Shielding calculations with MCNPX at the European spallation source

Riccardo Bevilacqua, Lali Tchelidze, Günter Muhrer, Eric Pitcher
European Spallation Source, Lund, Sweden

Abstract

The European Spallation Source (ESS) is a collaboration of 17 European partner countries established to project, build and operate the world's most powerful neutron source in Lund, Sweden. The construction of the facility started in 2014, and ESS is expected to produce the first neutrons in 2019. Monte Carlo calculations are required to design the appropriate shielding needed to guarantee the radioprotection of the workers and of the public. We present here the results obtained with the MCNPX radiation transport code for front-end building of the 2 GeV proton linear accelerator. We have modelled the RFQ, the MEBT and the DTL components of the accelerator, and we have calculated the dose contribution to the water-cooling room, adjacent to the front-end building, as a function of several shielding solutions. We show that 80% of the contribution to the neutron and gamma dose comes from the first three tanks of the DTL, and that a 1 m ordinary concrete shielding wall is necessary to guarantee a prompt dose below 3 μSv/h in the areas accessible during operation.

Introduction

The European Spallation Source (ESS) will be the world's most powerful neutron source. The facility was expected to be built in Lund, Sweden, and the construction phase was expected to start in 2014; we expect to produce the first neutrons in 2019.

At ESS, protons will be linearly accelerated up to 2 GeV and neutrons will be produced by the interaction of a 5 MW beam with a rotating tungsten target. The baseline of the ESS facility is described in detail in the Technical Design Report [1]. Monte Carlo calculations were performed at ESS as part of the design effort, in order to guarantee appropriate shielding for the radioprotection of the ESS workers, the visiting scientists and the public. We present here calculations relative to the warm section of the ESS linac, where proton energies are available up to 90 MeV. The MCNPX code is widely used for shielding calculations at accelerator facilities around the world allowing the transport of all relevant particles. Nuclear interactions may be described by both models, experimental data and evaluated cross-sections.

Geometry of the front-end building area

The aim of this work was to design the shielding of the front-end building (FEB) of the ESS linear accelerator. In the baseline design of the ESS facility, the FEB will be located below the ground surface, and will be covered by a 5 m thick berm. The berm thickness will be the same for the whole length of the accelerator tunnel, and has been calculated to account for 1 W/m proton beam losses along the linac [2]. There is no planned shielding separating the FEB from the linac tunnel, and no access will be allowed in the FEB during operation of the accelerator.

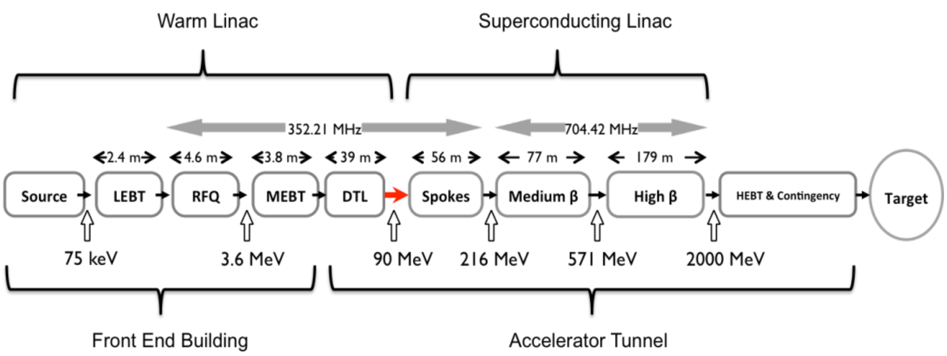
Access to the FEB – with beam off – should be guaranteed from the adjacent water-cooling room (WCR), after a certain cooling time for activation of the accelerator components (activation is not discussed in this work). According to the ESS baseline requirements, the WCR has been designated as a radiation supervised area with a maximum allowed prompt dose of 3 µSv/h during operation of the accelerator.

