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Memo

Date: *May 27, 2014 **Update July 8, 2014***

To: *RSC, D. Phillips and D. Kayran*

From: *D. Beavis*

Subject: *ERL Shielding Holes, Seams, and Penetrations for 3.5 MeV Beam*

Introduction

Several updates were added after the RSC meeting of June 25, 2014.

There have been several changes to the shielding since the original analysis was conducted. In addition, the analysis did not examine the potential dose that could escape through the shielding seams between the shield blocks. Several of the walls have single layers of shielding. Imperfections in the shielding blocks and the floor cause gaps to exist at many of these seams. In particular, the single layer roof has several gaps between roof beams exceeding 1cm in width. The focus of the presented analysis will be for 3.5 MeV electron beam to examine the shielding changes and imperfections.

The following are examined in this report:

1. Shielding seams transverse to the beam direction.
2. Shielding seams running in the direction of the beam.
3. The end-wall seam between the wall and the roof beam.
4. The change in the laser port.
5. The change in the cryo-piping ports.
6. Sensitivity to the beam loss location for selective examples.

Conclusions

It is concluded that the present shielding configuration is sufficient for low power beam and radiation surveys. Most results present are for 100 Watts of beam loss. The actual power of the beam for the low power is expected to be less than 10 Watts and radiation surveys will more likely be conducted at 1 Watt. The radiation surveys should provide some check on how well the seams are sealed around the side and end walls of the facility. The roof seams are an issue that needs additional consideration. This report will be updated or supplemented to include analysis for 25 MeV electron beam and the shielding surveys that will be conducted at low power tests.

It would be useful to have a better understanding of what limits the maximum sustainable power for beam loss. The lower power test may provide data on the limits that the present chipmunks can provide.

Simulation

The Monte Carlo code MCNPX 2.7c[1] was used to examine the dose from electrons striking material inside the ERL enclosure. In this report copper was used as the target material. The target was a rod of copper 10 cm long and with varying radius, but typically a 0.1 cm radius. In some simulations a 4cm diameter disk of copper was used. The thickness was usually 1cm. The relative location of the target to the seam or penetration can cause large changes in the potential dose that is calculated outside the shield. In most examples a location is chosen that is expected to create a nearly maximal dose outside the shield.

The electron and photon dose per electron is plotted in Figure I for 0.1 cm radius copper rod as a function of distance along the beam direction. For a thin target the electron dose from scattered electrons exceed the photon dose in the backward and sideward direction. If the target thickness is increased the photon dose has a small change but the electron dose decreased substantially. The doses per electron on target can be used to estimate the potential dose rates through shielding using Tenth-Value Layers (TVLs) or as the entrance dose challenging a penetration.

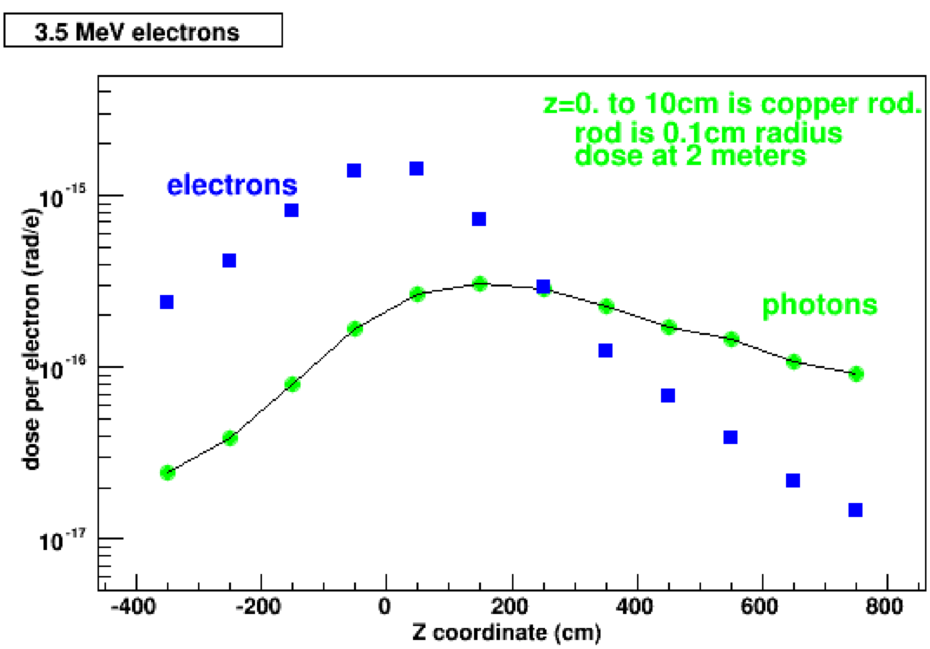

Figure I: The dose per electron 2 meters from a copper rod as a function of z. The dose is given for electrons and photons separately.

