BNL-225333-2024-TECH

EIC-ADD-TN-087

Preliminary Transverse Shielding Analysis for the 1010-C RF Building

C. Schaefer

February 2024

Electron-Ion Collider

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP)

EIC TECHNICAL NOTE

BROOKHAVEN NATIONAL LABORATORY

AUTHOR: C. Schaefer

DATE: February 2024

TITLE: Preliminary Transverse Shielding Analysis for the 1010-C RF Building, Revision 1

Introduction

EIC is planning to construct a new building on the outer ring berm at 10 o'clock which will provide RF power to cryogenically-cooled beam line components in the electron and hadron storage rings. The distance of the building from the RHIC Tunnel and the amount of soil shielding required are the focus of this report. Siting the building closer to the RHIC Tunnel is desirable from an RF operations viewpoint since the waveguide runs and RF power losses will be minimized, but this may require the use of higher density shield materials, e.g., concrete, in addition to soil shielding. The radiological source terms are the prompt radiation hazards from the Hadron Storage Ring (HSR) and Electron Storage Ring (ESR) beam losses in the 10 o'clock sector and the lateral dose rates propagated through the shields. See Figure 1 below.

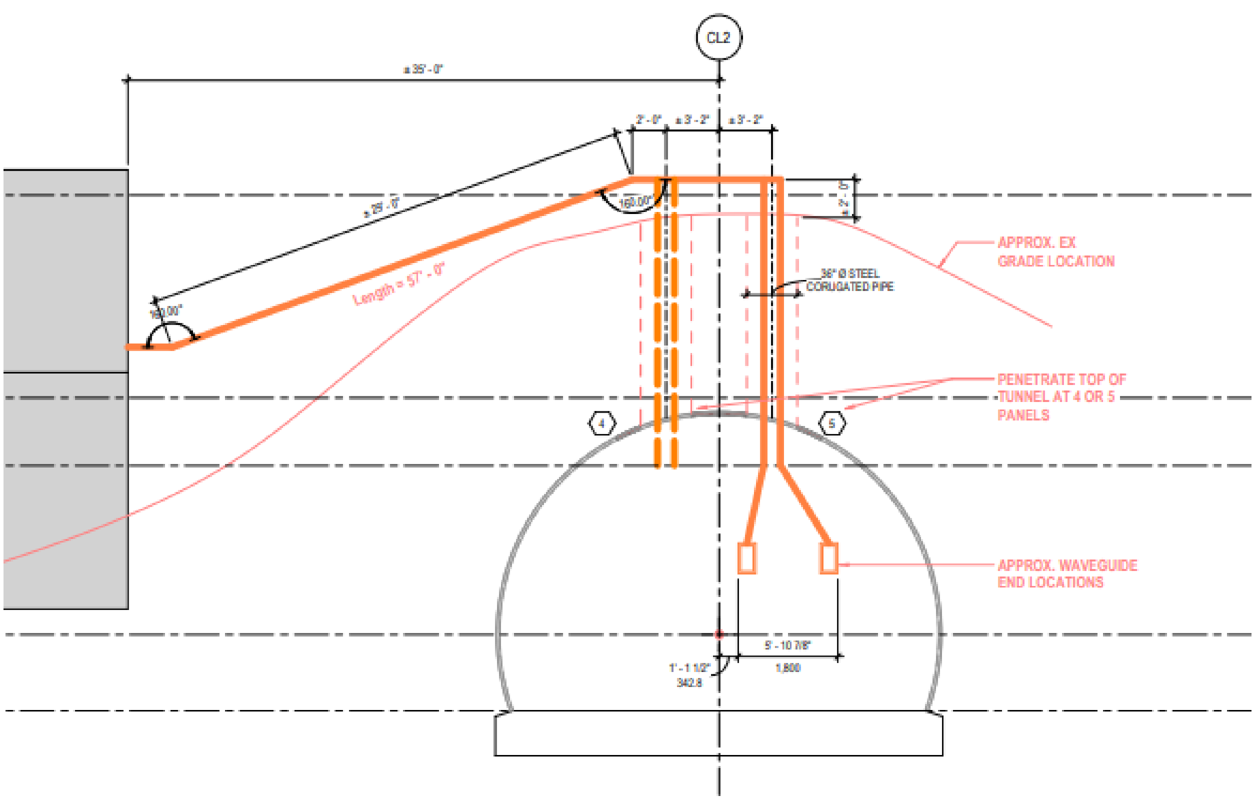


Figure 1. 1010-C RF Building and Tunnel Geometry Including Vertical Waveguide Penetrations