As a reference, we note that at the SNS facility a 80 cm thick ordinary-concrete wall has been installed immediately upstream the Drift Tube Linac (DTL) [3,4]. There, the FEB is designed as an accessible area during operation, with a prompt dose limit of 2.5 uSv/h. However, at SNS the beam energy at the tunnel entrance is 2.5 MeV, whereas at ESS the maximum proton energy in the FEB is 3.6 MeV.

Accelerator components

We have modelled three components of the warm section of the proton linear accelerator: the Radio Frequency Quadrupole (RFQ), the Medium Energy Beam Transport (MEBT) and the normal conducting DTL. The first two components are located in the front-end building, whereas the DTL is located in the first section of the accelerator tunnel. A schematic drawing of the ESS linac is presented in Figure 1. Our work did not include the ion source and the Low Energy Beam Transport (LEBT), since the energies of the protons in these components (up to 75 keV) are below the threshold for neutron production in copper: 2.167 MeV for ^{65}Cu(p,n) and 4.215 MeV for ^{63}Cu(p,n).

Figure 1. The ESS linear accelerator



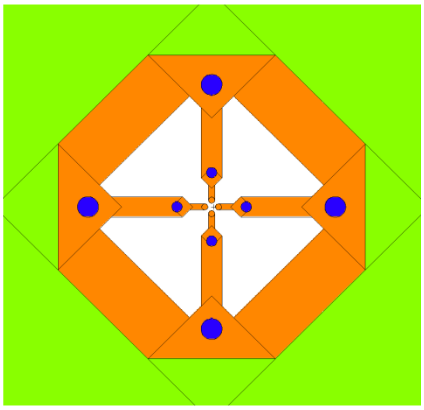
RFQ

The RFQ accelerates the 75 keV protons from the LEBT up to 3.6 MeV. We have modelled the RFQ taking in account the actual design of the section orthogonal to the proton beam line. In the MCNPX model, the RFQ was built with Cu in its natural isotopic composition. Cooling water channels were also included in the model, in the actual position of the RFQ design. To account for the modularity of the RFQ design, we have reduced the materials density according to the actual design. The RFQ is 461.1 cm long and has a diameter, averaged along its length, of 28.8 cm. The eight cooling water channels have diameters of 2.0 cm (four outer channels) and 1.0 cm (four inner channels).

Figure 2 shows the section of the MCNPX model of the RFQ. The orange material is Cu, the blue corresponds to the eight water channels, the green material is the air in the FEB. In our model, we have assumed ideal vacuum inside the RFQ (white material Figure 2).

We have simulated a point-like loss of the proton beam on the internal tips of the RFQ. In our calculations, we have assumed a loss of 1 W/m, and the maximum proton energy available in the RFQ, which corresponds to 3.6 MeV. Hence, since the RFQ has a length of 461.1 cm, we have normalised our results for a loss of 4.6 W. To account for different scenarios, we have simulated the proton beam loss for each of the four internal tips and at different positions along the length of the RFQ. However, due to the 2.167 MeV threshold for the $^{65}Cu(p,n)$ reaction, neutrons can be produced in the RFQ only in the last section of its length.

Figure 2. Section of the MCNPX model of the RFQ



MEBT

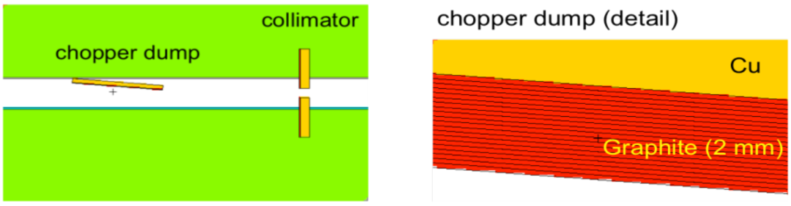
We have accounted for three scenarios of proton beam losses in the MEBT: the protons impinging on three sets of collimators, the protons diverted on the beam chopper dump and a point-like loss in the MEBT beam pipe. Since there is no acceleration in the MEBT, all the protons have an energy of 3.6 MeV, which is the exit kinetic energy from the RFQ.

