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Specifications for the ARIEL eHall Shielding

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History of Changes

Release Number	Date	Description of Changes	Author(s)
#1	2014-01-24	Initial release including the north wall shielding analysis completed by C. Dunning.	M. Trinczek

1 Introduction and Scope

The purpose of this design note is to provide the specifications for the eHall shielding necessary for radiation protection of personnel outside shielding while the ARIEL electron linear accelerator (e-linac) operates at different output and beam orientations. It is to address the cases of both abnormal and accidental beam loss and of chronic beam losses under normal operation.

The design note includes requirements for the full eHall shielding envelope except for the north wall at beam height where the beamline will bend the beam into an opening in the shielding wall and direct it into the tunnel. The shielding requirements for the opening in the north shielding wall are being finalized and will be added to a future release of this design note.

The primary orientation that has been considered is for 500kW at 75MeV with beam directed northwards towards the ARIEL tunnel. A separate simulation was carried out to determine the specifications for the 100kW main beam dump in the eHall and results have been documented in TRI-DN-13-29 design note[1]. As well, the situation for 500kW at 75MeV with beam directed to the south or southeast, to account for the possibility of a future accelerator ring has been considered and is planned for a future phase.

In accordance with TRIUMF's prompt radiation hazard policy [TSN 1.8, Document-544], the shielding was designed to be sufficient to limit the dose rate outside the shielded area to less than 50mSv/hr under an abnormal or accidental beam loss and to less than 10μSv/hr for chronic beam losses under normal operation. A conservative chronic beam loss for the accelerator is $1{:}10^{5}$ per meter, and for a total of ten meters amounts to 10^{-4} of full power, or 50W. Therefore designing the shielding for an accidental loss limit of 50mSv/hr will allow for sufficient shielding to remain below 5μSv/hr during normal operation and thus provide a margin of safety. This chronic dose rate limit is for low-occupancy areas.

The geometry of the eHall was built in FLUKA [1] to determine the necessary thickness of the appropriate shielding material for a given accelerator output/beam orientation. Accidental beam losses were generated by running an electron beam of appropriate energy down a vacuum-filled, 3mm-thick stainless steel beam pipe onto a 10cm-thick target of iron (representative of a magnet yoke). Ambient dose-rate plots of photons (gamma rays), neutrons, and total radiation were generated for the different scenarios, allowing the required thicknesses and geometries of the shielding to be determined. Included in this summary are plots of the geometry that, hopefully, help make sense of the words, along with example dose equivalent plots that illustrate the methodology used to obtain the radiation fields.

The employed right-handed coordinate system starts at (0,0,0) on the floor in the southwest corner of the eHall. Within the simulation (X,Y,Z) corresponds to (west,up,north) so the beam-line position of X = -740cm means 740cm eastwards from the west wall of the eHall. All dimensions are in centimeters unless otherwise noted.

[1] TRI-DN-13-29 100 kW e-Linac Dump – Local and Upstream Shielding, M. Nozar, Dec, 2013 (Document-103968)

Within FLUKA, different settings, limits, and thresholds were employed. New Defaults were used as the overall setting for the performed simulations. This was augmented with different Physics options to turn on Evaporation and Photonuclear reactions in the required materials. The electron and photon production thresholds within materials were set to 100keV and 10keV, respectively, as were the transport cutoffs within regions. Moderate Importance Biasing was used in select regions and the Lam-Bias was used to reduce the inelastic interaction length of photons by a factor of 0.02 while the EMF-Bias was used to activate leading-particle biasing in certain regions.

2 Specifications for Shell of eHall and Penetrations

The specifications for the shielding have been verified using a general methodology. Dose rate equivalent maps of different sections of the geometry have been inspected for hot spots using the TRIUMF-approved, standard dose-conversion coefficients of AMB74 within FLUKA. For each case an average was taken over an appropriately sized area and the dose equivalent was recorded (normally at a distance of 50cm) for gammas, neutrons, and total radiation. This methodology will be made clearer by going through a specific example in the next section.

2.1 **Roof Beams**

The existing roof beams are used. They have been modeled as regular concrete and are 150cm thick. The ARIEL team decided that the roof beams will be made immovable and will be grouted together; hence the air gaps between the roof beams have been changed to concrete in the simulation.

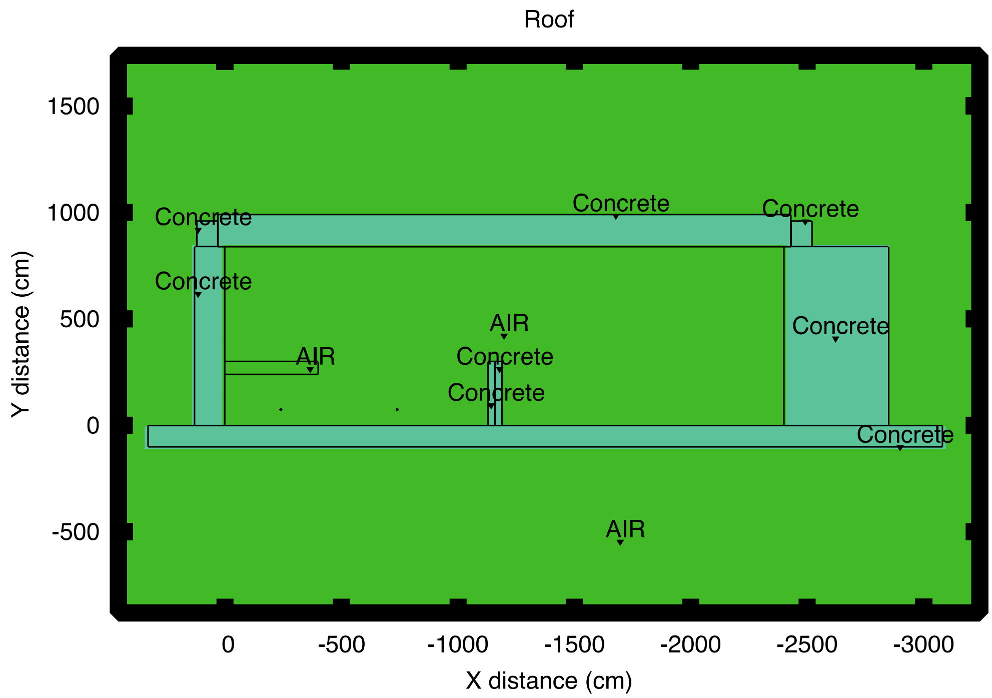

Figure 2-1 Vertical slice through eHall looking north. Note the additional concrete at the left and right ends of the roof beams.

The original shielding is thin at the west and east ends of the roof beams. Additional (to the roof beams) concrete shielding is required to give 90cm by 120cm (width by height) total along each end, positioned tight against the roof beam and sitting on the wall.

To determine if the roof thickness (Y=840 – 990cm) is adequate, a simulation of a full-point loss of 500kW of 75MeV beam was stopped at Z = 1060cm and the resulting radiation fields inspected. Figure 2-2 shows the dose equivalent fields for gammas averaged about the height of the beam line, but it is more important to examine the radiation fields in the top part of the roof (900<Y<1000cm) as in Figure 2-3. The examples show the gamma fields, but similar maps are also done for neutron and total fields.

