Optimization of n_TOF-EAR2 using FLUKA

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ABSTRACT: In 2014 a new vertical flight path was installed at the neutron time-of-flight facility, n_TOF, at CERN. The beam line optimization of this second experimental area (EAR2) was performed by FLUKA simulations with a detailed model of the facility, including the spallation target, neutron beam line, magnet, collimators and beam dump. The beam profile as well as neutron and gamma fluxes were calculated at the measurement position, 150 cm from the exit of the second collimator. The design of the collimator system was optimized taking into account the shape of the beam, the neutron flux and the background. The effect of the background of each studied configuration was evaluated from the response of a C6D6 detector at the measurement position. The design of the beam dump was modified according to each configuration to reduce the backscattered radiation. Among the studied configurations, a final collimator with a conical closing aperture was found to be the best compromise between a high flux and low background at the experimental station. By scoring the neutron flux at the measurement position and taking the air and windows at the nominal sample position into account, the neutron beam has a radius of 2.5 cm and the outside background is three orders of magnitude lower than the maximum flux. The ratio between background and maximum flux is similar to that in the first experimental area (EAR1), but the maximum flux in EAR2 is 30 to 50 times higher than in EAR1 for neutron energies between 100 eV and 30 keV, respectively.

KEYWORDS: Spectrometers; Instrumentation and methods for time-of-flight (TOF) spectroscopy; Neutron detectors (cold, thermal, fast neutrons)

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1 Introduction

The n_TOF facility at CERN is dedicated to time-of-flight (TOF) measurements of neutron cross sections with high-energy resolution. Neutrons are produced by spallation reactions when 20 GeV/c protons extracted from the Proton Synchotron at CERN impinge on a massive lead target. The proton beam has a nominal intensity of \(7 \times 10^{12}\) protons/pulse, a pulse width of 7 ns RMS, and a minimum repetition rate of 1.2 s. The lead target is surrounded by a 1 cm thick layer of cooling water and an additional 4 cm thick layer of borated-water in the forward direction, which together moderate the initially fast neutrons and broaden the neutron energy spectrum from thermal energies up to a few GeV. Photons are produced during the spallation reactions (\(\gamma\)-flash) and during neutron moderation [1].
Table 1. Calculated neutron energy resolution $\Delta E/E$ in EAR1 and EAR2 [1, 2].

| Neutron Energy | Neutron energy resolution $\Delta E/E$ (%) |
|----------------|------------------------------------------|
| 1 eV           | EAR2: 0.43, EAR1: 0.032                  |
| 1 keV          | EAR2: 0.85, EAR1: 0.054                  |
| 1 MeV          | EAR2: 4.10, EAR1: 0.530                  |

1.1 EAR1

The first experimental area (EAR1) is horizontally located 185 m from the spallation target and due to this long flight path the neutron energy, $E_n$, can be determined with high resolution. Along the 185 m tunnel a sweeping magnet (200 cm long, 1.5 T) deflects the charged particles in the beam and the neutron beam is shaped by two collimators. The second collimator is placed at 178 m from the spallation target and has sections made of borated polyethylene and steel, with dimensions depending on whether the measurements are being performed in capture or fission mode [2]. After the experimental area, the beam line continues for more than 10 m in order to minimize the background due to scattering in the beam dump.

