MODELLING OF THE RADIATION AND SHIELDING OF THE SOUTH AFRICAN ISOTOPE FACILITY USING FLUKA

A. H. BARNARD
iThemba LABS
Cape Town, South Africa
Email: hbarnard@tlabs.ac.za

P. BEUKES, J. I. BROODRYK, G. F. STEYN, I. L. STRYDOM
iThemba LABS
Cape Town, South Africa

Abstract

The South African Isotope Facility (SAIF) is a radioisotope production facility currently under construction at iThemba LABS in Cape Town. A commercial 70 MeV proton cyclotron from IBA with a number of beam lines equipped with isotope production stations are being installed in retrofitted concrete vaults. The completion of SAIF will greatly increase the radioisotope production capability of iThemba LABS and enable the existing Separated Sector Cyclotron to be dedicated to nuclear research activities. As part of the design process of the SAIF facility, radiation and shielding calculations were performed using FLUKA to assess the expected dose levels for radiation safety purposes. An overview of the simulations is provided, discussing the FLUKA setup and initial validation simulations performed to gain confidence in the results. A more detailed discussion of some specific systems is given, specifically: A multi-layered iron-wax-lead neutron shield of the isotope production stations; a louvre type shield for use in pre-existing air ducting labyrinths; access labyrinths used by a robotic target transport system; and radiation leakage through gaps between the concrete roof beams in the vaults. As part of an experimental validation campaign an experiment to assess the leakage rate between the roof beams was performed in an existing vault and this is compared to the FLUKA predictions.

1. INTRODUCTION

The South African Isotope Facility (SAIF) is a new radioisotope production facility under construction at iThemba LABS in Cape Town, where it will replace an existing isotope production system based on the 34-year-old K=200 Separated Sector Cyclotron (SSC) [1]. The SAIF project, shown in Fig. 1, is being constructed in retrofitted concrete vaults and consists of a central vault containing a 70 MeV proton cyclotron from IBA as well as two production vaults located on opposite sides of the cyclotron vault. Each production vault is connected to the cyclotron vault with two beam lines, enabling four target stations to be served by the dual-port cyclotron. The completion of SAIF will greatly increase the radioisotope production capability of iThemba LABS, and enable the existing Separated Sector Cyclotron to be dedicated to nuclear research activities. As part of the design process of the SAIF facility, radiation and shielding calculations were performed using FLUKA to assess the expected dose levels for radiation safety purposes.

2. FLUKA SETUP

For these simulations the default PRECISIO card was used. This results in longer simulations, but produces the best results. This setting activates low energy neutron transport (LOW-NEUT card), and a particle transport threshold of 100 keV is applied for all species, except neutrons, which are transported down to thermal energies (PART-THR card). The physics cards consisted of COALESCE to activate coalescence and EVAPORAT to activate the new evaporation model with heavy fragmentation.

Substantial use was made of BIASING to speed up calculations through the thick shielding. Alternatively, a two-step method was used, where the phase space of radiation reaching a subregion was recorded in a first simulation and then a second simulation was run that sourced its primary particles by sampling from the previously recorded phase space. The recording was made using a USRBDX card and USERWEIG to run the fluscw.f function each time a particle crossed into the recording region (preferably a BLCKHOLE). The fluscw.f function writes the particle details to a recording file. A second simulation then selects primary particles by sampling randomly from the recording file. This is done using a modified version of the source.f function. The recorded particles can also be used to construct a more continuous phase space, for example by Gaussian fitting. Selecting primary particles from a continuous phase space gives smoother results.

Scoring was performed using USRBIN and AUXSCORE was used to select the EWT74 option which used worst case fluence to dose equivalent conversion coefficients.

3. SHIELDING OF THE SAIF VAULTS

The main sources of radiation include the cyclotron due to a conservatively assumed 5% beam loss (37.5 uA) on the cyclotron walls, beam striking Faraday cups in the cyclotron vault (50 uA), Faraday cups in the production vaults (5 uA) and the target bombardment stations (375 uA). In all these cases the maximum proton energy of 70 MeV is used. The main shielding is provided by three concrete vaults shown in Fig. 1, with nominally 3 m thick walls, and removable concrete roof beams that can be stacked in 0.75 m high layers, shown in Fig. 2. The cyclotron vault roof will be 2.25 m thick, while the production vaults have 1.5 m thick roofs. Additionally, the isotope production stations are provided with a multi-layered local shielding system, reducing the dose and activation of material in the production vaults by a factor of around 1000.