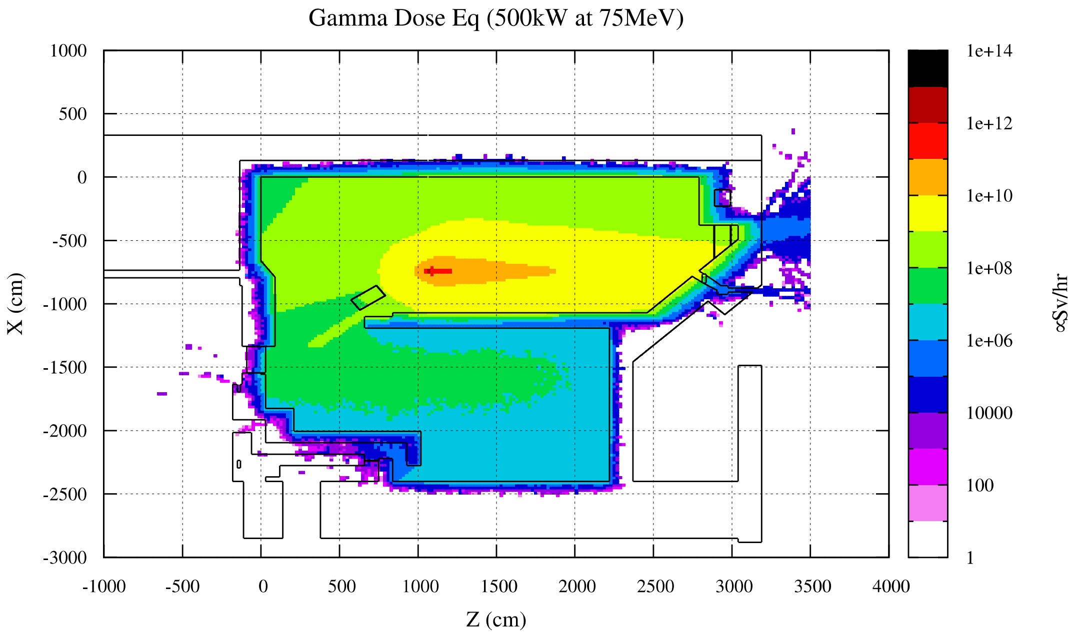

Figure 2-2 Dose rate equivalent for gammas averaged about the beam line.

Since Figure 2-3 displays the relevant map for what radiation may penetrate the roof beams, it is inspected to determine where the highest rate may exist. In this case, the region of X = -1000 to -500cm and Z = 1200 to 1700cm was chosen and plots of dose equivalent as a function of Y (the dimension through the roof beams) were examined. Figure 2-4 shows the dose equivalents through and above the roof beams for gammas, neutrons, and total radiation.

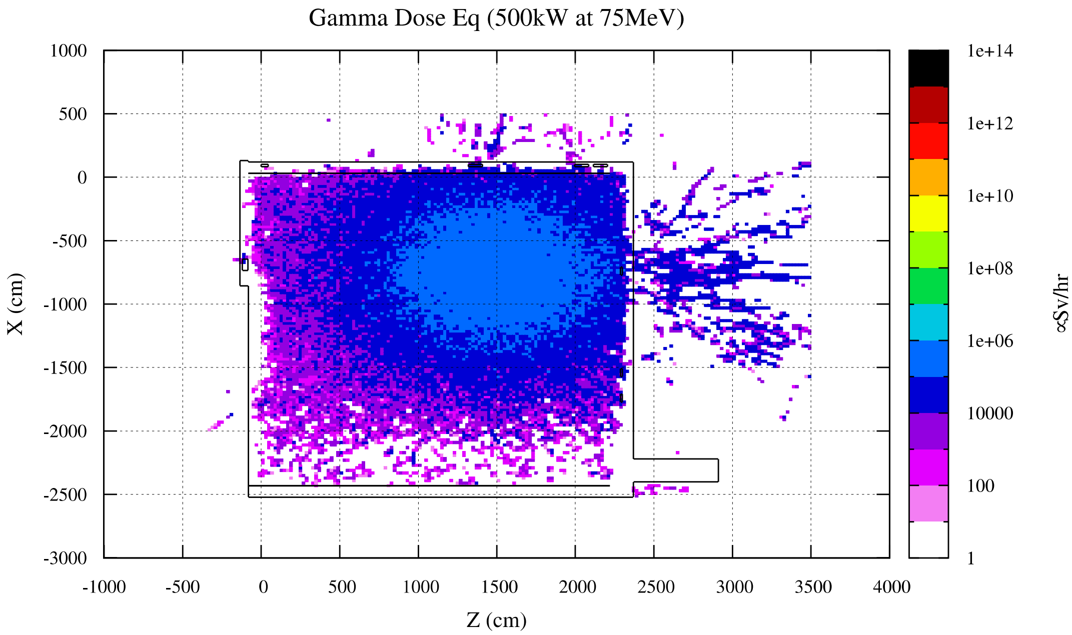

Figure 2-3 Dose rate equivalent for gammas averaged around the height of the roof beams (900 < Y < 1000cm).

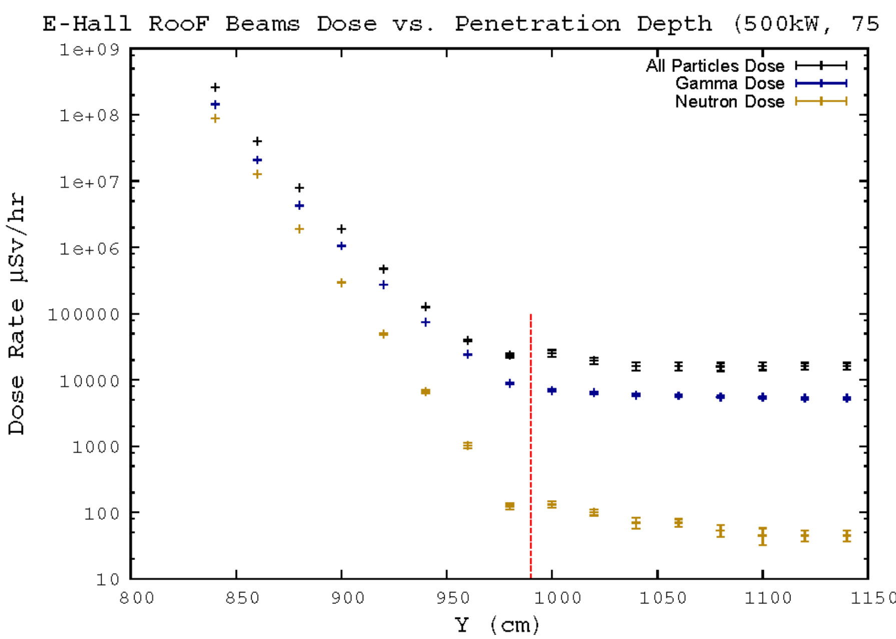

Figure 2-4 Dose equivalent through and above the roof beams. The red line denotes the top of the roof beams.

The roof beams run from Y = 840 to 990cm (hence the strongly decreasing dose equivalent in that region) and the dose rate value is taken at Y = 1040cm (i.e. 50cm above the face of the roof). To be conservative, the values reported in the Table 2-1 are from the upper error bars and rounded up to the nearest 5μSv/hr.

Table 2-1 Dose rates above the roof beams for an accidental full power beam loss

	Gammas (μSv/hr)	Neutrons (μSv/hr)	Total (μSv/hr)
Above roof beams at Y = 1040cm	6125	80	18675

Based on these values, the roof beams provide sufficient shielding (i.e. < 50mSv/hr).