In the MEBT, there are three sets of collimators, each composed by four elements, orthogonal to the proton beam line. Each component of the collimator consists in a 2 mm graphite absorber coupled to 20 mm of Cu for heat dissipation. To account for the cooling water channels in the Cu elements, we have modelled a uniform medium composed by 85% Cu and 15% water. The MEBT chopper dump consists in a graphite absorber 2 mm thick, and a thicker layer of Cu (10 mm). The dump is tilted at 5 degrees, and has a transverse size of 200 X 50 mm^2. The beam pipe was modelled as a 1.6 mm thick stainless steel (316L) tube. The MCNPX geometry used in these calculations is presented in Figure 3.

We modelled the beam loss on each collimator as a Gaussian beam of 3.6 MeV protons depositing 1% of the full current (62.5 mA) on all the four elements, the jaws being opened at 3 sigma from the beam centre (corresponding to 1.70 X 10^{14} protons/second). The size of the beam was respectively 2 X 3 mm^2, 3 X 3.6 mm^2 and 2.6 X 1 mm^2 at the position of the first, second and third collimator. The beam loss on the MEBT chopper dump was modelled as a Gaussian beam of 3.6 MeV protons, impinging orthogonally on the graphite absorber (5.68 X 10^{14} protons/second). Finally, we modelled a point-like 4 W beam loss on the beam pipe (7.0 X 10^{12} protons/second), and at an incident angle of 0.1 radians.

Since the range of 3.6 MeV in 1.7 g/cm^3 graphite is 0.135 mm, all the incident protons are stopped in the graphite absorbers, both in the collimators and in the chopper dump. The neutron production threshold for ^{12}C is 19.6 MeV, hence neutrons can be produced only via the $^{13}C(p.xn)$ reaction with threshold 3.2 MeV. In the MCNPX model of the problem, we assumed the natural isotopic composition of carbon, accounting for 98.9% ^{12}C, and 1.1% ^{13}C.

Figure 3. MCNPX model of the MEBT chopper dump, (left) one of the collimators and the beam pipe (right) and section of the chopper dump

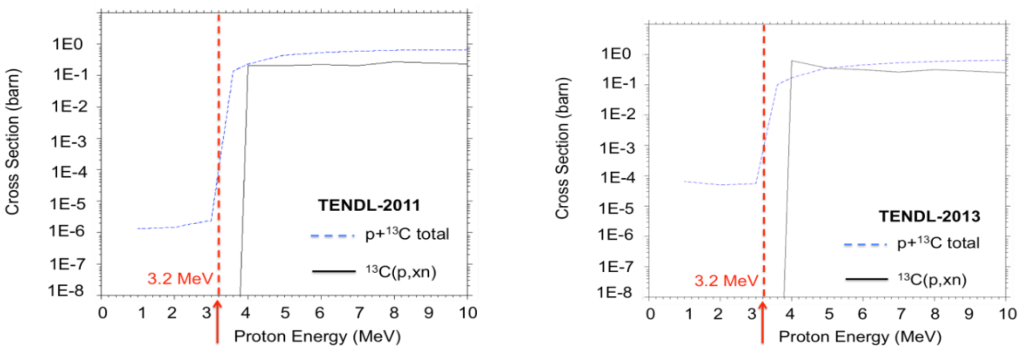


A digression on ^{13}C(p,xn)

There is no ENDF/B-VII proton data library available for ^{13}C, however, these cross-section data are included in the – TALYS based – TENDL library [5]. The data in the TENDL library are delivered both in ENDF format and in ACE format, to be used in MCNPX calculations. We have observed that, whereas the TENDL ACE files behave as expected above 4 MeV, the 3.2 MeV threshold for the ^{13}C(p,xn) reaction is not correctly represented (Figure 4). This seems to be due to the fact that the conversion to the ACE file for this reaction data was performed in steps of 1 MeV [6]. Moreover, we have observed a large discrepancy between the TENDL-2011 and TENDL-2013 cross-sections near threshold, independently from the used library format. Finally, as we can observe in Figure 4 (right panel) in the TENDL-2013 ACE file, the partial ^{13}C(p,xn) cross-section at 4 MeV is higher than the total p + ^{13}C reaction cross-section.

