technological challenge, since so far spallation targets have operated have operated only at the MW level (MEGAPIE and SNS).

An alternative way, originally proposed for SINQ by F. Gröschel and L. Zanini [1] is analyzed in this work, and consists in the use of thin fissile layers of ^{235}U to boost the neutron flux. In this paper we describe and analyze two concepts to boost the neutron flux: the *Local Neutron Booster* which can increase the neutron flux in two beam lines, and the *Global Neutron Booster* that can increase the general neutron flux in the entire facility. Calculations have been performed using MCNPX 2.5.0 [2].

2. Local Neutron Booster

The first approach consisted in increasing locally the neutron flux, by designing a booster that would give a significant enhancement of the neutron flux only at some beam lines in SINQ. This approach, if applied experimentally, would have the advantage of providing the validation of the booster concept with a relatively simple experiment, in view of the design of a global booster for the whole facility. In SINQ, the best place for performing such an experiment would be at the water scatterer in sector 20 (Fig. 1). The water scatterer consists of seven aluminium tubes filled with H_2O, that scatter neutrons to the sectors 40 and 80, where some neutron beam lines and experiments are placed (such as the EIGER).

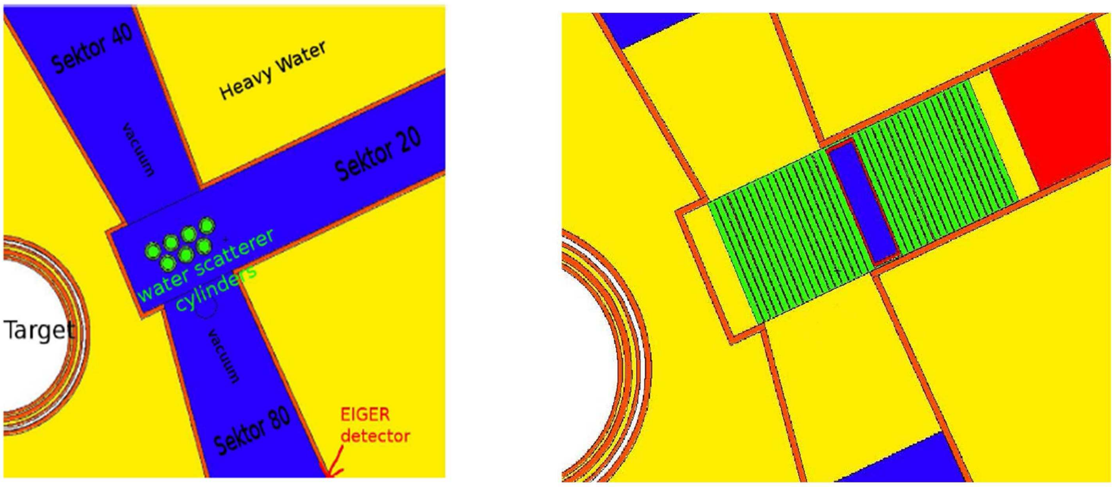

FIG. 1. Left: MCNPX geometry of the water scatterer area next to the SINQ target. Right: one of the possible modifications using thin fissile layers.

A flux increase can be achieved by replacing the water scatterer with fissile layers; one has to make other changes in the geometry. Several sensitivity studies were performed by varying the amount of fissile material, its position in sector 20, and the geometrical configuration [3]. As an example we discuss one configuration (Fig. 1), in which several layers of pure ^{235}U are placed close to the target in sector 20. On the sides of this wafer structure, in the beam inserts, two moderator boxes are placed, to slow down the fast neutrons produced by fission.

In the center of the wafer structure, a closed box, with walls containing fissile material, serves as fast neutron irradiation facility. The concept was originally proposed in Ref. [4] for a thermal reactor. The walls of the box are thick enough so that most of the thermal neutrons incoming are fully absorbed and induce fissions, while the fast neutrons do not interact. As a result, the neutron flux inside the box is a pure fast neutron fission spectrum.