2.2 West Wall

This wall has been modeled as regular concrete and is 130cm thick and soil has been placed to the outside of the wall, underground. There are 4 existing penetrations/chases emanating from the top of the wall and all have been modeled as built. The dose rates at the opening of the penetrations are acceptable when "filled" with only air and will only get better once filled with services. As with all penetrations, the standard practice is that any leftover space in the cross section should be filled. These have been assessed with beam running to the north and to the south. Once the final position of the future ring is known, another simulation of the beam running to the west can be performed. If there are issues, it is anticipated that any additional shielding can be done local to the final beam line.

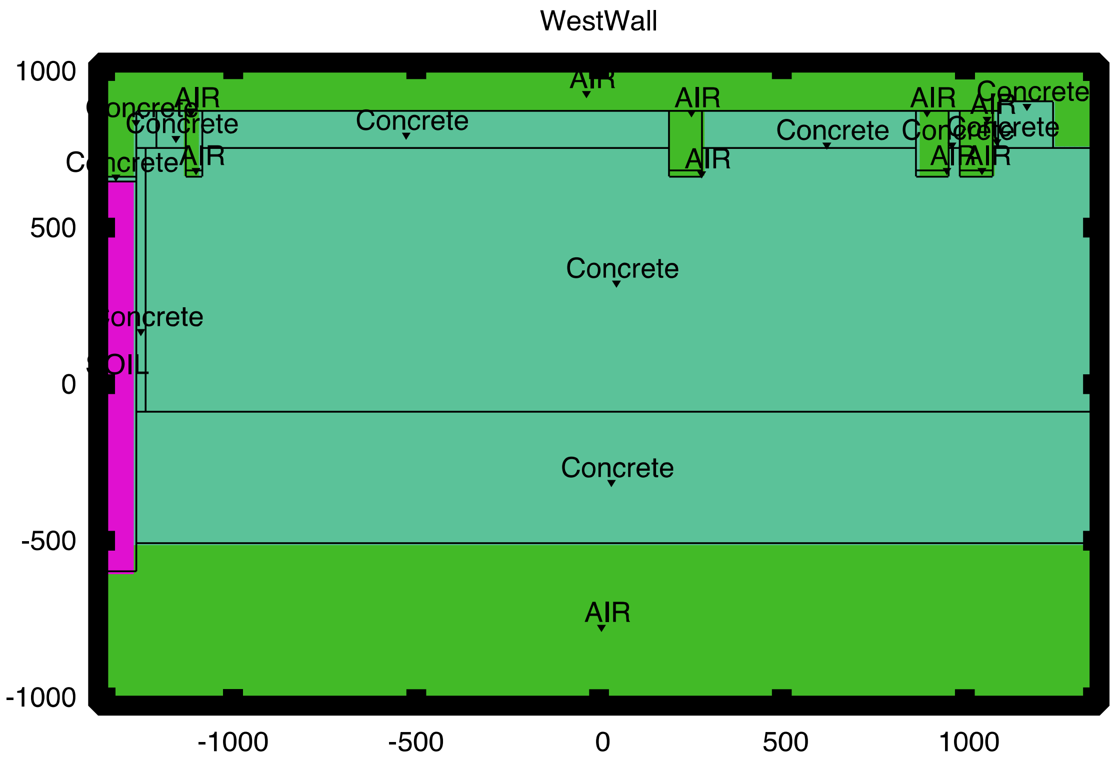

Figure 2-5 Vertical slice through eHall looking at the west wall and showing the penetrations/chases.

The dose rate values for the west wall have been recorded in four different places. A general field in the soil is taken about beam height and across from the loss point at Z = 1060cm at X = 180cm (the wall is from X = 0 to 130cm) which is 50cm into the soil. For the four chases, the values are also taken at X = 180cm and are averaged for a couple of meters in Y and Z adjacent to the chase. The averaging regions were chosen to give the highest representative field. The two chases at the north end of the west wall are treated as one region in Table 2-2 below.

Table 2-2 Dose rates at Penetrations in the west wall

	Gammas (μSv/hr)	Neutrons (μSv/hr)	Total (μSv/hr)
In soil at beam height across from loss point	1310	< 50	1310
Chase W1 Z = 0cm, Y = 750cm	100	285	370
Chase W2 Z = 1320cm, Y = 750cm	12900	3380	15810
Chases W3 and W4 Z = 1995cm, Y = 750cm	2105	1055	3130

It should be noted that the values at the second chase W2 are the highest because it is located the closest to the loss point. If the loss point were moved downstream (to larger Z) than the values for chase W2 would decrease and the values for chases W3 and W4 would increase. Nevertheless, these values are representative of the dose equivalents along the west wall and remain at reasonable values.

2.3 East Wall

This wall has been modeled as regular concrete and is 450cm thick. There is a penetration of 240cm by 240cm intended to represent the doorway into the cyclotron vault which is fronted by the southeast maze.

Since the east wall is so thick, very little radiation from the eHall can penetrate through the concrete and into the cyclotron vault area and this is confirmed by the simulations. However the radiation fields of the maze need to be considered.

The southeast maze has already been constructed from shielding blocks and has been modeled as it was to be built. It allows access from the eHall into either the Service Annex or to the cyclotron vault. It was important that the roof of the maze be 90cm of concrete or thicker at the south end, and the access-control door leading to the cyclotron vault should include a lining of 5cm-thick polyethylene to reduce neutron flow into the vault area. With future ring operation, it may be necessary to increase the shielding in the direction towards the man-door to the Service Annex, but this could be accomplished with shielding local to the beam line.

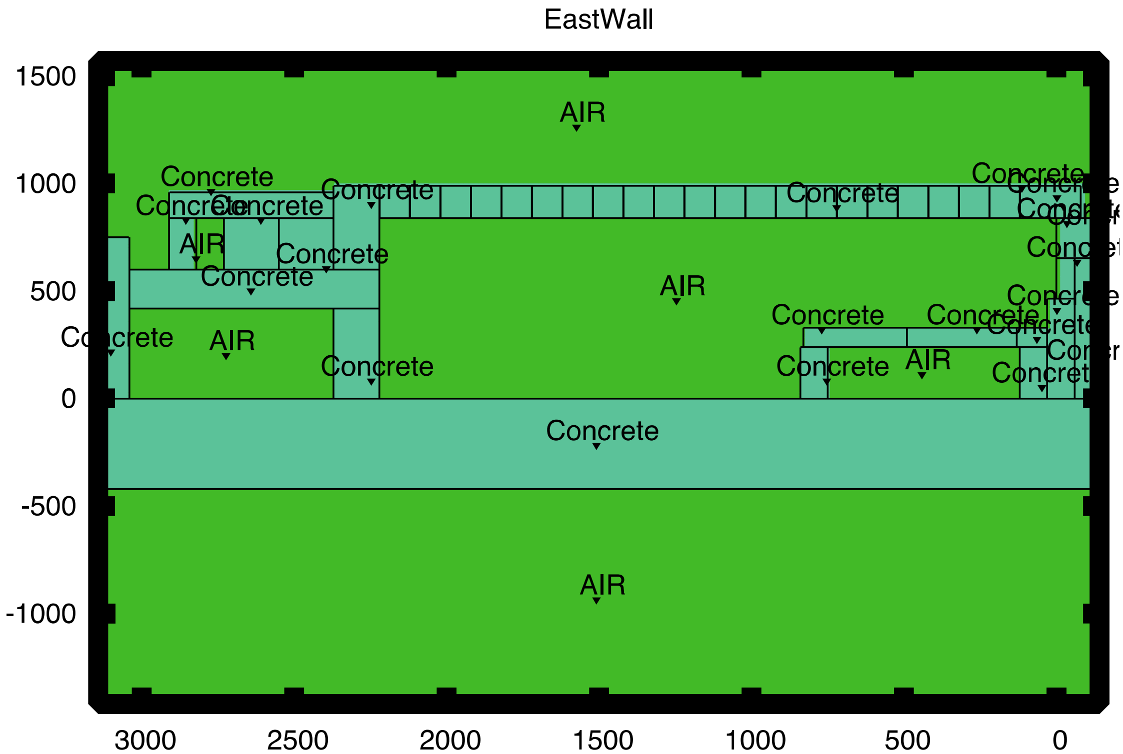

Figure 2-6 Looking towards the east wall. The southeast maze is partially shown in the lower right which leads to the cyclotron vault.