It is expected that this facility will not be continuously occupied during operations. The shielding design considers EIC's draft Shielding Policy that states shielding and other controls for areas where access is controlled for radiological purposes will be designed so that an ambient dose of 100 mrem per year (i.e., no more than 50 micro-Rem hr^{-1} for 2000 hours) to a worker is not likely during routine operations meaning that workers will not need to be monitored for radiological exposure as per the BNL Radiological Control Manual[1].

Assumptions

- This is a preliminary shielding report based upon EIC's architect's 30% preliminary design of the 1010 sector buildings. It is assumed that some features may change as the design matures.
- ESR and HSR beam losses are assumed to occur as thick target (point) losses in the 1010 sector of the RHIC Ring
- Routine losses are assumed to be 1% of worst case losses[2].
- Soil density is assumed to be 1.7 g cm^{-3}.
- The ESR centerline is 4.8 meters from the tunnel wall and the HSR centerline is 3.1 meters from the tunnel wall closest to building 1010-C.
- Vertical waveguide berm penetrations are not evaluated in this report.

Beam Parameters

EIC's Interaction Regions and Detector Interface Group provided preliminary ESR loss estimates for the planned modes of electron beam operation at 5, 10, and 18 GeV[3]. Operation at 10 GeV contains the most stored beam energy and is used in this analysis.

Electron Energy	beam lifetime (min)	bunches	bunch intensity	total intensity	min lifetime (minutes)	% of beam on transfer absorber	total losses (e-/s)	losses on the transfer absorber (e-/s)	max losses on collimators (e-/s)	power on the absorber (W)
5 GeV	30	1160	1.72E+11	2.00E+14	10	71	3.44E+11	2.44E+11	3.33E+11	195.39
10 GeV	120	1160	1.72E+11	2.00E+14	10	91	3.44E+11	3.13E+11	3.33E+11	500.86
18 GeV	300	290	6.20E+10	1.80E+13	10	96	3.10E+10	2.98E+10	3.00E+10	85.71

Table 1 ESR Beam Loss Estimates

From the table above it is seen that 91% of the electron beam (500 Watts) is expected to be collected on the RCS-to-ESR Transfer Absorber which will be in the 12 o'clock sector. The remaining beam (~ 50 Watts) will be lost elsewhere. Fifty (50) and 0.5-Watt losses in the 10 o'clock sector adjacent to the 1010-C RF building are analyzed.

Similarly, the Interaction Regions and Detector Interface Group provided preliminary hadron loss estimates[4]. An average 4-hour beam store time is assumed. From the EIC Master Parameters Table[5], and assuming electron-proton operation in high divergence operation mode, a proton beam in the HSR with an energy of 275 GeV, 1190 bunches, and a bunch intensity of 6.9E+10 will contain 8E+13 total protons. It is assumed that 1% of the beam interacts with the primary collimator and that 10% of the beam that does interact escapes from the collimator and is lost elsewhere. The approximate beam loss rate is then 0.1% of stored beam in 4 hours at non-collimator locations or 2E+10 protons/hour (0.25 Watts). This is conservatively assumed to be lost entirely in the 10 o'clock sector.

Approach

A semi-empirical approach to estimating transverse bulk shielding requirements is used. For electron losses, a thick target approximation as described in Sullivan[6] is the basis for estimating transverse shielding requirements. The radiation near the loss point will be dominated by gamma rays and x rays. Equations 3.4 and 3.5 are used to estimate gamma ray and high-energy neutron dose rates at 90 degrees to the loss point and at a one-meter distance. Meeting the shielding requirement for high-energy neutrons will ensure low-energy neutrons are adequately shielded. For Hadron losses, the Moyer model is used to estimate transverse shielding requirements.

