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Memo

date: *April 8, 2013 (Updated: June 17, 2013)*

to: *C-AD RSC, PK Job (PS), S. Walker (RCD), and Z. Zhong (PS RSC)*

from: *D. Beavis*

subject: *Simple MCNPX Evaluation of NSLSII Linac Side Wall Shielding*

This note addresses issues for the NSLSII Linac. However, the energy range may also cover future electron machines that may be operated at C-AD. I wanted to archive the calculations and decided that the C-AD RSC memos page would be a satisfactory location. For C-AD it is hoped that this will be a useful reference for ATF-II and e-RHIC machines.

Introduction

The side walls of the NSLSII linac have been evaluated using simple empirical methods. References provide yields of transverse neutrons and photons produced by electrons striking various materials up to the top energy of the linac, 250 MeV. The photon and neutron dose is then calculated outside the light concrete shielding using attenuation coefficients. These coefficients are derived from broad beam conditions in the forward direction. This leads to conservative estimates for the side wall shielding. A simple evaluation will be conducted using MCNPX and compared to estimates using the empirical shielding techniques. It will be concluded that for the homogeneous concrete sidewall the simple formula technique overestimates the dose outside the shield by a factor of 5 when compared to MCNPX. The transverse dose rates will be used for estimated of leakage out of penetrations in the shielding wall.

Updated Changes

The original report has been updated to include the following changes:

- A more careful comparison to the estimation of the Swanson method, which was provided by P.K. Job.
- An examination of the radiation as a function of the rod radius, which was thick (4 cm radius) and provided self shielding.
- An estimate of the radiation from a valve and a flag which are thin targets for which fault studies may be conducted.

Estimation Technique

The Monte Carlo program MCNPX[1] can be used to calculate the dose outside of complex or simple shielding for either hadrons or electrons. The easiest technique is to simplify the geometry to two dimensions and extract the characteristics of the external radiation field. It is assumed that a pencil beam of electrons strike a copper rod that is 10cm long and 4cm in radius. Figure 1 displays a plan view of the model used in MCNPX. The red wall represents the light concrete with a total thickness of 100cm and a density of 2.35 gm/cc. The walls extend from z=-700cm to z=+900cm. The inside radius of the tunnel is 300cm. The copper target starts at z=0. There are no other materials in the model. The photons are tracked to an energy of 10 keV, the electrons to 50 keV, and the neutrons to all energies. The side wall is divided into layers of 25cm thickness to tally the fluence of neutrons and photons as they are transported through the wall. The fluence can be converted to dose by using energy dependent fluence to dose conversion factors.

The dose is tabulated in 100cm bins in z. A systematic flaw with this technique is that the dose includes radiation that is moving both towards the inside and outside. However, this leads to an overestimate of the dose for locations inside the material. The dose is calculated per electron incident on the copper rod. The photon dose resulting from 50 MeV electrons striking the copper target are displayed in Figure 2. Figure 3 shows the photon dose as a function of z for 200 MeV electrons. The photon dose on the inner wall peaks about 300cm downstream of the target.

A few simple trends can be seen for both the 50 MeV and 200 MeV photon results. The first is that the dose along the transverse wall roughly scales with the beam power, thus for fixed current it will increase linearly with beam. Secondly, it is clear that the dose on the inside of the shielding wall is nearly constant after the peak in the radiation pattern. This implies that the entrance dose for penetrations far downstream of the beam loss point can have substantial entrance dose. As the shielding becomes thicker the peak in the radiation pattern becomes more pronounced with the dose falling much faster in the backward direction. The full width at half maximum outside the one meter shield is rough 4-5 meters. These trends are useful for considering the shielding design.

The peak dose outside a shield is always a quantity to consider in the design of the shield and the protection system. We will need to assume an amount of beam lost to arrive at an actual dose or dose rate outside the shield. A current of 220 nano-Coulombs will be considered for this report. The results can be scaled to any current that is possible. The 220 nano-Coulombs equates to $4.95*10^{15}$ electrons per hour. It is assumed that this current can be lost in a target material such as the copper rod used in MCNPX. The peak dose rate outside the shield is then estimated to be 3.5 mrads/hr for 50 MeV electrons and 11 mrads/hr for 200 MeV.

[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).

