Cornell's ERL User Area Shielding Considerations

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The proposed Energy Recovery Linac (ERL), to be located at Cornell University, is currently having various components designed and assembled to test it's ground breaking goals. At the same time, we are starting to look into the overall layout and construction of this add on to the existing CESR. One design feature of great importance is the shielding of radiation from workers in the user area, where experiments will be preformed. This is what we will focus. Due to time constraints, we will only discuss the straight section of the shielding wall.

I. INTRODUCTION

A. Layout

As of now, the proposed design of the ERL's user area can be seen in figure 1. The shielding wall design is a ratchet wall, which may be seen in figure 2. The list of lattice components on the beam side of the wall is as follows:

- 4 m dipole magnets
- 5 m insertion devices
- Vertical and horizontal kickers
- Quadrupole magnets
- Sextupole magnets
- Beam collimators

All of these components can cause radiation to escape the beam line. This is the source of radiation we will be considering.

B. Radiation Concerns

The shielding wall is designed to protect personnel against several sources of radiation. The main source is the continuous electron beam loss, but the wall is also designed for protection against electrons lost due to collimators, and total beam loss at a point. There are several possible radiation components produced by the electron interactions, but the main three are bremsstrahlung photons, giant resonance neutrons (GRN), and high energy neutrons (HEN).

1. *Bremsstrahlung Photons*

Photons are produced when the lost electrons collide with matter. These photons then can then create more photons through a few mechanisms. More photons or electrons may be produced in atom excitation, Compton Scattering, or pair production. All of these cause more photons of different energies to be created. This is how the electromagnetic cascade is produced.

The energy of the photons in this cascade can range anywhere from 0.5 MeV, up to the incident electron energy. Although these photons are predominately peaked in the forward direction, there is a non-negligible transverse term, that must be considered. These photons can cause other forms of radiation, as discussed below.

2. *Neutrons*

GRNs are produced when the photons which are incident upon a nucleus have energy greater than the nucleon binding energy ($\sim$10 MeV). For GRNs to be produced, the photon energy must be between 7-30 MeV, and is produced by photonuclear interactions. This form of radiation is distributed isotropically.

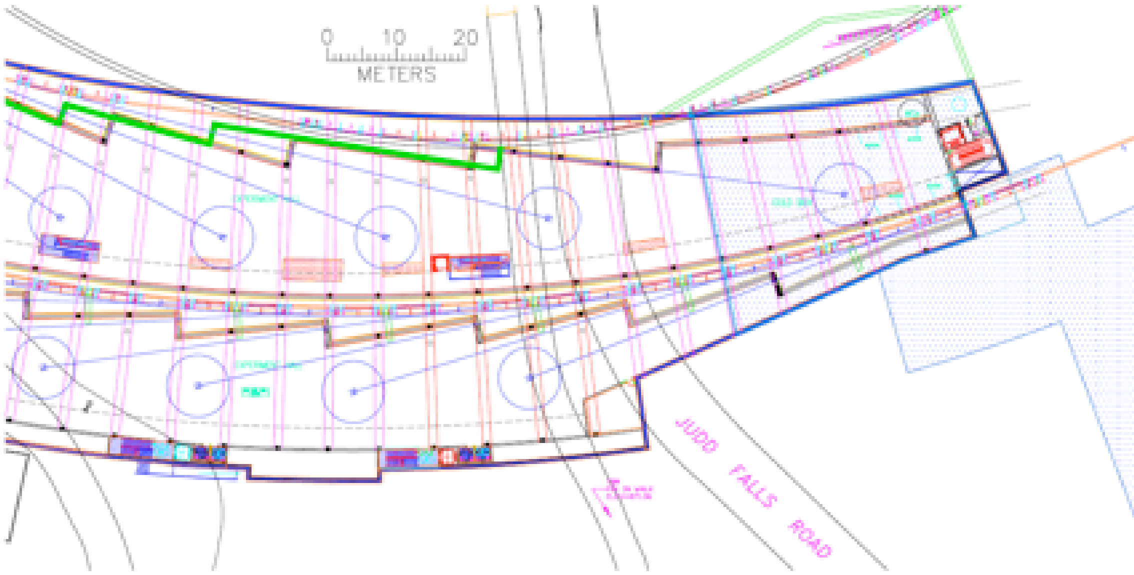

Figure 1: ERL user area layout.