The total amount of fissile material can vary, and in our sensitivity studies calculations were made with 1 kg, 2 kg and 4 kg of pure ^{235}U. Results with 4 kg are shown in Table 1, while in Fig. 2 the calculated neutron flux density for the configuration of Fig. 1 (with spacing between layers of 1 cm and 1.5 cm) is shown. It is apparent that the fluxes (both the thermal flux at the exit of the target block, and the fast flux inside the box) depend on the layer spacing, and the best results are obtained with a larger spacing.

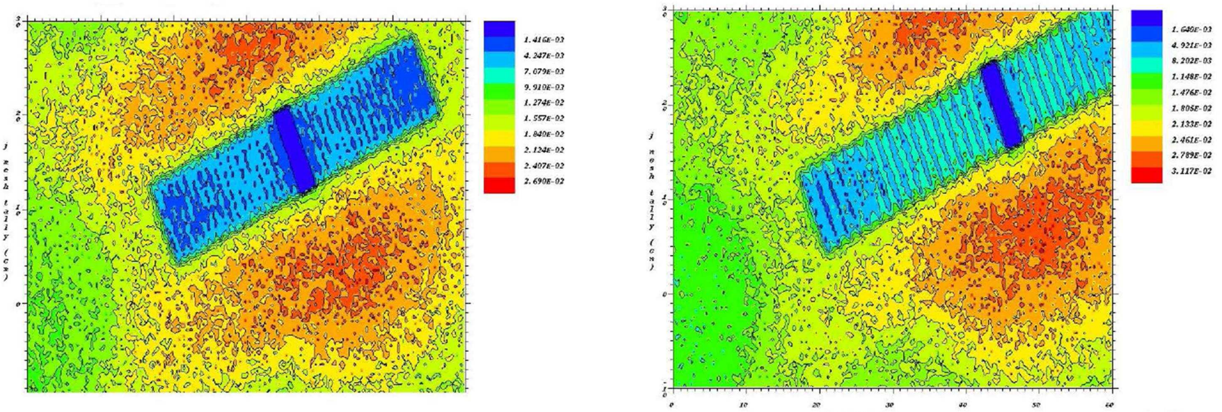

FIG. 2. Calculated neutron flux density with the local booster with 1 cm spacing (left) and 1.5 cm spacing (right).

TABLE 1: Calculated thermal flux (E< 1 eV) at the exit of the SINQ target block (EIGER beam line), relative gain with respect to the original configuration of Fig. 1, and flux (with E> 1 eV) inside the box.

Layer spacing (mm)	ϕ_{th} exit target block (n/cm^2/s/mA)	Gain	ϕ (E> 1 eV) inside box (n/cm^2/s/mA)
5	2.6×10^{9}	1.8	1.7×10^{14}
10	4.1×10^{9}	2.9	2.7×10^{14}
15	4.6×10^{9}	3.2	3.1×10^{14}

From our analysis the following main results are found:

1. A wafer configuration is better than using a simple cylindrical configuration with similar mass.
2. By studying the positioning of the device, it was found that the best configuration is close to the target with some moderator material in the beam line.
3. An optimization study of the geometry of the wafer was performed, including a sensitivity study on the spacing between layers.
4. The fast neutron device concept works. The maximum fast flux obtained is higher than 3×10^{14} n/cm^2/s/mA; however, 4 kg of enriched uranium are needed to reach this performance.

3. Global Neutron Booster

As discussed in Ref. [5], the idea of the Global Neutron Booster consists in placing a thin uranium layer around the spallation target. Depending on the amount of fissile layer, on the geometry and on the criticality factor of the system, the neutron flux can be increased significantly. We studied the configuration with MCNPX using the last two targets used in SINQ: the MEGAPIE target (irradiated in 2006), and the solid target 7 (irradiated in 2007 and 2008).