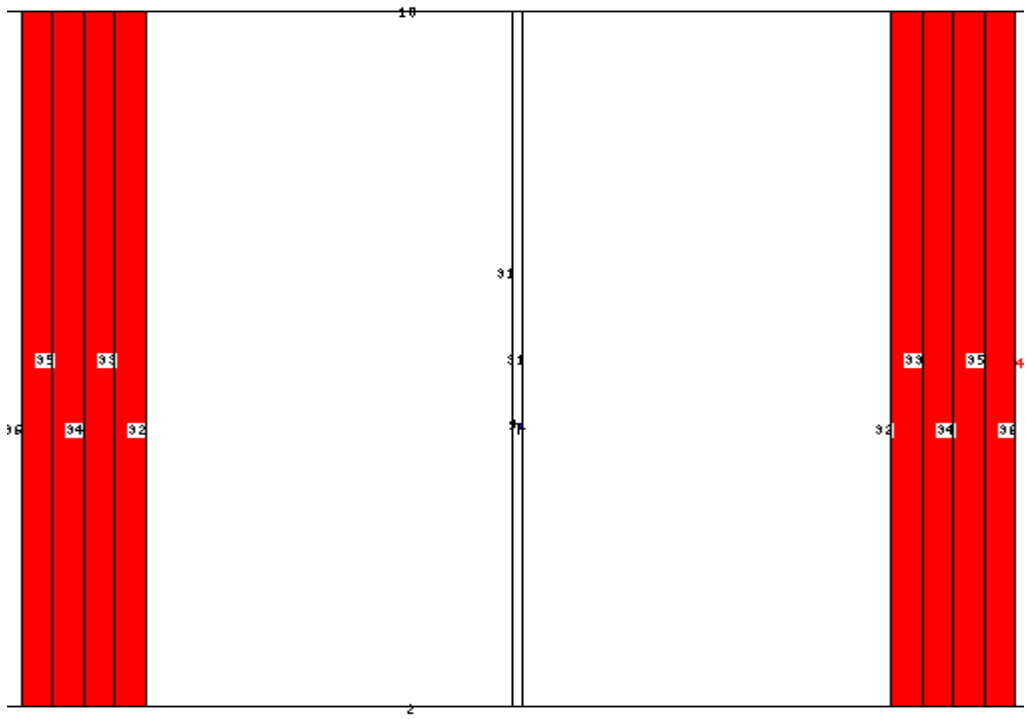

Figure1: MCNPX model of the linac tunnel. The light concrete (red) is 100cm thick and has an interior radius of 300cm. The side wall extends from z=-700cm to z=900cm.