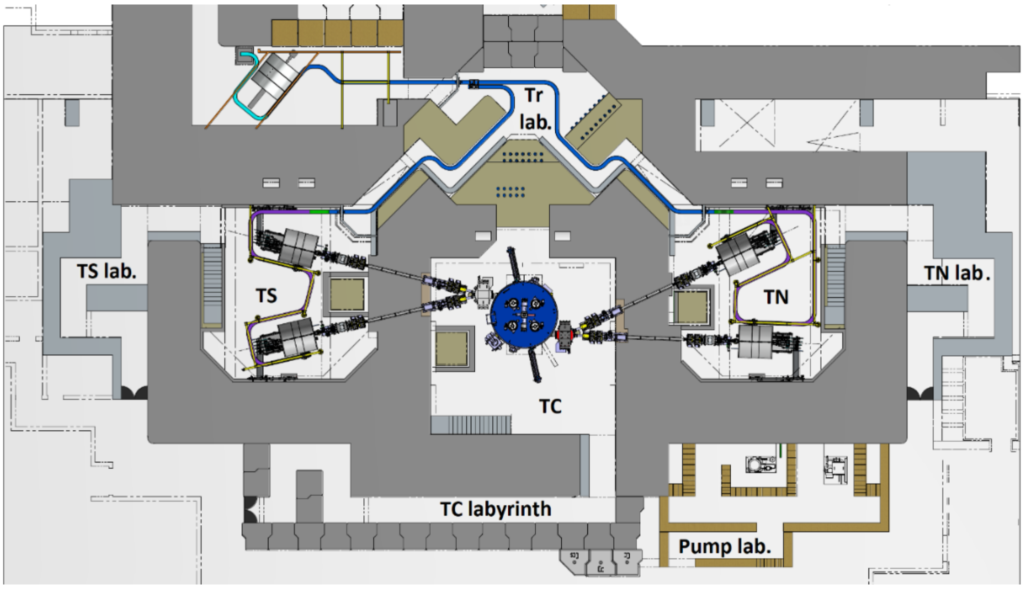

FIG. 1: Layout of SAIF facility, showing the central cyclotron vault (TC) and two production vaults (TN and TS) containing the four isotope production stations. The access labyrinths to the vaults (TS lab, TC lab, TN lab) and the robotic trolley labyrinth (Tr lab) are shown as well as the pump room and its labyrinth (Pump lab).

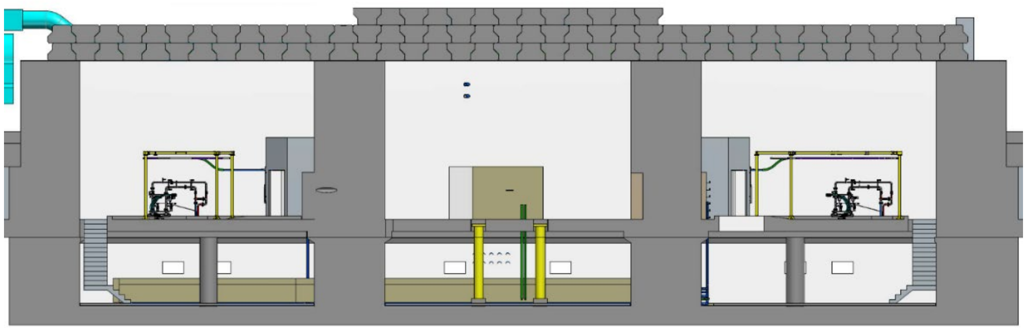

FIG. 2. Vertical section of the SAIF vaults showing the roof thicknesses as well as the vaults and the basements.

The concrete vaults are existing structures previously used for particle therapy. New concrete access labyrinths have been constructed, both for people and for a robotic target transporter. Modifications to the existing air ducting labyrinths cast into the walls have been necessary to improve the shielding.