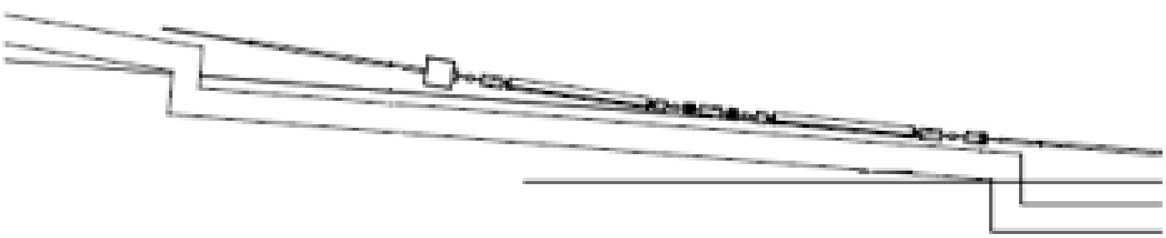

Figure 2: Ratchet shielding wall.

If the incident photon energy is above the threshold for producing pions (∼140 MeV), then they have to be taken into consideration. These pions interact with the nucleus to create HENs, which are not distributed isotropically. The transverse component is appreciable and should be accounted for.

Muons may also be created for photon energies above 211 MeV. The direct rate at which bremsstrahlung-produced muons and pions are created was not considered for this report.

Due to the immense size of the shielding wall, a point kernel method was used for the calculation of dose rates on the personnel side of the wall.

II. POINT KERNEL METHOD

The point kernel method is used to calculate particle flux at a point due to a point source [4]. See figure 3. Scattered particles are not taken into consideration by this method (see figure 4). However, these paths are accounted for by

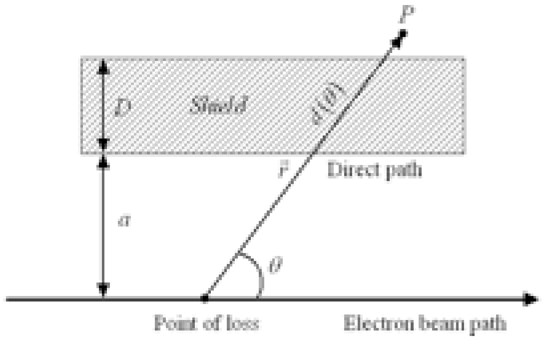

Figure 3: Straight line path of radiation.

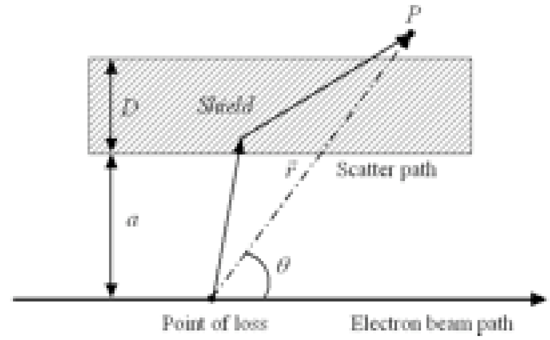

Figure 4: Indirect path of radiation.

use of an appropriate build-up factor. The equation is as follows:

$$H\left(d,\theta\right)=\frac{H_{\theta}}{r^{2}}e^{-\frac{d(\theta)}{\lambda}}$$

where:

$$\begin{aligned}
H\left(d,\theta\right) &= \text{Dose equivalent at depth } d \text{ and angle } \theta \text{ in the shield.}\\
H_{\theta} &= \text{(constant) Dose equivalent extrapolated to zero depth in the shield at angle } \theta \text{ and unit distance from the point source.}\\
r &= \text{Distance from the source to the point of interest outside the shield.}\\
d(\theta) &= \text{Effective shield thickness.}\\
\lambda &= \text{Effective attenuation length for the dose equivalent through the shield.}
\end{aligned}$$