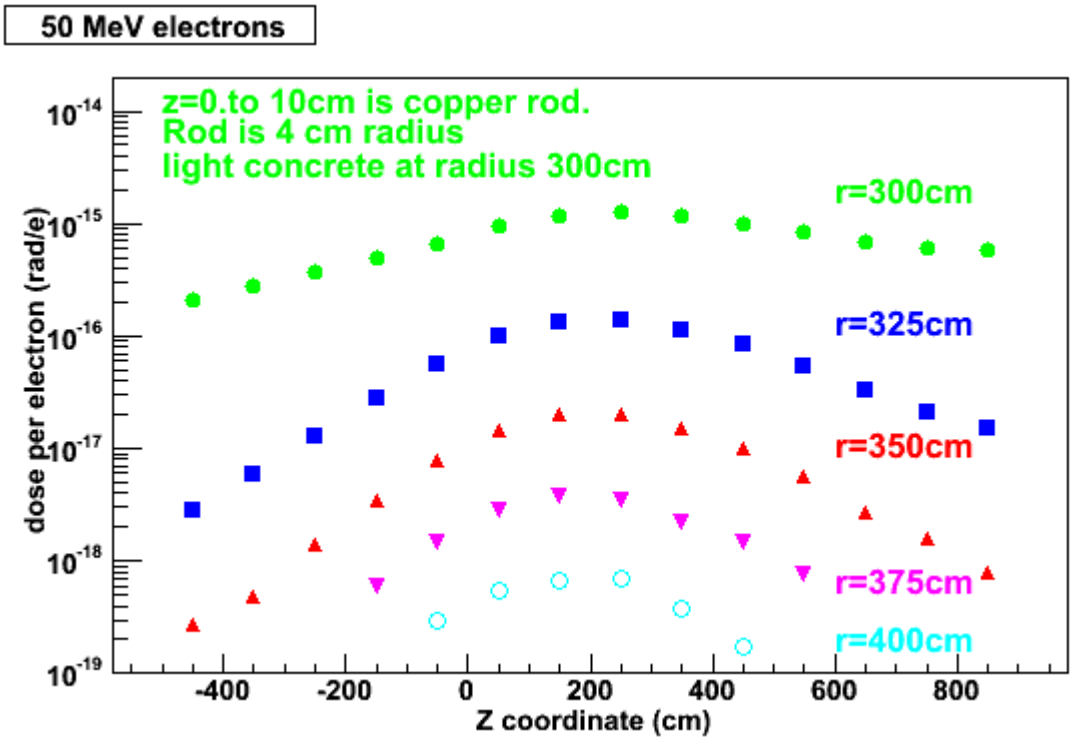

Figure 2: Photon dose as a function of z for different depths in the light concrete side-shield wall for 50 MeV beam hitting a copper target.

We can compare the MCNPX results to the analysis provided[2] in Tech. Note 12. In that note, the dose outside 90 cm of light concrete was calculated to be 0.25 mrem/hr when 0.66% of the 200 MeV electron beam was lost on a local target. This can be scaled to 100cm of concrete and the beam current used above and results in 232 mrads/hr. This is a factor of 21 times higher than the MCNPX result. In the update analysis section below a more careful comparison has been conducted by P.K. Job and when coupled with new analysis with a rod of smaller diameter the ratio is a factor of 5 instead of 21.

The neutron dose as a function of z is displayed in figure 4. The distributions are similar for 50 MeV and 200 MeV. The statistics are limited so only a few points can be plotted at a depth of 25cm. Changes to the input parameters would be needed to track the neutrons deeper into the shield. Since the main purpose of this report was the examination of the side wall for photon shielding additional neutron calculations will be deferred for now. The neutron fluence at the inside shielding surface have sufficient statistics to allow use for penetration analysis.

The attenuation factor for light concrete given in footnote 2 is 40 gm/cm^2. Taking into account the distance change from 3 to 4 meters and the attenuation of the light concrete the neutron dose rate outside the shield wall is estimated to be 6 mrem/hr for a loss of 220 nano-Coulombs per second. The neutron dose is about half of the photon dose outside the shield.