3.1. Calculations with the MEGAPIE target

As first step the so-called ``unperturbed" case was considered, in which the spallation target is surrounded by the heavy water tank without any of the inserts that are actually present in SINQ. The uranium layer as shown in Fig. 3 was added to the model of the MEGAPIE target. The device is a cylindrical layer, of 0.5 mm thickness with an external radius of 11 cm and height 60 cm. The total mass of ^{235}U is 3.93 kg. Calculations were also performed with a configuration with 0.25 mm thick using 1.97 kg of ^{235}U.

Reference fluxes (thermal, fast and total) at different distances from the target, without uranium, were calculated to provide the reference configuration. For the calculations with uranium, two configurations were tested: the first one with the thin uranium layer only, and a second one adding a layer of H_2O in the space (about 1 cm thick) between the uranium cylinder and the target. In Fig. 3 the comparison between original and boosted thermal fluxes are shown.

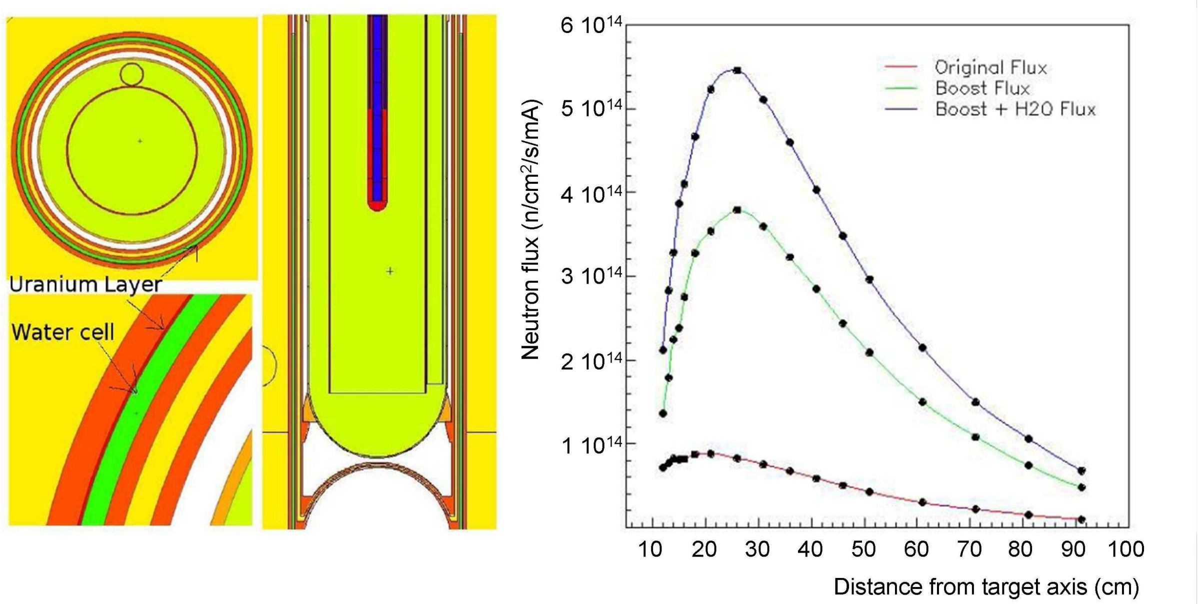

FIG. 3. Left: MCNPX geometry of the bottom of the MEGAPIE target with indicated position for the uranium layer and the water moderator. Right: radial distribution for the reference case and for two boosted cases in the unperturbed configuration.

The effect of adding the uranium is large, but also the additional water layer has an effect: with the unperturbed configuration a gain in the peak flux of a factor 4 is reached in the case of the uranium configuration and of 6.45 in the case with H_2O (Fig. 3 right).