4. INITIAL VALIDATION OF THE FLUKA SIMULATIONS

To check if the FLUKA simulations of the concrete vaults were producing reasonable results, a few initial simulations were performed and the results compared to measurements and published results.

4.1. Source term and attenuation length of neutrons in concrete

A Fluka model was made of a 70 MeV proton beam striking a thick copper target, with the resulting neutron radiation passing through a concrete wall. The neutron dose equivalent in the forward direction was measured at various depths in the wall, and the result was a near exponential decrease, corresponding to an attenuation length of 44 g/cm^2. This corresponded well to published attenuation lengths for various elements present in concrete, ranging from 39-43 g/cm^2 [2]. The source term in the forward direction (the dose equivalent produced per proton striking the copper target) was simulated to be 0.75 x 10^{-16} Sv/proton which is about 55% of the published value. This shows the FLUKA simulations to be accurate to within a factor of about two.

4.2. Neutron dose rate of a proton beam striking a Faraday cup

A physical experiment was performed using the SSC at iThemba LABS where a 10 uA 66 MeV proton beam was stopped on a number of copper Faraday cups [3]. The dose rate was then measured on the outside of concrete slabs with thicknesses ranging from 1.5 m to 2 m. This setup was modelled in FLUKA, and a comparison between the measured and simulated results is given below in Table 1. In these cases, FLUKA is accurate to within less than a factor of two.

TABLE 1. EXPERIMENTAL AND FLUKA DOSE RATES FOR DIRECT CONCRETE PENETRATION

Location	Concrete Thickness (cm)	FLUKA dose rate (uSv/h)	Experimental dose rate (uSv/h)	Difference (%)
FC-11X	150	260	210	24
FC-4I	150	260	190	36
FC-7I	200	7	6	17

5. MULTI-LAYERED NEUTRON SHIELD IN THE ISOTOPE PRODUCTION STATION

The radiation emitted by the 375 uA 70 MeV proton beam striking the isotope production target is attenuated by a movable local shield, referred to as the isotope production station (IPS), that almost encloses the target. The IPS is made up of three layers: 50 cm iron, 20 cm borated paraffin wax, and finally 4 cm lead [4]. The iron slows down fast neutrons, the wax thermalizes the neutrons and most of the neutrons are then absorbed by boron, resulting in a soft gamma, while a small fraction of the neutrons is absorbed by hydrogen, resulting in a hard gamma. These gammas are attenuated by the final lead layer. Previous studies have optimised the thickness of the layers to reduce the overall dose, but considered simplified geometries [5]. The practical construction of the IPS introduced several potential weaknesses in the shielding, and these had to be modelled carefully to obtain a suitable design.

5.3. Gaps between movable sections

The IPS consists of three sections, a front, middle and rear section, and they can slide along rails to open the station in order to insert or extract a target, or for other maintenance. This can result in gaps between the sections, through which radiation can escape, especially since the large shape of the IPS means that manufacturing errors of around 5 mm can be expected. The solution, determined using FLUKA modelling, is to step the mating surfaces where the sections meet to create a mini labyrinth, as shown in Fig. 3.

5.4. Access for helium supply pipes

The beam pipe entering the IPS is terminated by a set of two helium cooled vacuum windows located inside the shielding. A supply and return pipe provide the helium gas, and a suitable route for these pipes is required.

The access route must not deteriorate the shielding, but it must also be as simple as possible, since the vacuum window assembly will need replacing from time to time. The solution is to use straight pipes, running perpendicular to the beam, but offset 13 cm sideways and 5 cm backwards from the target, as shown in Fig. 3. The pipes also point downwards, directing escaped radiation into the floor.