Two locations need to be considered within this maze, shown in Figure 2-7. The first is in the leg that leads to the cyclotron vault. The radiation fields in the position at X = -2300cm and Z = 700cm are shown in Table 2-3 below as this is where someone from the cyclotron vault could stand while the eHall is being used. The second position is outside of the second leg that leads to the Service Annex at a position of X= -1960cm and Z = -240cm and the dose equivalent fields are also shown in the table. (N.b. It is expected to have to limit occupancy further upstream in the cyclotron vault portion of the maze when losses for the east-directed portion of the ring are considered.)

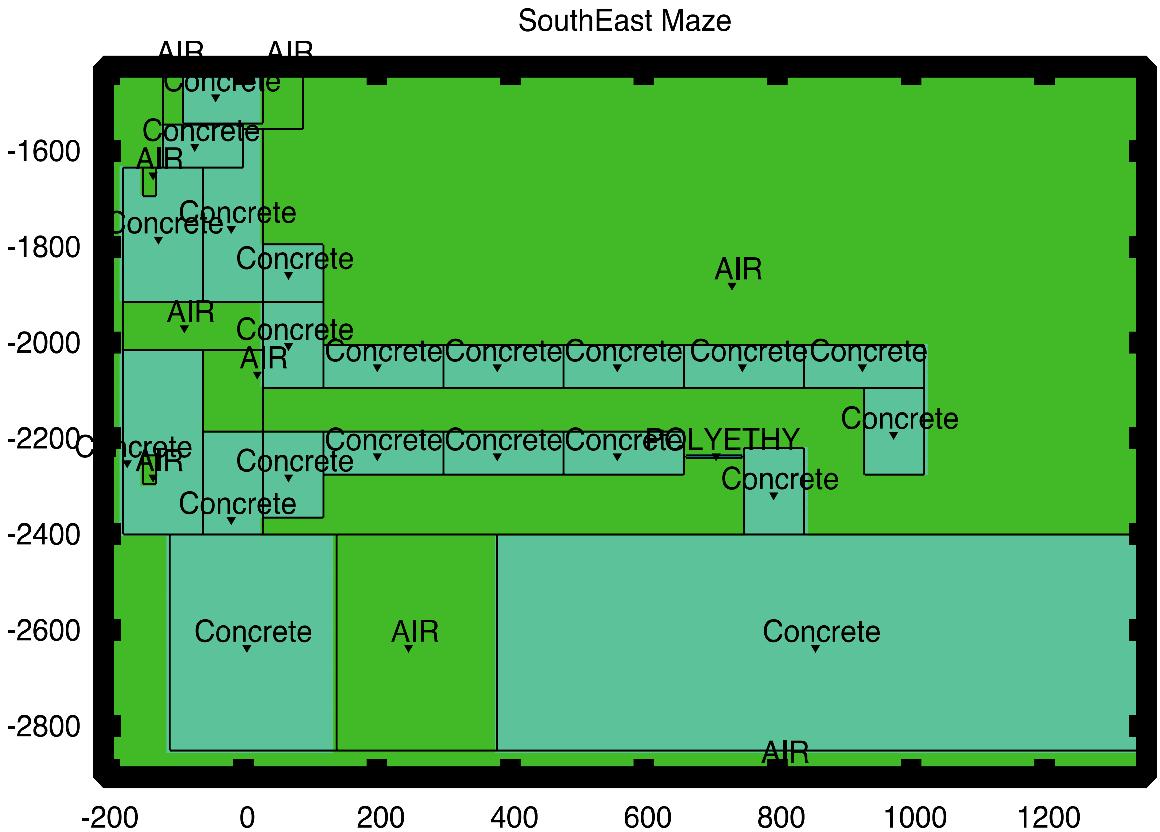

Figure 2-7 Plan view (X vs. Z) of the southeast maze showing access to both the Service Annex and the cyclotron vault.

Table 2-3 Dose rates at the southeast maze exits into the cyclotron vault and service annex

	Gammas (μSv/hr)	Neutrons (μSv/hr)	Total (μSv/hr)
Leg to Cyclotron Vault X = -2300cm, Z = 700cm	5205	34145	38905
Service Annex X= - 1960cm, Z = -240cm	150	355	485

In both cases the fields are dominated by neutrons and demonstrate the advantage of having a longer leg in a maze.

2.4 South Wall

This wall has been modeled in great detail with regular concrete and includes the original wall that has been thickened with newly poured concrete and has all 6 penetrations and chases along with the man-door into the southeast maze (covered above) and the large double door into the hall. It is assumed that the double-door opening will be filled with concrete blocks that are a minimum of 120cm thick. Depending on the placement of the future ring, it may be necessary to augment the double-door plug with shielding placed locally to the beam line.

The 3 west-most penetrations require special attention. The chase S3 located at X = -1485cm and Y = 650cm must be filled; there was no planned use for this chase.

The penetration S2 located at X = -920cm and Y = 640cm, in line with the access hatch in the floor of the eHall, will be used for cryogenic piping. The 4 cryogenic pipes must have a chase of 10cm thick polyethylene of as small a cross section as possible and extend a minimum of 120cm into the Service Annex at the B1 level.

The chase S1 located at X = -700cm and Y = 640cm which is to be used in the ventilation system has very little concrete on its south side and this necessitates that additional floor-to-ceiling concrete shielding be placed at the B1 level of the Service Annex in the northwest corner in between the wall and the above-mentioned cryogenic chase and extending a minimum of 100cm southwards. As well, the entire length of the Service Annex corridor at ground level requires a minimum of 60cm of concrete along its north wall to a height of at least 180cm. This is to allow for a loss of beam travelling south in the future ring.