It is more interesting to study the effect of the neutron global booster in the real configuration of the SINQ facility, with all the structural materials, beam ports, and moderators in the model. In this case, besides the radial analysis the fluxes at the exit of the SINQ block in the sectors 30 (NEUTRA), 50 (ICON) and 80 (EIGER), were calculated.

The configuration with a fissile layer of 0.5 mm with and without 3.5 mm of water was calculated, for a total mass of 3.93 kg of ^{235}U and with 0.25 and 0.13 mm thick layers with water, for about 2 and 1 kg of ^{235}U. The results are plotted in Fig. 4 (left) and compared with the reference configuration without uranium. The peak thermal flux in the real configuration is reduced with respect to the unperturbed one by a factor of 0.66. The boosted fluxes are also reduced. A gain factor of 2.8 with the configuration with a 0.5 mm thick layer is obtained; in this case the power deposited on the layer is about 2.5 MW. With 0.13 mm of layer thick we obtain a gain factor of 1.75 and the power deposited is of 990 keV.

3.2. Calculations with the solid target

The effect of the global booster with a solid target was also studied. The geometry of the target 7 (irradiated at SINQ in 2007 and 2008) was used.

Like in the MEGAPIE case, the analysis with the real configuration of the SINQ facility was performed. With this configuration the thermal flux with the uranium layer placed between the longitudinal coordinates -30 cm < *z* < 30 cm was computed (*z* = 0 corresponds to the center of the cold D_2 moderator), with and without a reflector placed above the lead rods. With the reflector the performance improves. We also performed a calculation shifting the layer by 10 cm upwards (-20 cm < *z* < 40 cm), obtaining a better performance. The use of fissile material with the solid target gives a relative larger flux increase than in the MEGAPIE case, even if the absolute peak flux with the solid target is still lower. Results are shown in Fig. 4 (right). Results for calculations at the beam lines for both MEGAPIE and target 7 are shown in Table 2.

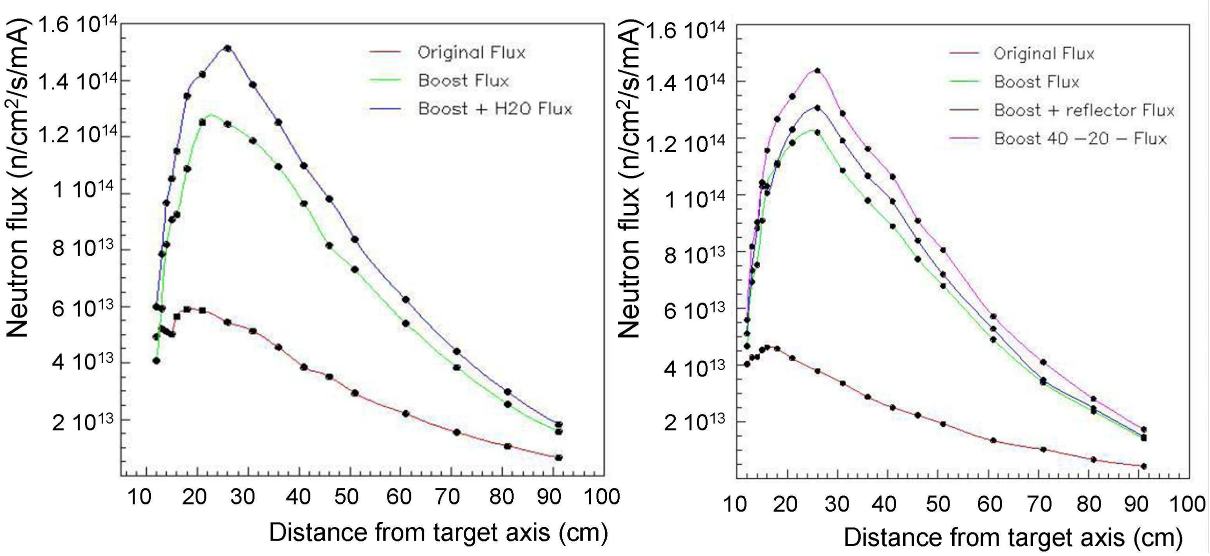

FIG. 4. Radial distribution of the thermal neutron flux for the reference case and for boosted cases in the real configuration with MEGAPIE (left) and Target 7 (right).