Figure 5 shows the MCNPX calculations for the neutron production yield from a thick target of ^{13}C, for incident proton energies from 3.6 MeV to 6 MeV. The calculations were performed using respectively the MCNPX built-in model, the TENDL-2011 data and the TENDL-2013 data for the ^{13}C(p,xn) reaction. These results were compared with the experimental yields from Bair et al. [7], which are available in the EXFOR database, for proton energies above 4 MeV. We observe that at 5 MeV and at 6 MeV, the three sets of calculations agree with the experimental data. At 4 MeV, both TENDL-2011 and TENDL-2013 give results consistent with the data from Bair et al. whereas the MCNPX model overestimates the neutron production yield. At lower energies, the three sets of data give discrepant results. In the present shielding calculations, we decided to use the built-in MCNPX model to account for the ^{13}C(p,xn) reaction: this choice is both conservative, since the model gives higher yields, and consistent, given the discussed shortcomings relative to the TENDL ACE files (Figure 4).

Figure 4. Total p + ^{13}C and partial ^{13}C(p,xn) cross-section data as included in the ACE version of the TENDL-2011 (left panel) and TENDL-2013 (right panel) nuclear data files



The threshold at 3.2 MeV for the ^{13}C(p,xn) reaction is indicated in both plots.

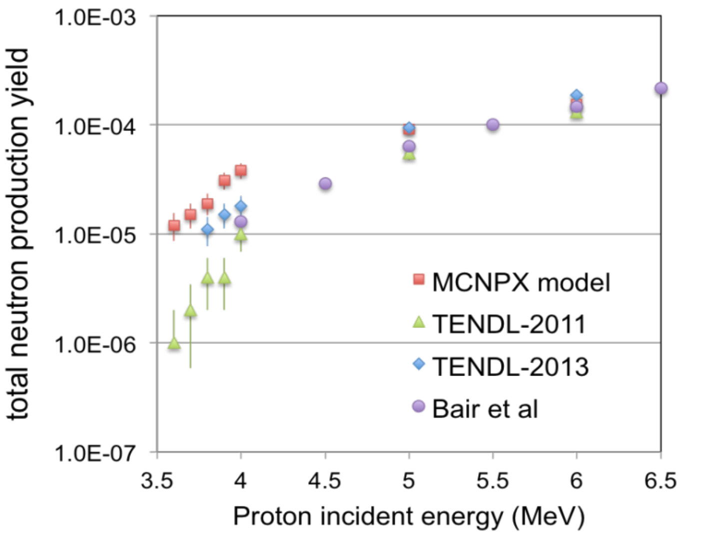
DTL

The DTL is composed of five independent tanks. Table 1 lists the technical information about each of these tanks. The 3.6 MeV protons entering the DTL are accelerated up to 90 MeV over a length of 40 meters. In the MCNPX calculations we followed the ESS design requirements and assumed a beam loss of 1 W/m, however, preliminary results show that the expected average total power loss over the 40 metres of the DTL will account for 0.25 W [8].

We modelled the DTL as presented in Figure 6. Each tank was designed as a vacuum stainless steel beam pipe, with a 50 μm internal coating of Cu. The cells were not modelled independently, but their average length was computed and divided by the total length of each tank: this number was then used as scaling factor for the density of the materials included in the MCNPX geometry. In the ESS DTL design, each second cell is occupied by a Sm_2Co_{17} permanent magnet, which was included in the Monte Carlo simulations. The free cells will be either empty, or will contain steerers and beam diagnostic instruments; since these instruments and their position were not identified yet, in the present study we have assumed all the free cells to be empty. To account for the Sm_2Co_{17} magnet, we included the actual transverse geometry, and reduced the material density along the beam direction accordingly to the actual volumes.