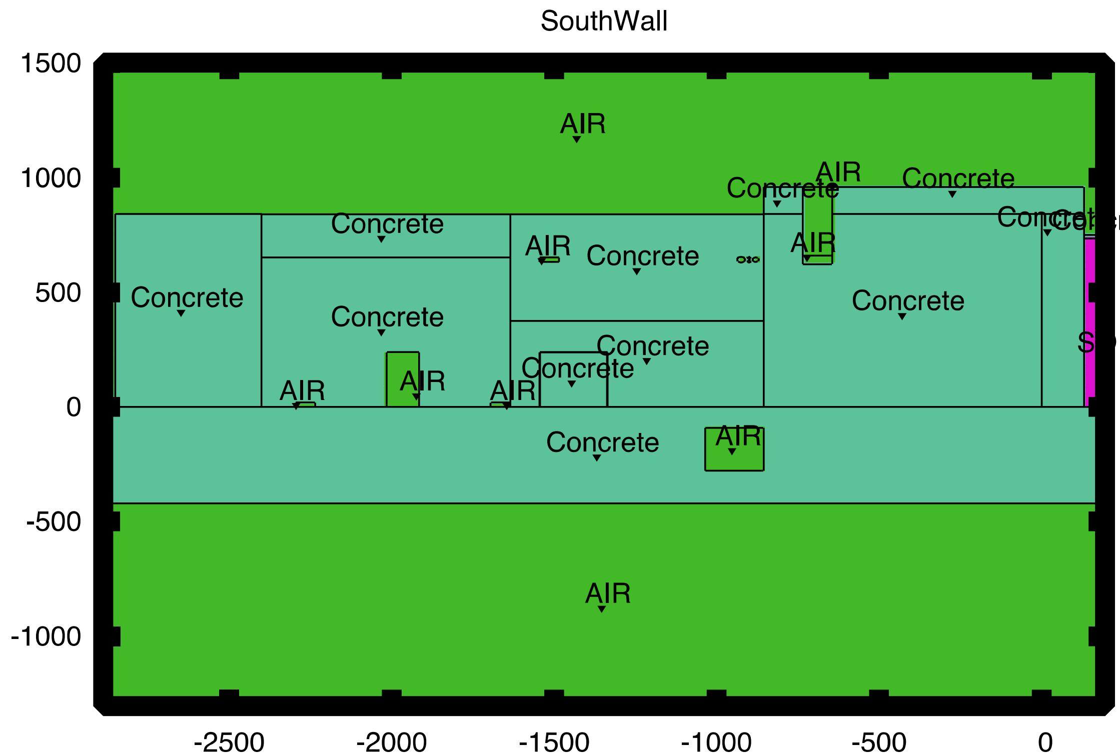

Figure 2-8 Looking to the south wall (Y vs. X) showing the different concrete panels and the penetrations and chases.

Even for operation of running beam to the north, without a ring, chase S3 needs to be filled as radiation fields are ~ 1Sv/hr; detailed analysis is not required.

Table 2-4 Dose rates at south wall penetrations and double doors

	Gammas (µSv/hr)	Neutrons (µSv/hr)	Total (µSv/hr)
S2 with new chase X = -920cm, Y = 640cm at Z = -200cm	6125	7050	12785
Corridor near chase S1 at Z = -180cm	2060	< 100	2085
Double doors at Z = -140cm	355	510	845

2.5 North Wall and Ceiling

A more detailed simulation of the north end of the eHall will be performed to specify exactly how tight a penetration is needed where the beam line exits the eHall and enters the tunnel. Additional information will need to come from a simulation of a proton beam in the future BL4N.

In this simulation, the original wall has been modeled as regular concrete and is 150cm thick. There is a (perhaps too large) penetration in it of 635cm by 240cm to allow for the tunnel, of which 150cm of its opening is partially filled with movable shielding blocks at the west end.

There is also new shielding needed along the north end of the eHall, to construct the adjoined tunnel leading from the cyclotron for the future BL4N into the ARIEL tunnel. The ultimate thickness of this wall is driven primarily by the anticipated future proton-beam current. For e-linac operation, less shielding is required. There is a 150cm thick by 1270cm long concrete wall extending westwards from the cyclotron east wall. This wall is 420cm tall inside the eHall, intended to reach the underside of the newly poured-in-place concrete ceiling (which is 180cm thick) at the north end of the eHall, and then extends up to the topside of the existing roof beams. Above the new concrete ceiling, this wall continues all the way to the west wall.

Along the top surface of this wall, there are three openings for j-shaped conduits in order to pass electrical services from the top of the roof beams into the eHall. The openings are 64cm by 12cm and are roughly centered within the wall's thickness. They exit into the eHall below the roof beams from the south side of this new wall at a height of 734cm; simulations show that the dose rates at these openings meet requirements.

Within the eHall (and below the ceiling), the new wall angles northwest to the existing north wall. Its height remains 420cm as it joins the new poured-in-place ceiling above, but its thickness needs to increase to 360cm of concrete where it joins the north wall. Its thickness can be less towards the centre of the eHall down to a minimum of 210cm. Once again, the ultimate thickness of this angled wall will be driven by the proton-beam requirements of BL4N and will need a thickness of 360cm made from concrete and steel. For e-linac operation, it is required that for the first 300cm or so from the north wall, the angled wall is 360cm thick before becoming thinner.

Within this region of the wall will be the penetration for the electron beam line to the tunnel; a future detailed simulation will provide specifications and will be in Phase 2 of this design note.

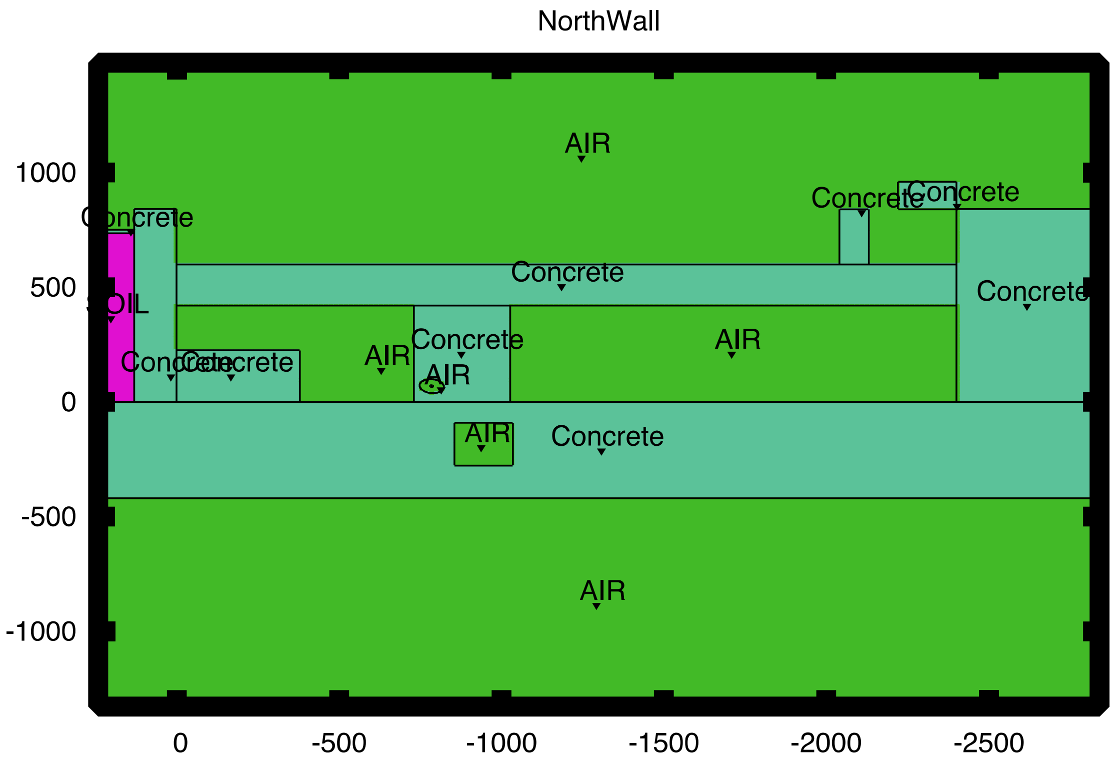

Figure 2-9 A vertical slice of the eHall looking north showing the poured-in-place ceiling, the outer concrete shielding of the beam dump and the location of where the electron beam line exits the eHall to enter into the tunnel.