TABLE 2: Summary of the main results for the global booster in SINQ with MEGAPIE and with the solid target 7. Thermal neutron fluxes in n/cm^2/s/mA are indicated. The power deposited in the fissile layer for 1 mA proton current is also indicated.

Configuration	NEUTRA	ICON	EIGER	Gain NEUTRA	Gain ICON	Gain EIGER	Power (MW)	k_{eff}
MEGAPIE								
Original	3.76×10^7	8.06×10^8	1.39×10^9	-	-	-	0	
0.5 mm	8.64×10^7	1.90×10^9	4.35×10^9	2.3	2.4	3.1	1.85	0.73
0.5 mm + H_2O	1.02×10^8	2.25×10^8	3.55×10^9	2.7	2.8	2.6	2.47	0.78
0.25 mm + H_2O	7.86×10^7	1.81×10^8	2.77×10^9	2.1	2.2	2.0	1.55	0.69
0.13 mm + H_2O	6.48×10^7	1.41×10^8	2.28×10^9	1.7	1.8	1.6	1.0	
TARGET 7								
Original	2.71×10^7	5.43×10^8	8.69×10^8	-	-	-	0	
0.5 mm	9.77×10^7	2.02×10^9	2.90×10^9	3.6	3.7	3.3	2.57	0.87
0.25 mm	6.57×10^7	1.39×10^9	2.09×10^9	2.4	2.6	2.4	1.48	0.78

3.3. Criticality Considerations

Analyzing the values obtained it is seen that with both targets the gain factors in the unperturbed cases are much bigger that in the real cases; this happens because in the real configurations the *k* are lower than in the unperturbed ones. Criticality factors *k* are indicated in Table 2.

Another interesting result is the considerable difference of gains, with MEGAPIE, between the booster configuration with and without water (we remind that only a 3.5 mm thick layer of water was added), and the corresponding increase of the criticality factor.

For the same reason, a bigger *k* is obtained with the solid target with respect to MEGAPIE, because the water used for the cooling of the solid target increases the criticality factor.

We also found from further simulations with the MEGAPIE target, that the *k*, and therefore the gain factor, can be increased by using a thicker inner water layer; this means that one can use less fissile material to obtain the same results: therefore, for a fixed maximum amount of power deposited in the fissile layer (for instance, 1 MW for a 1 mA proton beam), one could reduce the thickness of the layer, and increase the thickness of the moderating water close to it.

3.4. Power and cooling issues

The power deposition in the uranium layer is very high, as shown in Table 2 where the values for 1 mA proton current are summarized. One must distinguish between the unperturbed and the real cases because in the first case a power of more than 7 MW (in the cases of MEGAPIE) is reached, while in the real situation the performance and the power deposited are much lower. The power values taken in consideration are those computed with the real configuration. Some preliminary evaluations on the cooling have been made by S. Dementjev and S. Joray [6].

Two cooling options have been considered for 1 MW power coming from the uranium layer, plus 1 MW power deposited in the LBE by the proton beam: water cooling and LBE cooling. In the case of water cooling, the limitation comes from the low heat transfer coefficient and low boiling point, which implies risk of local water boiling on the surface, local thermal stresses and cracks. In the case of LBE cooling, the limitation comes from the low heat capacity (140 J/kg/K for LBE, 4190 J/kg/K for water), and correspondingly high LBE inlet-outlet temperature difference, large temperature fluctuations during beam trips, high thermal stresses and fatigue. From preliminary evaluations, it appears possible to remove a thermal power of the order of 1 MW from the booster with both LBE or water flows. In the case of water cooling, it is better to separate the cooling loops, and have one cooling loop for the target and one for the booster.