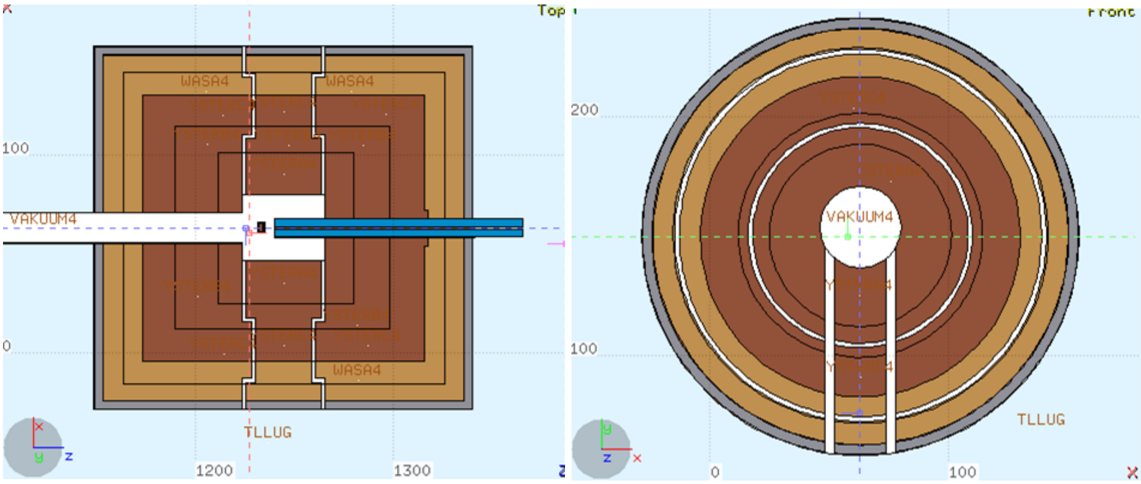

FIG. 3. – Cross sections of the IPS. Left: the three shielding sections (front, middle and rear) with their stepped mating pattern produces small labyrinths (white lines). Right: helium access pipes entering the IPS in a straight line but offset from the target and pointing downwards.

5.5. Access for helium supply pipes

The beam pipe entering the IPS is terminated by a set of two helium cooled vacuum windows located inside the shielding. A supply and return pipe provide the helium gas, and a suitable route for these pipes is required. The access route must not deteriorate the shielding, but it must also be as simple as possible, since the vacuum window assembly will need replacing from time to time. The solution is to use straight pipes, running perpendicular to the beam, but offset 13 cm sideways and 5 cm backwards from the target, as shown in Fig. 3. The pipes also point downwards, directing escaped radiation into the floor.

5.6. Water cooling pipes

The water cooling to the target is provided by an inlet and outlet pipe, positioned concentrically around each other, and pointing in the forward direction away from the target, as shown in Fig. 4. From a shielding point of view this is not ideal, since a lot of fast neutrons will be ejected down the water-cooling pipes, and the water will not provide as good shielding as iron. On the other hand, the water-only section is long and narrow, providing a small solid angle as seen from the target, and the water will scatter some neutrons into the surrounding iron. The leakage was modelled and found not to be significant. Overall, the main source of radiation leaving the IPS remains the neutrons emitted backwards from the target down the beam pipe as shown in Fig. 5.

6. LOUVRE TYPE SHIELD FOR USE IN PRE-EXISTING AIR DUCTING LABYRINTHS

The existing concrete vaults contain cast-in air ducting labyrinths. Simulations showed that these labyrinths were inadequate for stopping neutrons. Different possibilities were considered, ranging from adding more concrete to extend the labyrinths, to lining the inside walls of the vaults with an iron-plastic cladding to limit the neutrons entering the ducting. In the end it was decided to install a louvre type shield inside the air ducting where the existing ducting exits the vaults. The louvres are made of mild steel, and are shown in Fig. 6, while their effect on the radiation travelling down the air ducting is more-or-less equivalent to 50 cm of concrete, as shown in Fig. 7.