1.2 EAR2

To meet the demand of the neutron science community for a neutron time-of-flight facility with a higher flux [3], the feasibility of a second experimental area (EAR2) was studied at n_TOF. EAR2 is a vertical experimental area with a 20 m long flight path at 90° with respect to the primary proton beam. Preliminary studies showed that the shorter flight path would provide a 25 times higher neutron flux than in EAR1 [1], which opens the door to measurements that could not be performed before, such as studies of very small samples and on isotopes with very small cross-sections. Figure 1 shows a preliminary comparison of the neutron fluxes in EAR1 and EAR2. The shorter flight path also implies a higher neutron rate, which is important for studies of radioactive samples, since the ratio between the neutron-induced signals and the background from the sample activity is increased by a factor of around 300. The prompt $\gamma$-flash (composed of spallation photons and photons produced by the interaction of high energy neutrons with the beam line elements) is expected to be less intense and softer than in EAR1 [1]. Since the effect of the $\gamma$-flash in some detectors masks the signal from neutron reactions for the first few $\mu$s, its reduction may allow measurements up to higher energies than in EAR1. It can also be seen from figure 1 that the energy range at EAR2 is limited to 300 MeV compared to some GeV at EAR1, which is located in forward direction with respect to the proton beam. On the other hand, the shorter flight path implies that a lower energy resolution. The energy resolution at EAR2 is lower by about an order of magnitude relative to EAR1 (table 1).

After being produced in the spallation target, the neutrons pass the layer of moderating water. In the beam line to the second experimental area a first collimator is followed by a sweeping magnet and a second collimator, as pictured in figure 2. The first 1 m long collimator is used to shape the neutron beam and to reduce the main background from the target. The sweeping magnet, located
10 m above the spallation target, cleans the beam from charged particles, and the 3 m long second collimator defines the beam geometry at the measurement position.

The optimization of the beam line was challenged by several constraints. Due to civil engineering reasons the dimensions of the experimental room are fixed so that there is no freedom to place the beam dump further away from the measurement region. Also the weight of the beam dump is limited and thus the materials that can be used are limited. The position of the second collimator is also fixed. The proximity of the beam dump and collimator to the experimental area is a major obstacle due to the background produced by both elements. It was decided by the collaboration that a maximum flux over an area of 1 cm in diameter at the measurement position was necessary, but that the neutron beam should be limited to 5 cm in diameter so that the detectors can be placed close to the centre of the beam. Several configurations were studied in search of the best design to fulfil the requirements.

2 FLUKA simulations using a simplified geometry

The Monte Carlo simulations to optimize the EAR2 beam line were performed using the FLUKA Monte-Carlo code [4–6]. In a first step, a simplified geometry was used to define the geometry for the first and second collimator. With this configuration, a detailed model of the experimental area, from the spallation target up to the beam dump, including the first collimator, magnet and second collimator, was developed similarly to the already existing model of EAR1.

2.1 Geometry of the second collimator

The collimators had to be shaped to produce a neutron beam with the smallest halo radius and highest neutron flux possible. The simplified FLUKA model of the collimators shown in figure 3 was based on the previous optimization for EAR1 [2]. The first collimator in the beam line to EAR2 consists of iron, whereas the second collimator is composed of two parts, a first 2 m section of iron and a second 1 m section of borated-polyethylene (BPE). Alternative materials to BPE
will be discussed later, because this part is important for the reduction of the neutron and photon background. Iron is certainly one of the most practical shielding materials for high-energy neutrons, since it is cheap and effective at attenuating high-energy neutrons. Polyethylene is good at moderating low-energy neutrons and the boron admixture leads to an enhanced neutron absorption via the \((n,\alpha)\) reaction and to a softer \(\gamma\) background [7]. The optics of the collimating system is sketched in figure 3 to indicate the radius of the halo, \(R_{\text{halo}}\), and actual beam radius, \(R_{\text{beam}}\). In the simplified simulations the contribution of air in the measurement region was neglected and only neutrons coming directly from the spallation target have been considered.

The three investigated shapes of the second collimator are illustrated in figure 4: (i) a cylindrical aperture, (ii) a conical-closing aperture following the focusing optics and (iii) a double-conical aperture, with the opening section following the defocusing optics. The conical aperture was ex-
Figure 4. Investigated shapes of the 2nd collimator.

pected to yield a smaller halo radius than a cylindrical configuration. The double-conical design was tested to avoid the background originating from the interaction of the defocusing component of the neutron beam with the end of the collimator.