From these preliminary considerations it is apparent that the main limit on the gain that can be reached with the Global Neutron Booster comes from the cooling. From the calculated power depositions the following approximate relation between the power deposited in the layer and the gain factor *f* can be deduced:

$$P = k_t I(f - 1) \quad f > 1,$$

where P is the power deposition (MW), I the current in mA, f is the gain factor and k_t is a target-dependent factor, approximately equal to 1.4 MW/mA for the MEGAPIE target and to 1 MW/mA for the solid target 7. For instance, with a liquid metal target, for a gain of 2, and a current of 1 mA, the power on the fissile layer is of about 1.4 MW.

4. Conclusions and future work

We have studied the effect of the fissile layers with two spallation targets, MEGAPIE and target 7, in two configurations of the facility: unperturbed (without the beam inserts) and the real case with all the beam ports and the structural materials.

The following important conclusions can be drawn:

1. There is a big difference between unperturbed and perturbed case, giving very different *k*, power depositions and fluxes. For instance, in the case of MEGAPIE, with a 0.5 mm layer, and additional H_2O layer, the *k* is 0.91 unperturbed, and 0.78 perturbed. Consequently, the power decreases from 7.8 MW to 2.5 MW, and the flux gain decreases from 6.2 to 2.8.
2. These large differences are clearly due to the change in the geometry and the reduction of moderating material going from the unperturbed to the real case.
3. In the real case the power deposited in the layer decreases to a level which is probably coolable.
4. The increase with the solid target is about a factor of 3.6, *k* is bigger than with the liquid metal target because of the moderation effect of the cooling water inside the target itself.
5. We found that the fission rate from the layer can be significantly increased if a relatively thin (3.5 mm or more) loop of normal water is placed close to the target. This could be either the cooling loop, in case water is chosen as a coolant, or a moderator layer for an LBE-cooled target. This is an important factor to include in a possible development of a uranium boosted target. By adjusting properly the layer of water around the fissile layer one could optimize the performance and use less fissile material.

In a realistic design of the global booster, the fissile layer should be placed inside the safety hull, thus reducing the external diameter of the layer.

Future activities on this subject could follow two directions, from the calculation and experimental point of view.

From the calculation side, there are a number of issues that have not been treated in this report, such as reactivity problems, burn up and fission product poisoning. Additionally, more realistic geometries, with the fissile layers inside the safety hull, and with details on the structural materials and possible cooling loops, should be implemented and simulated.

From the experimental side, one could start with measurements in the sector 20, by placing small amounts (less than 150 g) of enriched uranium. This would allow validating the concept of the fast neutron island, and also to measure small flux gains at the beam lines with the limited amount of fissile material.

Acknowledgments

We are grateful to the following colleagues from PSI: S. Dementjev and S. Joray for cooling estimates; E. Lehmann for suggesting the SAPHIR geometry and providing documentation; E. Manfrin for suggestions on the wafer geometry.

References

[1] F. Gröschel, L. Zanini, *Concepts for a neutron flux booster in SINQ using thin fissile layers*, PSI internal report TM-34-08-03, 2008.

[2] D. B. Pelowitz et al., *MCNPX User's Manual Version 2.5.0*, Los Alamos National Laboratory report, February 2005.

[3] A. Aiani and L. Zanini, *MCNPX calculations of a neutron booster in SINQ using thin fissile layers,* PSI internal report TM-85-08-06, 2008.

[4] J. Magill, P. Peerani, *Improving the incineration of minor actinides in thermal reactors by generation of fast islands with thin fissile films*, EC-ITU internal report.

[5] J. Galy et al., *A neutron booster for spallation sources-application to accelerator driven systems and isotope production*, Nuclear Inst. and Methods in Physics Research, A 485, 739, 2002.

[6] S. Dementjev and S. Joray, private communication, 2008.