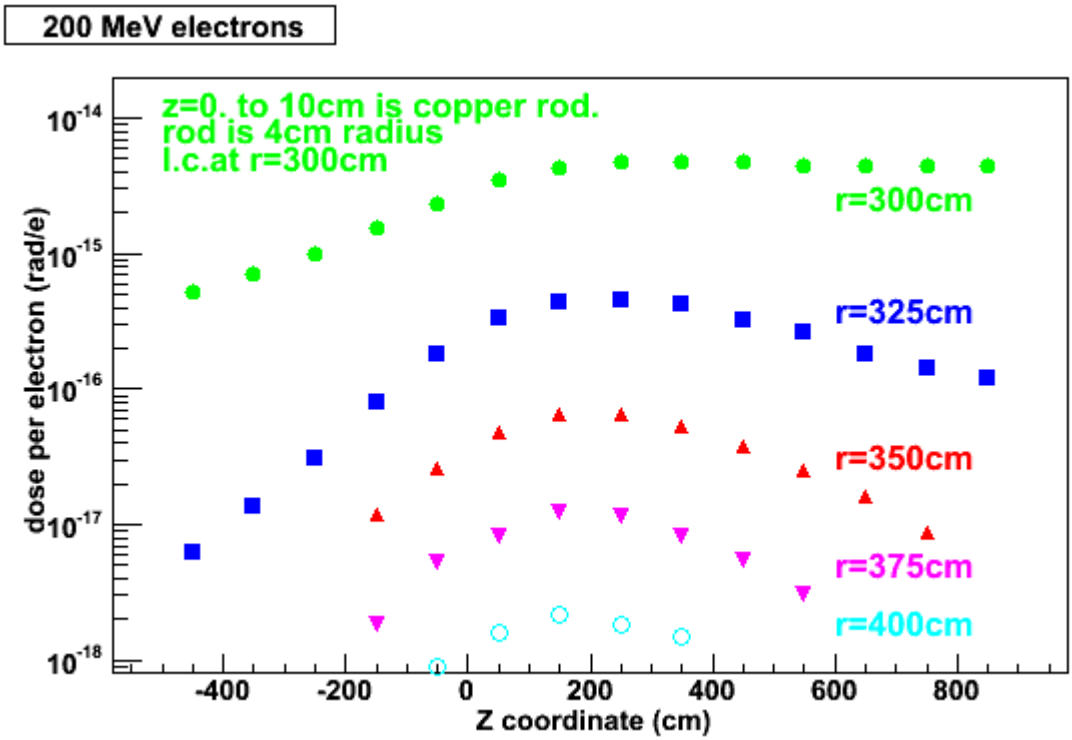

Figure 3: Photon dose as a function of z when 200 MeV electrons strike a copper target.

[2] P.K. Job and W.R. Casey, "Preliminary Radiological Considerations for the Design and Operation of NSLS II Linac", NSLS II Technical Note 012, July 25,2006

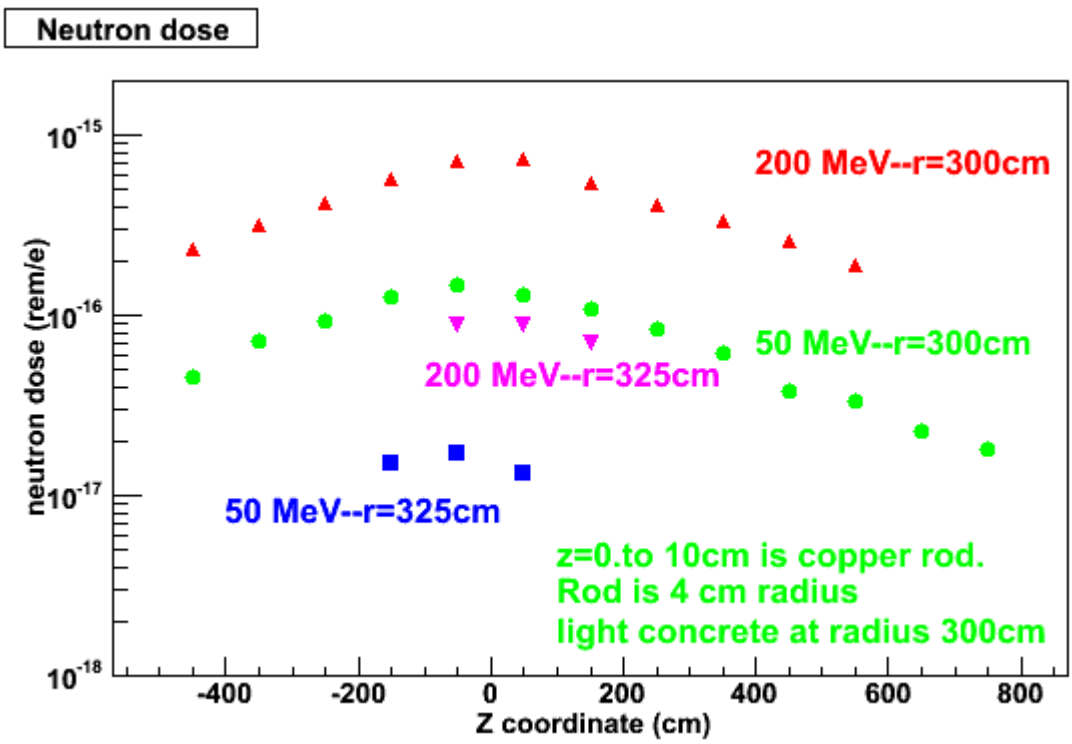

Figure 4: Neutron dose as a function of z for 50 and 200 MeV neutrons striking a copper rod.

The dose outside the shield for a continuous 200 MeV beam fault of 220 nano-Amps results in a total dose[3] rate outside the uniform side shield of 17 mrem/hr. The routine levels based on a 10% beam loss would be less than 2 mrem/hr and is expected to be conservative. These dose rates of radiation can be easily controlled by administrative processes and radiation detectors are not required[4].