The neutron beam profile for each configuration is displayed in figure 5. For the cylindrical (i) and the double conical closing (iii) configurations there is a reduction in the maximum flux. The double conical configuration leads to a more accentuated decrease of the background because the smallest aperture of the collimator is further away from the measurement position (150 cm from the exit of the 2nd collimator), so the background coming from the interaction of the beam with the collimator (where the highest background contribution comes from) is reduced by the larger distance from the measuring position. With the double conical-opening aperture, the background is 2–3 orders of magnitude lower than for the other configurations, while the maximum flux is reduced by 50%. Analyzing all results, it turns out that the second configuration (ii) with a cylindrical first collimator and a second collimator with conical closing aperture provides a good compromise between maximum neutron flux and low background, since the other configurations lead to a 50% flux reduction and the conical closing aperture also provides a background 5 orders of magnitude lower than the maximum flux.

2.2 Apertures of the first and second collimator

With the chosen collimator geometry, but still with the simplified geometry, the apertures of the collimators were varied in order to understand the effect on the halo radius. In addition, a figure of merit (FOM$_1$) was defined to compare the different configurations. This FOM$_1$ is the ratio of the central flux $\Phi_{1\text{cm}}$ over an area of 1 cm in diameter and the square of the halo radius, $R_h$, which
defines the minimum distance between detector and sample since the detector has to be outside the neutron beam,

\[ FOM_1 = \frac{\Phi_{1\text{cm}}}{R_h^2} \]  \hspace{1cm} (2.1)

Figure 6 shows a comparison of the $\Phi_{1\text{cm}}$ values obtained in EAR2 and EAR1 at 150 cm from the 2nd collimator for fixed values of the halo radius values and different radii $R_1$ of the 1st collimator. The results show that the maximum flux is obtained for $R_h > 2.5$ cm and a 1st collimator $R_1 = 10$ cm.

The FOM\(_1\) results are plotted in figure 7 for various combinations of $R_1$ and $R_h$. The adopted configuration was the one corresponding to $R_1 = 10$ cm and $R_h = 25$ mm, representing the best compromise between a reduced halo, hence a reduced background, and a maximized flux.

3 Simulations using the complete geometry

The adopted collimator configuration was used to model the geometry of the EAR2 in detail for further FLUKA simulations of the resulting neutron flux, beam profile and background in the experimental area. In this context, the background contribution from the beam dump has also to be considered as it is only 4 m distant from the measurement position. The beam dump had been already optimized [8] but further modifications were made, as discussed below. A C\(_6\)D\(_6\) detector was also implemented in the geometry to study the response for each configuration. The investigated cases were optimized with respect to the capture setup because the final halo radius of 2.5 cm is wide enough to perform fission measurements as well. Also, as fission measurements are performed with in-beam detectors, the background from the collimators, beam dump and the ambient room is not as crucial as in capture measurements. At first, the effect of the Mylar windows in the beam line and the air in between was neglected for saving computing time, but this contribution will be discussed later as well.
Figure 6. Central flux $\phi_{1cm}$ for various collimator/halo combinations versus the radius of the 1$^{st}$ collimator [10].

Figure 7. FOM$_1$ for various collimator/halo combinations versus the radius of the 1$^{st}$ collimator. The adopted configuration is circled [10].
Table 2. TOF to neutron energy conversion.

| TOF interval (µs) | Neutron energy range |
|-------------------|----------------------|
| < 1               | > 2 MeV              |
| 1–10              | 2 MeV–20 keV         |
| 10–100            | 20 keV–200 eV        |
| 100–1000          | 200 eV–2 eV          |
| > 1000            | < 2 eV               |

3.1 Source file and transport routines

A previously developed routine was modified and used to score all gammas and neutrons emerging from the spallation target and entering the beam pipe with a maximum acceptance angle of 3° in a source file. All other particles entering were discarded. The type, position, time, energy and direction of the particles were scored in a plane 1.5 cm on top of the target. Using this source file, another routine was used to transport the particles towards the experimental area. These were emitted from their scoring position with a smoothing angle of 1°, i.e., with a maximum randomized isotropic emittance of 1°. Using this one-step method it was possible to reduce the computing time of running $4.5 \times 10^{10}$ particles per configuration (enough to obtain satisfactory statistics) from several weeks to less than 3 days. With this method, however, it is not possible to reproduce the resolution function. In addition, when changing the direction of the particles, their energy should also be changed but, as the effect was proven to be minimal, this change was neglected.