[1] MCNPX version 2.7C was used for the analysis. D. PELOWITZ (ed.), "MCNPX User's Manual", Version 2.7.0, Los Alamos National Laboratory, LA-CP-11-00438 (2011).

North End Wall Seam at 9 foot Elevation

The north end wall is designed with roof beams spanning over the top of the concrete walls forming the labyrinth. Initial inspection the seam over both walls revealed that the roof beam was almost an inch above the concrete sidewall and both seams over the two end walls are at essentially the same elevation. A flange of 1cm thick copper was used to approximate the electron beam striking an object. The flange was located at the end of the five-cell cavity with a distance to the first wall of the labyrinth of 540 cm. The geometry is shown in Figure 2. The concrete roof before the labyrinth is included in the simulation. The concrete roof ends half way over the second end wall forming a ledge. Water pipes are run along this ledge as well as cable tray supports.

A 3.5 MeV electron beam was directed at the center of the flange. At the edge of the concrete end wall the photon dose per electron is $3.2*10^{-20}$ rads/e. 100 Watts of beam corresponds to $6.44*10^{17}$ e/hr. The dose rate for the beam striking the flange is 21 mrads/hr. The dose rate is sensitive to the flange thickness. If the flange is changed to a thickness of 0.1 cm then the dose rate for photons increases to 110 mrads/hr. The dose from electrons can be ten times higher for thin objects if there is no material to absorb the electrons that are scattered. The calculations were repeated for the flange located at a position that simulates the Faraday cup that will be used in the first beam test location. In this case the flange is 1200 cm from the first labyrinth wall. The dose rates are a factor of two smaller than the results for the flange downstream of the five-cell cavity. A layer of Pb has been placed along the outer crack on the ledge to reduce the dose rates.

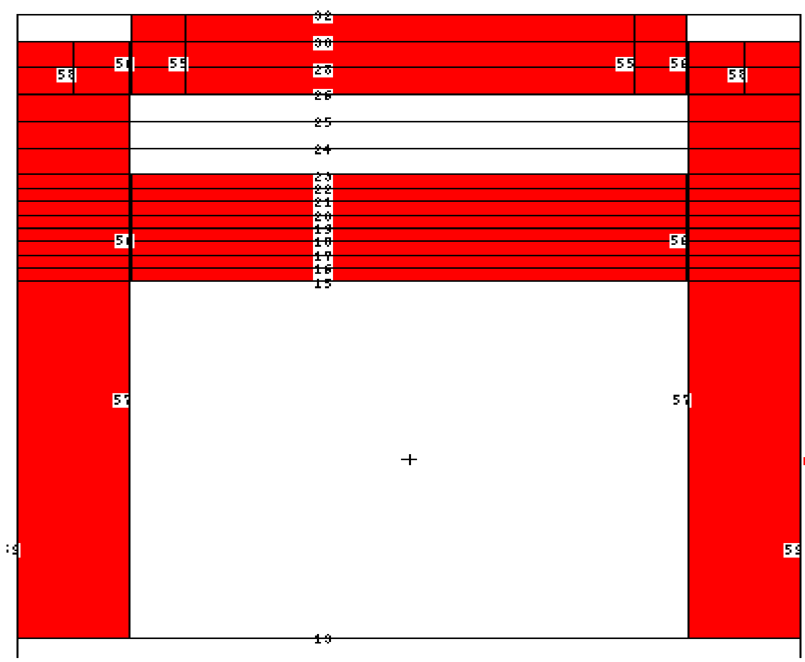

Figure II: The simple model of the two concrete walls and the walkway between them. The 2.54 cm seam is between surfaces 56 and 57. The dose was scored at surfaces and with point detectors.

The effectiveness of the Pb can be estimated using published TVLs. The Pb bricks placed along the seam will be 5 cm high and 10 cm thick. Using a TVL of 3.5 cm provides an attenuation[2] of $1.5*10^{-3}$ for 10cm of Pb. The Pb will completely remove the electrons[3] that are scattered from thin targets. For 100 Watts of 3.5 MeV beam the dose rate at the side wall is reduced to 0.1 mrem/hr. The estimated attenuation is expected to be conservative. A source of uniform photon fluence with fixed-energy was used as a second method to estimate the attenuation of a Pb brick on top of concrete. The results are presented in Table I. The results are in good agreement with the use of TVLs.

Table I: Photon Dose Attenuation for 10 cm of Pb

Photon Energy (MeV)	Attentuation
3.0	$1.7*10^{-3}$
2.0	10^{-3}
1.0	$1.3*10^{-4}$
0.5	$2.2*10^{-5}$
0.2	$4*10^{-6}$

The same geometry was used to estimate the dose rate for 100 Watts of 25 MeV electons striking a 1cm thick disc of copper 540 cm from the labyrinth wall. The photon dose rate was calculated to be 270 mrads/hr after the concrete wall. Including the electron dose rate increases the dose rate to 640 mrads/hr. The scattered electrons do not contribute as much to the total dose at the higher energy. The dose averaged photon energy is approximately 3 MeV so one would expect a dose rate of 0.35 mrads/hr with 10 cm of Pb after the seam[4]. The calculation was repeated for a 1mm thick disc. The dose rate is substantially lower since the electrons to not lose a substantial portion of their energy in the target.