A. Calculations

For the majority of our calculations, we have used an expression for point losses in various components along the electron beam in the user area. This expression is as follows [2]:

$$\dot{H}\left(d,\theta\right)=\sum_{i}\frac{\left(H_{\theta}\right)_{i}}{r^{2}}e^{-\frac{d(\theta)}{\lambda_{i}}}$$

where i runs over the radiation components. The units used are:

$$\begin{aligned}
\dot{H} &\quad \text{is in} \quad \frac{\frac{\text{mram}}{\text{hr}}}{\frac{\text{e}^{-}}{\text{s}}}\\
H_{\theta} &\quad \text{is in} \quad \frac{\frac{\text{mram}}{\text{hr}}\text{m}^{2}}{\frac{\text{e}^{-}}{\text{s}}}\\
r &\quad \text{is in} \quad \text{m}\\
d &\quad \text{is in} \quad \frac{\text{g}}{\text{cm}^{2}}\\
\lambda &\quad \text{is in} \quad \frac{\text{g}}{\text{cm}^{2}}
\end{aligned}$$

In addition, we have decided to neglect the radiation loss due to air. This is for a couple reasons. The first is that with this term neglected, we are actually overshooting the dose rates measured on the far side of the wall, which does not pose any danger to the workers of the facilities. The second is that the term is negligible compared to the shielding material. For heavy concrete, the attenuation length is on the order of 2×10^{1} cm, while for air, it is around 4×10^{4} cm [1] [2].

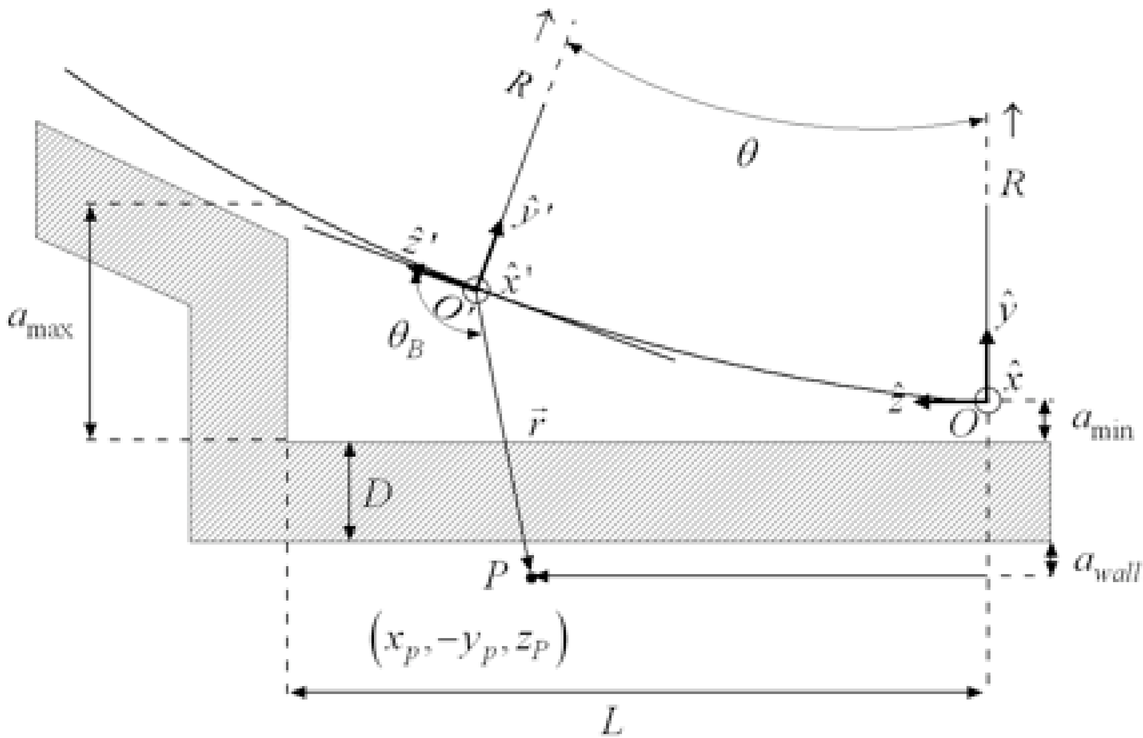

Figure 5: ERL ratchet shielding wall geometry.