There is a new poured-in-place concrete ceiling at the north end of the eHall. It should be 180cm thick and must cover the northeast section of the eHall from the west wall to the new angled shielding wall and from the north wall southwards to below the roof beams. The area above the future BL4N will be covered with shielding blocks. Figure 2-10 shows the total equivalent dose rate attenuation through the concrete slab carried out for a full beam loss of 50MeV and 500kW electrons directly below the roof slab. The roof slab extends from Y=420-600cm and the total dose rate is well below the 50mSv/hr limit. There will be a hatch through this ceiling to allow access to the beam dump and general access to the eHall. As with other hatch blocks at TRIUMF, they must be “stepped” to minimize the escape of radiation.

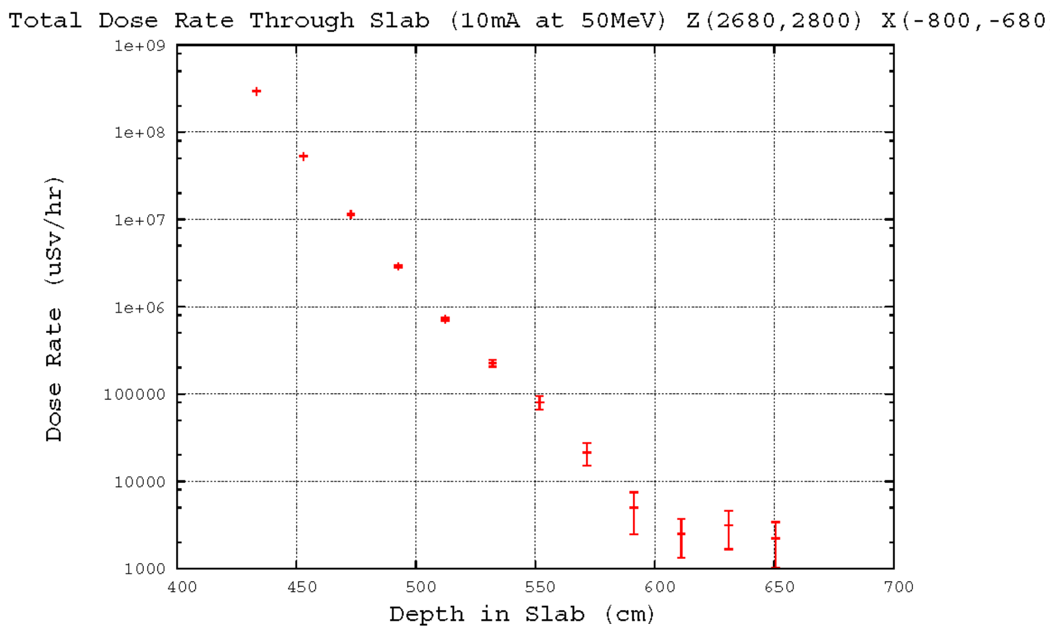

Figure 2-10 Total dose equivalent through the 180cm thick ceiling slab at the north end of the hall.

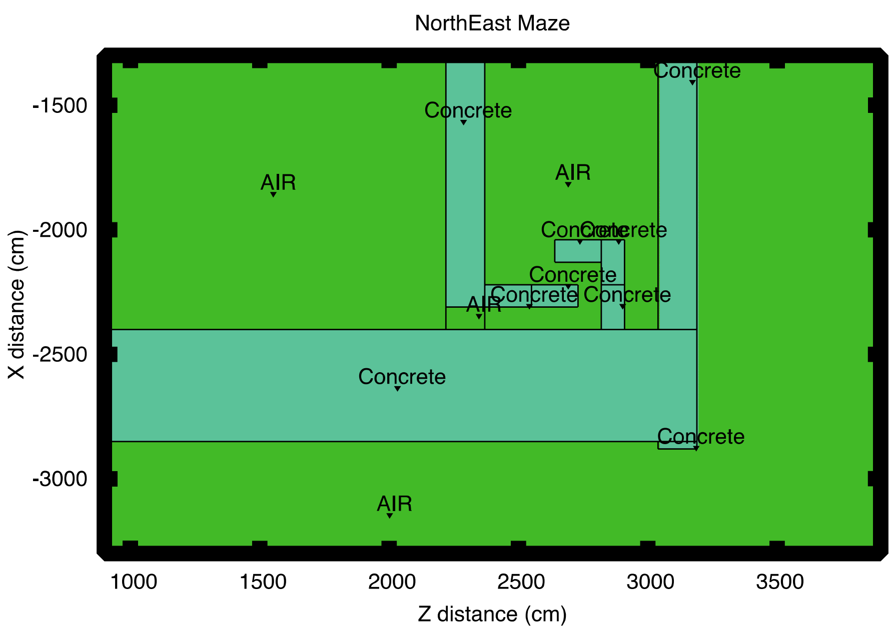

Figure 2-11 Plan view (X vs. Z) of the northeast maze positioned over the BL4N shielding blocks.

The final design of the northeast maze has not been determined, but the proposed design shown in Figure 2-11 is thus far adequate for all envisioned beam conditions and is driven primarily by neutron propagation down the maze opening. The dose rates at the maze exit for an upstream loss are shown in Table 2-5. There will be some flexibility in the final block orientation but any design will need to be verified by simulation. The current simulations show that the outer portion of the maze (Z > 2800cm or X >-2200cm) can be constructed with blocks that are two instead of three foot thickness. As well, because the nearest occupancy is at the vault roof, the ceiling of the maze outside the north wall can be made entirely of two foot thick blocks.

Table 2-5 Dose rates for different beam losses in worst case locations along the north wall for current and future installation

Locations & Beam Loss	Gammas (μSv/hr)	Neutrons (μSv/hr)	Total (μSv/hr)
Northeast Maze Exit (Loss at Z=1060cm)	25	7035	7080
Upper North Wall (Loss at Z = 1060cm)	21960	90	161250
Upper North Wall with Cryomodule (Loss at Z=663cm)	63000	950	126550
Upper North Wall with Cryomodule & Lead (Loss at Z=663cm)	9300	0.9	10500

Later phases of the accelerator configuration in the eHall may include a recirculation ring. Owing to the strongly forward peaked bremsstrahlung radiation, the ring configuration presents the most stringent requirements for both the north and south walls. For the south wall, a local shielding wall is planned to provide protection at lower elevations, and at higher elevation there is soil in the straight ahead direction. The upper north wall, however, above the 284’ elevation, has a low occupancy area behind the 5 foot thick shielding wall. This area is shown in Figure 2-12 and is located above the lower ceiling on the left hand side of the eHall.