During the recent installation of the beam dump the roof beams over the inner wall were lowered to decrease the height of the seam over the first wall. It is expected that this change will substantially reduce the dose rate for beam losses.

Roof and Wall seams Transverse to the Beam

There are a series of seams that are transverse to the direction of the beam. The side walls have relatively narrow gaps in the vertical seams and are typically spaced about every 10 feet. The roof has seams every two feet and some of the gaps are larger than 1 cm. Since several of the

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[2] See NCRP report No. 144, Figure 4.1.

[3] It was noted during the RSC meeting that an estimate should be made for the bremsstrahlung from the electrons. MCNPX was used to obtain the exiting photon dose for 2 MeV electrons striking the Pb block. The 2 MeV is well above the electron average energy. The resultant dose was 20 times lower than the dose from the initial gamma rays striking the Pb.

[4] The electron bremsstrahlung was estimated assuming it was generated by 8 MeV electron s on the Pb. This rough estimate was eight times lower than the dose from the incident gammas. The 8 MeV is the approximate dose-averaged electron energy incident on the Pb.

roof gaps are large it is worthwhile to examine them first even though the concrete shielding roof is excluded of personnel. The building roof is estimated to be 6 meters above the shielding and will be roped off and excluded of personnel[5] pending results from the initial radiation surveys.

The simulations are conducted using rotational symmetry about the z-axis[6]. The electron beam strikes a 0.1cm radius copper rod that extends from z=-5cm to z=5cm. The roof seam gap starts at z=0 and extends to z=gap size. The simple model[7] used to estimate the dose is shown in Figure III. The dose for photons and electrons was estimated 30 cm above the seam and then 6 meters above the seam which corresponds to the approximate roof location. This analysis was conducted for the copper rod for seams of several different gap sizes. For 100 Watts of 3.5 MeV electrons the photon and electron dose rates are given in Table II.

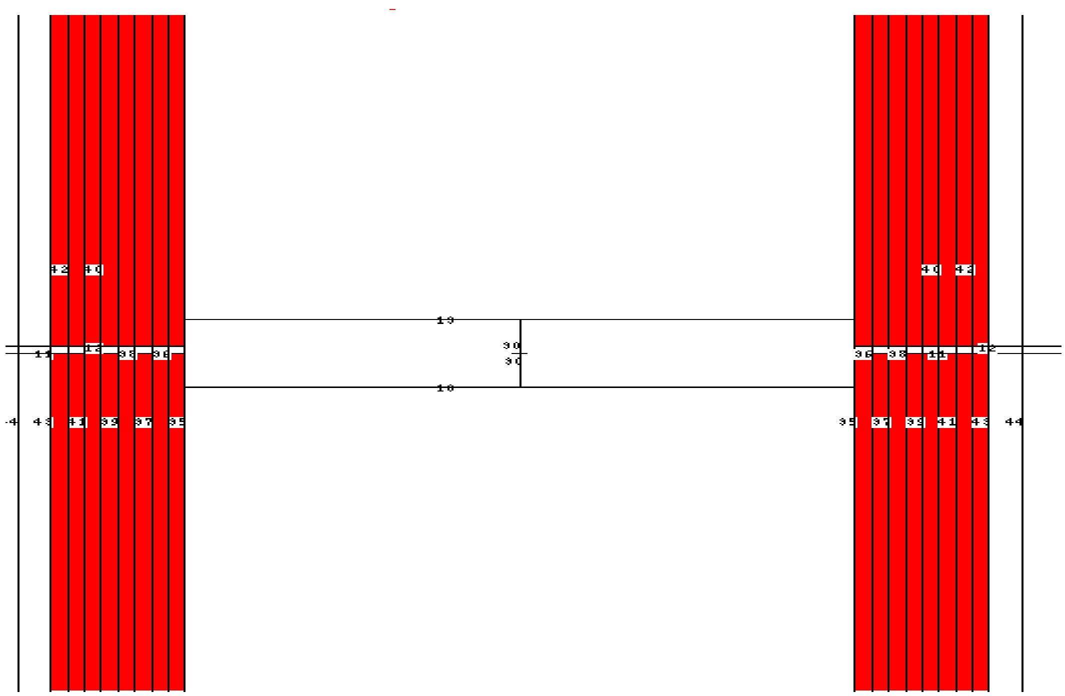

Figure III: Model of the 1cm gap between roof beams. The seam is located at z=0. to 0.5 cm. The target rod is 0.1 cm in diameter and is located from z=-5cm to 5 cm.