The objective is to reduce dose rates through a combination of distance and shielding to 50 microrem (μRem) hr^{-1} at the building 1010-C wall closest to the soil berm. Based on the current design, the distance from the ESR centerline to the tunnel wall is 4.8 meters, and the distance from the tunnel wall to the building is 6 meters. This equates to about an 115-times dose rate reduction assuming a point source propagation (i.e., one over R^2). An approximate 9.1-meter distance currently exists from the center of the HSR to the building. The number of TVLs in soil were then estimated to further reduce dose rates to the goal of 50 μRem hr^{-1}.

ESR Evaluation

Bremsstrahlung and photo-neutron dose rates are evaluated separately, and each assigned a dose rate budget (or contribution) of 25 μRem hr^{-1} at the building wall. A 50-Watt point beam loss will produce a 250 Rem hr^{-1} gamma dose rate at 1 meter and 90 degrees to the direction of beam travel. This is reduced to 2.2 Rem hr^{-1} (2.2E+06 μRem hr^{-1}) at an unshielded distance of 10.8 meters. A reduction factor of (2.2E+06/25 = 8.8E+04) or 4.9 TVLs is needed to achieve 25 μRem hr^{-1}. Similarly, a 1.8 Rem hr^{-1} high-energy (HE) photo-neutron dose rate is reduced to 16 mrem hr^{-1} (1.6E+04 μRem hr^{-1}) at 10.8 meters from the beam pipe. A reduction factor of (1.6E+04/25 = 6.4E+02) or 2.8 TVLs is required.

From Table 41 of Sullivan[7], the equilibrium tenth-value layer (TVL) for high-energy bremsstrahlung in soil from 3-7 GeV electrons is 120 g cm^{-2} or 0.71 meters. 4.9 TVLs equates to 3.5 meters. Similarly, from Table 43 of reference six, the TVL for high-energy (HE) photo-neutrons in soil from 20 GeV electrons is 276 g cm^{-2} or 1.6 meters, and 2.8 TVLs equates to 4.5 meters. An additional half-value layer (HVL = 0.3TVL) is added to each as a safety factor.

For the routine 0.5-Watt beam loss scenario, the 1-meter gamma ray and HE neutron dose rates are reduced by a factor of 100x, and the same process is repeated. The results are summarized in Table 2 below.

	Rem h^{-1} at 1-m	**Rem h^{-1} Unshielded at 10.8-m**	**Shielding TVLs Needed**	**TVL, m**	**HVL, m**	**Soil Shield Needed, m**
Gamma, (50 W)	2.5E+02	2.2E+00	4.9	0.7	0.2	3.7
HE Neutron, (50 W)	1.8E+00	1.6E-02	2.8	1.6	0.5	5.0
Gamma, (0.5 W)	2.5E+00	2.2E-02	2.9	0.7	0.2	2.3
HE Neutron, (0.5 W)	1.8E-02	1.6E-04	0.8	1.6	0.5	1.8

Table 2 Soil Shielding Estimates for 50-Watt and 0.5 Watt ESR Losses

At 50 Watts, the shielding requirement is 5.0 meters and is dominated by the HE photo-neutron source term. At 0.5 Watts, the shielding requirement is 2.3 meters and is dominated by high energy bremsstrahlung.

HSR Evaluation

For proton losses in the HSR, the Moyer method as described in NCRP Report 144 is the basis for estimating transverse shielding requirements[8]. The Moyer method expresses the dose equivalent on the shield surface and has proven reasonably accurate over the energy range of 5 to 350 GeV[9].