We performed independent calculations for each DTL tank. The 1 W/m proton beam loss was modelled as protons impinging on the internal Cu drift tube (with internal radius ranging from 10 to 12 mm, see Table 1), at an angle of 0.01 radians with respect to the beam direction. In the present work, we assumed a discrete source term: each tank was divided into ten sections (c.a 70 cm each), and the protons with the maximum energy for a specific section were transported from the most upstream position in that section. For each source position, the protons were equally distributed at eight equally spaced angles – on the plane normal to the beam direction. The number of protons per second was calculated for the maximum kinetic energy in each of the 10 sections/tanks.

Figure 5. Neutron production yield from a thick ^{13}C target, calculated with the MCNPX code using the built-in MCNPX model (squares), the TENDL-2011 data (triangles) and the TENDL-2013 data (diamonds)



MCNPX results are compared with experimental data by Bair et al. [6] (circles).

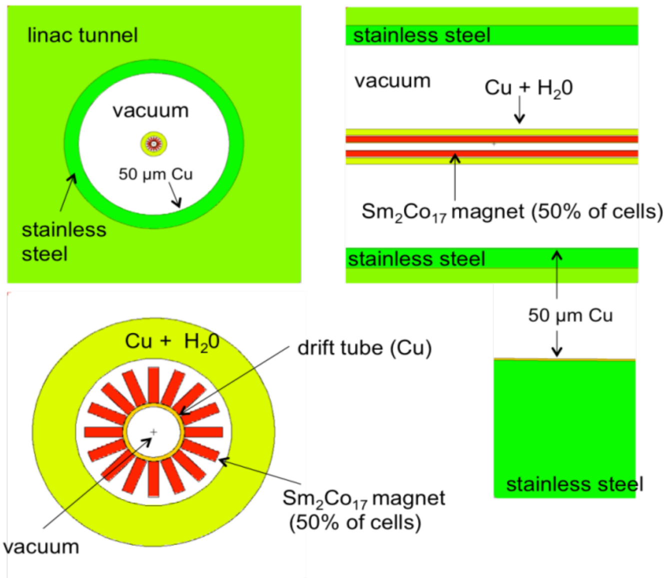
DTL's Faraday cup

In the present work we also simulated the Faraday cup placed at the end of the first DTL tank, 7.62 m downstream the linac tunnel. The Faraday cup was modelled as a 1 mm carbon foil, followed by a 5 mm carbon absorber at a distance of 20 mm; the foils were placed in a stainless steel housing, 5 mm thick. The Faraday cup is designed to absorb a beam pulse of 10 µs, at a repetition rate of 14 Hz and full current (62.5 mA). The protons impinging on the Faraday cup have a kinetic energy of 21 MeV. Four other Faraday cups will be placed at the downstream end of each of the remaining DTL tanks, however, they were not modelled as part of this work.

Table 1. DTL parameters for each tank

Parameter	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5
Cells per tank	61	34	29	26	23
Accelerating field (MV m^{-1})	3.00	3.16	3.07	3.04	3.13
Bore radius (mm)	10	11	11	12	12
Number of modules	4	4	4	4	4
Length (m)	7.62	7.10	7.58	7.85	7.69
Beam output energy (MeV)	21.29	39.11	56.81	73.83	89.91