B. Straight Wall Equations

Here, we will only look at the straight sections of the wall. The geometry can be seen in figure 5, with the definitions of variables as follows:

D = Thickness of shielding wall.
a_{min} = Closest distance from shielding wall to beam line.
a_{max} = Furthest distance from shielding wall to beam line.
a_{wall} = Furthest point from shilding wall a calculation will be made.
R = Radius of curvature of the beam path.
θ = The angle from $\hat{y}$ to $\hat{y}'$.
L = Length of shielding wall from O to the ratchet.

The O' system origin is at $[x_o, R(1-\cos\theta), R\sin\theta]$ according to the O system. Knowing this, we can find the following:

$$r = \left[(x_o - x_P)^2 + (R(1-\cos\theta) + |y_P|)^2 + (R\sin\theta - z_P)^2\right]^{1/2} \quad (1)$$

$$d(\theta) = \frac{D}{\sin(\theta_B - \theta)}$$

$$\theta_B = \arcsin\left[\frac{R(1-\cos\theta) + |y_P|}{r}\right] + \theta$$

where:

$$\theta_B \;=\; \text{The angle from } \hat{z'} \text{ to } r.$$

We may simplify eq (1) to

$$r = \left[\left(R\,(1-\cos\theta) + |y_P|\right)^2 + \left(R\sin\theta - z_P\right)^2\right]^{1/2}$$

if we let $x_o = x_P$. This is the case when we are in the plane of the electron beam.

III. RESULTS OF POINT KERNEL

We obtained our results by using the point kernel method programmed in MATLAB, using numerical integration over θ. A Labotta Quadrature method was used, and is MATLAB function quadl.

A. Dimensions and Values Used

The dimensions of our simulated wall, shown in figure 5, are as follow:

$$\begin{aligned}
a_{min} &= 0.2 \text{ m} \\
a_{max} &= 5.8446 \text{ m} \\
a_{wall} &= 0.2 \text{ m} \\
D &= 0.8 \text{ m} \\
L &= 26 \text{ m} \\
R &= 254 \text{ m} \\
\rho &= 3.5 \ \frac{\text{g}}{\text{cm}^3} \text{ (for concrete)} \\
\lambda_{Brem} &= 50 \ \frac{\text{g}}{\text{cm}^2} \text{ (for concrete)} \\
\lambda_{GRN} &= 45 \ \frac{\text{g}}{\text{cm}^2} \text{ (for concrete)} \\
\lambda_{HEN} &= 115 \ \frac{\text{g}}{\text{cm}^2} \text{ (for concrete)} \\
E_{beam} &= 5 \text{ GeV}
\end{aligned}$$

Along with these parameters, there were a few other equations used. Instead of using H_θ, we used F_{H_i}, then converted them into the correct units by the equation

$$\dot{h}\left(\frac{\frac{\text{mrem}}{\text{hr}}}{\frac{\text{e}^-}{\text{sec}}}\right) = 5.77 \times 10^7 F_{H_i}\left(\frac{\text{mrem}}{\text{J}}\right) E_{beam}\,(\text{GeV})\,. \qquad (2)$$

