Preliminary Neutron Study of the SPIRAL2-NFS Collimation System

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INTRODUCTION

The NFS (Neutrons For Science) facility is primarily composed of two parts: (1) a beam converter hall for conversion of light ions – protons of up to 33 MeV and deuterons of up to 40 MeV energies – delivered by LINAG of SPIRAL2 into neutrons and (2) a TOF hall for in-flight measurements [1]. These two halls are separated by a thick concrete wall with a collimation system built into the wall (Fig. 1). The role of the collimation system is to define a well-collimated neutron beam and, therefore, its design is of special importance to the beam characteristics. The present report covers results with respect to designing and optimization of the NFS collimation system.

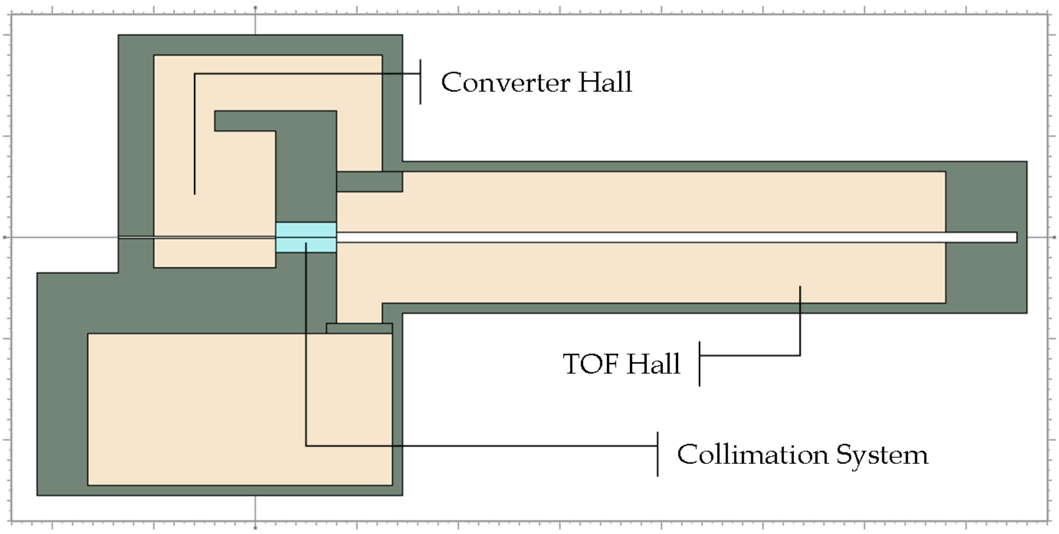


Fig. 1. Schematic view of the NFS facility.

1. TOOLS

1.1 Computer codes and nuclear data libraries

Neutronic simulations of the NFS facility were performed on the basis of MCNPX Version 2.4-2.5 computer code with ENDF/B-VI, ENDF/B-VII, JEFF3.1, JENDL-3.3, LA150 nuclear data libraries used wherever applicable [2,3,4,5,6,7].

1.2 Neutron sources

Three neutron sources were employed for neutronic simulations: monoenergetic 30 MeV isotropic point-like neutron source for basic preliminary calculations (source No 1), quasi-monoenergetic neutron source produced in 30 MeV p + ^{7}Li reactions (source No 2), and 'white spectrum' neutron source produced in 40 MeV d + ^{9}Be reactions (source No 3). The whole specification of these sources can be found in Appendix A.

2. PRELIMINARY STUDY

2.1 Calculation model

For the sake of simplicity, the following model was used for preliminary calculations: it is composed of a 30 MeV monoenergetic isotropic point-like neutron source (source No 1) and a collimator wall of 2 m thickness with a channel of 25 cm diameter filled with different materials (Fig. 2). The distance between the source and the wall is 1 m. The results obtained are normalized per 1 neutron of 'ideal beam'. While the model allows one to investigate simple problems with regard to neutronics of the collimation system, its scope is limited rather severely. This is because neutron environment behind the collimator wall (i. e. in the TOF hall) is highly dependable on the structure of the initial neutron beam; especially, its spatial profile and angular distribution. Therefore, once simple preliminary calculations were completed, source No 1 was retired in favor of source No 2.

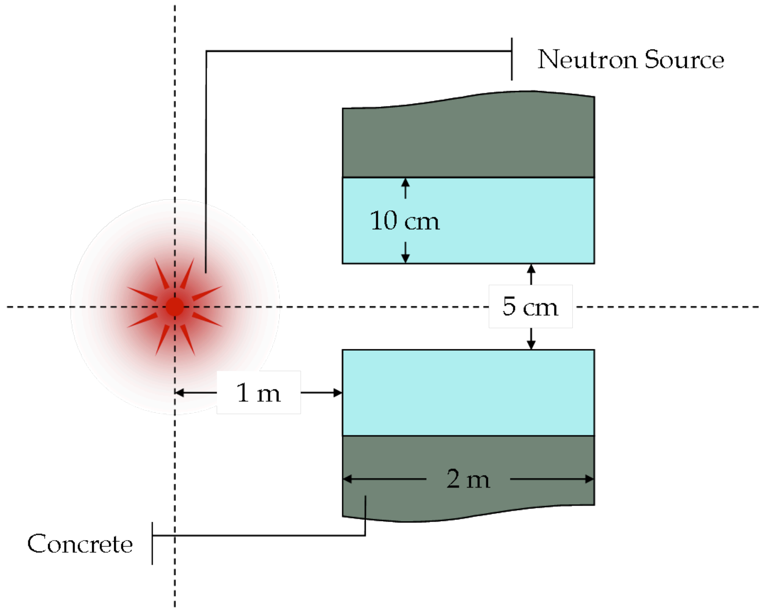


Fig. 2. Preliminary calculation model.

2.2 Methodology

In order to assess the basic performance of a collimation system by small number of numerical parameters, the following methodology was employed (Fig. 3). Neutrons propagated from the converter hall into the TOF hall are subdivided into two parts: (1) 'signal' or 30 MeV neutrons propagated through the collimator channel directly and (2) 'noise' consisting of neutrons produced in the system by elastic scattering of source neutrons out of the beam (distortion) plus all other neutrons produced by inelastic scattering and (n,Xn) reactions. These two parts – usually taken at the outer surface of the collimator wall – are then compared with each other in terms of signal-to-noise ratio.

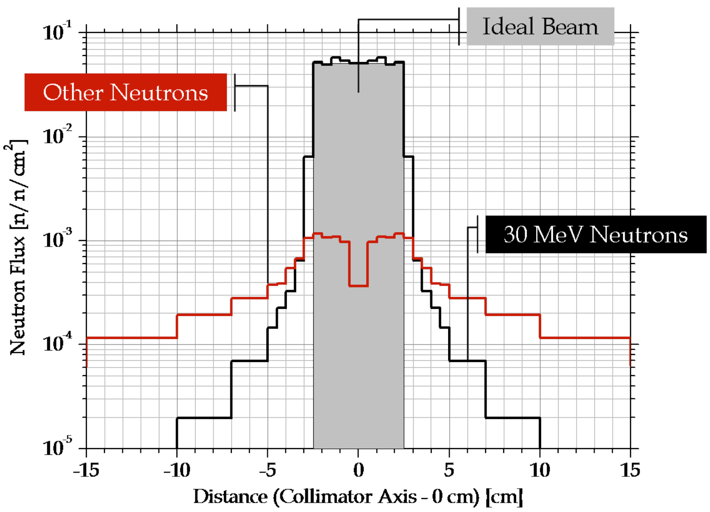


Fig. 3. Typical neutron beam profile at the outer surface of the collimator wall: 'signal' is 30 MeV neutrons propagated at distance between -2.5 cm and +2.5 cm from the collimator axis and 'noise' is all other neutrons including beam distortion.

2.3 Material categorization

The first task studied was material survey: materials to be used for the collimation system should have large total macroscopic scattering cross sections to reduce high energy part of the noise. Simple numerical analysis shows that in semi-classical approximation macroscopic scattering cross sections are proportional to mass density of the material in question and inversely proportional to its mass number in the power of 1/3÷1 (Fig. 4). Based on this observation, several collimators made of various materials were simulated (Fig. 5). Iron and copper were identified as the best choice for the scattering part of the collimation system from the viewpoint of their performance and also, presumably, their cost.

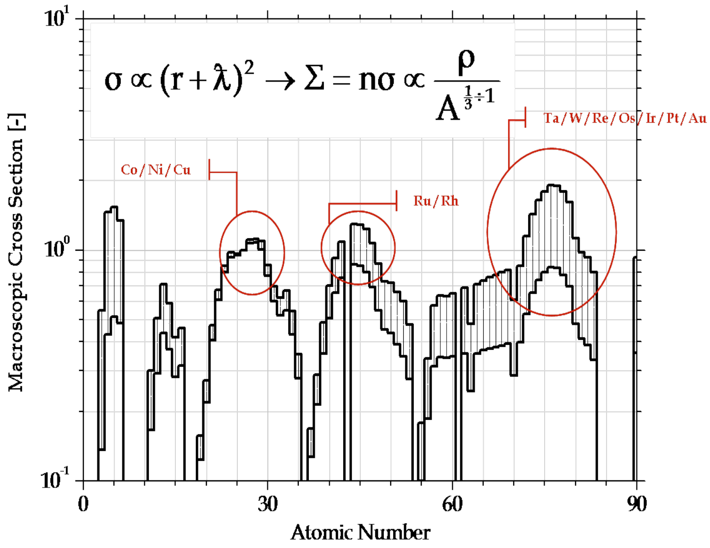


Fig. 4. Estimation of macroscopic scattering cross sections in semi-classical approximation: two lines correspond to two extreme values (1/3 and 1) of the power in the formula shown in the picture.

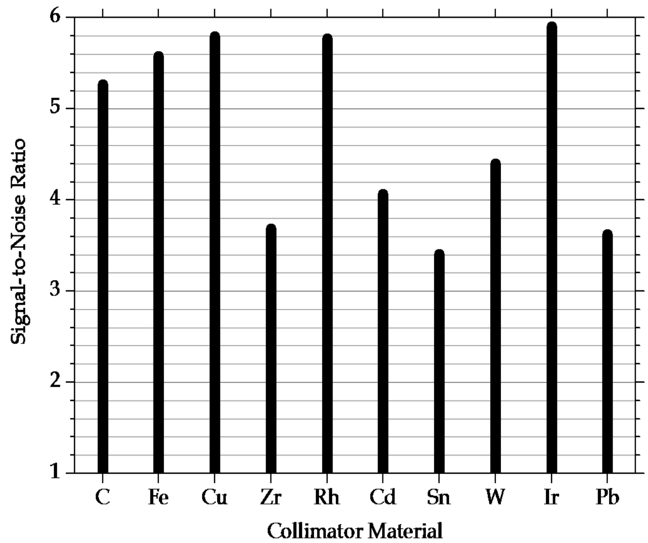


Fig. 5. Signal-to-noise ratio (see text for definition) at the outer surface of the collimator wall produced by collimators made of various materials.

2.4 Neutron noise spectrum

It is instructive to compare neutrons produced by different collimators in terms of their energies. Two extreme cases are shown in Fig. 6. One can see that a good scattering material (iridium) would reduce high energy part of neutron spectrum by scattering away high energy neutrons to below several MeV.

The flip side of this process is that neutron spectrum below several MeV is greatly increased. Borated polyethylene – a good moderator/absorber material – would reduce neutron spectrum below several MeV; however, it would not be capable to significantly alter its high energy part. Therefore, optimized design of the collimation system should contain both scattering materials and moderators/absorbers arranged geometrically in the best possible way in order to reduce neutron noise both in its high energy part and below several MeV.

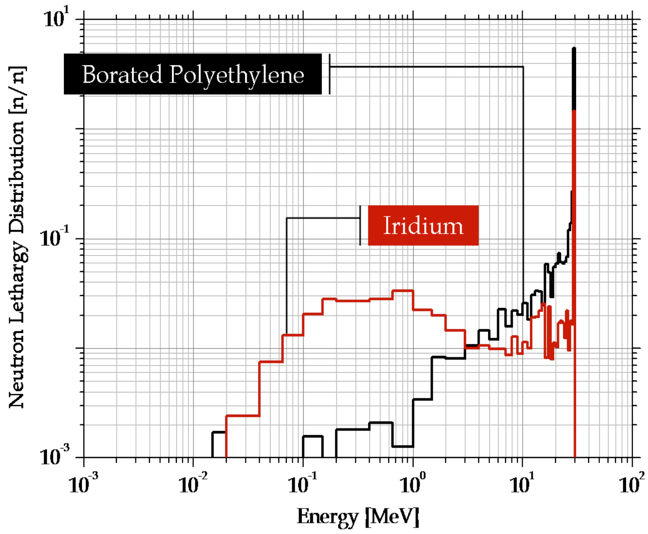


Fig. 6. Neutron noise in terms of neutron lethargy distribution at the outer surface of the collimator wall produced by collimators made of iridium and of borated polyethylene.

3. Optimization of the collimation system

3.1 Calculation model

Calculation model mostly used throughout this section consists of three parts made primarily of concrete (Fig. 7): a collimator, a TOF vault, and a beam dump. The length of the TOF hall is set to 30 m. The thickness of the collimator wall is increased to 3 m up from 2 m used in the previous study. The initial size of the collimator channel is reduced from 5 cm to 2 cm diameter. The neutron source of 30 MeV p + ^{7}Li origin (source No 2) is situated at 1 m distance from the collimator wall. Its spatial profile is of normal distribution with σ = 0.5 cm. Only forward part (±90°) of the source was simulated. The results are normalized per 1 source neutron.