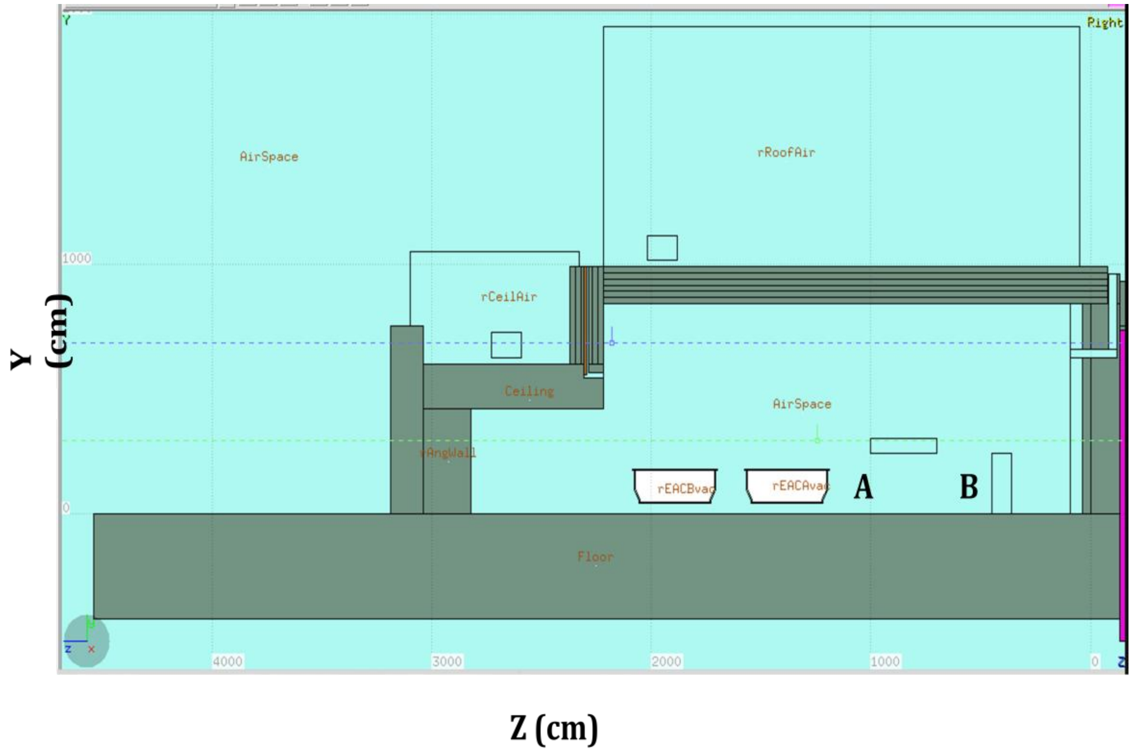

Figure 2-12 Electron Hall layout showing the cryomodules. The beam is directed along the Z-Axis towards the left. The upper north wall area is in the upper left above the lower ceiling.

It has been found that for a high energy upstream loss, a configuration that will only be possible when the ring is added to the accelerator, the strong forward directed bremsstrahlung radiation penetrates through the north wall above the 284' elevation resulting in dose rates that have the potential to exceed 50mSv/hr. Several configurations were investigated and the results are given in the Table 2-5. The first examined a loss of 75MeV electrons at Z=1060cm, marked at location 'A' in Figure 2-12, and results in a total dose rate of over 160mSv/hr.

Further simulations were carried out to incorporate the cryo-modules, the as-built locations of service penetrations in the north wall, and to investigate options for local shielding. In addition, the beam loss point was moved to the most upstream point on the ring where the beam is directed northwards. This corresponds to Z=663cm and is shown as location 'B' in Figure 2-12. The result of shifting the beam loss point further upstream is that the cryomodules do not provide as much shielding. A simulation was carried out with a 1.9cm thick lead shield over top of the beam line which results in sufficient shielding. This simulation also included a 50% fill of the penetrations with copper, to reproduce the expected cable fill ratio for the penetrations. The dose rates in Table 2-5 are the highest found in the vicinity of the penetration 2m east of the beamline. The lead shield would need to be 20cm wide and extend along the beam line from Z=700-1050cm. It may prove that such a shield is not compatible with beamline components and that a vertical shield is preferable. This will be investigated further when the ring is designed.

2.6 **B3 Tunnel**

There is a tunnel at the B3 level running under the floor of the eHall that will be used for service distribution, shown in Figure 2-13. There are four hatches that allow access through the floor into this tunnel and could allow radiation to enter the B3 level of the Service Annex.

The first hatch, positioned at the foot of the south wall (and is partially under the new concrete of the south wall) will be used to pass the cryogenic pipes that run down the south wall into the tunnel for distribution to the accelerator system. This hatch will either have a chimney high to provide a chase in a close geometry around the pipes or will be filled with 90cm of concrete with cored holes for the pipes to pass through.

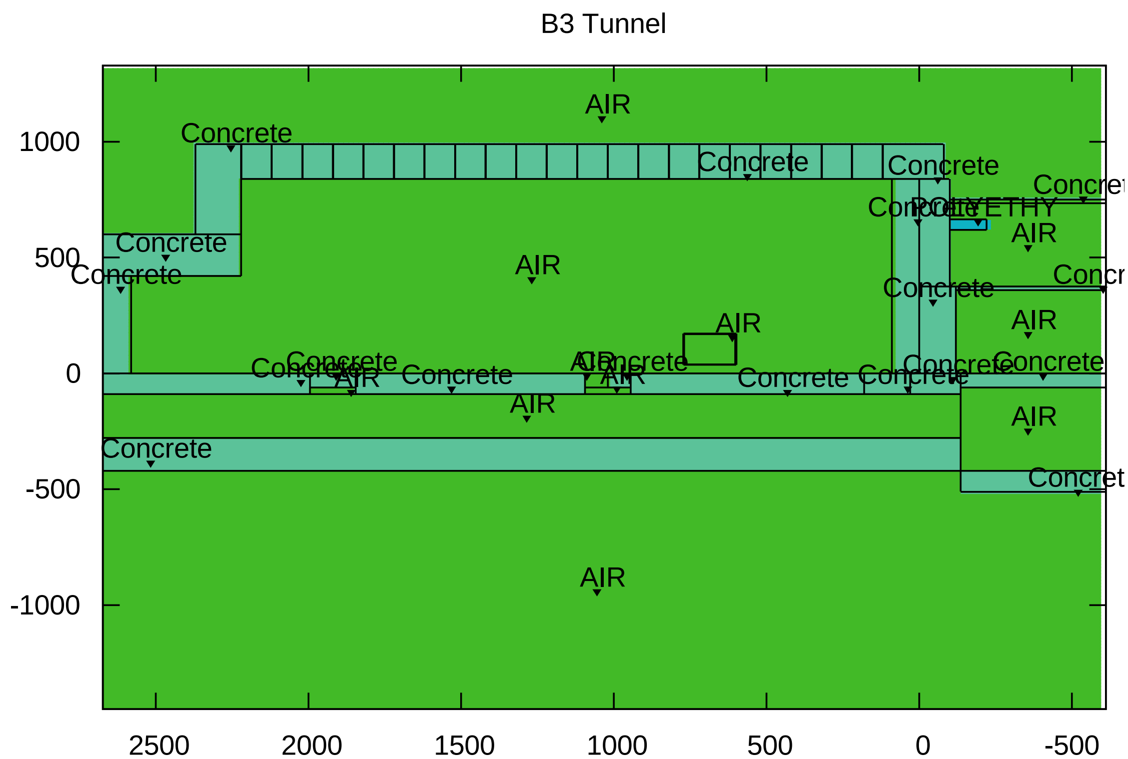

Figure 2-13 B3 tunnel with hatches running under floor in the eHall

The second hatch (from the south wall) will be partially plugged with 60cm of concrete, leaving just one quarter of its area open to feed services through. This opening is right next to the beam line and leads to the highest possible radiation fields to reach the tunnel entrance at the Service Annex. Simulations were run with a beam loss next to the opening in the second hatch and dose equivalent fields were recorded just outside the tunnel entrance of the B3 level of the Service Annex at Z = -180cm.

The as-built configuration has the hatch completely filled with cryogenic lines emerging through separately cored holes east of the hatch. The total cross section of the holes is less than the assumed opening in the simulation, so the dose rates for the as-built will be acceptable.