3.2 Time interval routine

For characterizing the n_TOF facility the results are to be presented in terms of time-of-flight and not in energy intervals. To this purpose, a routine was used to sort the results into five time intervals listed in table 2.

3.3 Beam profile

Figure 8 shows the beam profile at 150 cm distance from the second collimator for the adopted configuration. The resulting neutron beam has no flat zone because the measuring position is beyond the focal point, the halo has a radius of 2.5 cm and the background is 4 orders of magnitude lower than the maximum flux. The shoulder observed at 3–5 cm radius is due to backscattered neutrons from the beam dump.

3.4 Gap around 2nd collimator

By default there is a 9.5 cm wide empty gap around the 2nd collimator, which was required for the installation of the beam line and for the alignment of the 2nd collimator. Several materials were considered to be inserted in this gap to reduce the radiation escaping through it. The top and bottom images of figure 9 show the neutron flux at EAR2 for the TOF intervals <1 µs and 10–100 µs, respectively, for an empty gap (A, left panel), the gap filled with 4.8 mm diameter stainless steel balls (B, middle), and with an additional ring-shaped lithium-polyethylene (Li-Poly) block on top.
of the 2\textsuperscript{nd} collimator to reduce the radiation coming from the dispersion of the beam (C, right panel). The Li-Poly block is 44 cm in radius and 20 cm high. As expected both the fast and intermediate energy neutrons escaping from the gap around the collimator are successfully attenuated by the stainless steel balls, thus avoiding a ring-shaped beam in the configurations (B) and (C). Also the background flux is clearly reduced in these cases, especially for the 10–100 $\mu$s TOF interval.

### 3.5 Simulations with a C\textsubscript{6}D\textsubscript{6} detector

A ring-shaped C\textsubscript{6}D\textsubscript{6} detector with 10 cm in height and with internal and external radii of 5.5 and 13.12 cm was introduced in the FLUKA geometry at the measurement position, 150 cm from the 2\textsuperscript{nd} collimator. The detector dimensions were chosen because the C\textsubscript{6}D\textsubscript{6} detectors used at n\textsubscript{f}TOF are 7.62 cm thick and will be placed 5.5 cm from the center of the beam, corresponding to the radius of the beam pipe at the measurement position. To simulate the response of the detector, the energy deposited in the detector was calculated for several setups taking into account the contribution from the walls and from the dump. For the adopted setup (reference geometry), the energy deposited in the C\textsubscript{6}D\textsubscript{6} detector due to all the particles and to neutrons is presented in table 3. Since FLUKA calculates the average deposited energy on the crystal by one primary proton, the results were multiplied by the number of protons in one bunch ($7 \times 10^{12}$).

A possibility to decrease the background in the C\textsubscript{6}D\textsubscript{6} detector is to place a cylindrical lead absorber around the neutron beam and below the measurement position as indicated in figure 10. The dimensions of the absorber (65 cm long and 10 cm outer radius) were chosen to leave enough space below for the shutter and beam monitors. With the absorber, the energy deposition by all particles could be reduced by 65\% on average (table 3).
Figure 9. Top: neutron flux at EAR2 with an empty gap around the 2nd collimator (A), with stainless steel balls in the gap (B), and with an additional lithium-polyethylene block on top (C) for the TOF interval < 1 µs. Bottom: the same simulations for the TOF interval 10–100 µs.