The highest dose rates are most likely to occur near penetrations depending on how well the penetrations have been shielded. The three cableway ports are approximately 30cm by 30 cm. The front portion of the cableway[5] has a Pb shield 10cm thick with a hole 10 cm high and 25 cm wide. Footnote 2 gives attenuation factor for Pb as 25 gr/cm^2 for gammas and 161gm/cm^2 for neutrons. The 10cm of Pb reduces the gamma dose 10^{-3}. This provides for an entrance dose to the 250cm^2 hole area of 12.5 rads/hr. The dose out the back of the penetration can be estimated by assuming that the entrance dose bounces once off the inside walls of the penetration and exits though the hole in the Pb shield on the back side of the cableway. This method is the same as used in the SAD for the labyrinth estimates and is discussed in many references[6]. The estimated photon dose rate out the hole in the back Pb is 16 mrads/hr.

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[3] The neutron and gamma doses do not peak at the same z location, which makes this summation conservative.
[4] This is based on the current shielding policy, which requires an interlocking radiation monitor if the dose rate can exceed 100 mrem/hr.
[5] See NSLSII drawing LBT-SHLD-7100. At present there has been no material added to the Pb, such as concrete
[6] See NCRP Report No. 144 as an example. Figures 4.12 are used for a rough abledo coefficient of 0.03. For neutrons Figure 4.13 can be used for an albedo coefficient of 0.01.

It has been noted that there may be a small vertical height that can be approximated as a direct hole through the shielding. A simple technique for this can be found in Sullivan[7] to treat this example. An angle to the hole entrance of 45 degrees will be used with an area of 1cm by 25 cm. The dose that exits the back side of the penetration[8] is 60 mrads/hr. The dose rate in an MCI is still sufficiently small that no interlocking radiation monitor is required for protection.

The dose rate from neutrons out the cableway penetration can be estimated with similar means. The initial Pb only reduces the neutron dose rate by 0.49. A simple treatment is to assume that the entire front of the cable is covered with Pb. The neutron dose rate after the Pb would be 1460 rem/hr. Using the curves from Sullivan it is estimated that 600 mrem/hr of neutrons exit out the back of the penetration. This dose rate would require an interlocking radiation monitor. This estimate is rather crude and the ability to crash 220 nano-amps of the 200 MeV beam in a short component directly across from the penetration may not be possible. It is suggested that the fault studies examine the penetrations and be used to determine a more realistic expectation for dose rates out the penetrations. Then the appropriate protection scheme developed. This example does point to the fact that when shielding the accelerator, one must not forget about the neutrons.

Updated Analysis

Fault studies will be conducted at the NSLSII linac when it is restarted. Two objects that may be used to compare the calculations to actual beam faults are vacuum valves and the beam flags. The vacuum valves are about 6mm thick and the flags are about 0.6 mm thick. The valves and the flags will be approximated as copper rather than stainless steel and since flags are typically rotated 45° the flag thickness will be approximated as 0.85 mm. For each the radius will remain the 4 cm previously used.

The results are shown in Figure 5 for the rod (10cm long), the valve and the flag for 200 MeV electrons striking the material. There is a substantial difference between the rod, valve and the flag. A flag and a valve are convenient to use as targets since they have known positions and thickness. However, the flags may be too thin to provide for measurements outside the shielding. The impact of the radius at z=0 is seen on the distribution. Since the rod is 10 cm long the impact on the dose distribution is not apparent, but the 4cm rod radius is substantially larger than the Moliere radius (1.1 cm). This implies that the rod dose rates may have substantial self shielding.

[7] A.H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Partcile Accelerators, Nuclear Technology Publishing, 1992. See Figures 2.24 to 2.27 and associated text.

[8] Most penetration formulas expect that the two transverse dimensions of the penetration are within a factor of two. For the purpose of obtaining an estimate we ignore the fact that in our case the ratio is much larger.