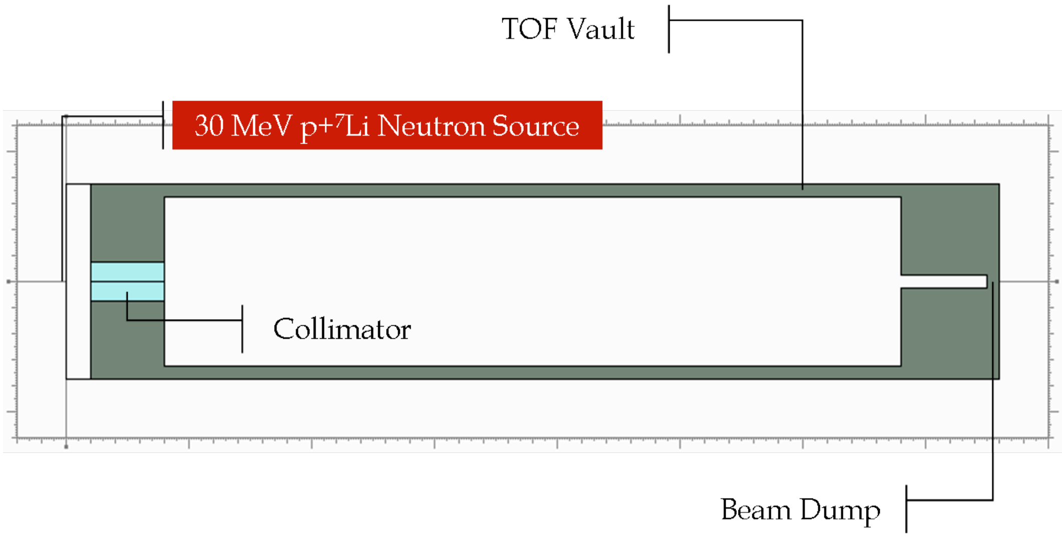


Fig. 7. Simplified model of the TOF hall.

3.2 Methodology

The main optimization parameter used here is neutron background in the TOF hall: it is total neutron current outside the neutron beam as a function of distance from the collimator wall. Finer results are represented in the form of neutron background spectrum. Due to rather high calculation uncertainties (Fig. 8), spectra were analyzed in five broad groups labeled successively: 'Thermal' (< 1 eV), 'Slow' (1 eV – 0.01 MeV), 'Resonance' (0.01 - 1 MeV), 'Fast' (1 - 25 MeV), and 'HE (High Energy)' (> 25 MeV).

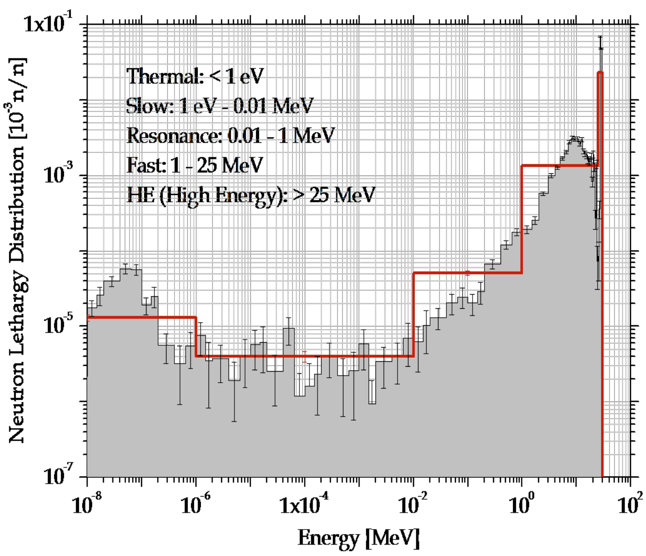


Fig. 8. Typical neutron spectrum integrated over the outer surface of the collimator wall.

3.3 Collimator channel

Simple geometrical considerations suggest that a collimator channel of conical shape would suit better than that of straight cylindrical one for a point-like initial source. It is because secondary particle production from outer ribs of the collimator channel is suppressed in the case the channel is conically shaped. However, since the size of the collimator channel is comparable to the size of the source itself (a few cm), neutronic simulations are required to optimize its exact shape. The results show that by means of increasing the size of the collimator exit from 20 mm up to 33 mm diameter – and at the same time decreasing the size of its entry from 20 mm down to 6 mm diameter in order to keep the size of the beam spot and, subsequently, the value of neutron flux more or less the same at large distances from the wall – neutron background in the part of the TOF hall adjacent to the wall would be reduced by about 1 order of magnitude (Fig. 9). The collimator channel of 31/8 mm of exit/entry diameter is selected further as a reference one.

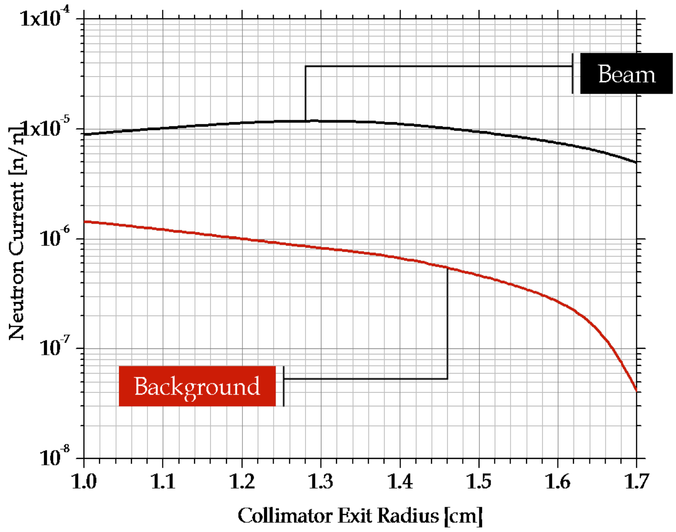
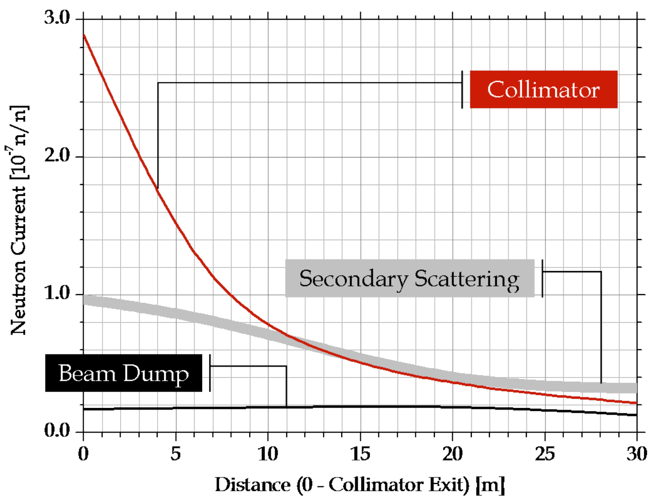


Fig. 9. Neutron current at the outer surface of the collimator wall as a function of the collimator exit radius: 'beam' – total neutron current inside the neutron beam, 'background' – total neutron current outside the neutron beam.

3.4 Neutron scattering in the TOF hall

To quantify the influence of basic parts of the TOF hall on the beam characteristics, a series of neutronic simulations were performed with the aforementioned parts of the TOF hall – the collimator, the TOF vault, and the beam dump – made entirely of either 'ideal material' (perfect absorber) or 'real material' (concrete). The results were analyzed in terms of contributions of these individual parts into neutron background in the TOF hall, i. e. total neutron current outside the beam. The approach is illustrated in Fig. 10. One can see that neutron background is dominated by contribution of the collimator: either directly or through secondary scattering of neutrons off the TOF vault (the TOF vault itself does not interact with the beam directly). Primary contribution of the beam dump is relatively small: 0.1-0.3% of the beam current (the beam current is about 8.6×10^{-6} n/n, see Fig. 9).



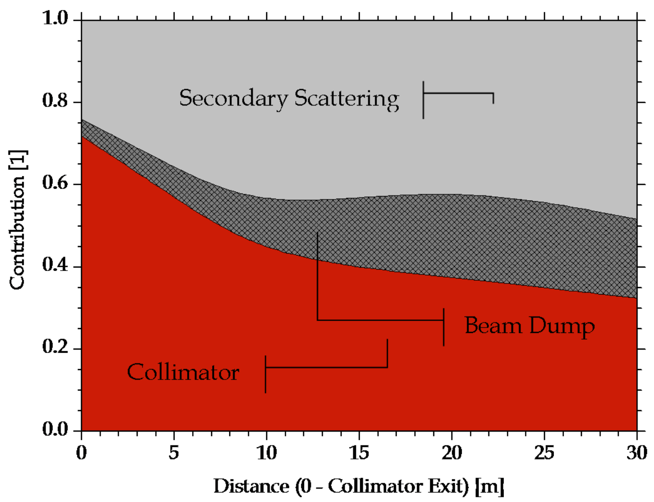


Fig. 10. Contribution to neutron background from basic parts of the TOF hall (the collimator, the TOF vault, the beam dump): absolute values (top) and relative values (bottom).

3.5 Sandwich collimator design

Neutron noise spectra (see Fig. 6) suggest the way to designing of the collimation system named further a 'sandwich' design: one can put a layer of scattering material followed by a layer of moderator/absorber. The results of neutronic simulations in terms of neutron current outside the beam (neutron background) at the outer surface of the collimator wall are shown in Fig. 11-13. Iron reduces high energy part of neutron background by 2 times, but produces many neutrons below 1 MeV; borated polyethylene reduces thermal part by 2 times, but does not change its high energy part (Fig. 11-12).

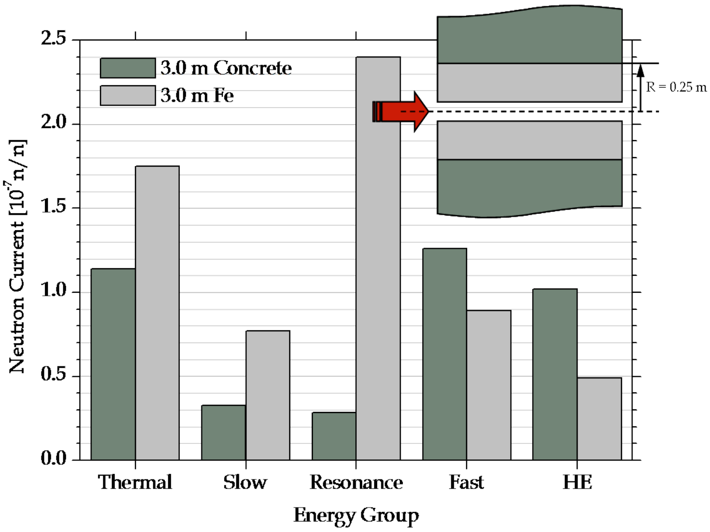


Fig. 11. Neutron current outside the neutron beam at the outer surface of the collimator wall: role of scattering material.

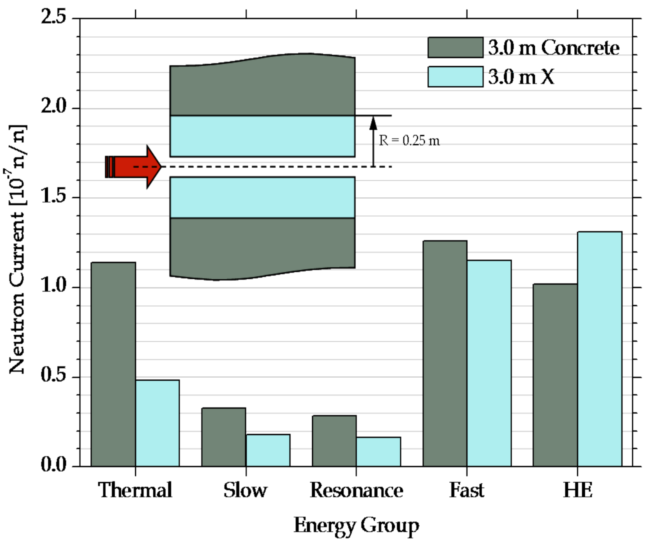


Fig. 12. Neutron current outside the neutron beam at the outer surface of the collimator wall: role of moderator/absorber (X denotes 5%B+POLY-C2H4).

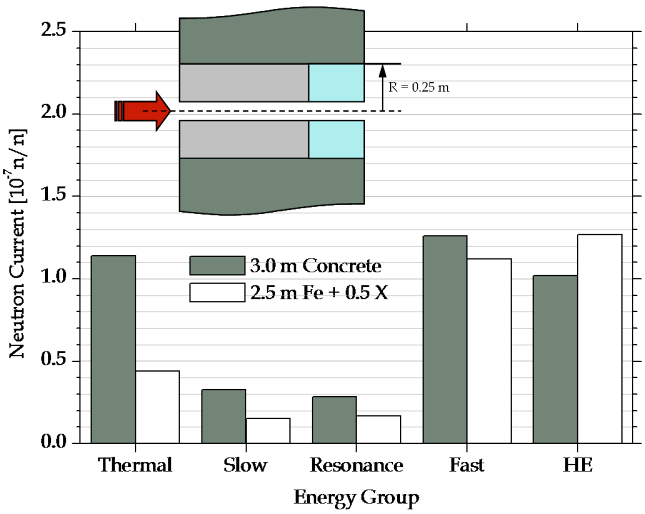


Fig. 13. Neutron current outside the neutron beam at the outer surface of the collimator wall: scattering material + moderator/absorber sandwich design (X denotes 5%B+POLY-C2H4).

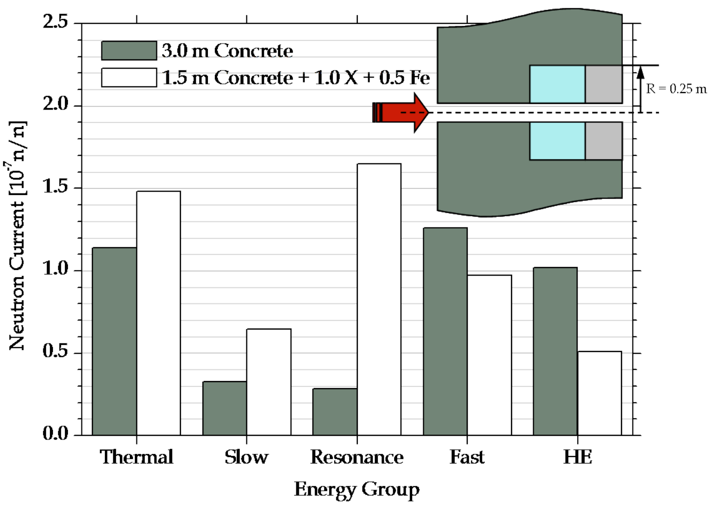


Fig. 14. Neutron current outside the neutron beam at the outer surface of the collimator wall: moderator/absorber + scattering material sandwich design (X denotes 5%B+POLY-C2H4).