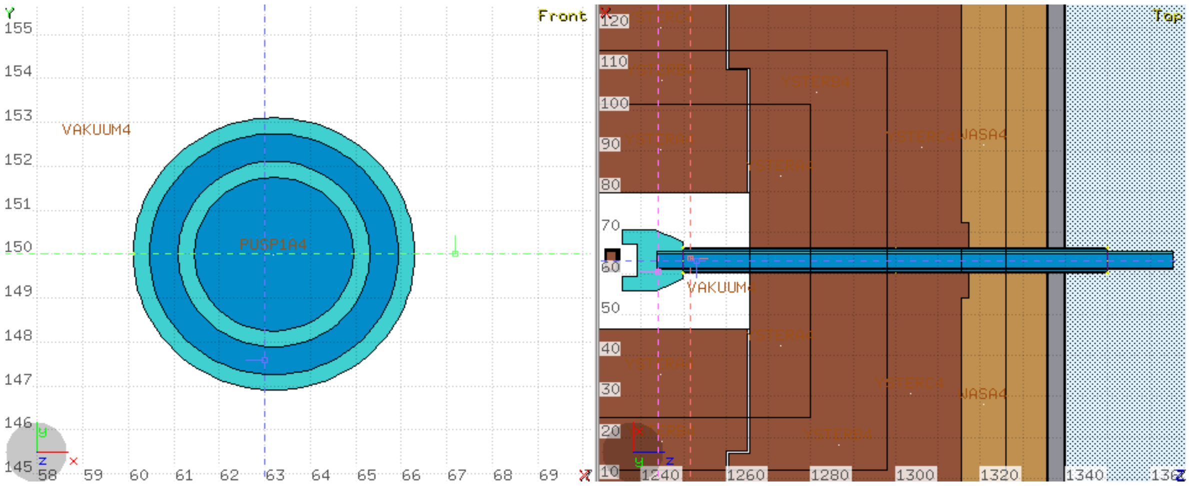

FIG. 4: Concentric water pipes leave the IPS in the forward direction, potentially weakening the shielding. The outer light-blue colour is stainless steel, and the inner dark-blue colour is water. In the right hand picture the forward direction is to the right.

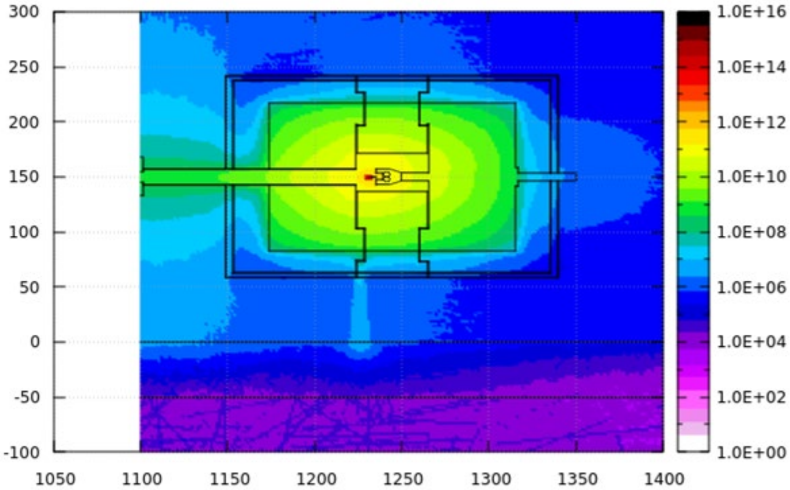

FIG. 5: Dose rate (uSv/h) due to a 375 uA 70 MeV proton beam on the target in the IPS. There is no discernible leakage through the mating labyrinth. The dose rate in the forward direction (to the right) is similar to the dose rate vertically upwards, indicating that the leakage through the water pipes is not significant. The leakage through the Helium access pipes is noticeable but is directed straight downward into the concrete floor.