[5] RCD personnel will enter the building roof over ERL to conduct radiation surveys to document the risk. The RCTs may enter with C-AD experts that assist them in the surveys.
[6] The use of rotation symmetry reduces the computation time substantially. It will overestimate the dose for a flat surface such as the roof as the measurement point moves away from the beamline.
[7] A photo of a large roof seam is shown in Picture I.

Table II: Dose Rate for 100 Watts of 3.5 MeV Electrons Striking a Thin Copper Rod

Seam gap (cm)	location	particle	Dose rate (mrads/hr)
2.0	1 foot above seam	photon	**80**
2.0	1 foot above seam	electron	6600
2.0	At building roof	photon	1.6
2.0	At building roof	electron	230
1.0	1 foot above seam	photon	**36**
1.0	1 foot above seam	electron	1800
1.0	At building roof	photon	1
1.0	At building roof	electron	120
0.5	1 foot above seam	photon	**7**
0.5	1 foot above seam	electron	900
0.5	At building roof	photon	0.4
0.5	At building roof	electron	60
0.2	1 foot above seam	photon	**0.4**
0.2	1 foot above seam	electron	270
0.2	At building roof	photon	0.4[8]
0.2	At building roof	electron	20

Most of the seams are less than 0.5 cm and even with the scrapping location almost directly underneath the gap should not be an issue (7 mrads/hr). The photon dose rates on the building roof are not much of a concern for 100 Watt beam losses at most locations. Even for a 2 cm seam gap the photon dose rates are less than 2 mrads/hr on the building roof. However, there are circumstances where the dose rate on the building roof could be unacceptable. This will be discussed later in this section.

The dose rate from electrons appears to be a potential concern. However, it only requires about 2 g/cm^2 of material for absorb most of these electrons. The 10 meters of air provides 1.2 g/cm^2 and the building roof material probably provides sufficient material to eliminate most of the electron dose on the building roof. The beam pipe is typically 0.15 cm thick stainless steel or in some locations is constructed of thicker AL vacuum boxes. There are loss locations where the scattered electrons do not transverse much material to escape the beam transport system. For locations outside the shielding that are closer than the building roof the electron dose may be more relevant.

The center of the 10cm copper rod is more than 3 radiation lengths from the initial beginning of the rod. 3.5 MeV electrons have a range of 0.27 cm in copper. Therefore, the highest electron and photon dose rates outside the seam may be caused when the front of the rod is closer to the gap. Figure IV displays the sensitivity of the dose results as a function of where the target front surface is relative to the roof seam. The dose from electrons is not shown but is approximately a factor of ten higher. The dose out a seam has a narrow band in target locations where the photons

[8] This data point most likely is an anomaly, but the cause has not been resolved.

and electrons stream directly out of the enclosure and the dose is dominated by $1/r^2$. Once the target is shifted and a reflection is required for radiation to propagate through the crack the dose drops several orders of magnitude. The building roof dose is then dramatically different from the dose exiting the shield since the scattering point is near the entrance of the crack.

Figure I can be used to estimate the dose when adjusted for $1/r^2$. The dose rates for 100 Watts of 3.5 MeV electrons are:

Table III: Dose Rate through a 1cm Roof Seam at 1 Foot Above the Seam

Particle	Dose rate from Figure 1 (rads/hr)	Dose rate from calculations (rads/hr)
Photon	40	11
Electron	180	80

There is reasonable agreement between the simple technique and the more detailed calculations.