In order to reduce both high energy part and thermal part of neutron background, Fe + 5%B+POLY-C2H4 sandwich design was employed (Fig. 13). However, this design does not work because borated polyethylene does not scatter away high energy neutrons at outer ribs of the collimator channel. One can see that only last several tens cm of the collimator matter. This is essentially the reason why iron layer does not influence neutron background in the TOF hall (compare Fig. 12-13). Quite obviously, 'reverse' sandwich design would not work either (Fig. 14).

3.6 Ring shape collimator design

The problem of the sandwich design is secondary particle production from outer ribs of the collimator channel. This problem can be solved by arranging layers in ring fashion: thin inner part (iron) would scatter away high energy neutrons, while thick outer part (borated polyethylene) would then absorb them (Fig. 15). The rings – inner ring of 10 cm outer diameter and outer ring of 1 m outer diameter – were optimized rather roughly. Nevertheless, one can see that both high energy part and thermal part of neutron background are thus reduced. Neutron spectrum produced by ring shape collimation system with conically shaped collimator channel and the one produced by initial non-optimized collimation system made of concrete with straight cylindrical collimator channel are compared in Fig. 16. Conically shaped collimator channel and ring shape collimator design reduce high energy part of the background spectrum by almost 1 order of magnitude (7-9 times), while thermal part is reduced by about 3 times.

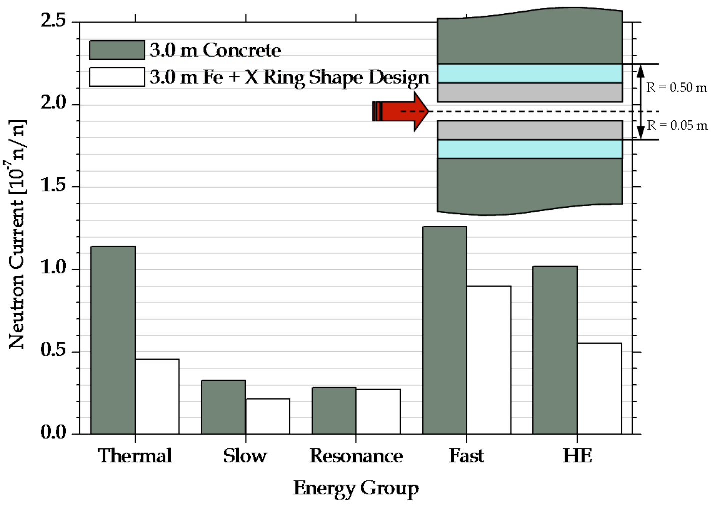


Fig. 15. Neutron current outside the neutron beam at the outer surface of the collimator wall: ring shape design (X denotes 5%B+POLY-C2H4).

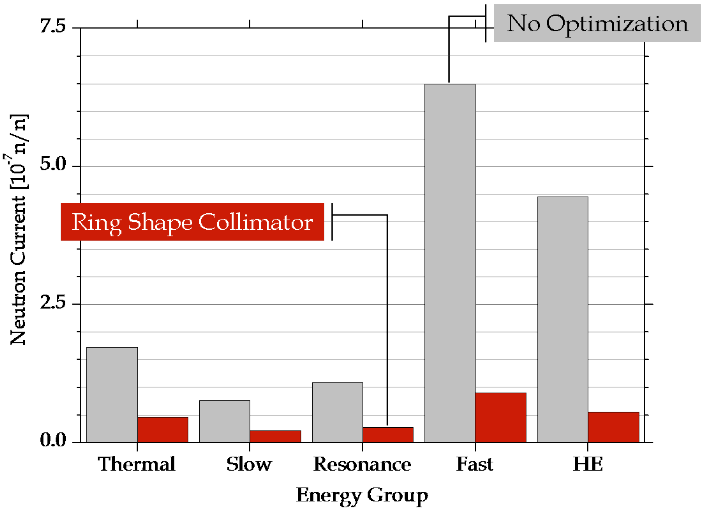


Fig. 16. Neutron current outside the neutron beam at the outer surface of the collimator wall: comparison of non-optimized collimation system made of concrete with straight cylindrical channel and ring shape collimation system (see text for description) with conically shaped channel.

4. VACUUM BEAM DUCT AND NEUTRON ENVIRONMENT

4.1 Vacuum beam duct

To determine whether a vacuum beam duct would be necessary, the TOF hall was filled by air instead of vacuum used in previous studies. The results obtained are illustrated in Fig. 17. The presence of air increases neutron background in the TOF hall approximately by 1 order of magnitude at large distances (> 20 m) from the collimator wall (see Fig. 17, bottom). Therefore, a vacuum beam duct of 2.5 mm wall thickness made of steel has been studied (Fig. 18). The beam duct ends by a steel window of 2.5 mm thickness in the middle of the TOF area. The comparison between Fig. 18, top and bottom, shows rather clearly the effect of the beam window: the neutron background down the TOF hall is increased again by means of neutron scattering off the window. It should be noted that 2.5 mm of steel (8.6×10^{-2} n/barn/cm density) is roughly equivalent to about 4 m of air (5.4×10^{-5} n/barn/cm density) in terms of thickness. Therefore, it seems necessary to use a vacuum beam duct extended throughout the TOF hall from the collimator wall to the beam dump. The beam duct can be interrupted in some place in order to install an experimental setup under vacuum conditions or, alternatively, in air with ingoing beam duct being closed by a thin window.

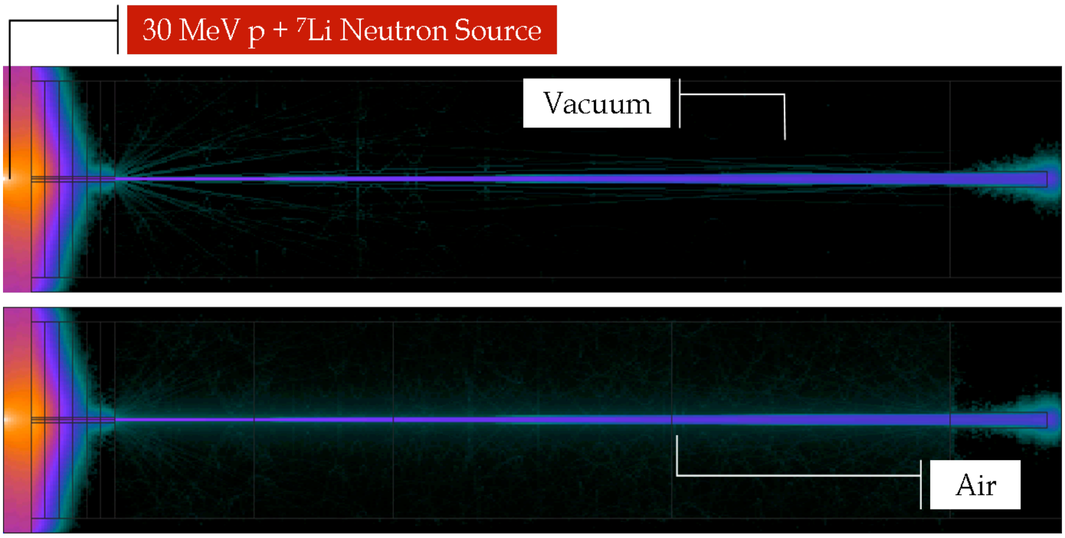


Fig. 17. Comparison of neutron environment in terms of total neutron flux in the TOF hall without air (top) and with air (bottom).

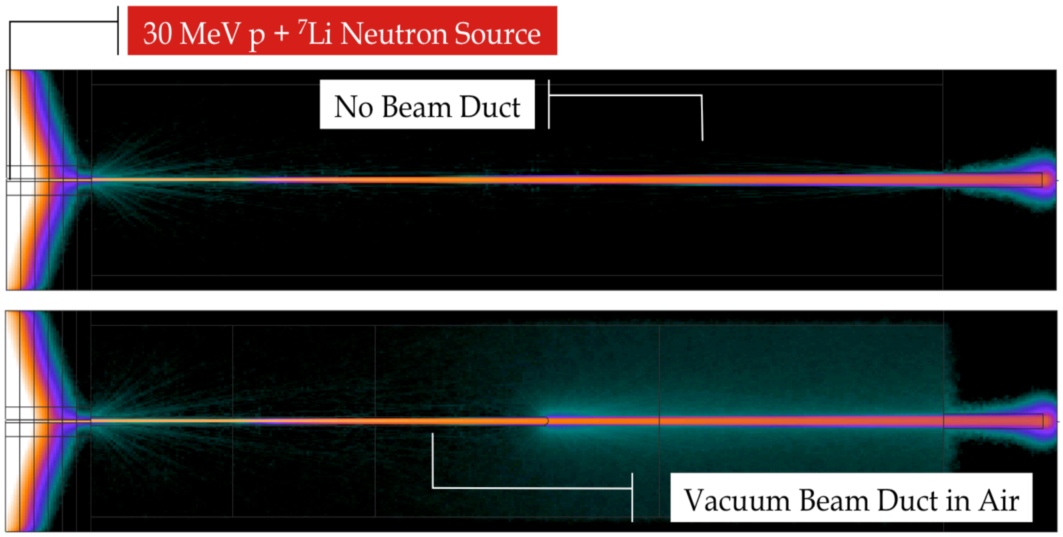
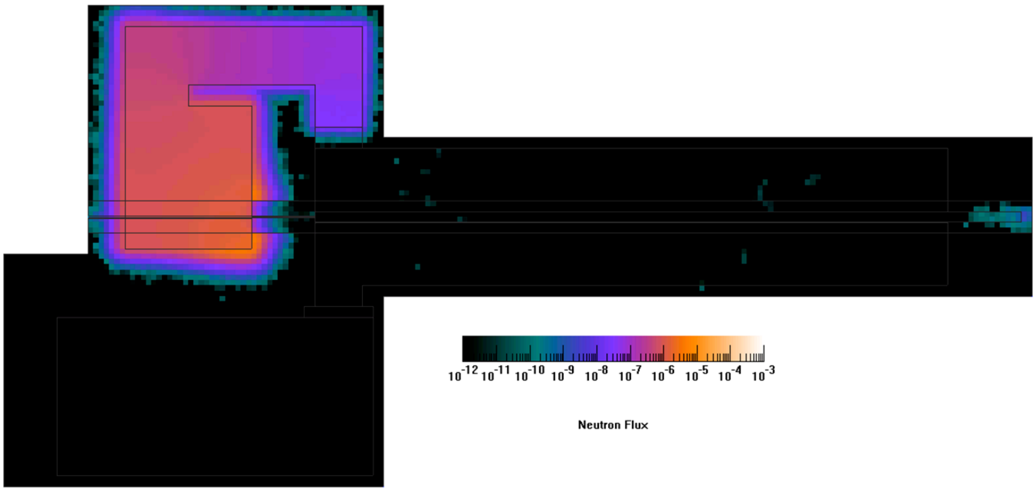


Fig. 18. Comparison of neutron environment in terms of total neutron flux in the TOF hall without vacuum beam duct (top) and with vacuum beam duct (bottom).

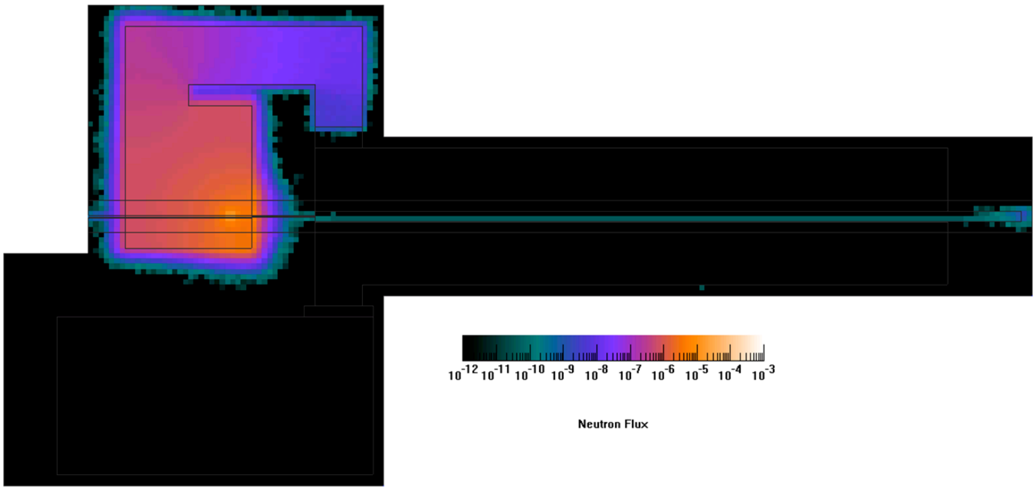
4.2 Neutron environment in the NFS facility

In addition to designing and optimization of the collimation system, the whole neutronic response of the NFS facility was also investigated. Neutron distribution over the NFS facility is shown in Fig. 19. Ring shape collimation system – with conically shaped collimator channel and vacuum beam duct extended from the collimator wall to the beam dump – was employed. One can see that neutron background in the TOF hall is rather small and thermal part of the beam itself is negligible comparing to its high energy part.