Table 3. Average energy deposition per cm$^3$, per 7x10$^{12}$ protons on target, in the C$_6$D$_6$ detector for the reference geometry with and without the lead absorber sketched in figure 9.

| TOF interval | Average energy deposition (MeV/cm$^3$) without/with Pb absorber |
|--------------|------------------------------------------------------------------|
| All TOF intervals | All particles / Neutrons  | 65.0 ± 2.0 / 21.0 ± 1.0 / 9.0 ± 0.2 / 8.0 ± 0.2 |
| 10–100 µs     | 0.171 ± 0.030 / 0.070 ± 0.001 / 0.022 ± 0.001 / 0.021 ± 0.001 |
3.5.1 Composition of the 2nd collimator

Different materials for the 2nd section of the second collimator (blue section of figure 10) were studied. In the initial simulations, the upper section of the 2nd collimator was assumed to consist of BPE, because B$_4$C was too expensive and difficult to machine. A simpler solution consisting of a quasi-conical liner in the BPE part, which was approximated by a set of B$_4$C cylinders, is sketched in figure 11. The simulations to quantify the possible background reduction due to the use of different materials were made without the contributions of the walls and the beam dump, and the obtained results are show in table 4. The comparison shows that the neutrons and gammas are more effectively absorbed by the B$_4$C liner. Compared to pure BPE in the second section, the reduction of the background due to the liner is between 40% and 80%, whereas a pure B$_4$C section would lead to a further reduction by only 20%–30%. Accordingly, the solution with the B$_4$C liner represents an efficient and affordable improvement of the beam line in EAR2. Since the final optimization of this part of the 2nd collimator was done in the end of the study, the results presented after table 4 were obtained using the 2nd part of the 2nd collimator as being pure B$_4$C.

3.5.2 Background contributions from the different components of EAR2

The influence of the walls, beam dump and collimator has been studied by making use of the blackhole material available in FLUKA simulations, which is assumed to be an infinitely absorbing
Figure 11. Second collimator with B₄C liner.

Table 4. Average energy deposition in the C₆D₆ detector for different compositions of the upper section of the second collimator. The contribution of the walls and beam dump were not taken into account.

| TOF interval | Material      | Average energy deposition per 7x10¹² protons (MeV/cm³) |
|--------------|---------------|----------------------------------------------------------|
|              |               | All particles                                           | Neutrons                                |
| All TOF intervals | Pure BPE   | 15 ± 0.6                                                 | 4.0 ± 0.2                               |
|                | Pure B₄C     | 5.7 ± 0.12                                               | 1.5 ± 0.03                              |
|                | B₄C liner    | 9.0 ± 0.1                                                | 2.1 ± 0.02                              |
| 10–100 µs      | Pure BPE     | 1.5E-2 ± 5.0E-3                                          | 1.0E-5 ± 5.0E-6                         |
|                | Pure B₄C     | 2.4E-3 ± 4.0E-4                                          | 5.0E-6 ± 1.0E-6                         |
|                | B₄C liner    | 3.6E-3 ± 4.0E-4                                          | 6.0E-6 ± 1.0E-6                         |
material and is used to terminate particles. The energy deposited in the detector was calculated by excluding each of the components in the experimental area separately. At this point, the interruption in the beam line by Mylar windows at the measurement position was not included. Therefore, the effect of the windows and of the air in between the windows was not yet taken into account.

When the beam dump is excluded by the blackhole option, the energy deposited in the detector for all particles in the 10–100 µs TOF interval, is 21 keV/cm$^3$ compared to 30 keV/cm$^3$ when all the components are active. This means that about 30% of the dose in the detector is coming from the dump and 70% from the collimator and the walls. If the walls are defined as blackhole, the dose in the detector amounts to 15 keV/cm$^3$, thus 50% of the remaining background is due to backscattered radiation from the walls. Concerning this contribution, the use of borated concrete was too expensive to be an option, while a layer of borated polyethylene would only help at thermal energies. The contribution from the collimator is reduced with the Pb absorber and the Li-Poly block described before.