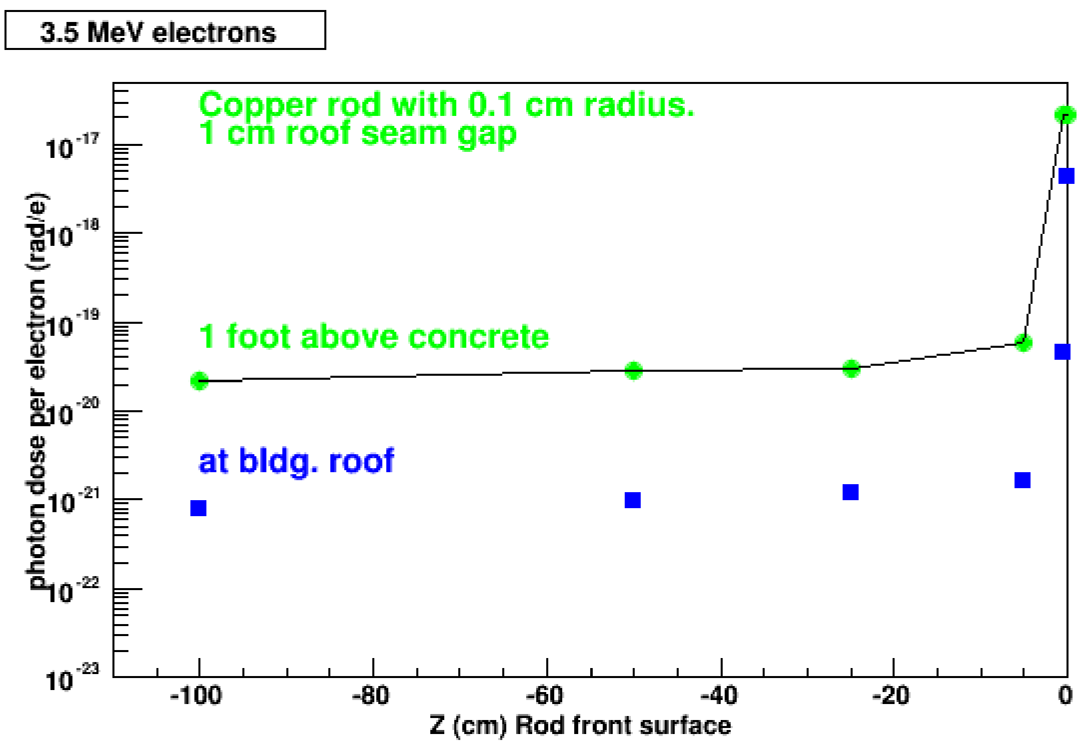

Figure IV: Photon dose from a rod as a function of the location of the rod front surface to the roof crack. The green circles are at 1 foot above the seam. The blue squares are on the building roof.

The distance used for the beam line to the roof is approximately the same as the distance from the gun beam to the east side wall. One can use the numbers without modification for vertical seams on the east-side wall. The east-side wall typically had small vertical seams. Recently an effort was made to reduce all side wall gaps to less than 2mm by placing steel plates into the seam providing 15 cm to 30 cm of steel. The seams were visually inspected and most are now much smaller than 0.2 cm. The photon dose through a 0.2 cm seam the dose rate is expected[9] to be 0.4 mrads/hr or less unless the front surface of the target is directly across from the seam. The front of the target was aligned with the start of the seam to estimate the photon dose outside of a 0.2 cm gap was calculated. The 100 Watts of 3.5 MeV electron beam produced a photon dose rate of 13,000 mrads/hr one foot outside the shielding gap. This could create unacceptable radiation levels if possible.

The west-side wall is more than twice the distance from the low energy beam line. Thus the dose rate challenging the gaps should be 4 times lower. Some of the seams were large and have been filled with steel plates. A barrier keeps personnel away from this wall for a distance of more than six feet. The increase in distance will help to reduce the potential dose for sources that are not directly in line with the vertical seams.

The vertical side wall seams have apparent dose rates that can be daunting for sources aligned directly across from a vertical seam. However, there are only five vertical seams along the low energy transport for each of the east and west side walls. Table IV provides comments for the five seams on each of side walls. The numbering starts with one and for the vertical seam at the upstream end of the gun.

Table IV: Comments on Vertical Side Wall Seams

Vertical Seam number	East Wall	West wall
1	Upstream of gun beam	Upstream of gun beam
2	Blocked by 2 foot heavy concrete	Clocked by Large heavy concrete block
3	Has line of sight for low energy but not first beam test	Has line of sight for low energy but not first beam test
4	Covered by second layer of concrete	Covered by steel block but overlap small
5	Adjacent to dump shielding	Blocked by steel

The vertical seams are satisfactory for the first beam test. The seams in which additional analysis or examination are highlighted in red. The third vertical seam is an issue for beam into the transport section upstream of the five-cell cavity.

[9] The results from Table II have been used.

The issue is to assure that no beam losses will not occur directly across from a transverse seam or to reduce the dose that can propagate through the gap.

Horizontal Seams

The horizontal seams between shielding blocks should have similar behavior as the transverse seams. The main difference is the horizontal seams have been positioned so they are at a different elevation than the beam. Therefore, the direct illumination through the seam by particles produced in the target is avoided. The copper rod was simulated with geometry that approximates to the east wall. The seam is 56 cm above the beam height and the inside surface of the concrete is 260 cm. The statistics were rather poor[10] but consistent with $3*10^{-19}$ rads/e of photon dose for a 0.2 cm gap. The result is in good agreement[11] with Figure IV for the roof gaps. Secondary sources can illuminate the sidewall seams with photons that can go directly through the seams. The requirement for scattering should make these potential sources 100 times lower in illuminating the seam but there is less attenuation. These secondary sources can add to the total dose.

The horizontal side wall gaps have been decreased in size with steel plate and many are much smaller than 0.2 cm.

Laser Port

The laser port was originally a rectangular port with dimensions 3 by 4 inches. The port was shadowed by the shielding[12] for the one megawatt waveguide. It became desirable to have the laser port in another location so a 3 inch diameter hole was bored through the shielding at a location approximately transverse to the first beam halo scrapers. The dose rate out the original laser port was estimated assuming that the port was shadowed by approximately two feet of heavy concrete. The new laser port is not shadowed for beam losses in the upstream transport. The dose rates out the laser port have been estimated using MCNPX in two stages. The first calculation provided the energy distribution and dose for electrons and photons. These distributions were binned in energy and then used as a source input in MCNPX. The source directed photons and electrons onto the area of the port based for the existing geometry. The simple model[13] of the shield wall with the Al spacer and the 1 inch lead shield is shown in Figure IV.