The third hatch will be completely plugged with 60cm of concrete and the fourth hatch resides “under” the north wall in the “doghouse” and is very far from the tunnel entry at the Service Annex. Immediately adjacent to the third hatch two 10” diameter holes have been cored. Again these holes represent a smaller cross-section than that assumed for the second hatch simulation and are located further from the tunnel entrance in the Service Annex, so the dose rates will be below the acceptable limit.

The fourth hatch will be investigated if necessary in the second phase of the design note.

Table 2-6 Dose Rates at the B3 Level of the Service Annex for Beam Losses in the eHall

	Gammas (μSv/hr)	Neutrons (μSv/hr)	Total (μSv/hr)
B3 level of Service Annex at Z = -180cm	2715	8725	11230

It is noted that any radiation that enters the tunnel from the open fourth hatch does not contribute to the field in the Service Annex when the loss point is upstream. Provided that the cryogenic pipes are tightly fit through the penetration in the first hatch, there should not be a problem with excessive radiation at the B3 level of the Service Annex.

3 Other Shielding and Summary

Figure 3-1 shows the geometry of the simulation in the eHall at the beam-line height of 75cm. There are internal shielding components that will reduce fields either to equipment inside the eHall or bolster the function of the shell of the eHall.

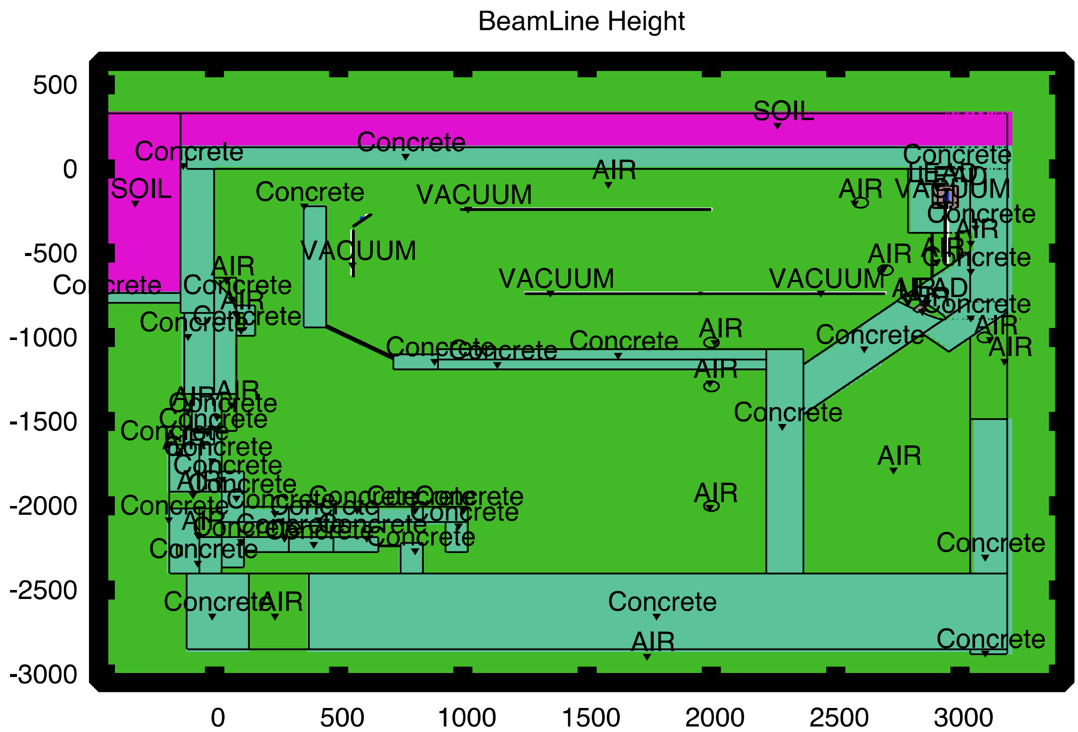

Figure 3-1 Plan view of eHall at the beam-line height of 75cm.

The north/south shielding wall is the primary internal wall used to provide shielding for equipment placed in the "klystron-gallery" area of the eHall. This has been modeled as assembled from the existing concrete blocks. It must fully abut the new, north shielding wall and extends some 15m to the south towards the eGun area. The area of lowest radiation field will be close to the wall and on the floor.

To give a general sense of its effectiveness, this wall will decrease an accidental loss gamma dose equivalent peak value from 10^{10}μSv/hr near the beam line down to 10^{7}μSv/hr in the general area behind the wall. Similarly, neutron dose equivalent values decrease from 10^{9}μSv/hr down to 10^{7}μSv/hr. Both the gamma and neutron values fall another factor of 10 down to 10^{6}μSv/hr right next to the wall (see Figure 2-2). As discussed at the start of the design note, the level of chronic loss assumed for shielding design is $1{:}10^{5}$ per meter loss. However, operating experience at Jefferson Lab for a similar accelerator, leads us to expect that worst case operating chronic losses per meter will be an order of magnitude less at $1{:}10^{6}$ per meter, and typical chronic losses could be reduced by another order of magnitude. Therefore scaling for a distributed loss we can expect dose rates behind the wall of $\approx$ 10μSv/hr.

Originally it was planned to have a wall in front of the eGun to protect it and any associated electronics from radiation fields generated from the higher-energy end of the accelerator, but this has since been deemed unnecessary.

The future south wall is a concrete wall to be assembled from blocks and is proposed to provide necessary shielding to the south when the future ring is built. For access, it has been arbitrarily placed 200cm from the West Wall and is roughly 550cm long, 150cm thick and 300cm tall. Its placement (and perhaps ultimate height) will be dictated by the final position of the ring. It will help prevent ring-operation losses from reaching the Service Annex.

Once the future ring placement has been decided, it may be necessary to augment the specified shielding with carefully placed, additional local shielding. One potential location is at the south end of the ring when the beam is directed eastwards. Here, it may be beneficial to place a small (say, 30cm-diameter), thin (say, 5cm-thick) piece of Pb at beam height next to a bender. With such strategically placed local shielding many radiation issues can be solved with little impact on floor space and at reduced cost.

Other than the area at the north end of the roof beams at the 284' elevation where additional local shielding on the upstream portion of the ring will be required, all areas outside the shielding remain below the desired 50mSv/hr radiation level for accidental full losses. Assuming a chronic loss of $1{:}10^6$ per meter, will mean that the dose rate in these areas (~ 2µSv/hr) will also meet the requirements for low-occupancy levels (<10µSv/hr).

For the high-occupancy levels outside the south end of the eHall (say, the offices on the south side of the eHall at an elevation of 302'), the radiation field restrictions are more stringent. Here, chronic losses should be below 0.5µSv/hr, a factor of 20 less than for low-occupancy areas. If we similarly reduce the accidental loss rate of 50mSv/hr for the low-occupancy area by a factor of 20, we obtain an accidental loss rate limit of 2.5mSv/hr as guidance for the high-occupancy area. While statistics are poor, when averaged over the large office area, the dose equivalent rates are found for 500kW of 75MeV beam running to the north, and as shown in Table 3-1 are well below the required level.

Table 3-1 Dose rates in the office area at elevation 302' on the south side of the eHall

	Gammas (µSv/hr)	Neutrons (µSv/hr)	Total (µSv/hr)
Office area to south of eHall at Y = 1140cm	60	125	180

A chronic beam-loss simulation with a distributed source will be done to confirm these dose rates and the results included in the second phase of the design note.

4 References

[1] www.fluka.org

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