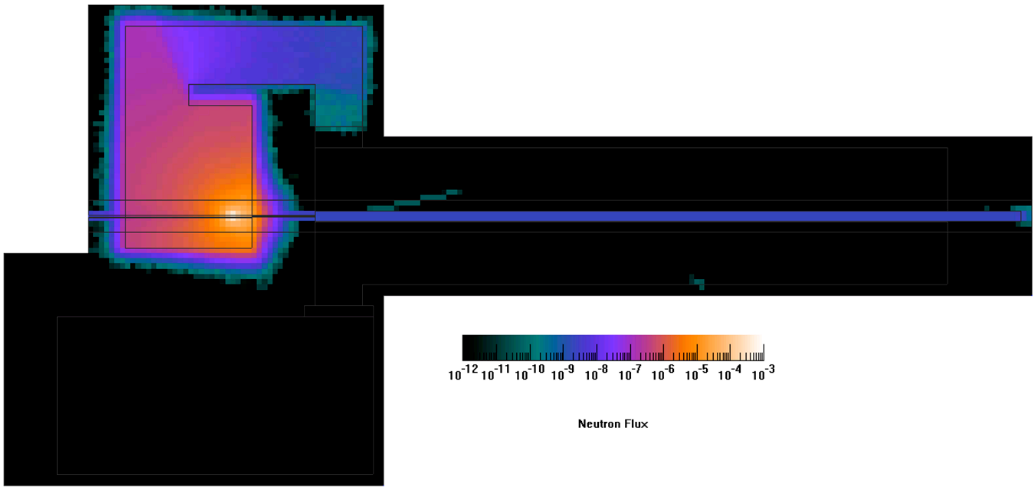
THERMAL: < 1 EV



SLOW + RESONANCE: 1 EV – 1 MEV



FAST + HIGH ENERGY: > 1 MEV



TOTAL OVER ALL ENERGIES

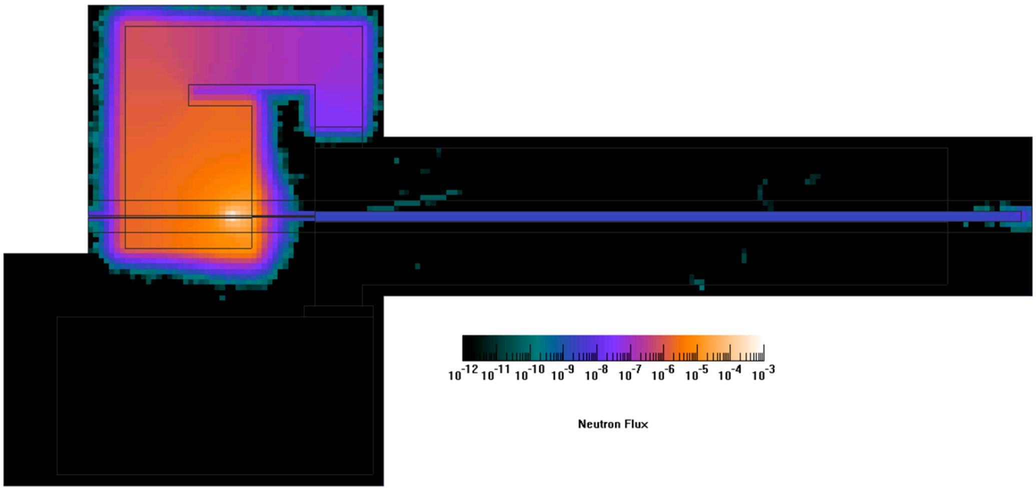


Fig. 19. Neutron spectrum in the NFS facility estimated in 3 broad groups (first 3 pictures) and in total (last picture).

CONCLUSIONS

The NFS (Neutrons For Science) facility is primarily composed of a beam converter hall and a TOF hall separated by a thick concrete wall with a collimation system built into the wall. The role of this system is to define a well-collimated neutron beam. The main results obtained with respect to designing and optimization of the collimation system are summarized hereafter.

During preliminary phase of the study presented materials suitable for the collimation system were indentified. Iron was selected as a primary material for scattering part of the collimator, while borated polyethylene was used as a moderator/absorber.

The shape of the collimator channel was optimized. It was found that conically shaped collimator channel of 31/8 mm of exit/entry diameter would reduce neutron background in the part of the TOF hall adjacent to the collimator wall by approximately 5 times (comparing to that of straight cylindrical channel) without compromising neutron beam intensity.

Main parts of the TOF hall were then compared with each other in terms of their neutronic response. It was confirmed that the collimation system is by far the biggest contributor into neutron background in the TOF hall and, therefore, optimization of other parts of the hall (like, for example, the beam dump) is not advisable without first optimizing the collimation system.

Several design layouts for the collimation system were studied. Initially promising 'sandwich' design – with several layers of different materials arranged along the axis of the beam – was proved not to be suitable due to its selectivity: some designs reduce high energy part of neutron background in the TOF hall and other designs reduce its low energy part, but not both.

A ring shape collimation system was proposed instead. The layers were arranged in ring fashion: thin inner part of the system scatters away high energy neutrons and thick outer part then absorbs them. Comparing to non-optimized collimation system made of concrete with straight cylindrical collimator channel, ring shape collimator design with conically shaped collimator channel would reduce neutron background in the nearest part of the TOF hall by almost 1 order of magnitude (7-9 times) in high energy part of the spectrum and by about 3 times in thermal part of the spectrum.

It was found also that a vacuum beam duct extended from the collimator wall to the beam dump all along the length of the TOF hall would be necessary in order to reduce neutron background in the farther part of the TOF hall produced by neutron scattering in air.

Overall, the ring shape collimation system with conically shaped collimator channel and the vacuum beam duct were found to improve neutron environment in the TOF hall without compromising the neutron beam itself.

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Appendix A. NEUTRON SOURCE SPECIFICATION

A.1 Objective

Within the NFS proposal, light ion beams delivered by LINAG of SPIRAL2 are to be converted into high intensity neutron beams. Two types of reactions are considered for the task of conversion: proton induced nuclear reactions on lithium produce quasi-monoenergetic neutrons and deuteron induced nuclear reactions on beryllium or carbon produce neutrons of 'white spectrum'. Specification of these sources is presented below.

A.2 Proton + lithium neutron source

Quasi-monoenergetic neutrons are produced in p + ^{7}Li nuclear reactions by proton irradiation of a thin (1-2 mm) lithium target. In order to obtain these neutrons, p + ^{7}Li nuclear reactions were directly simulated by MCNPX Version 2.4 code using nuclear data tables of Los Alamos origin. The target was modeled by a disk of 1 mm thickness and several cm diameter made of pure ^{7}Li of 0.534 g/cm^{3} density. An example of MCNP source specification is shown below.

```
C ======================================================================= SOURCE ==
SDEF      SUR  0002
          CCC  0001
          ERG  3.000E+01
          DIR  1.000E+00
          VEC  0.000E+00  0.000E+00  1.000E+00
            X  D001
            Y  D002
            Z -1.000E-01
          PAR  0009
C --------------------------------------------------------------------------------
SP001    -041  1.177E+00
SP002    -041  1.177E+00
C --------------------------------------------------------------------------------
```

Irradiated surface of the target (surface No 2) is Z = –0.1 cm and its outer surface is Z = 0 cm. The target (cell No 1) is used as a cookie-cutter cell. Proton energy is set to 30 MeV. Proton beam profile is of normal distribution with σ = 0.5 cm (distributions No 1 and No 2). This source can be built into a MCNP input for a run.