F_{H_I} has different forms for each of the different forms of radiation. Therefore, i runs over the three forms of radiation we are considering. Also, the conversion from F_{H_i} to H_θ, eq (2), is only valid if you look at the conversion for 1 m from the source. For bremsstrahlung radiation [3],

$$F_{H_{Brem}} = 16.7 E_{beam}\left(2^{-\frac{\theta_B}{\theta_{1/2}}}\right) + 833\left(10^{-\frac{\theta_B}{21}}\right) + 25\left(10^{-\frac{\theta_B}{110}}\right),$$

with

$$E_{beam}\theta_{1/2} = 100 \text{ MeV}^\circ.$$

For the neutron radiation, we have made the assumption that it is isotropic. This is accurate for the GRNs(section I B 2), however, for the HENs, this is not true. It is believed that the difference is negligible for this calculation. In the future, this simulation may be rerun without this assumption, after a proper value for $F_{H_{HEN}}$ is found using a Monte-Carlo calculation. For now, we will use

$$F_{H_{GRN}} = 0.63 \text{ and } F_{H_{HEN}} = 0.075.$$

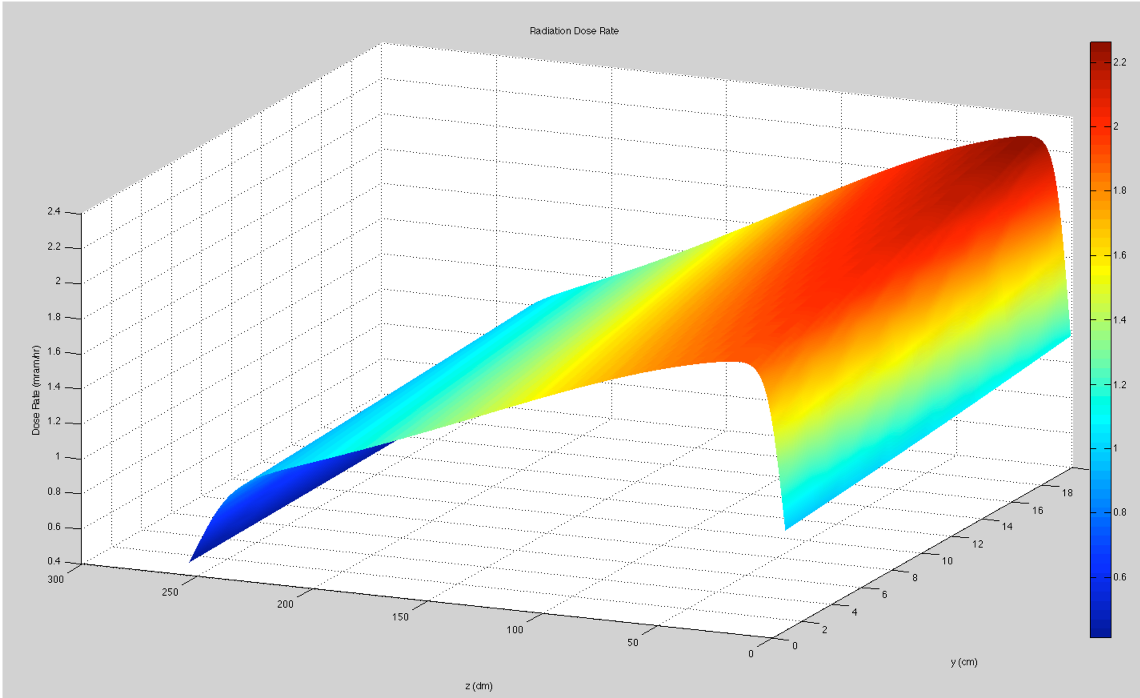

Figure 6: Total Radiation Dose Rate

B. Straight Wall Results

The goal for this shielding wall is to have dose rates low enough so workers would not be required to wear radiation badges. We were able to obtain a peak radiation spike at 2.3 mrem per hour. We had hoped to find a dose rate of 0.05 mrem per hour. As expected, the Bremsstrahlung photons and HENs were the main sources of radiation, however, GRNs did have an appreciable contribution. These results are for a continuous electron loss of 3 pA per m.

Due to time constraints, we were not able to find a suitable build-up factor and account for scattered particles. This will bring our dose rate up even further.