### 3.5.3 Influence of air and Mylar windows

The results shown so far did not take into account the air and the Mylar windows in the beam line at the measurement position, but neutron interactions with these light materials contribute significantly to the background in the detector. To understand the role of both components, a second figure of merit, FOM$_2$, was defined:

$$FOM_2 = \int_0^h \frac{P_{\text{air}} \cdot dx}{R^2 + x^2} + \frac{2 \cdot P_{\text{Mylar}}}{h^2 + R_d^2}$$  \hspace{1cm} (3.1)

here $h$ is the distance between the Mylar windows, $dx$ the air increment in the direction of the beam, $R$ the distance between the windows and the detector, and $R_d$ the distance between the detector and the beam (figure 12). The interaction probabilities, $P_i$, with air and with the Mylar windows are based on the respective total cross sections for a neutron energy of 200 eV, which corresponds to the lower edge of the 10–100 µs TOF interval. For the sake of simplicity, air and Mylar were assumed to consist of nitrogen and carbon, which represent 78% and 63% of the total composition, respectively.

The relative contributions of air and Mylar windows are illustrated in table 4. The further the windows are from each other and consequently from the detectors, the lower is their influence on the background, but this behavior is overcompensated by the effect of the air between the windows. Because the trend of FOM$_2$ exhibits no minimum, the best option is always to choose the shortest possible interruption of the beam pipe.

Meanwhile, the computing time for each simulation had reached several weeks, 40% being spent for treating the interactions with the 1st collimator (as measured by an appropriate routine). In view of the large number of configurations needed to be tested it was decided to reduce the computation time by using a two-step method, similar to the technique described in section 3.1. The information for gammas and neutrons entering the second collimator was written into a source file provided that the acceptance angle was $< 15^\circ$, because only these particles are reaching the floor of EAR2 within a radius similar to the outer radius of the gap around the collimator.

With this two-step method it was possible to reduce the computation time by a factor of 5. However, the results obtained in this way differ by $\sim 30\%$ from data obtained with the full cal-
Figure 12. Scheme of the measurement position showing the parameters used to calculate the background contributions from the air and Mylar windows.

Figure 13. FOM$_2$ behavior with the distance between the Mylar windows.
Table 5. Average energy deposition per cm$^3$ per $7 \times 10^{12}$ protons in the C$_6$D$_6$ detector with and without air and Mylar windows.

| TOF interval (µs) | Without air & Mylar windows | With air & Mylar windows |
|------------------|-----------------------------|--------------------------|
|                  | All particles | Neutrons | All particles | Neutrons |
| < 1              | 6.00 ± 0.12 | 1.7 ± 4.0E-2 | 8.2 ± 0.25 | 2.8 ± 0.06 |
| 1–10             | 6E-2 ± 2.0E-3 | 3.0E-2 ± 1.0E-3 | 3.25 ± 0.035 | 3.18 ± 0.03 |
| 10–100           | 2.5E-2 ± 2.0E-3 | 1.5E-4 ± 1.0E-5 | 5.5E-2 ± 3.0E-3 | 2.3E-2 ± 5.0E-4 |
| 100–1000         | 6.2E-2 ± 1.2E-2 | 1.0E-5 ± 1.0E-6 | 9.0E-2 ± 9.0E-3 | 2.5E-4 ± 5.0E-5 |
| > 1000           | 4.6E-2 ± 4.0E-3 | 1.0E-5 ± 0.00 | 2.7E-1 ± 1.4E-2 | 4.0E-4 ± 5.0E-5 |

culation, mostly because scattering effects were underestimated. This difference was acceptable though, because the simulations served predominantly to compare differences between similar configurations. Table 5 shows the resulting energy deposition in the C$_6$D$_6$ detector with and without air and Mylar windows, assuming a distance of 10 cm between 100 µm thick windows. As expected, the energy deposition in the detector is strongly affected by these materials.