A.3 Pre-prepared proton + lithium neutron source

Due to low yield of p + ^{7}Li reaction (9.3×10^{-4} n/p or 5.8×10^{9} n/μC) and small thickness of the target, a long run – up to and more than 32-bit memory limit of 2 billion source particles – and an elaborated system of variance reduction cards are required to accumulate sufficient statistics. Therefore, the approach described above appears to be of little practical use. To solve this problem, a pre-prepared double-differential p + ^{7}Li neutron source was built to be directly used in MCNP runs. Given below is full specification of such a source. The source is of histogram type. The energy range was subdivided into 30 bins (every 1 MeV up to 30 MeV) and the angular range was subdivided into 15 bins (every 5 degrees from 0° to 30°, every 10 degrees from 30° to 90° and every 30 degrees from 90° to 180°). Since the target is very thin, both forward and backward neutrons are set to be born on the same surface (surface No 1), while the target itself is not modeled. Depending on the task in hand, backward part of the neutron source can be omitted entirely. Several examples of neutron distributions are shown in Fig. A1.

```
C ====================================================================== SOURCE ==
SDEF      SUR  0001
          CCC  0001
          ERG
         FDIR  D004
          DIR  D003
          VEC  0.000E+00  0.000E+00  1.000E+00
            X  D001
            Y  D002
            Z  0.000E+00
          PAR  0001
C ---------------------------------------------------------------------------------
SP001    -041  1.177E+00
SP002    -041  1.177E+00
C ---------------------------------------------------------------------------------
#         SI003      SP003
         -1.000E+00  0.000E+00
         -8.660E-01  3.140E-05
         -5.000E-01  9.245E-05
          0.000E+00  1.451E-04
          1.736E-01  5.537E-05
          3.420E-01  7.125E-05
          5.000E-01  8.132E-05
          6.428E-01  9.243E-05
          7.660E-01  9.421E-05
          8.660E-01  8.801E-05
          9.063E-01  4.134E-05
          9.397E-01  3.968E-05
          9.659E-01  3.655E-05
          9.848E-01  3.045E-05
          9.962E-01  2.072E-05
          1.000E+00  7.349E-06
C ---------------------------------------------------------------------------------
DS004  S  115
          114
          113
          112
          111
          110
          109
          108
          107
          106
          105
          104
          103
          102
          101
C ---------------------------------------------------------------------------------
#         SI101      SP101
          0.000E+00  0.000E+00
          1.000E+00  2.080E-07
          2.000E+00  1.240E-07
          3.000E+00  1.910E-07
          4.000E+00  2.380E-07
          5.000E+00  2.560E-07
          6.000E+00  2.630E-07
          7.000E+00  2.680E-07
          8.000E+00  3.060E-07
```

```
          9.000E+00  3.140E-07
          1.000E+01  2.620E-07
          1.100E+01  2.280E-07
          1.200E+01  1.910E-07
          1.300E+01  1.860E-07
          1.400E+01  1.470E-07
          1.500E+01  1.190E-07
          1.600E+01  9.299E-08
          1.700E+01  8.300E-08
          1.800E+01  8.200E-08
          1.900E+01  9.100E-08
          2.000E+01  3.300E-08
          2.100E+01  8.700E-08
          2.200E+01  5.100E-08
          2.300E+01  8.000E-09
          2.400E+01  6.400E-08
          2.500E+01  0.000E+00
          2.600E+01  9.793E-10
          2.700E+01  0.000E+00
          2.800E+01  2.052E-06
          2.900E+01  1.403E-06
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI102      SP102
          0.000E+00  0.000E+00
          1.000E+00  4.229E-07
          2.000E+00  3.170E-07
          3.000E+00  5.450E-07
          4.000E+00  6.550E-07
          5.000E+00  7.409E-07
          6.000E+00  8.010E-07
          7.000E+00  8.749E-07
          8.000E+00  8.360E-07
          9.000E+00  9.220E-07
          1.000E+01  8.150E-07
          1.100E+01  7.580E-07
          1.200E+01  5.830E-07
          1.300E+01  4.970E-07
          1.400E+01  4.270E-07
          1.500E+01  3.410E-07
          1.600E+01  2.590E-07
          1.700E+01  2.210E-07
          1.800E+01  2.240E-07
          1.900E+01  2.170E-07
          2.000E+01  9.000E-08
          2.100E+01  2.020E-07
          2.200E+01  1.360E-07
          2.300E+01  3.798E-08
          2.400E+01  1.810E-07
          2.500E+01  0.000E+00
          2.600E+01  2.979E-09
          2.700E+01  1.959E-09
          2.800E+01  6.398E-06
          2.900E+01  3.218E-06
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI103      SP103
          0.000E+00  0.000E+00
          1.000E+00  5.780E-07
          2.000E+00  4.589E-07
          3.000E+00  8.709E-07
          4.000E+00  1.065E-06
          5.000E+00  1.162E-06
          6.000E+00  1.370E-06
          7.000E+00  1.432E-06
          8.000E+00  1.403E-06
          9.000E+00  1.379E-06
          1.000E+01  1.302E-06
          1.100E+01  1.170E-06
          1.200E+01  9.350E-07
          1.300E+01  8.050E-07
          1.400E+01  7.090E-07
          1.500E+01  5.779E-07
          1.600E+01  4.349E-07
          1.700E+01  3.330E-07
          1.800E+01  3.689E-07
          1.900E+01  3.880E-07
```

```
          2.000E+01  1.310E-07
          2.100E+01  3.450E-07
          2.200E+01  1.670E-07
          2.300E+01  1.240E-07
          2.400E+01  2.970E-07
          2.500E+01  1.000E-09
          2.600E+01  4.918E-09
          2.700E+01  3.918E-09
          2.800E+01  1.029E-05
          2.900E+01  2.351E-06
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI104      SP104
          0.000E+00  0.000E+00
          1.000E+00  6.250E-07
          2.000E+00  6.370E-07
          3.000E+00  1.296E-06
          4.000E+00  1.398E-06
          5.000E+00  1.621E-06
          6.000E+00  1.871E-06
          7.000E+00  1.877E-06
          8.000E+00  1.984E-06
          9.000E+00  1.940E-06
          1.000E+01  1.764E-06
          1.100E+01  1.464E-06
          1.200E+01  1.222E-06
          1.300E+01  1.053E-06
          1.400E+01  9.130E-07
          1.500E+01  7.500E-07
          1.600E+01  5.800E-07
          1.700E+01  4.360E-07
          1.800E+01  4.610E-07
          1.900E+01  4.840E-07
          2.000E+01  1.970E-07
          2.100E+01  4.920E-07
          2.200E+01  1.590E-07
          2.300E+01  2.880E-07
          2.400E+01  2.140E-07
          2.500E+01  1.979E-09
          2.600E+01  3.000E-09
          2.700E+01  5.592E-08
          2.800E+01  1.258E-05
          2.900E+01  1.920E-07
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI105      SP105
          0.000E+00  0.000E+00
          1.000E+00  6.390E-07
          2.000E+00  7.569E-07
          3.000E+00  1.717E-06
          4.000E+00  1.746E-06
          5.000E+00  2.145E-06
          6.000E+00  2.315E-06
          7.000E+00  2.438E-06
          8.000E+00  2.375E-06
          9.000E+00  2.423E-06
          1.000E+01  2.115E-06
          1.100E+01  1.758E-06
          1.200E+01  1.468E-06
          1.300E+01  1.317E-06
          1.400E+01  1.073E-06
          1.500E+01  8.950E-07
          1.600E+01  7.100E-07
          1.700E+01  5.719E-07
          1.800E+01  5.610E-07
          1.900E+01  5.480E-07
          2.000E+01  3.249E-07
          2.100E+01  6.440E-07
          2.200E+01  9.400E-08
          2.300E+01  4.430E-07
          2.400E+01  1.250E-07
          2.500E+01  1.000E-09
          2.600E+01  2.979E-09
          2.700E+01  1.464E-06
          2.800E+01  9.008E-06
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
```

```
C ------------------------------------------------------------------------------
#         SI106      SP106
          0.000E+00  0.000E+00
          1.000E+00  6.859E-07
          2.000E+00  1.012E-06
          3.000E+00  1.999E-06
          4.000E+00  2.001E-06
          5.000E+00  2.566E-06
          6.000E+00  2.708E-06
          7.000E+00  2.686E-06
          8.000E+00  2.832E-06
          9.000E+00  2.662E-06
          1.000E+01  2.478E-06
          1.100E+01  1.966E-06
          1.200E+01  1.725E-06
          1.300E+01  1.393E-06
          1.400E+01  1.164E-06
          1.500E+01  9.099E-07
          1.600E+01  7.270E-07
          1.700E+01  6.490E-07
          1.800E+01  6.480E-07
          1.900E+01  4.200E-07
          2.000E+01  4.679E-07
          2.100E+01  5.810E-07
          2.200E+01  4.500E-08
          2.300E+01  6.370E-07
          2.400E+01  1.600E-08
          2.500E+01  1.979E-09
          2.600E+01  3.958E-09
          2.700E+01  3.988E-06
          2.800E+01  4.367E-06
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C ------------------------------------------------------------------------------
#         SI107      SP107
          0.000E+00  0.000E+00
          1.000E+00  1.373E-06
          2.000E+00  2.643E-06
          3.000E+00  4.492E-06
          4.000E+00  4.899E-06
          5.000E+00  5.841E-06
          6.000E+00  6.399E-06
          7.000E+00  6.451E-06
          8.000E+00  6.679E-06
          9.000E+00  6.030E-06
          1.000E+01  5.231E-06
          1.100E+01  4.555E-06
          1.200E+01  3.728E-06
          1.300E+01  2.989E-06
          1.400E+01  2.482E-06
          1.500E+01  1.919E-06
          1.600E+01  1.501E-06
          1.700E+01  1.510E-06
          1.800E+01  1.460E-06
          1.900E+01  6.539E-07
          2.000E+01  1.429E-06
          2.100E+01  5.489E-07
          2.200E+01  8.300E-07
          2.300E+01  6.669E-07
          2.400E+01  3.000E-09
          2.500E+01  0.000E+00
          2.600E+01  1.308E-06
          2.700E+01  1.159E-05
          2.800E+01  7.949E-07
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C ------------------------------------------------------------------------------
#         SI108      SP108
          0.000E+00  0.000E+00
          1.000E+00  1.354E-06
          2.000E+00  3.763E-06
          3.000E+00  5.175E-06
          4.000E+00  5.990E-06
          5.000E+00  6.989E-06
          6.000E+00  6.990E-06
          7.000E+00  7.213E-06
          8.000E+00  7.137E-06
```

```
          9.000E+00  6.240E-06
          1.000E+01  5.247E-06
          1.100E+01  4.402E-06
          1.200E+01  3.628E-06
          1.300E+01  2.933E-06
          1.400E+01  2.316E-06
          1.500E+01  1.759E-06
          1.600E+01  1.673E-06
          1.700E+01  1.586E-06
          1.800E+01  7.700E-07
          1.900E+01  1.278E-06
          2.000E+01  8.690E-07
          2.100E+01  5.070E-07
          2.200E+01  9.790E-07
          2.300E+01  1.296E-08
          2.400E+01  2.979E-09
          2.500E+01  8.409E-07
          2.600E+01  1.241E-05
          2.700E+01  2.141E-06
          2.800E+01  1.000E-09
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI109      SP109
          0.000E+00  0.000E+00
          1.000E+00  1.506E-06
          2.000E+00  4.708E-06
          3.000E+00  5.624E-06
          4.000E+00  6.959E-06
          5.000E+00  7.625E-06
          6.000E+00  7.579E-06
          7.000E+00  7.787E-06
          8.000E+00  7.158E-06
          9.000E+00  5.990E-06
          1.000E+01  5.025E-06
          1.100E+01  3.973E-06
          1.200E+01  3.273E-06
          1.300E+01  2.445E-06
          1.400E+01  1.947E-06
          1.500E+01  1.683E-06
          1.600E+01  1.488E-06
          1.700E+01  9.459E-07
          1.800E+01  1.136E-06
          1.900E+01  1.050E-06
          2.000E+01  3.700E-07
          2.100E+01  9.899E-07
          2.200E+01  3.100E-08
          2.300E+01  2.980E-09
          2.400E+01  6.969E-07
          2.500E+01  1.007E-05
          2.600E+01  2.367E-06
          2.700E+01  4.000E-09
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI110      SP110
          0.000E+00  0.000E+00
          1.000E+00  2.130E-06
          2.000E+00  4.792E-06
          3.000E+00  6.106E-06
          4.000E+00  7.505E-06
          5.000E+00  7.772E-06
          6.000E+00  7.925E-06
          7.000E+00  7.591E-06
          8.000E+00  6.377E-06
          9.000E+00  5.490E-06
          1.000E+01  4.447E-06
          1.100E+01  3.392E-06
          1.200E+01  2.653E-06
          1.300E+01  1.995E-06
          1.400E+01  1.546E-06
          1.500E+01  1.519E-06
          1.600E+01  9.889E-07
          1.700E+01  1.051E-06
          1.800E+01  1.036E-06
          1.900E+01  3.759E-07
```

```
          2.000E+01  9.500E-07
          2.100E+01  3.200E-08
          2.200E+01  3.959E-09
          2.300E+01  3.820E-07
          2.400E+01  4.303E-06
          2.500E+01  9.509E-07
          2.600E+01  6.938E-09
          2.700E+01  0.000E+00
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C ------------------------------------------------------------------------------
#         SI111      SP111
          0.000E+00  0.000E+00
          1.000E+00  2.592E-06
          2.000E+00  4.835E-06
          3.000E+00  6.694E-06
          4.000E+00  7.421E-06
          5.000E+00  7.746E-06
          6.000E+00  8.036E-06
          7.000E+00  6.871E-06
          8.000E+00  5.630E-06
          9.000E+00  4.474E-06
          1.000E+01  3.554E-06
          1.100E+01  2.811E-06
          1.200E+01  2.046E-06
          1.300E+01  1.587E-06
          1.400E+01  1.499E-06
          1.500E+01  1.052E-06
          1.600E+01  9.669E-07
          1.700E+01  1.055E-06
          1.800E+01  3.570E-07
          1.900E+01  7.450E-07
          2.000E+01  2.595E-08
          2.100E+01  4.000E-09
          2.200E+01  1.899E-07
          2.300E+01  9.650E-07
          2.400E+01  9.394E-08
          2.500E+01  2.000E-09
          2.600E+01  0.000E+00
          2.700E+01  0.000E+00
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C ------------------------------------------------------------------------------
#         SI112      SP112
          0.000E+00  0.000E+00
          1.000E+00  2.468E-06
          2.000E+00  4.148E-06
          3.000E+00  5.722E-06
          4.000E+00  6.307E-06
          5.000E+00  6.462E-06
          6.000E+00  6.118E-06
          7.000E+00  5.127E-06
          8.000E+00  4.140E-06
          9.000E+00  3.295E-06
          1.000E+01  2.487E-06
          1.100E+01  1.831E-06
          1.200E+01  1.402E-06
          1.300E+01  1.270E-06
          1.400E+01  9.869E-07
          1.500E+01  7.278E-07
          1.600E+01  8.869E-07
          1.700E+01  2.819E-07
          1.800E+01  6.990E-07
          1.900E+01  1.796E-08
          2.000E+01  6.950E-09
          2.100E+01  2.410E-07
          2.200E+01  7.330E-07
          2.300E+01  9.959E-09
          2.400E+01  2.979E-09
          2.500E+01  1.000E-09
          2.600E+01  0.000E+00
          2.700E+01  0.000E+00
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
```

```
C -----------------------------------------------------------------------------
#         SI113      SP113
          0.000E+00  0.000E+00
          1.000E+00  7.621E-06
          2.000E+00  1.444E-05
          3.000E+00  1.802E-05
          4.000E+00  1.906E-05
          5.000E+00  1.796E-05
          6.000E+00  1.542E-05
          7.000E+00  1.224E-05
          8.000E+00  9.587E-06
          9.000E+00  7.076E-06
          1.000E+01  5.187E-06
          1.100E+01  4.117E-06
          1.200E+01  3.254E-06
          1.300E+01  3.023E-06
          1.400E+01  2.256E-06
          1.500E+01  2.183E-06
          1.600E+01  1.181E-06
          1.700E+01  6.038E-07
          1.800E+01  1.450E-07
          1.900E+01  5.849E-07
          2.000E+01  6.330E-07
          2.100E+01  5.569E-07
          2.200E+01  3.979E-09
          2.300E+01  0.000E+00
          2.400E+01  0.000E+00
          2.500E+01  0.000E+00
          2.600E+01  0.000E+00
          2.700E+01  0.000E+00
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI114      SP114
          0.000E+00  0.000E+00
          1.000E+00 6.157E-06
          2.000E+00 1.150E-05
          3.000E+00  1.356E-05
          4.000E+00  1.352E-05
          5.000E+00  1.126E-05
          6.000E+00  8.952E-06
          7.000E+00  6.746E-06
          8.000E+00  5.012E-06
          9.000E+00  3.685E-06
          1.000E+01  3.084E-06
          1.100E+01  2.227E-06
          1.200E+01  2.633E-06
          1.300E+01  1.687E-06
          1.400E+01  1.529E-06
          1.500E+01  2.409E-07
          1.600E+01  2.794E-08
          1.700E+01  2.100E-07
          1.800E+01  4.100E-07
          1.900E+01  4.981E-09
          2.000E+01  1.000E-09
          2.100E+01  1.000E-09
          2.200E+01  0.000E+00
          2.300E+01  0.000E+00
          2.400E+01  0.000E+00
          2.500E+01  0.000E+00
          2.600E+01  0.000E+00
          2.700E+01  0.000E+00
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
#         SI115      SP115
          0.000E+00  0.000E+00
          1.000E+00  2.267E-06
          2.000E+00  4.282E-06
          3.000E+00  4.925E-06
          4.000E+00  4.576E-06
          5.000E+00  3.601E-06
          6.000E+00  2.881E-06
          7.000E+00  2.036E-06
          8.000E+00  1.491E-06
```

```
          9.000E+00  1.349E-06
          1.000E+01  8.349E-07
          1.100E+01  1.429E-06
          1.200E+01  3.119E-07
          1.300E+01  9.300E-07
          1.400E+01  2.000E-09
          1.500E+01  9.898E-10
          1.600E+01  4.630E-07
          1.700E+01  2.399E-08
          1.800E+01  0.000E+00
          1.900E+01  0.000E+00
          2.000E+01  0.000E+00
          2.100E+01  0.000E+00
          2.200E+01  0.000E+00
          2.300E+01  0.000E+00
          2.400E+01  0.000E+00
          2.500E+01  0.000E+00
          2.600E+01  0.000E+00
          2.700E+01  0.000E+00
          2.800E+01  0.000E+00
          2.900E+01  0.000E+00
          3.000E+01  0.000E+00
C -----------------------------------------------------------------------------
```

It is important to note that neutron distributions obtained are almost independent of the initial proton beam profile due to small thickness of lithium target. Therefore, the same source specification can be used for different initial proton beam profiles with outgoing neutron spatial distribution (distributions No 1 and No 2 above) taken to be the same as proton one.