Conclusion

This is just the start of what needs to be done for the shielding of the ERL. We still need to find an appropriate build-up factor and implement it on this calculation, as well as in future calculations. Such future calculations to be done include the ratcheted part of the shielding wall, and sky-shine radiation. These results are only for the same plane as the beam line. We would like to extend this to the full three dimensions, to make sure the radiation leaking into the surrounding atmosphere is negligible.

Acknowledgements

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[1] John R. Lamarch. *Introduction to Nuclear Engineering,* 2nd ed. (Addison-Wesley, Boston, 1983).
[2] Seymour Lipschutz, John Liu, and Murray R. Spiegel. Schaum's Outlines Series, *Mathematical Handbook of Formulas and Tables*, 2nd ed. (McGraw Hill, New York, 1999).

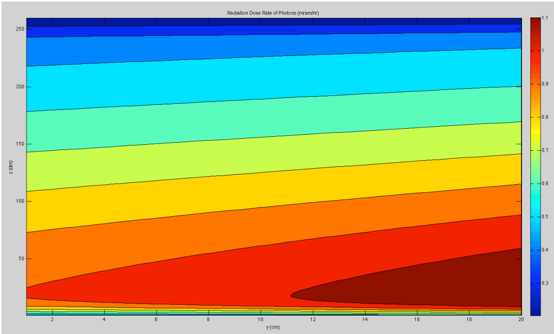

Figure 7: Bremsstrahlung Photons Dose Rate

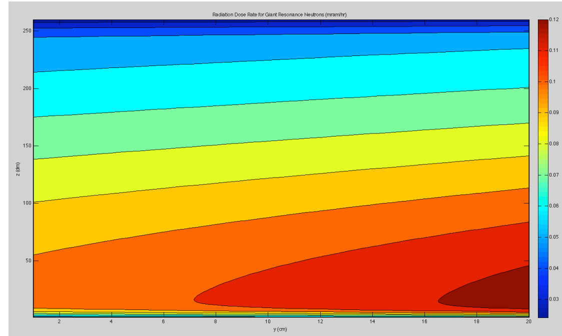

Figure 8: Giant Resonance Neutrons Dose Rate

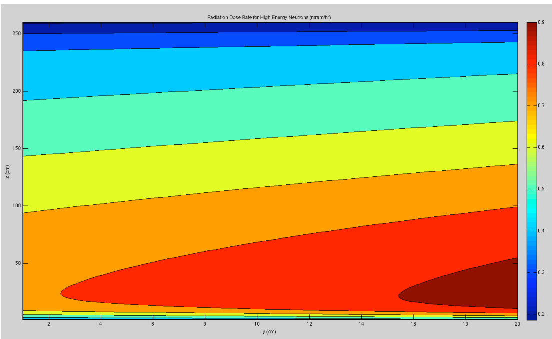

Figure 9: High Energy Neutrons Dose Rate

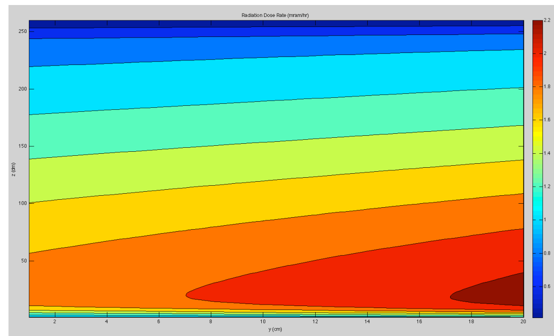

Figure 10: Total Radiation Dose Rate

[2] "Advanced Photon Source: Radiological Design Considerations", H. J. Moe, APS-LS-141 Revised, July 1991, Argonne National Laboratory, p.8.

[3] "Advanced Photon Source: Radiological Design Considerations", H. J. Moe, APS-LS-141 Revised, July 1991, Argonne National Laboratory, p.20.

[4] *Radiation Protection for Particle Accelerator Facilities*, NCRP Report No. 144, December 31, 2003, Revised January 7, 2005, National Council on Radiation Protection and Measurements, Bethesda, MD., p. 162.