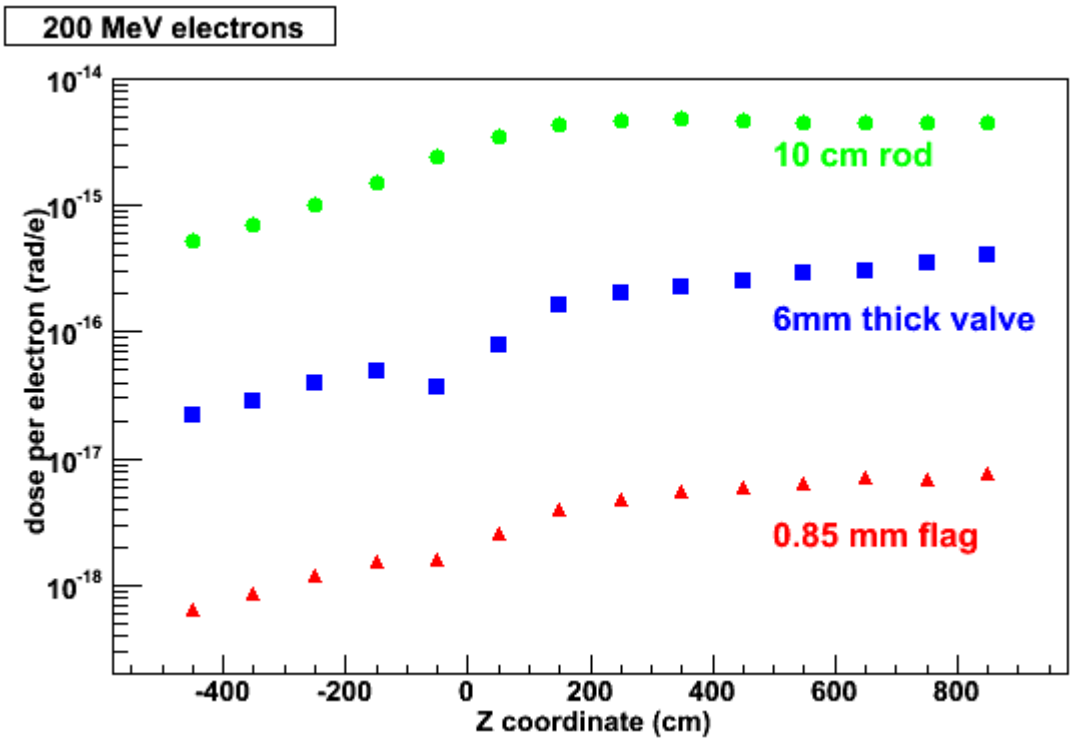

Figure 5: The photon dose at the concrete wall at a distance of three meters for the copper rod 10 cm long, a copper gate valve 6 mm thick and a copper flag 0.85 mm thick.

The rod length was kept at constant and the radius was changed to examine the impact of material radius on self shielding. Figure 6 displays the dose on the inside of the concrete wall for rods of radii 4cm, 2cm, 1cm, and 0.5cm. In the region of 90 degrees the 4 cm radius rod has a photon dose that is reduced by approximately a factor of two.

P.K. Job[9] has used the Swanson[10] method to provide a more accurate comparsion of the methods given by Swanson and the MCNPX results for the linac shielding wall. In addition a factor of two increase to the photon dose will be applied for the MCNPX results, which corresponds to a copper rod of radius 1cm. The neutron results are much less sensitive and will be left unchanged. The dose rate on the inside of the wall is higher in MCNPX than Swanson. However, the dose rate outside the concrete is a factor of five smaller than the dose rate given by Swanson. The greater reduction in dose is expected in the method by Swanson since a constant attenuation factor is used independent of energy.

[9] P.K. Job, "Dose Rates at the Klystron Gallery Wall Due to Beam Loss on the Linac Accelerating Structure (Comparison Between Swanson and MCNP)", April 22, 2013.
[10] W. Swanson, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, IEAE 1979, Tech. Report Series No. 188.

Table 1: Beamloss 15 nC/s at 200 MeV, Power Dissipated= 3 Watts

	Swanson		MCNP	
	Bare at 3 m	**1m concrete at 3 m**	**Bare at 3 m**	**1 m concrete at 3 m**
Photon Dose rates (mrem/h	1666	7.75	2700	1.50
Neutron Dose rates (mrem/h)	333	0.52	236	0.40

The simple model used has no material in the forward direction and no beam optics. The radiation in the forward direction will typically encounter the downstream machine components which will cause additional radiation along the sidewall eventually decrease the radiation (shadowing) along the sidewall in the forward direction.