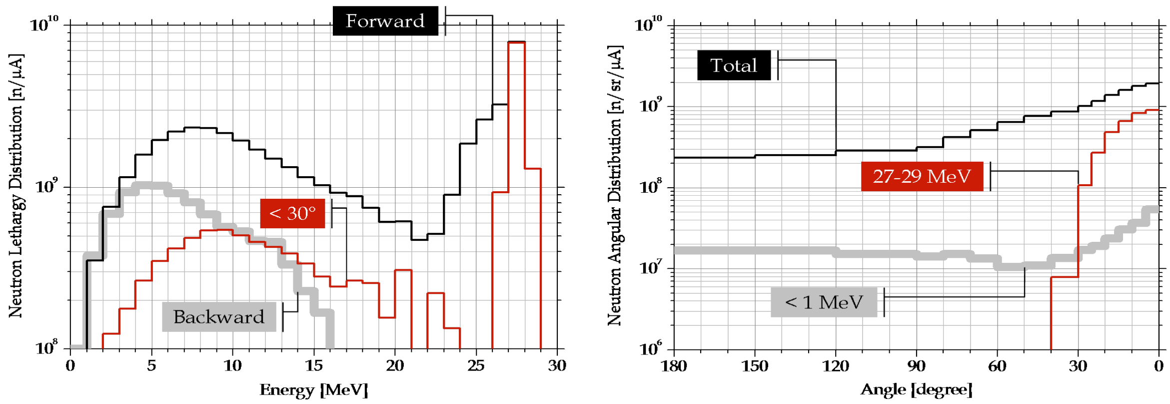

Fig. A1. Pre-prepared 30 MeV p + ^{7}Li neutron source: examples of neutron distributions

A.4 Deuteron + beryllium neutron source

Neutrons of white spectrum are produced in d + ^{9}Be stripping reactions by deuteron irradiation of a thick (about 1 cm) beryllium target. Due to the absence of nuclear data tables and reliable interaction models, it seems meaningless to simulate d + ^{9}Be nuclear reactions directly. Therefore, d + ^{9}Be source was constructed from the data available in literature [8]. One such a dataset – found for neutrons produced by 40 MeV deuterons in forward direction – was logarithmically interpolated in order to obtain one continuous function of energy in 0-40 MeV range and angle in 0-90° range. This function then could be used to construct d + ^{9}Be source in any form desired. For example, one can produce a histogram distribution by integrating it over suitable limits. Specification of d + ^{9}Be neutron source with bin structure similar to that used for p + ^{7}Li neutron source is given below.

```
C ==================================================================== SOURCE ==
SDEF      SUR  0001
          CCC  0001
          ERG
         FDIR  D004
          DIR  D003
          VEC  0.000E+00  0.000E+00  1.000E+00
            X  D001
            Y  D002
            Z  0.000E+00
          PAR  0001
C -----------------------------------------------------------------------------
SP001    -041  1.177E+00
SP002    -041  1.177E+00
C -----------------------------------------------------------------------------
#         SI003      SP003
          0.000E+00  0.000E+00
          1.736E-01  3.480E+10
          3.420E-01  4.403E+10
          5.000E-01  5.335E+10
          6.428E-01  5.665E+10
          7.660E-01  5.490E+10
          8.660E-01  5.603E+10
          9.063E-01  2.758E+10
          9.397E-01  2.701E+10
          9.659E-01  2.476E+10
          9.848E-01  2.273E+10
          9.962E-01  1.890E+10
          1.000E+00  8.260E+09
C -----------------------------------------------------------------------------
DS004  S  112
          111
          110
          109
          108
          107
          106
          105
          104
          103
          102
          101
C -----------------------------------------------------------------------------
#         SI101      SP101
          0.000E+00  0.000E+00
          1.000E+00  3.694E+08
          2.000E+00  3.206E+08
          3.000E+00  2.784E+08
          4.000E+00  2.435E+08
          5.000E+00  2.223E+08
          6.000E+00  2.152E+08
          7.000E+00  2.266E+08
          8.000E+00  2.431E+08
          9.000E+00  2.647E+08
          1.000E+01  2.884E+08
          1.100E+01  3.120E+08
          1.200E+01  3.352E+08
          1.300E+01  3.566E+08
          1.400E+01  3.781E+08
          1.500E+01  3.938E+08
          1.600E+01  4.030E+08
          1.700E+01  3.959E+08
          1.800E+01  3.842E+08
          1.900E+01  3.616E+08
          2.000E+01  3.343E+08
          2.100E+01  3.028E+08
          2.200E+01  2.682E+08
          2.300E+01  2.324E+08
          2.400E+01  1.983E+08
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         2.500E+01  1.674E+08
         2.600E+01  1.397E+08
         2.700E+01  1.156E+08
         2.800E+01  9.516E+07
         2.900E+01  7.905E+07
         3.000E+01  6.582E+07
         3.100E+01  5.484E+07
         3.200E+01  4.571E+07
         3.300E+01  3.812E+07
         3.400E+01  3.168E+07
         3.500E+01  2.588E+07
         3.600E+01  2.108E+07
         3.700E+01  1.717E+07
         3.800E+01  1.399E+07
         3.900E+01  1.139E+07
         4.000E+01  9.283E+06
C ------------------------------------------------------------------------------
#        SI102      SP102
         0.000E+00  0.000E+00
         1.000E+00  8.185E+08
         2.000E+00  7.738E+08
         3.000E+00  7.319E+08
         4.000E+00  6.951E+08
         5.000E+00  6.674E+08
         6.000E+00  6.467E+08
         7.000E+00  6.359E+08
         8.000E+00  6.537E+08
         9.000E+00  6.846E+08
         1.000E+01  7.194E+08
         1.100E+01  7.491E+08
         1.200E+01  7.728E+08
         1.300E+01  7.952E+08
         1.400E+01  8.163E+08
         1.500E+01  8.251E+08
         1.600E+01  8.114E+08
         1.700E+01  7.888E+08
         1.800E+01  7.557E+08
         1.900E+01  7.097E+08
         2.000E+01  6.544E+08
         2.100E+01  5.974E+08
         2.200E+01  5.404E+08
         2.300E+01  4.774E+08
         2.400E+01  4.172E+08
         2.500E+01  3.607E+08
         2.600E+01  3.066E+08
         2.700E+01  2.598E+08
         2.800E+01  2.187E+08
         2.900E+01  1.841E+08
         3.000E+01  1.549E+08
         3.100E+01  1.303E+08
         3.200E+01  1.096E+08
         3.300E+01  9.224E+07
         3.400E+01  7.758E+07
         3.500E+01  6.507E+07
         3.600E+01  5.455E+07
         3.700E+01  4.573E+07
         3.800E+01  3.835E+07
         3.900E+01  3.216E+07
         4.000E+01  2.697E+07
C ------------------------------------------------------------------------------
#        SI103      SP103
         0.000E+00  0.000E+00
         1.000E+00  1.708E+09
         2.000E+00  1.454E+09
         3.000E+00  1.240E+09
         4.000E+00  1.081E+09
         5.000E+00  9.817E+08
         6.000E+00  9.092E+08
         7.000E+00  8.552E+08
         8.000E+00  8.224E+08
         9.000E+00  8.197E+08
         1.000E+01  8.252E+08
         1.100E+01  8.264E+08
         1.200E+01  8.236E+08
         1.300E+01  8.202E+08
         1.400E+01  8.146E+08
         1.500E+01  8.036E+08
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         1.600E+01  7.825E+08
         1.700E+01  7.536E+08
         1.800E+01  7.185E+08
         1.900E+01  6.787E+08
         2.000E+01  6.280E+08
         2.100E+01  5.762E+08
         2.200E+01  5.223E+08
         2.300E+01  4.677E+08
         2.400E+01  4.148E+08
         2.500E+01  3.645E+08
         2.600E+01  3.177E+08
         2.700E+01  2.749E+08
         2.800E+01  2.369E+08
         2.900E+01  2.040E+08
         3.000E+01  1.753E+08
         3.100E+01  1.503E+08
         3.200E+01  1.289E+08
         3.300E+01  1.106E+08
         3.400E+01  9.488E+07
         3.500E+01  8.146E+07
         3.600E+01  7.025E+07
         3.700E+01  6.063E+07
         3.800E+01  5.234E+07
         3.900E+01  4.518E+07
         4.000E+01  3.901E+07
C -----------------------------------------------------------------------------
#        SI104      SP104
         0.000E+00  0.000E+00
         1.000E+00  2.872E+09
         2.000E+00  2.226E+09
         3.000E+00  1.726E+09
         4.000E+00  1.387E+09
         5.000E+00  1.193E+09
         6.000E+00  1.060E+09
         7.000E+00  9.675E+08
         8.000E+00  8.892E+08
         9.000E+00  8.539E+08
         1.000E+01  8.319E+08
         1.100E+01  8.088E+08
         1.200E+01  7.853E+08
         1.300E+01  7.618E+08
         1.400E+01  7.362E+08
         1.500E+01  7.110E+08
         1.600E+01  6.861E+08
         1.700E+01  6.522E+08
         1.800E+01  6.165E+08
         1.900E+01  5.815E+08
         2.000E+01  5.363E+08
         2.100E+01  4.906E+08
         2.200E+01  4.424E+08
         2.300E+01  3.973E+08
         2.400E+01  3.536E+08
         2.500E+01  3.124E+08
         2.600E+01  2.757E+08
         2.700E+01  2.411E+08
         2.800E+01  2.105E+08
         2.900E+01  1.838E+08
         3.000E+01  1.602E+08
         3.100E+01  1.391E+08
         3.200E+01  1.208E+08
         3.300E+01  1.049E+08
         3.400E+01  9.126E+07
         3.500E+01  7.967E+07
         3.600E+01  7.005E+07
         3.700E+01  6.165E+07
         3.800E+01  5.426E+07
         3.900E+01  4.775E+07
         4.000E+01  4.203E+07
C -----------------------------------------------------------------------------
#        SI105      SP105
         0.000E+00  0.000E+00
         1.000E+00  3.842E+09
         2.000E+00  2.827E+09
         3.000E+00  2.083E+09
         4.000E+00  1.612E+09
         5.000E+00  1.346E+09
         6.000E+00  1.168E+09
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          7.000E+00  1.056E+09
          8.000E+00  9.672E+08
          9.000E+00  9.185E+08
          1.000E+01  8.856E+08
          1.100E+01  8.523E+08
          1.200E+01  8.193E+08
          1.300E+01  7.863E+08
          1.400E+01  7.501E+08
          1.500E+01  7.151E+08
          1.600E+01  6.804E+08
          1.700E+01  6.366E+08
          1.800E+01  5.928E+08
          1.900E+01  5.509E+08
          2.000E+01  5.007E+08
          2.100E+01  4.514E+08
          2.200E+01  4.030E+08
          2.300E+01  3.573E+08
          2.400E+01  3.143E+08
          2.500E+01  2.746E+08
          2.600E+01  2.397E+08
          2.700E+01  2.080E+08
          2.800E+01  1.805E+08
          2.900E+01  1.569E+08
          3.000E+01  1.366E+08
          3.100E+01  1.186E+08
          3.200E+01  1.028E+08
          3.300E+01  8.918E+07
          3.400E+01  7.755E+07
          3.500E+01  6.808E+07
          3.600E+01  6.008E+07
          3.700E+01  5.306E+07
          3.800E+01  4.686E+07
          3.900E+01  4.138E+07
          4.000E+01  3.655E+07
C -------------------------------------------------------------------------------
#         SI106      SP106
          0.000E+00  0.000E+00
          1.000E+00  4.931E+09
          2.000E+00  3.403E+09
          3.000E+00  2.354E+09
          4.000E+00  1.738E+09
          5.000E+00  1.399E+09
          6.000E+00  1.180E+09
          7.000E+00  1.054E+09
          8.000E+00  9.611E+08
          9.000E+00  9.004E+08
          1.000E+01  8.569E+08
          1.100E+01  8.144E+08
          1.200E+01  7.733E+08
          1.300E+01  7.324E+08
          1.400E+01  6.876E+08
          1.500E+01  6.450E+08
          1.600E+01  6.031E+08
          1.700E+01  5.533E+08
          1.800E+01  5.059E+08
          1.900E+01  4.617E+08
          2.000E+01  4.119E+08
          2.100E+01  3.649E+08
          2.200E+01  3.217E+08
          2.300E+01  2.807E+08
          2.400E+01  2.434E+08
          2.500E+01  2.098E+08
          2.600E+01  1.805E+08
          2.700E+01  1.553E+08
          2.800E+01  1.338E+08
          2.900E+01  1.156E+08
          3.000E+01  1.005E+08
          3.100E+01  8.719E+07
          3.200E+01  7.549E+07
          3.300E+01  6.532E+07
          3.400E+01  5.680E+07
          3.500E+01  5.021E+07
          3.600E+01  4.452E+07
          3.700E+01  3.948E+07
          3.800E+01  3.502E+07
          3.900E+01  3.106E+07
          4.000E+01  2.754E+07
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C -----------------------------------------------------------------------------
#          SI107      SP107
           0.000E+00  0.000E+00
           1.000E+00  1.217E+10
           2.000E+00  7.952E+09
           3.000E+00  5.205E+09
           4.000E+00  3.641E+09
           5.000E+00  2.815E+09
           6.000E+00  2.363E+09
           7.000E+00  2.096E+09
           8.000E+00  1.892E+09
           9.000E+00  1.737E+09
           1.000E+01  1.627E+09
           1.100E+01  1.524E+09
           1.200E+01  1.422E+09
           1.300E+01  1.323E+09
           1.400E+01  1.217E+09
           1.500E+01  1.116E+09
           1.600E+01  1.020E+09
           1.700E+01  9.144E+08
           1.800E+01  8.172E+08
           1.900E+01  7.292E+08
           2.000E+01  6.399E+08
           2.100E+01  5.585E+08
           2.200E+01  4.859E+08
           2.300E+01  4.188E+08
           2.400E+01  3.597E+08
           2.500E+01  3.071E+08
           2.600E+01  2.617E+08
           2.700E+01  2.234E+08
           2.800E+01  1.910E+08
           2.900E+01  1.638E+08
           3.000E+01  1.412E+08
           3.100E+01  1.217E+08
           3.200E+01  1.046E+08
           3.300E+01  8.998E+07
           3.400E+01  7.775E+07
           3.500E+01  6.820E+07
           3.600E+01  5.990E+07
           3.700E+01  5.261E+07
           3.800E+01  4.621E+07
           3.900E+01  4.059E+07
           4.000E+01  3.566E+07
C -----------------------------------------------------------------------------
#          SI108     SP108
           0.000E+00  0.000E+00
           1.000E+00  1.414E+10
           2.000E+00  8.747E+09
           3.000E+00  5.425E+09
           4.000E+00  3.603E+09
           5.000E+00  2.678E+09
           6.000E+00  2.291E+09
           7.000E+00  2.021E+09
           8.000E+00  1.792E+09
           9.000E+00  1.600E+09
           1.000E+01  1.465E+09
           1.100E+01  1.345E+09
           1.200E+01  1.225E+09
           1.300E+01  1.111E+09
           1.400E+01  9.962E+08
           1.500E+01  8.860E+08
           1.600E+01  7.862E+08
           1.700E+01  6.867E+08
           1.800E+01  5.977E+08
           1.900E+01  5.195E+08
           2.000E+01  4.498E+08
           2.100E+01  3.885E+08
           2.200E+01  3.333E+08
           2.300E+01  2.854E+08
           2.400E+01  2.442E+08
           2.500E+01  2.078E+08
           2.600E+01  1.766E+08
           2.700E+01  1.502E+08
           2.800E+01  1.277E+08
           2.900E+01  1.085E+08
           3.000E+01  9.226E+07
           3.100E+01  7.843E+07
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          3.200E+01  6.665E+07
          3.300E+01  5.676E+07
          3.400E+01  4.843E+07
          3.500E+01  4.141E+07
          3.600E+01  3.542E+07
          3.700E+01  3.030E+07
          3.800E+01  2.592E+07
          3.900E+01  2.217E+07
          4.000E+01  1.897E+07
C -------------------------------------------------------------------------------
#         SI109    SP109
          0.000E+00  0.000E+00
          1.000E+00  1.800E+10
          2.000E+00  9.889E+09
          3.000E+00  5.518E+09
          4.000E+00  3.700E+09
          5.000E+00  2.756E+09
          6.000E+00  2.285E+09
          7.000E+00  1.935E+09
          8.000E+00  1.679E+09
          9.000E+00  1.462E+09
          1.000E+01  1.286E+09
          1.100E+01  1.131E+09
          1.200E+01  9.896E+08
          1.300E+01  8.647E+08
          1.400E+01  7.515E+08
          1.500E+01  6.499E+08
          1.600E+01  5.616E+08
          1.700E+01  4.821E+08
          1.800E+01  4.125E+08
          1.900E+01  3.526E+08
          2.000E+01  3.011E+08
          2.100E+01  2.563E+08
          2.200E+01  2.172E+08
          2.300E+01  1.840E+08
          2.400E+01  1.558E+08
          2.500E+01  1.317E+08
          2.600E+01  1.120E+08
          2.700E+01  9.577E+07
          2.800E+01  8.186E+07
          2.900E+01  6.994E+07
          3.000E+01  5.974E+07
          3.100E+01  5.102E+07
          3.200E+01  4.358E+07
          3.300E+01  3.726E+07
          3.400E+01  3.188E+07
          3.500E+01  2.727E+07
          3.600E+01  2.333E+07
          3.700E+01  1.996E+07
          3.800E+01  1.707E+07
          3.900E+01  1.461E+07
          4.000E+01  1.250E+07
C -------------------------------------------------------------------------------
#         SI110   SP110
          0.000E+00  0.000E+00
          1.000E+00  1.897E+10
          2.000E+00  9.698E+09
          3.000E+00  5.104E+09
          4.000E+00  3.465E+09
          5.000E+00  2.605E+09
          6.000E+00  2.096E+09
          7.000E+00  1.721E+09
          8.000E+00  1.463E+09
          9.000E+00  1.247E+09
          1.000E+01  1.064E+09
          1.100E+01  9.064E+08
          1.200E+01  7.720E+08
          1.300E+01  6.578E+08
          1.400E+01  5.595E+08
          1.500E+01  4.745E+08
          1.600E+01  4.023E+08
          1.700E+01  3.411E+08
          1.800E+01  2.881E+08
          1.900E+01  2.431E+08
          2.000E+01  2.051E+08
          2.100E+01  1.722E+08
          2.200E+01  1.442E+08
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        2.300E+01  1.207E+08
        2.400E+01  1.012E+08
        2.500E+01  8.476E+07
        2.600E+01  7.176E+07
        2.700E+01  6.116E+07
        2.800E+01  5.213E+07
        2.900E+01  4.444E+07
        3.000E+01  3.788E+07
        3.100E+01  3.229E+07
        3.200E+01  2.752E+07
        3.300E+01  2.346E+07
        3.400E+01  2.000E+07
        3.500E+01  1.705E+07
        3.600E+01  1.453E+07
        3.700E+01  1.239E+07
        3.800E+01  1.056E+07
        3.900E+01  9.005E+06
        4.000E+01  7.677E+06
C ------------------------------------------------------------------------------
#       SI111   SP111
        0.000E+00  0.000E+00
        1.000E+00  1.600E+10
        2.000E+00  8.094E+09
        3.000E+00  4.280E+09
        4.000E+00  2.912E+09
        5.000E+00  2.207E+09
        6.000E+00  1.746E+09
        7.000E+00  1.416E+09
        8.000E+00  1.183E+09
        9.000E+00  9.911E+08
        1.000E+01  8.331E+08
        1.100E+01  7.003E+08
        1.200E+01  5.923E+08
        1.300E+01  5.015E+08
        1.400E+01  4.233E+08
        1.500E+01  3.558E+08
        1.600E+01  2.990E+08
        1.700E+01  2.512E+08
        1.800E+01  2.102E+08
        1.900E+01  1.757E+08
        2.000E+01  1.468E+08
        2.100E+01  1.220E+08
        2.200E+01  1.011E+08
        2.300E+01  8.376E+07
        2.400E+01  6.950E+07
        2.500E+01  5.769E+07
        2.600E+01  4.820E+07
        2.700E+01  4.044E+07
        2.800E+01  3.392E+07
        2.900E+01  2.846E+07
        3.000E+01  2.388E+07
        3.100E+01  2.003E+07
        3.200E+01  1.681E+07
        3.300E+01  1.410E+07
        3.400E+01  1.183E+07
        3.500E+01  9.929E+06
        3.600E+01  8.331E+06
        3.700E+01  6.991E+06
        3.800E+01  5.866E+06
        3.900E+01  4.923E+06
        4.000E+01  4.131E+06
C ------------------------------------------------------------------------------
#       SI112   SP112
        0.000E+00  0.000E+00
        1.000E+00  1.292E+10
        2.000E+00  6.459E+09
        3.000E+00  3.433E+09
        4.000E+00  2.341E+09
        5.000E+00  1.789E+09
        6.000E+00  1.391E+09
        7.000E+00  1.114E+09
        8.000E+00  9.135E+08
        9.000E+00  7.513E+08
        1.000E+01  6.215E+08
        1.100E+01  5.154E+08
        1.200E+01  4.327E+08
        1.300E+01  3.639E+08
```

```
         1.400E+01  3.047E+08
         1.500E+01  2.538E+08
         1.600E+01  2.113E+08
         1.700E+01  1.759E+08
         1.800E+01  1.457E+08
         1.900E+01  1.205E+08
         2.000E+01  9.969E+07
         2.100E+01  8.199E+07
         2.200E+01  6.717E+07
         2.300E+01  5.505E+07
         2.400E+01  4.522E+07
         2.500E+01  3.717E+07
         2.600E+01  3.062E+07
         2.700E+01  2.527E+07
         2.800E+01  2.085E+07
         2.900E+01  1.720E+07
         3.000E+01  1.419E+07
         3.100E+01  1.171E+07
         3.200E+01  9.664E+06
         3.300E+01  7.975E+06
         3.400E+01  6.581E+06
         3.500E+01  5.430E+06
         3.600E+01  4.481E+06
         3.700E+01  3.698E+06
         3.800E+01  3.052E+06
         3.900E+01  2.519E+06
         4.000E+01  2.079E+06
c ---------------------------------------------------------------------------
```