### 3.5.4 Optimization of the beam dump

Also the beam dump contributes significantly to the background in the C$_6$D$_6$ detector since it is only 4 m away from the measurement position [8]. In an attempt to further reduce the background, two configurations where studied. In the first a 5 cm thick lead block was placed at the end of the beam line (figure 14A) and in the second the beam line ends directly in the BPE block (figure 14B). Comparing the results obtained with both designs for the 10–100 µs TOF interval, the first configuration leads to a 60% reduction of the gamma background but to a 90% increase of the neutron influence. Taking into account all TOF intervals the second configuration, where BPE is the first material seen by the beam, is the best choice, leading to a reduction of 5% and 14% of the gamma and neutron background, respectively.

### 3.5.5 Final EAR2 beam line

In the final configuration a 1$^{st}$ collimator with a 10 cm radius cylindrical aperture was chosen. For the 2$^{nd}$ collimator a conical closing aperture was adopted with a base radius of 3.45 cm and an apex of 1 cm. In this way, the neutron beam at the measurement position 150 cm from the 2$^{nd}$ collimator is 5 cm in diameter. The 1$^{st}$ collimator is made of iron and the 2$^{nd}$ collimator is divided in two sections: the first 2 meters are made of iron and the last meter is borated polyethylene. A ring-shaped lithium-polyethylene block with a 44 cm radius and 20 cm high is placed on top of the second collimator to reduce the background from the gap around the 2$^{nd}$ collimator and from the collimator itself. The gap is filled with stainless steel balls, and a lead absorber of 65 cm in length and 10 cm in radius is placed inside the beam pipe below the measurement position. For the beam dump configuration (C) has been adopted (figure 14).
Figure 14. The investigated configurations of the beam dump. The version B) consisted of a combination of a 5 cm Pb block, BPE, iron, and concrete (in the direction of the beam). The green layer is B$_4$C. This version was modified by removing the lead block at the top B) so that the neutron beam enters into the BPE part directly.

4 Expected performance: beam profile and energy resolution

4.1 Neutron flux

The results of the full simulation for the final setup are illustrated in figure 15 and figure 16. The expected neutron flux over the central area at the measurement position (1 cm in diameter) is compared with the situation in EAR1 for the capture and fission configurations. The flux ratio between EAR2 and EAR1 (bottom panel) ranges from 30 to 50 for neutron energies between 100 eV and the maximum value at 30 keV. At higher energies the ratio drops to 25 and 10 at 1 MeV and 100 MeV, respectively.

Figure 16 shows a comparison of the neutron and gamma fluxes at the measurement position as a function of time-of-flight. Note that the gamma background decreases steeply towards shorter flight times, i.e. towards higher energies. This is of particular advantage in measurements of neutron capture cross sections, which — on average — decrease with the square root of the energy.

4.2 Beam profile and energy resolution

The beam profile for the final configuration of the EAR2 beam line, including the Mylar windows and the air in between, exhibits a sharp cutoff at 2.5 cm radius over more than 3 orders of magnitude (figure 17). Compared to the profile obtained with the simplified configuration (figure 8) this cutoff is clearly more pronounced and the background at large radius is also lower by almost a factor of 10. The shoulder at intermediate radii is lower than in figure 8, but extends to a larger radius of almost 15 cm due to scattering from the beam line components, which had been neglected before.