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[10] The results used were after 15 hours of CPU.
[11] A factor of 90 is used based on Table II to adjust for the difference in seam gap sizes used between the side wall calculation and Figure IV.
[12] http://www.c-ad.bnl.gov/esfd/RSC/Memos/ERL-Penetrations3.pdf
[13] A photo of the shield and laser tube is shown in Pic1 at the end of this report.

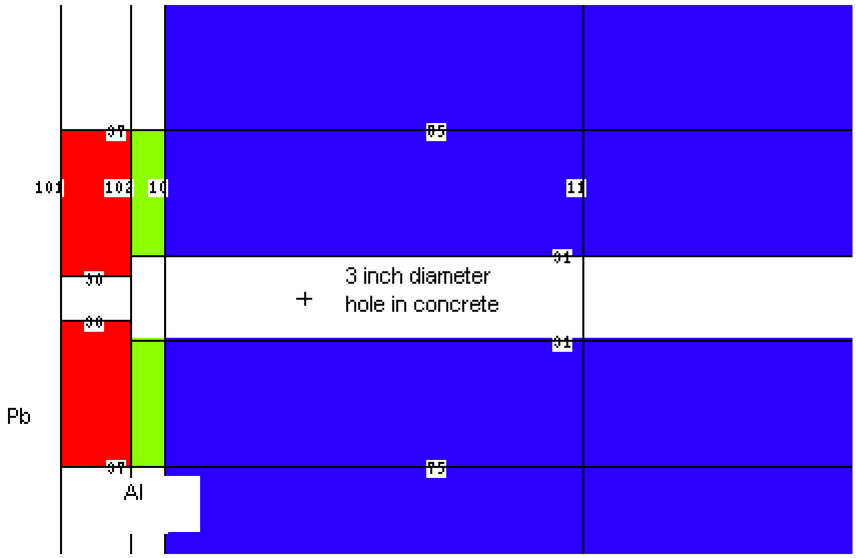

Figure IV: Pb shielding covering the entrance of the laser port inside the ERL shielding. The Al spacer does not shield the bored hole. The one inch diameter laser pipe is not shown.

The calculation used the 0.1 cm diameter rod on the beam line 255 cm away from east side wall and 137 cm above the port. For 100 Watts of 3.5 MeV electrons the dose immediately outside the port is 14 mrads/hr. At a distance of one foot from the wall the dose rate[14] is 10 mrads/hr. Beam faults with beam power of 1000 Watts are not expected to be sustainable although this assertion has not been proven. If necessary additional shielding can be placed inside the ERL enclosure if the laser pipe valve is moved. The old laser port has some critical length cables being routed to equipment and cannot be completely plugged. The Faraday cup for the first beam test has two feet of heavy concrete between it and the new laser port. The first halo scrapper has no shielding between it and the new laser port and will be used for a fault study if possible. The halo scrappers will be locked in the open position until the machine is ready to conduct fault studies on the scrapper.

Cryo-pipe Penetrations

The cryogenics piping penetrates the shielding at an elevation of 13 feet. Square ports with sides 12 inches where placed in the shielding for the piping. There are four such ports on the west wall. The area beneath the ports will be swept and access controlled. Access requirements may change after radiation surveys are conducted for the shielding seams[15] and cryo-piping. An

[14] The RSC asked to have this calrified as either photon dose, electron dose, or total dose. The numbers presented are the sum (total) of electron and photon dose.

[15] The access restriction was placed due to the large gaps in some of the shielding seams. Steel has been placed into these gaps to reduce the potential radiation.

example of the geometry[16] used in the MCNPX analysis is shown in Figure V. The correct pipe wall thickness is used but it is assumed that the pipes are empty.