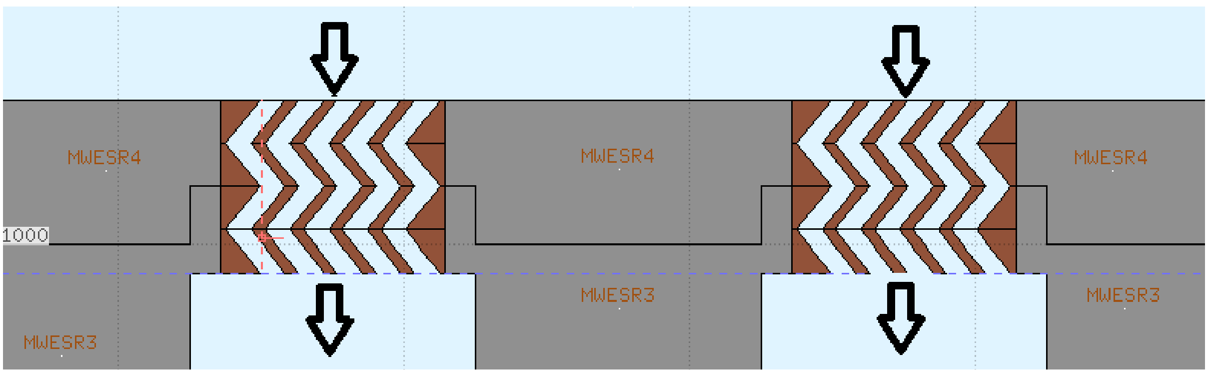

FIG. 6: The louvres (brown) are installed in existing ducting to allow for easy air passage (shown by arrows) while shielding against slow neutrons.

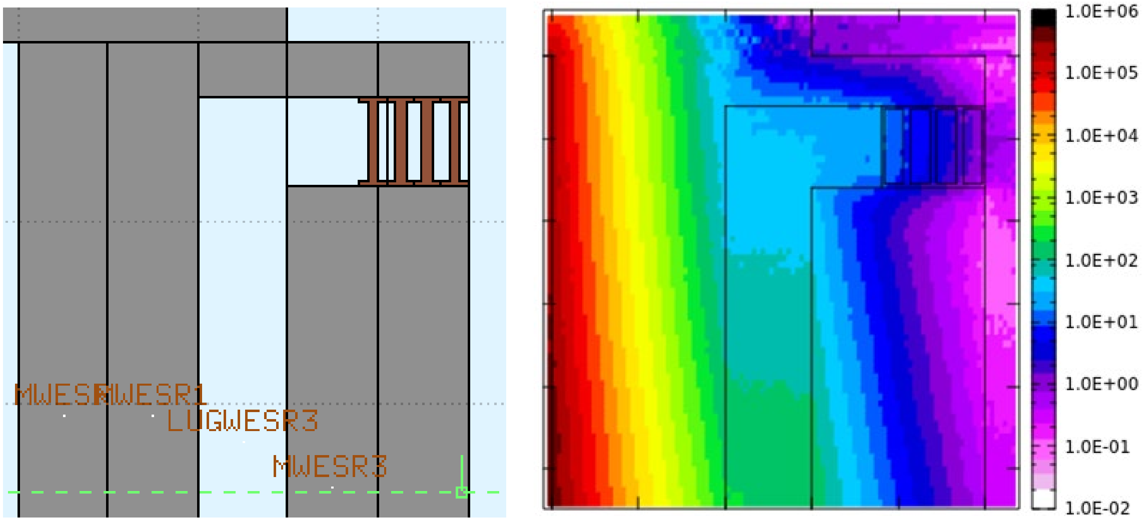

FIG. 7. – Left: This shows a cross section of the air ducting labyrinth inside a concrete wall, with the louvre shielding installed (top right of image). Right: Dose rate (uSv/h) due to 5 uA 70 MeV protons on a Faraday cup in the TS vault. The louvre provides shielding reduces the dose rate by a factor of 20.

7. ACCESS LABYRINTHS USED BY ROBOTIC TARGET TRANSPORT SYSTEM

The IPS is served by a robotic trolley that transports activated targets between the production vaults and hot cells located in a different part of the SAIF facility. The section of the route where the trolley enters and leaves the production vault is referred to as the trolley labyrinth. The trolley labyrinth also serves as a passageway for access between the different vaults, when people are transporting activated components and do not wish to leave the red-classified radiation area. The trolley labyrinth should therefore prevent radiation from travelling between any of the three areas that it is simultaneously serving. Fig 8. Shows the calculated radiation travelling through the trolley labyrinth during normal operation of one of the production vaults, while Fig 9. shows the gamma radiation from a fully irradiated target as it is being transported along the trolley labyrinth.