The drawback of this approach is that the neutron source specified above contains forward neutrons only because dataset on forward neutrons only was available (backward neutrons must be modeled separately). Another drawback is that the source does not provide information about neutron spatial distribution: neutron beam spatial profile can be very different from initial deuteron beam profile due to large thickness of the target. Yet another problem is that contribution of low energy neutrons (< 2 MeV) is overestimated due to the nature of interpolation (Fig. A2). Neutron yield in forward direction is found to be approximately 6.9×10^{-2} n/d or 4.3×10^{11} n/μC. This value appears to be somewhat higher than expected. Therefore, this source should be additionally validated. Two sources specified in the Appendix A – source No 2 and source No 3 – are compared with each other in Fig. A3.

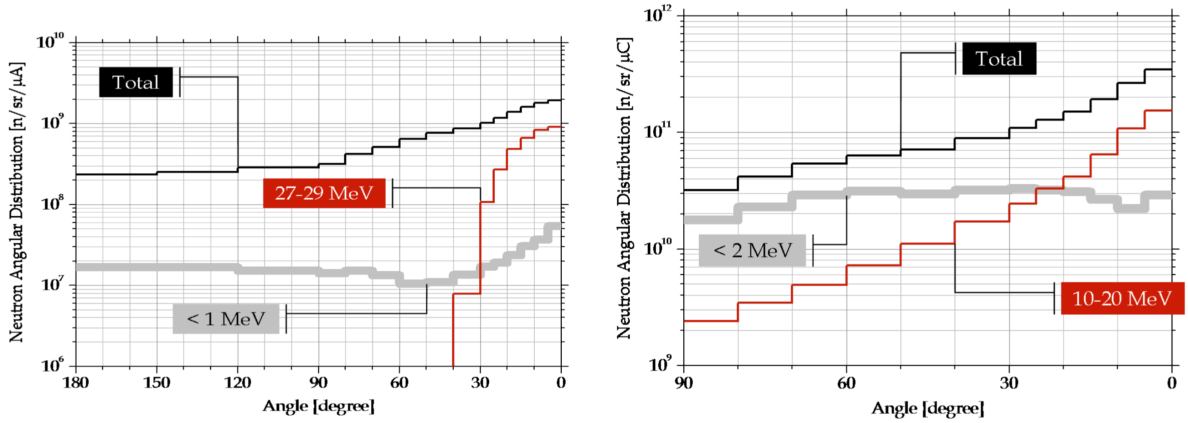

Fig. A2. Interpolated 40 MeV d + ^{9}Be neutron source: examples of neutron distributions

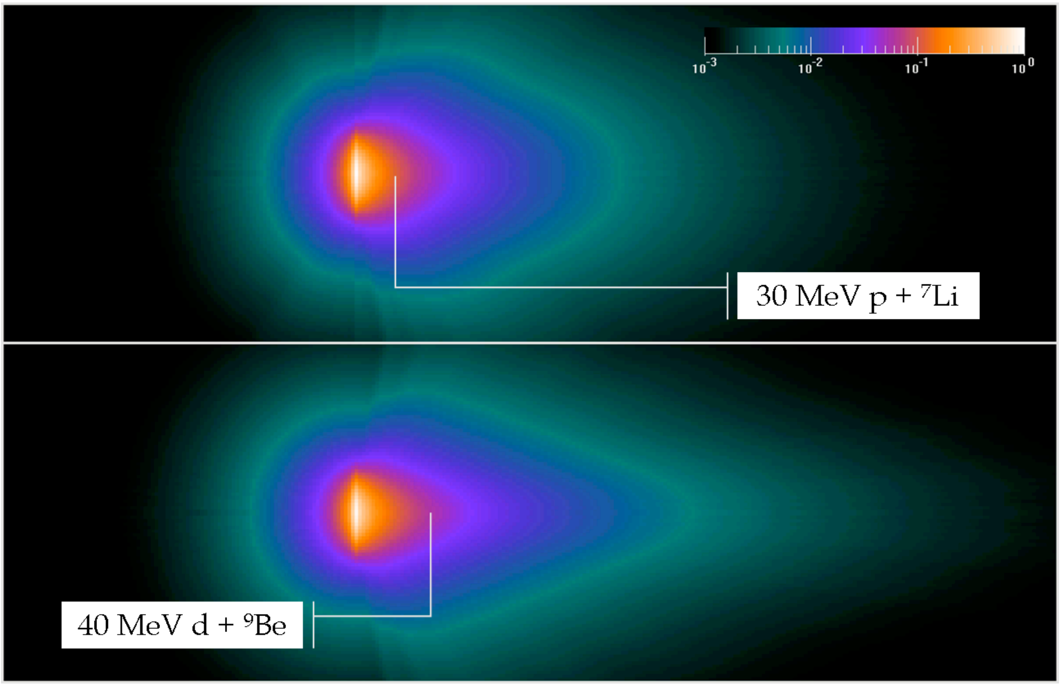

Fig. A3. Comparison of 30 MeV p + ^{7}Li neutron source and 40 MeV d + ^{9}Be neutron source