Figure 6. MCNPX model of the DTL



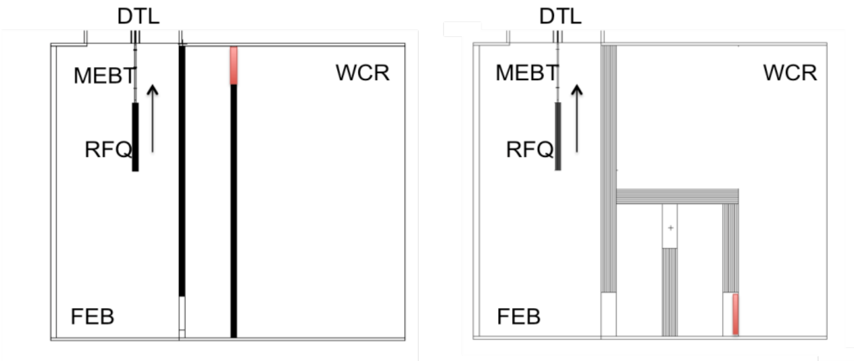
Scaled material densities account for the discrete DTL cells structure. Each second cell will contain a Sm_2Co_{17} permanent magnet. Eventual diagnostic instruments in the free cells were not taken into account.

Results

We have calculated the prompt neutron and gamma doses given by the beam losses on the MEBT's beam pipe, collimators and chopper dump, on the RFQ tips, on each of the five DTL tanks and on the Faraday cup at the end of the first DTL tank. These doses were reported at the door of the WCR, accessing the FEB: this location is the one offering the least shielding, and our MCNPX calculations confirmed that this location was the hottest point in the WCR.

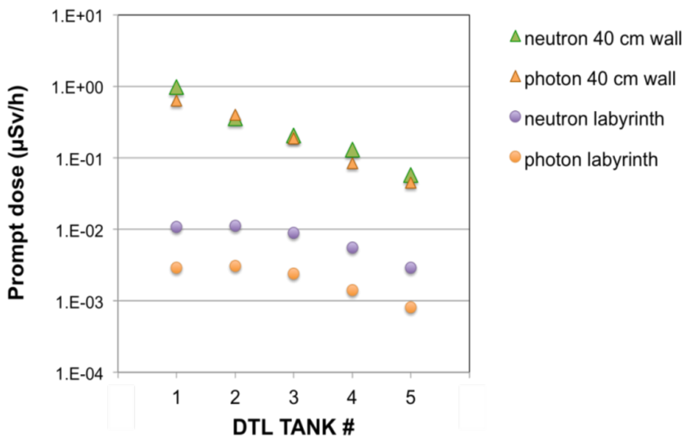
We have considered two shielding geometries, with the constrain that – to allow maintenance of the FEB equipment – the access between FEB and WCR should be at least 3 m wide and 2.50 m high. The first geometry (Figure 7, left panel) consists in a corridor, parallel to the linac, extending for the full length of the FEB; the corridor is 3 m wide, 20 m long, and it is defined by two ordinary concrete walls. The access is guaranteed by two doors (not providing radiation shielding), at the opposite extremes of the corridor. Calculations were performed for 40 cm thick shielding walls and for 1 m thick walls. The second geometry (Figure 7, right panel) consists in a labyrinth, 3 m wide, with three legs, respectively, 9 m, 7 m and 9 m long, and walls 1 m thick.

Figure 7. Front-end building (FEB) and water-cooling room (WCR), with the shielding geometries: (left panel) corridor with 40 cm thick shielding walls (right panel) and labyrinth with 1 m thick shielding walls



The corridor configuration with 1 m thick shielding walls is not shown in the figure. The doses reported here were calculated at the entrance door (red cell). The arrow indicates the direction of the proton beam.

Figure 8. DTL tanks contribution to the neutron and gamma prompt dose in the WCR for the corridor configuration and the labyrinth configuration



Dose contribution from MEBT and RFQ

Calculations for the MEBT and RFQ were conducted only for the first geometry (corridor), with 40 cm thick shielding walls. In this configuration the main contribution to the prompt neutron dose to the WCR from the MEBT came from the 4 W point-like loss on the stainless steel beam pipe, and accounted for 0.08 μSv/h. When calculating the contribution from the MEBT collimators and chopper dump, we observed that MCNPX did not produce any neutrons when transporting 10^7 protons: this is due to the fact that the Coulomb stopping power on graphite is much higher than the probability of undergoing nuclear interaction. To estimate an upper limit for the dose from these two components of the MEBT, we have assumed that 10^{-7} protons per source particle could reach the Cu inside the collimators and the dump. Even under this assumption, the neutron dose contribution to the WCR accounted for less than 10^{-8} μSv/h.