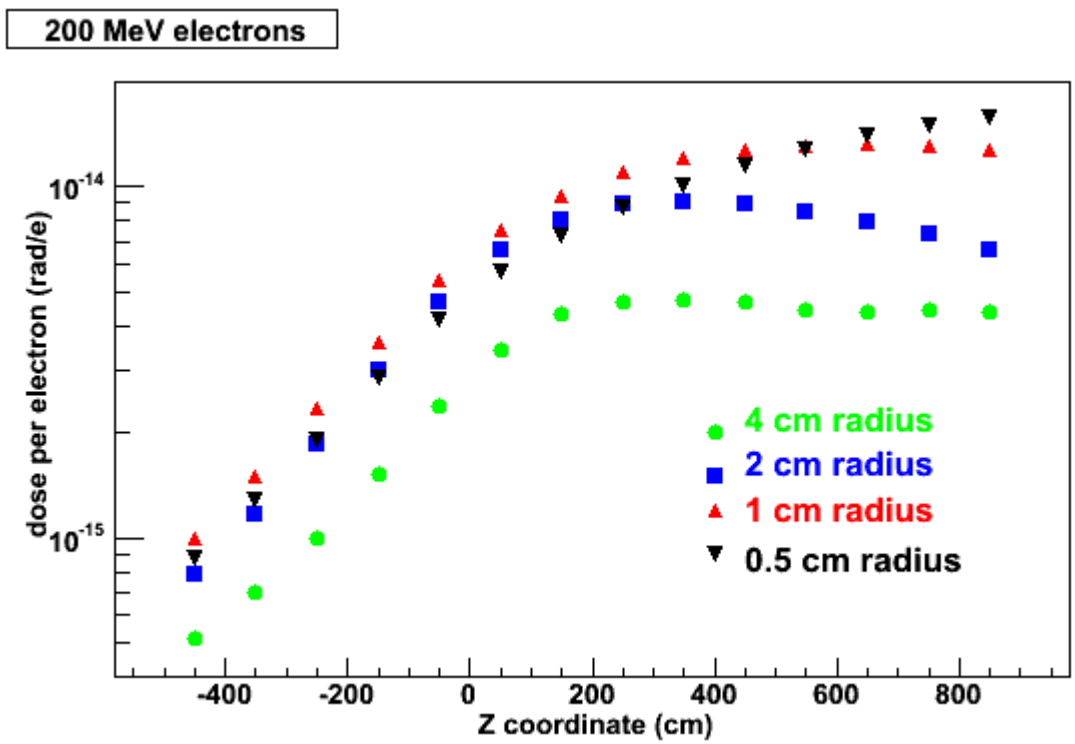

Figure 6: The photon dose along the wall of a 3 meter diameter light concrete tunnel for copper rods 10 cm long and with four radii.

Summary and Comments

A limited effort has been made to examine the effects of target size on the maximum possible radiation per electron. The radiation can be sensitive to the material. Copper was chosen since

the linac has long copper structures for RF and steel is the other common material close to the beam. However, other materials may exist just outside the beam pipe such as supplemental Pb shields. A Pb target for example can produce approximately twice[11] the neutrons at high energy as copper. Copper was considered a good representative target material for the Linac.

The results of beam fault studies are limited by several factors. These include determining the loss distribution of the beam and that they only characterize the present configuration. The more fault studies are relied on for design validation the more vigilant the configuration management process must be to ensure that a new configuration does not change the results concluded from a beam fault study. The two most important ingredients for a shield design are:

1. Understanding the shield design through analysis.
2. Controlling the design through configuration management.

A combination of validation measurements through beam fault studies combined with calculations, and a good configuration management process is a viable approach.

The results for 200 MeV electrons striking a copper target provide an initial neutron and photon fluence that can be used to estimate the dose outside the uniform shield wall and the cableway penetrations. The primary results are given in the table below:

Table 2 : 220 nano-amps of lost 200 MeV Electrons (with Update Photon numbers)

Condition	Photon dose (mrad/hr)	Neutron dose (mrem/hr)
Uniform 100cm concrete	22	6
Cableway penetration	120	600

It is expected to be unlikely to achieve a fault of this magnitude along the beam transport. The results do indicate that attention must be given to the neutrons in the shielding design especially for the penetrations. The penetrations could be studied in more detail with Monte Carlo techniques but with beam intensities during commissioning of 10 to 100 times lower than the 220 nano-Amps used in this report it may be more practical to conduct the beam fault studies and make final design considerations based on a combination of the measurements and the calculations.

CC:

I. Ben-Zvi

[11] See for example MNRP Report 144 Figure 3.12. At lower energies the difference can be even larger than a factor of two.