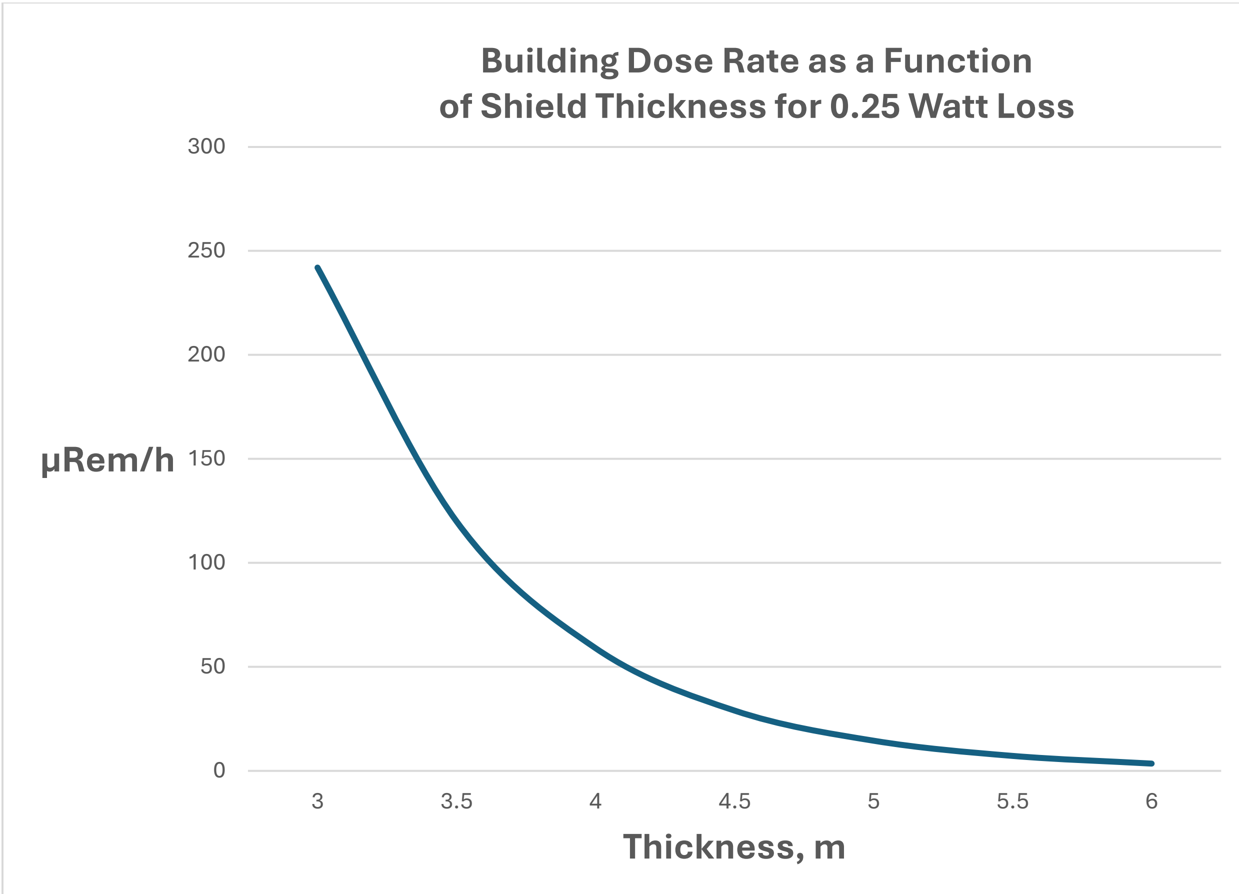
Neutrons are the dominant contributor to dose equivalent outside of well-shielded proton accelerators. Above about 150 MeV neutron attenuation lengths are nearly independent of energy and are much larger than for lower-energy neutrons meaning the hadronic cascade through the shield can be modeled based upon only the line-of-sight propagation of these particles. The dose rate is then proportional to the high-energy neutron fluence, and a multiplication factor is used to account for particle buildup in the cascade where the low-energy components decrease with the same attenuation length.

Rather than explain the development of the Moyer method in detail, the reader is encouraged to reference section 4.8 of NCRP Report 144. The Moyer Model equation is:

Equation 1: $H = R^{-2}\, \Psi(E_p)\, e^{-\beta\theta}\, e^{-t/\lambda}$, where

H is dose equivalent per interacting proton on the shield surface (Sv/proton)
R is the distance from the source to the shield surface (9.1 m)
Ψ is Source Strength parameter (2.54E-11 Sv-m^2 for 275 GeV protons)
β is the angular relaxation parameter = 2.3 $radian^{-1}$ that accounts for the angular distribution of neutrons contributing to the dose rate measurement point outside the shield
θ = is the angle subtended between the beam axis and a line between the point of interaction and the point on the shield surface (π/2 radians in this case)
t is the shield thickness in the direction of θ
λ is the high-energy neutron attenuation length in soil (0.73 m)

Equation 1 is plotted below for the 0.25-Watt routine loss case. To obtain a dose rate of 50 μRem h^{-1} at the outer building wall, a minimum of 4.1 meters of soil shielding is required.