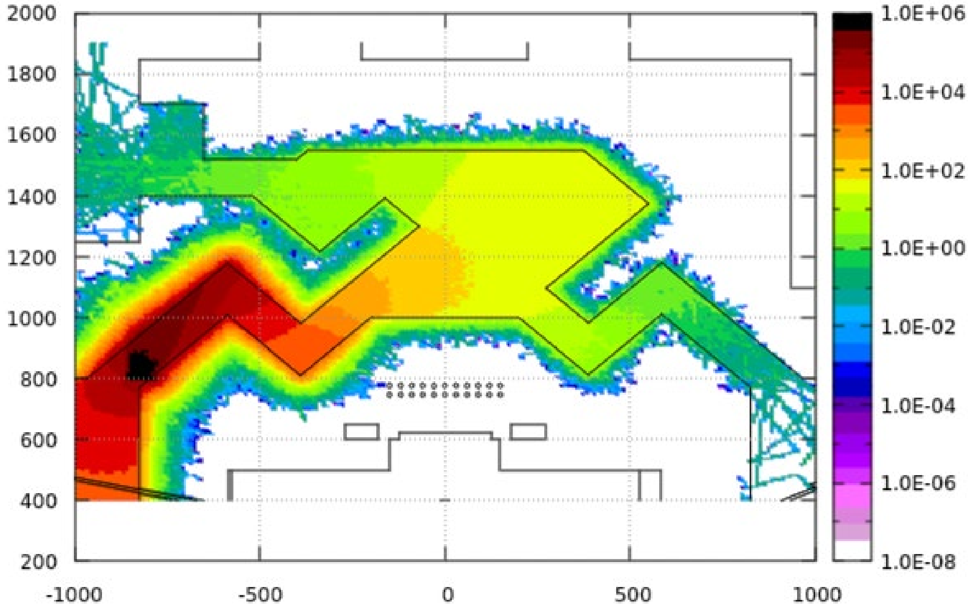

FIG. 8: Total dose equivalent (uSv/h) from 5 uA 70 MeV protons on a Faraday cup in the TS vault. This is a two-step simulation with the secondary source located at the trolley labyrinth entrance. The dose in the adjacent rooms is less than 1 uSv/h.

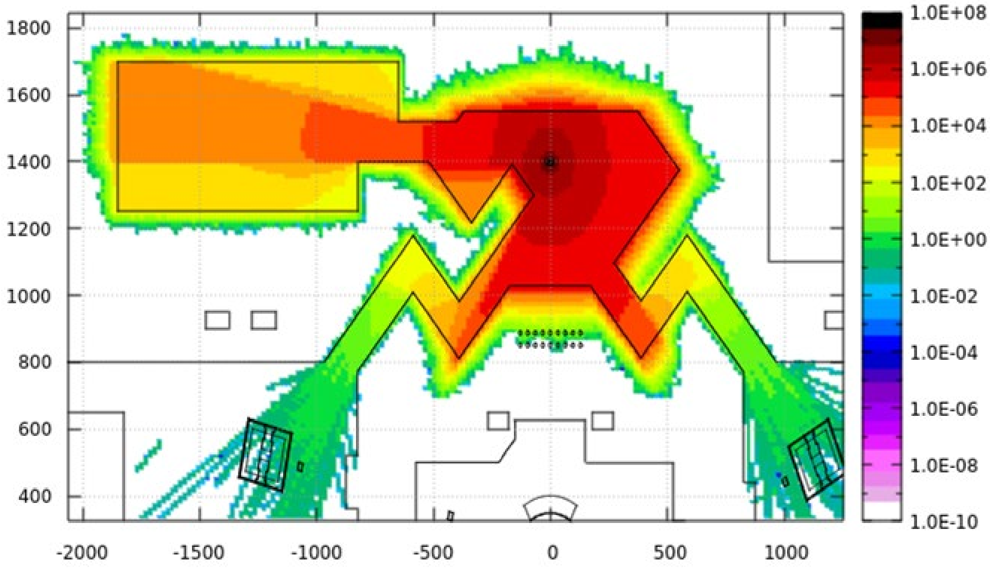

FIG. 9: Total dose equivalent (uSv/h) from 160 Ci of 22Na. This simulates the maximum dose expected when transporting a fully irradiated target through the trolley labyrinth.