The maximum neutron dose rate contributed by the RFQ was 0.13 μSv/h, assuming a 4.6 W point-like loss and 3.6 MeV protons. This is a very conservative assumption, since protons are accelerated in the RFQ from 75 keV up to 3.6 MeV, along its 4.6 length, and only protons above the 2.167 MeV threshold in ^{63}Cu may contribute to the neutron production. The range of 3.6 MeV protons in Cu is 46 μm, hence they cannot reach the cooling-water channels in the RFQ, where neutrons might be eventually produced via the ^{18}O(p,xn) reaction (threshold 2.575 MeV).

Dose contribution from DTL

For the corridor configuration of the shielding (Figure 7, left panel), with 40 cm walls, the prompt neutron dose in the WCR from the five tanks of the DTL was 1.97 μSv/h, and the prompt gamma dose was 1.43 μSv/h. Hence, our calculations showed that the DTL contribution to the prompt dose in the WCR was one order of magnitude larger than the combined contribution given by the MEBT and the RFQ. In this configuration, the total prompt dose exceeds the 3 μSv/h limit for the WCR.

In the labyrinth configuration (Figure 7, right panel), the prompt dose from the DTL was 0.0396 μSv/h and 0.0107 μSv/h, respectively for neutrons and gammas. Given the reduction by a factor 50 of the prompt neutron dose, and by more than a factor 100 of the prompt gamma dose contributed by the DTL tanks, we assumed that in this configuration the dose contribution from the MEBT and the RFQ were negligible. However, we can account for the fact that the MEBT and the RFQ increase the total dose by 10%. The resulting total prompt dose of 0.055 μSv/h is well below the required 3 μSv/h limit.

In Figure 8, we compare the contribution to the dose from each tank of the DTL, for the two configurations described in Figure 7. We observe that for the corridor configuration with 40 cm walls, the gamma and neutron dose contributions were equivalent, whereas in the labyrinth configuration the gamma dose is consistently lower (by a factor 3) than the neutron contribution. From the neutron and gamma flux maps, we observed that the largest contribution to the dose was coming from neutron penetration through the shielding wall. A MCNPX calculation for the corridor configuration and 1 m thick shielding walls showed that the neutron dose from DTL tank 1 reduced from 0.98 μSv/h to 0.016 μSv/h, and the gamma dose reduced from 0.68 μSv/h to 0.022 μSv/h; now the main contribution was given by radiation streaming through the corridor. The labyrinth configuration further reduced these values to 0.011 μSv/h and 0.003 μSv/h, respectively for neutrons and gammas. The large reduction in gamma dose is due to the three-leg geometry vs. the single-leg design of the corridor configuration.

Dose contribution from DTL's Faraday cup

We have finally calculated the dose contribution given by the proton beam on the Faraday cup at the downstream end of the first DTL tank. The prompt neutron dose was 0.0042 μSv/h and the gamma dose 0.0013 μSv/h. These results were obtained for the labyrinth configuration, and are consistently lower than the dose given by 1 W/m loss in the first three tanks of the DTL.

Conclusions

We have modelled the components of the ESS warm linac where protons have kinetic energies above the neutron production thresholds, and we have designed the shielding for the FEB to guarantee supervised access to the neighbouring WCR. Our calculations showed that the first three tanks of the DTL contribute to 80% of the total prompt dose in the WCR, and that the optimal shielding configuration is a labyrinth with 1 m thick concrete walls. The MEBT and the RFQ do not contribute significantly to the dose, compared to the DTL.

Acknowledgements

We acknowledge the input received from Franz Gallmeier (SNS) for the DTL calculations. This work was completed with the collaboration of Benjamin Cheymol, Renato de Prisco, Carl-Johan Hårdh, Giobatta Lanfranco and Aurélien Ponton at ESS, who provided information about the linac components and the geometry of the FEB.

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