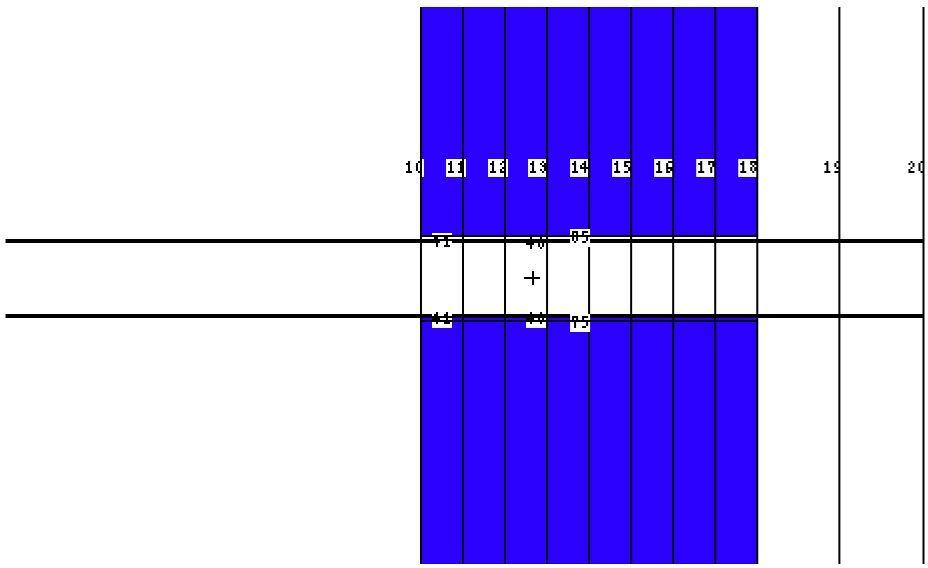

Figure V: Cross-sectional view of the round cryogenics pipe in the square hole for the west shielding. The pipe extends well into the enclosure but in the model is terminated two feet from the exterior of the shield wall.

The geometry was established for beam losses in the gun beam line. The distance from the beam line to the shielding wall is 6.1 meters. The beam line is 2.85 meters below the laser port center. The roof was not placed in most of the model calculations[17]. Electron and photon fluences were tallied on surface through the shield wall and outside. Of particular interest are the doses in the adjacent building which is the closest the personnel can approach with the barrier that has been placed between the west shielding wall the building skin.

The photon dose rates as a function of radius from the pipe axis is shown in Figure VI. The dose rates are given at 930 cm from the beam line, which is the position of the building wall. The two stage technique discussed for the laser port was also used for the cryo pipes. The structure in the electron dose is caused by the cryo pipe absorbing the scattered electrons but some outer areas of the port the electrons are not shielded by the pipe. The dose rate fo a 100 Watt loss in the lower energy beam line is less than 10 mrads/hr. An interlocking chipmunk is located approximately 60 cm from the vent pipe and 90 cm from the vacuum jacketed cryo pipe. The interlock threshold is 2.5 mrads/hr which would like the peak dose out either of these ports to less than 25 mrads/hr.

[16] A photo of the cryo-ports closest to the gun taken on the outside of the shielding is shown in Picture III. A photo from the inside showing the two cryo-ports near the five-cell cavity on the inside of the shielding is shown in Picture V.

[17] The roof was included in several simulations. Without the cryo-piping it could increase the dose rates for photons by a factor of two. When pipes were added into the same model the dose with a roof was almost identical to the dose without a roof.

This chipmunk is not effective[18] in limiting the dose out the upstream cryo-pipe ports for beam losses some early sections of the low energy transport.

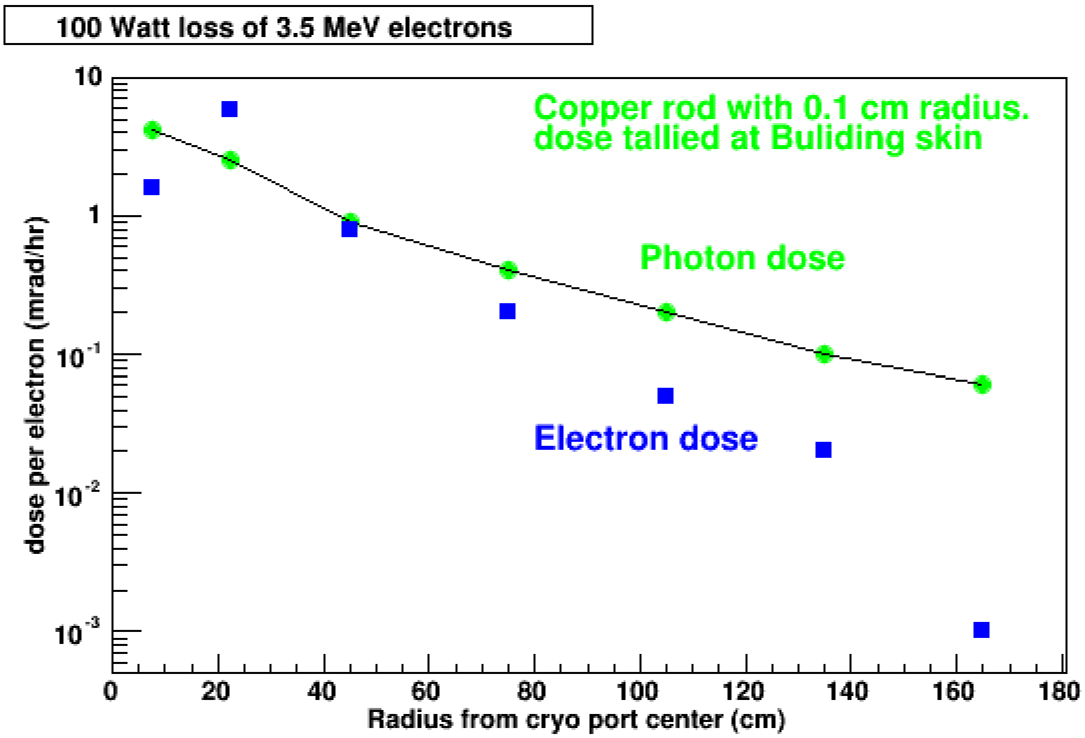

Figure VI: The dose rate as a function of radius from the cryo-port. Dose using surface dose averaged over annulus. The average radial position was used for the position. The vertical axis should be labeled as dose rate.