8. RADIATION LEAKAGE THROUGH GAPS BETWEEN CONCRETE ROOF BEAMS

The roofs of the vaults consist of stacked interlocking concrete beams. While the beams provide adequate vertical shielding, some radiation can escape through small gaps between the beams where they don't interlock perfectly. A physical experiment was performed at the SSC vault at iThemba Labs, where a 10uA 66MeV beam was stopped on a copper Faraday cup, and the leakage along an inter-beam gap was measured. This was found to be 75 uSv/h, which is significant. A long round sandbag was then inserted into the gap to various depths, and the dose rate was recorded outside the gap. For a 1 m bag the dose rate was reduced to 6 uSv/h, which is a 10-fold reduction, and provides an easy solution to this shielding problem.

This situation was also modelled in FLUKA, which was challenging since only a very small fraction of the neutrons in the vault escaped along the inter-beam gaps. The FLUKA simulation therefore made use of the two-step phase-space sampling to focus only on the region of interest, and this was further augmented with importance biasing in the gap and surrounding material. In agreement with the experimental observations it was found that the only significant escape of radiation was between the bottom layer of roof beams and the walls on which they rest. The results of these simulations and a comparison with the experimental values are shown in Table 2 while a plot of the radiation escaping down the gap is shown in Fig. 10.

TABLE 2. EXPERIMENTAL AND FLUKA DOSE RATES FOR LEAKAGE ALONG BEAM GAPS

Length of sand bag in inter-beam hole (cm)	FLUKA dose rate (uSv/h)	Experimental dose rate (uSv/h)	Difference (%)
0	35	75	53
50	13	24	45
100	3	6	50

9. CONCLUSION

FLUKA has proven to be an extremely useful design tool during the SAIF project. Initial validation tests provided confidence that the program is being used correctly and producing reliable results. From these tests it was clear that the FLUKA results correspond to actual measurements within a factor of 2 to 3. FLUKA simulations have assisted in the design of numerous shielding components that would have been extremely difficult to evaluate in a different manner.

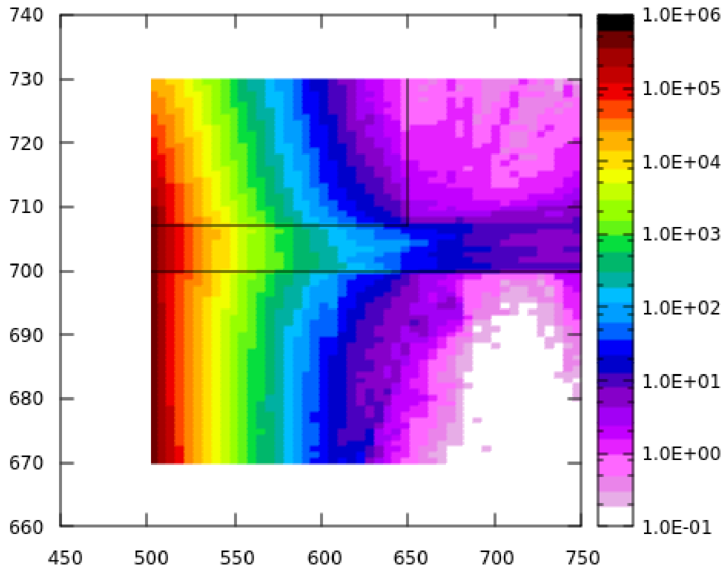

FIG. 10. – Total dose equivalent (uSv/h) of the radiation escaping through the gaps between the roof beams, produced by 37.5 uA (5% beam loss) 70 MeV protons striking the cyclotron vacuum chamber wall.

REFERENCES

[1] Conradie, J.L., et al., "The South African Isotope Facility", in Proc. 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver (2018) doi:10.18429/JACoW-IPAC2018-TUZGBF4

[2] Chen, C.C., et al., Calculations of neutron shielding data for 10–100 MeV proton accelerators, Radiation Protection Dosimetry, Volume 116, Issue 1-4, 20 December 2005, Pages 245–251, https://doi.org/10.1093/rpd/nci193

[3] Botha, A.H., iThemba LABS, unpublished data

[4] Steyn, G.F., et al., Development of new target stations for the South African Isotope Facility, Instruments 2.4 (2018): 29.

[5] Vermeulen, C. Production of Radionuclides with Medium Energy Protons with the Emphasis on Targetry, PhD dissertation, Stellenbosch University (2014)