The 0.25 Watts of HSR beam losses are the controlling factor for the soil berm shielding. The 4.1 meters required is larger than the 2.3 meters required for 0.5 Watts of ESR beam losses. Both beam powers are considered order-of-magnitude estimates of routine beam losses in the 1010 sector of the ring, which is unavoidable and chronic.

Reducing the Tunnel-to-Building Distance

Current planning is to site the building 6 meters from the tunnel as analyzed above. The shielding estimates above suggest this distance could be reduced. Shielding was subsequently estimated for a 5-meter distance from the tunnel to the building. This reduced the ESR and the HSR distances to the building to 9.8 and 8.1 meters respectively.

The worst case (50 Watt loss) and routine case (0.5 Watt loss) are recalculated assuming the smaller 9.8 meter distance and summarized in Table 3 below.

	Rem h^{-1} at 1-m	**Rem h^{-1} Unshielded at 9.8-m**	**Shielding TVLs Needed**	**TVL, m**	**HVL, m**	**Soil Shield Needed, m**
Gamma, (50 W)	2.5E+02	2.6E+00	5.0	0.7	0.2	3.8
HE Neutron, (50 W)	1.8E+00	1.9E-02	2.9	1.6	0.5	5.1
Gamma, (0.5 W)	2.5	2.6E-02	3.0	0.7	0.2	2.3
HE Neutron, (0.5 W)	1.8E-02	1.9E-04	0.9	1.6	0.5	1.9

Table 3 Soil Shielding Estimates for 50-Watt and 0.5 Watt ESR Losses Assuming a Tunnel-to-Building Distance of 5 Meters

Using the Moyer method as above for a reduced tunnel-to-building distance of 5 meters, the soil thickness needed for shielding against 0.25 Watts of HSR beam loss is increased from 4.1 to 4.3 meters. This exceeds the shielding needed for routine ESR losses. The HSR losses are again the controlling factor for the routine loss case.

Shielding Recommendations

As noted by Sullivan[10], "In general, beam losses are not predictable at the design stage of an accelerator. Therefore, it is often unnecessary to evaluate shielding requirements with great precision because the radiation source term is not well known."

Using preliminary order-of-magnitude beam loss estimates for the 1010 sector of the ring and evaluating a tunnel-to-building distance of 5 meters, a minimum of 4.3 meters of soil shielding between the outer tunnel wall and the 1010-C building surface closest to the berm is recommended to limit dose rates from routine operations to 50 μRem h^{-1} at the outer 1010-C building wall.

Uncertainties in the analysis are very likely smaller than those arising from the beam loss uncertainties. Monte Carlo (FLUKA) analysis is required for verification of the semi-empirical findings once facility designs have been finalized.

Active area monitors must be considered for limiting higher building dose rates for non-routine beam losses.

References

1. BNL Radiological Control Manual
2. Email from A. Drees, 2/2/2024
3. Email from M. Vallette, 3/27/2023
4. Email from A. Drees dated 6/12/2023
5. Master Parameters Table for the EIC, September 14, 2022
6. Sullivan A.H., A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, 1992.
7. IAEA Technical Report 188, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, 1979
8. NCRP Report No. 144, Radiation Protection for Particle Accelerator Facilities, 2003
9. McCaslin J.B, Swanson W.P., Moyer Model Approximations for Point and Extended Beam Losses, Nuclear Instruments and Methods in Physics Research, A256 pg. 418-426 (1987)
10. Sullivan A.H., Application of the Moyer Method to Transverse Shielding of a Linear Bremsstrahlung Source, Health Physics Society, 1994