Appendix B. MCNPX MODEL OF THE NFS FACILITY

Shown below is a simplified MCNPX model of the NFS facility. It contains geometry layout, source geometry, materials, mesh windows. Source distributions are specified in Appendix A. Numbering of the surfaces used for geometry specification is shown in Fig. B1 for convenience.

```
NAME:
C ================================================================== THE VAULT ==
0001      10 -2.300E+00
              0004 -0007 -0056  0065  0101 -0102:
             -0004  0013  0065 -0066  0101 -0102:
              0007 -0011  0062 -0063  0101 -0102:
C ------------------------------------------------------------------------------
             -0001  0005  0053 -0054  0102 -0104:
              0001 -0002 -0054  0061  0102 -0104  0201:
              0001 -0008  0052 -0061  0102 -0104:
             -0001  0003 -0051  0052  0102 -0104:
             -0003  0004  0052 -0056  0102 -0104  0201:
              0003 -0006  0055 -0056  0102 -0104:
              0006 -0007 -0056  0058  0102 -0104:
              0006 -0007 -0059  0061  0102 -0104:
             -0007  0009 -0061  0065  0102 -0104:
             -0009  0012 -0064  0065  0102 -0104:
             -0012  0013 -0052  0065  0102 -0104:
             -0004  0013  0052 -0066  0102 -0104:
C ------------------------------------------------------------------------------
              0007 -0010 -0059  0062  0102 -0103:
              0007 -0010  0058 -0063  0102 -0103:
              0010 -0011  0062 -0063  0102 -0103  0201:
C ------------------------------------------------------------------------------
              0002 -0006 -0057  0058  0103 -0104:
              0002 -0006 -0059  0061  0103 -0104:
              0008 -0009  0052 -0061  0103 -0104:
              0006 -0007 -0058  0059  0103 -0104:
C ------------------------------------------------------------------------------
              0007 -0011  0062 -0063  0103 -0106:
C ------------------------------------------------------------------------------
              0004 -0007 -0056  0065  0104 -0105:
             -0004  0013  0065 -0066  0104 -0105
              IMP:N=01
C =================================================================== TOF HALL ==
0002      07 -1.290E-03
              0002 -0010 -0058  0059  0102 -0103  0201:
              0002 -0006 -0059  0061  0102 -0103:
C ------------------------------------------------------------------------------
              0002 -0006 -0058  0059  0103 -0104
              IMP:N=01
C ======================================================= BEAM CONVERTER HALL ==
0003      07 -1.290E-03
             -0001  0003  0051 -0060  0102 -0104  0201:
             -0001  0003 -0053  0060  0102 -0104:
              0003 -0005  0053 -0055  0102 -0104:
             -0002  0005  0054 -0055  0102 -0104:
              0002 -0006 -0055  0057  0102 -0104
              IMP:N=01
C ============================================================ AUXILIARY HALL ==
0004      07 -1.290E-03
             -0009  0012 -0052  0064  0102 -0104
              IMP:N=01
C ====================================================================== WORLD ==
0005      00
            (-0004: 0007: 0056:-0065:-0101: 0105)
            ( 0004:-0013:-0065: 0066:-0101: 0105)
            (-0007: 0011:-0062: 0063:-0101: 0106)
              IMP:N=00
C ====================================================================== DOORS ==
0051      10 -2.300E+00
              0008 -0009  0052 -0061  0102 -0103
```

```
             IMP:N=01
C -------------------------------------------------------------------------------
0052      10 -2.300E+00
             0002 -0006 -0057  0058  0102 -0103
             IMP:N=01
C ================================================================= BEAM DUMP ==
0101      10 -2.300E+00
             0010 -0011 -0201  0202:
            -0011  0014 -0202
             IMP:N=01
0102      00
             0010 -0014 -0202
             IMP:N=01
C ============================================================ BEAM COLLIMATOR ==
0151      01 -9.400E-01
             0001 -0002 -0201  0203
             IMP:N=01
0152      26 -7.875E+00
             0001 -0002 -0203  0204
             IMP:N=01
0153      00
             0001 -0002 -0204
             IMP:N=01
C ======================================================== BEAM LINE STRUCTURE ==
0201      07 -1.290E-03
             0002 -0010 -0201  0205
             IMP:N=01
0202      08 -8.000E+00
             0002 -0010 -0205  0206
             IMP:N=01
0203      00
             0002 -0010 -0206
             IMP:N=01
C -------------------------------------------------------------------------------
0204      07 -1.290E-03
            -0001  0003 -0201  0207
             IMP:N=01
0205      10 -2.300E+00
            -0003  0004 -0201  0207
             IMP:N=01
0206      08 -8.000E+00
            -0001  0004 -0207  0208
             IMP:N=01
0207      00
            -0001  0004 -0208
             IMP:N=01

C ====================================================== SURFACE SPECIFICATION ==
0001      PX  1.000E+02
0002      PX  4.000E+02
0003      PX -5.000E+02
0004      PX -6.750E+02
0005      PX -2.000E+02
0006      PX  6.250E+02
0007      PX  7.250E+02
0008      PX  3.500E+02
0009      PX  6.750E+02
0010      PX  3.400E+03
0011      PX  3.800E+03
0012      PX -8.250E+02
0013      PX -1.075E+03
0014      PX  3.750E+03
C -------------------------------------------------------------------------------
0051      PY -1.500E+02
0052      PY -4.750E+02
0053      PY  5.250E+02
0054      PY  6.250E+02
0055      PY  9.000E+02
0056      PY  1.000E+03
0057      PY  4.250E+02
0058      PY  3.250E+02
0059      PY -3.250E+02
0060      PY  1.500E+02
0061      PY -4.250E+02
0062      PY -3.750E+02
0063      PY  3.750E+02
0064      PY -1.225E+03
```

```
0065      PY -1.275E+03
0066      PY -1.750E+02
C --------------------------------------------------------------------------------
0101      PZ -2.500E+02
0102      PZ -1.500E+02
0103      PZ  2.500E+02
0104      PZ  4.500E+02
0105      PZ  5.500E+02
0106      PZ  3.500E+02
C --------------------------------------------------------------------------------
0201      CX  7.500E+01
0202      CX  2.500E+01
0203      CX  5.000E+00
0204      KX  0.000E+00  1.512E-05  1.000E+00
0205      CX  2.525E+01
0206      CX  2.500E+01
0207      CX  5.250E+00
0208      CX  5.000E+00

C ======================================================================= TYPE ==
MODE      N
C ========================================================================== X ==
LCA       01J
LCB       01J
LEA       01J
LEB       01J
C ============================================================= NEUTRON SOURCE ==
SDEF      CCC  0207
          ERG
         FDIR  D004
          DIR  D003
          VEC  1.000E+00  0.000E+00  0.000E+00
            X  0.000E+00
            Y  D001
            Z  D002
          PAR  0001
```

(see Appendix A for source distributions)

```
C ==================================================== MATERIALS AND LIBRARIES ==
M01       01000  0.633333  $ 0.95POLYC2H4+0.05B
          05000  0.050000
          06000  0.316667
M07       07000  0.750000  $ AIR
          08000  0.250000
M08       24000  0.180000  $ SS316L
          25055  0.020000
          26000  0.650000
          28000  0.130000
          40000  0.020000
M10       01000  0.150000  $ CONCRETEMINE
          06000  0.100000
          08000  0.550000
          14000  0.100000
          20000  0.100000
M26       26000  1.000000  $ IRON
C ================================================================== TREATMENT ==
PHYS:N    1.500E+02  03J  1.500E+02
C ===================================================================== CUTOFF ==
NPS       1.000E+08
C ================================================================= PERIPHERAL ==
PRINT
PRDMP     03J
          001
C ========================================================= WEIGHT WINDOW CARDS ==
F991:N    010
C --------------------------------------------------------------------------------
WWG       991
          000
          000
          04J
          000
C --------------------------------------------------------------------------------
MESH     GEOM  REC
```

```
          REF  0.000E+00  0.000E+00  0.000E+00
       ORIGIN -1.100E+03 -1.300E+03 -2.750E+02
        IMESH  4.250E+02  6.000E+02  9.000E+02
               1.200E+03  1.300E+03  1.400E+03
               1.500E+03  1.725E+03  2.000E+03
               2.500E+03  3.000E+03  3.500E+03
               4.000E+03  4.500E+03  4.925E+03
        JMESH  8.250E+02  9.750E+02  1.225E+03
               1.375E+03  1.625E+03  1.825E+03
               1.925E+03  2.200E+03  2.325E+03
        KMESH  1.250E+02  2.000E+02  3.500E+02
               5.250E+02  7.250E+02  8.500E+02
C ======================================================================= MESH ==
TMESH
RMESH01:N
CORA01 -1.075E+03  194I  3.800E+03
CORB01 -1.275E+03  090I  1.000E+03
CORC01 -2.500E+02  031I  5.500E+02
ENDMD
```

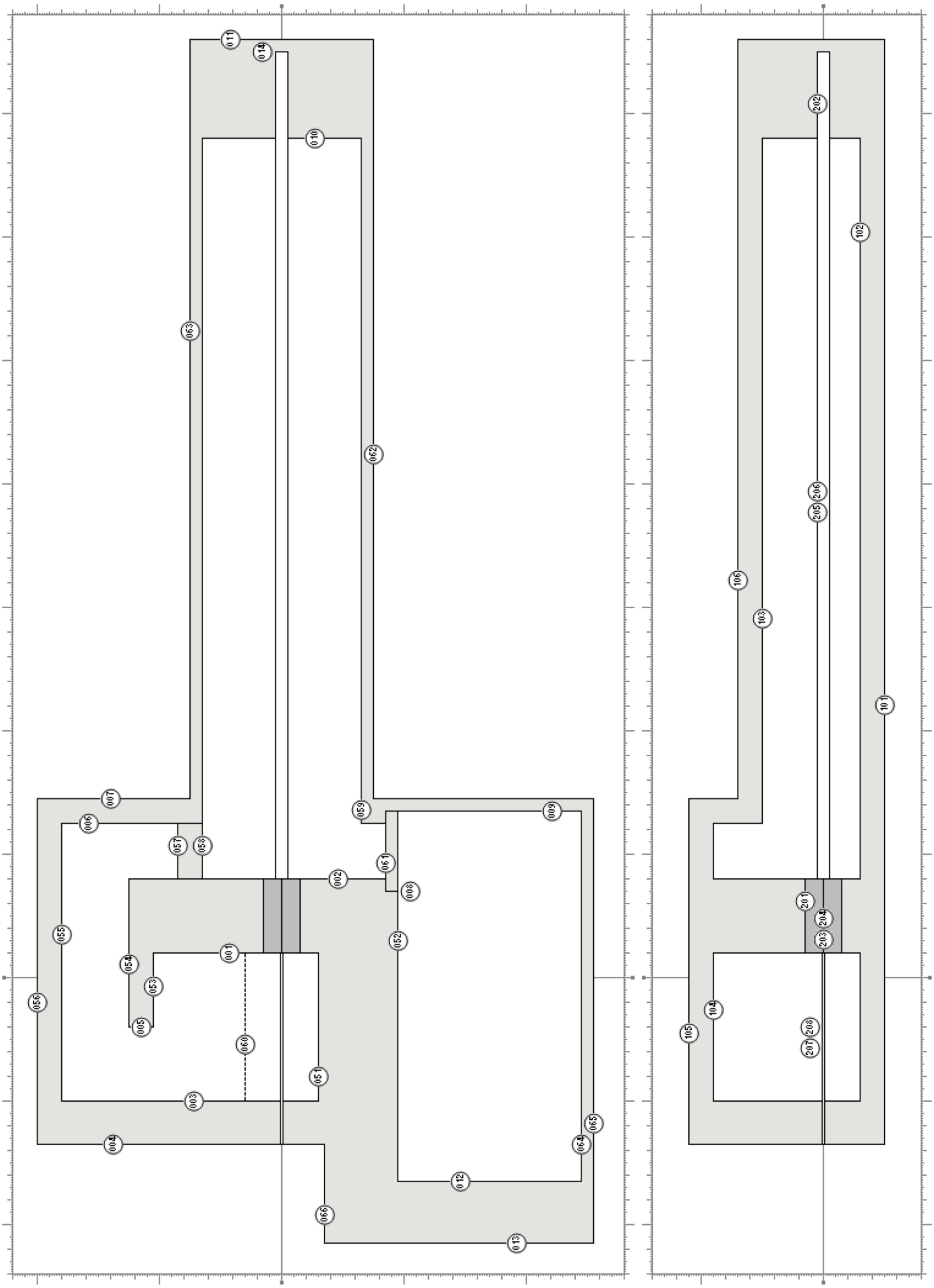

Fig. B1. Numbering of the surfaces used in MCNPX input

Appendix C. LIST OF COMPUTER FILES

An effort has been made to set up the NFS geometry and perform calculations producing the results described in this report. Since this work may serve as a basis for further investigations, the relevant computer files, stored on the servers of CEA-Irfu, are catalogued in the following directory structure containing in total about 500 Mb of data.

|– NFS

- **|– 20090529**
- **|– DAM**
- **|– DIRECTORY**
- **|– INI**
- **|– LI7BE9**
- **|– NFX1**
- **|– NFX2**
- **|– NFX3**
- **|– OLDSOURCEDATA**
- **|– SPECTRA**

The content of each directory is summarized in a top level file README.rtf which is reproduced below.

20090529

This folder contains files NFX0** used for optimization of the collimator channel shape (14 inputs, 14 outputs and 14 mdata files). The model consists of a collimator wall, a TOF vault and a beam dump. Neutron source is of p + Li origin.

The folder contains also 3 pictures and a slideset named NFX-20090529.ppt used in a discussion held on 2009/05/29.

DAM

This folder contains MCNP files and pictures with regard to neutronics of the door between the converter hall and the TOF hall.

DIRECTORY

The folder DIRECTORY contains basic files: reference models, weight window mesh files, pictures, etc; as well as also Microsoft Word documents used for preparation of various reports.

INI

The folder INI contains preliminary initial calculations. The model used consists of a collimator wall with a collimation system built inside it and a simple monoenergetic (30 MeV) isotropic point-like neutron source placed 1 m from the wall. Geometric parameters and material compositions of the wall and the collimation system are all varied. The purpose of the model is to study neutron transport through different collimators.

Files named INI*** (with numbers for 61 inputs and 61 outputs) employ collimator channel of straight cylinder shape, while files CON*** (10 inputs and 10 outputs) employ that of conical cylinder shape.

Selected results were presented at NFS meeting held on 2009/03/18. The slideset of that presentation ALT-20090318-INI.ppt is also there.

LI7BE9

This folder contains files LI7REF and LI7001 for p + Li neutron source calculated with lithium data of Los Alamos origin. Files LI7REF specify neutrons produced by point-like 30 MeV proton beam from 1 mm ^{7}Li target. Files LI7001 specify neutrons produced by normally distributed (σ = 0.5 cm) 30 MeV proton beam from the same target.

Double-differential neutron spectrum produced by LI7REF was used to construct files LI7REN. Files BE9REN specify d + Be neutron source. This source was produced by means of interpolation of experimental data available for 40 MeV d + Be target. These 2 sources – p + Li source and d + Be source – are then compared in Source Comparison.bmp.

NFX1

The folder NFX1 contains files used to estimate individual contributions of various parts of the geometry into total neutron background inside the TOF hall. The model consists of a collimator wall, a TOF vault and a beam dump. Neutron source is of p + Li origin. The results are summarized in NFX1.ppt.

NFX2

The folder NFX2 contains files used for optimization of the collimation system in so called 'sandwich design' (files numbered from 115 to 138) and in 'radial design' (files numbered from 201 and 202). The results are in 20091029.ppt, NFX1U.ppt and NFX1VAR.ppt.

There are also 2 MCNP runs done for d + Be neutron source with the same geometry model: NFD001 is without any collimation system (reference case) and NFD002 is with optimized collimation system.

NFX3

The folder NFX3 contains files used for calculations with a vacuum beam duct (files numbered 203 and 204). The model consists of a collimator wall, a TOF vault and a beam dump. Neutron source is of p + Li origin. The results can be found in the file NFX1TUBE.ppt.

OLDSOURCEDATA

This folder contains old (and usually unreliable) sources prepared by MCNP. Files FIN1** contain data for deuteron induced neutron sources and files FIN2** – data for proton induced neutron sources for various targets. Some results can be found in ALT-20080707-MEETING.ppt, ALT-20080924.ppt and Low energy neutron production by p + Ta reaction.doc (3 Microsoft Office files).

SPECTRA

This folder contains files for 3 group spectra inside the NFS facility. The results are in Microsoft Powerpoint file 3Group.ppt.

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