The resolution as a function of neutron energy can be evaluated by the FWHM of the equivalent distance distribution, which describes the energy broadening of a measured flight time due to the
neutron transport in the target-moderator assembly. While the full distribution is needed for the analysis of resolved resonances, the FWHM is a sufficient quantity for the time to energy calibration of smooth reaction yields. The equivalent distance is defined as \( L_t = v t_t \), where \( v \) is the velocity of the neutron when it escapes the target-moderator assembly and \( t_t \) is the time difference between the moment that the neutron is created and the time it leaves the target-moderator-assembly [12]. The energy resolution is related to the velocity resolution by

\[
\frac{E}{E} = (\gamma + 1) \cdot \gamma \cdot \Delta v/v
\]  

(4.1)

and \( \Delta v/v \) is in turn defined as

\[
\frac{\Delta v}{v} = 1/L \cdot (v \cdot \Delta T_s)^2 + (v \cdot \Delta T_0)^2 + \Delta L_t^2 + \Delta L_d^2)^{1/2}
\]

(4.2)

where \( L \) is the distance traveled by the neutron, \( \Delta T_0 \) and \( \Delta T_s \) are FWHM of the time distributions of the start and stop signals and \( \Delta L_d \) is the FWHM of an equivalent distance that expresses the broadening due to the neutron transport in the detector or sample [12].

Figure 15. Simulated neutron flux for the final EAR2 beam line at the measurement position (1 cm in diameter) in comparison with the situation in EAR1 [11].
The simulated equivalent distance distribution, $L_t$, for different $E_n$ values for EAR1 and EAR2 is presented in figure 18 and the FWHM of the equivalent distance distribution of EAR2 is compared with the corresponding values in EAR1 in figure 19. The equivalent distance distribution widens for higher neutron energies. Also, the shoulder present in the distributions for neutron energies between 1 eV and 1 keV is caused by the moderation processes in the materials that surround the spallation target.

5 Conclusions

The new vertical beam line at n_TOF has been optimized by means of comprehensive FLUKA simulations. Different configurations were studied for the apertures of the two collimators to obtain a well-defined neutron beam with a 2.5 cm radius at the measurement position. The adopted solution exhibits a beam profile with a sharp cutoff of more than 3 orders of magnitude and represents a best compromise between a high in-beam flux and low background in the halo. With this configuration it is expected to obtain a flux 30 to 50 times higher than in EAR1, for neutron energies between 100 eV and 30 keV. Attempts to obtain a higher flux by choosing a larger beam radius resulted in a corresponding increase of the background due to the interaction with the air and the Mylar windows at the measurement position as well as with the beam dump, which also contributes substantially to the background.

In order to decrease the background further, the adopted configuration was studied in simulations using a detailed model of the EAR2 geometry and introducing a $\text{C}_6\text{D}_6$ detector at the measurement position. Important improvements were obtained by placing a lithium polyethylene block on top of the second collimator to reduce the radiation coming from the dispersion of the
Figure 17. The beam profile for the final configuration. Note the sharp cutoff at 2.5 cm radius over more than 3 orders of magnitude.

Figure 18. Equivalent distance distribution for four different neutron energy decades in EAR2 and EAR1 [11].
beam and by filling the gap between the collimator and the shielding walls with stainless steel balls. Furthermore, it was found that the gamma background could be reduced by 70% by adding a lead absorber inside the beam pipe just below the measurement position.

For the upper section of the second collimator, B$_4$C was shown to be the best choice, but had to be excluded because of the high costs and due to machinery issues. Instead, a simpler solution consisting of borated polyethylene with a B$_4$C liner was developed. Also the effect of the Mylar windows in the beam line at the measurement position and the air in between the windows was investigated and found to increase the background by up to 100% in the 10–100 µs TOF interval. The chosen configuration of the beam dump was the one where the first material the beam hits is BPE.

Finally, one must have in mind that, even though the simulations are as realistic as possible, there are several sources of uncertainty, as the ones associated with the composition of materials, problems with the details of the geometry (such as remaining gaps that are neglected in the simulations), the assumed conical aperture of the 2nd collimator (which in reality is approximated by a step configuration), alignment issues, the used cross section data and the techniques used for decreasing the computation time. All these may ultimately affect the final results. Taking these uncertainties into account in a conservative approach, the simulated background is trustable on the estimated order of magnitude and the flux to ±20%.

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