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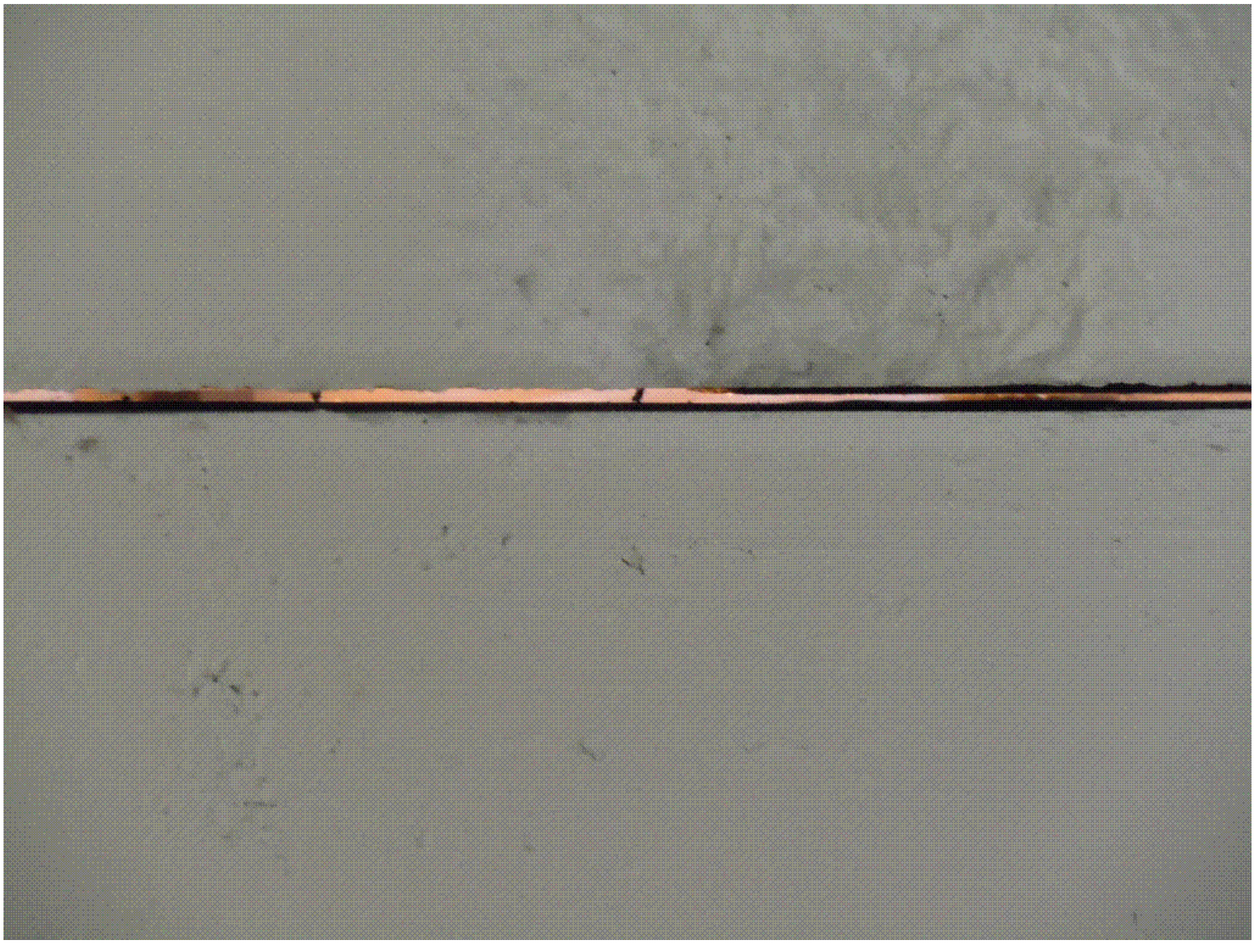
[18] The large shielding block at the south end of the ERL ring shadows the chipmunk from some loss locations in the upstream gun transport.

Photos of Areas of Interest:



Picture I: Examine of a gap (~1cm) between to roof beams. The photon is taken from inside the enclosure look up through the seam gap.

Picture II: Photon of the new laser port with the Al spacer, Pb shield and the stainless steel pipe for the laser beam.

Picture III: West side barrier with cryo-pipes exiting the shielding at an elevation of 13 feet above the floor.

Picture IV: The inside of the cryogenics pipes near the fiver cell-cavity.

Picture V: Shows one of the joints on the west wall. The steel plate can be seen in both the horizontal and vertical seams.