mu2e Preliminary Shielding Assessment Part 1

For Existing Anti-proton Source Facilities and the M4 beam line

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A preliminary shielding assessment is required by the Fermilab Radiological Controls Manual (FRCM) prior to construction of mu2e facilities. The purpose of this document is to fulfill that FRCM requirement. This assessment covers the existing Anti-proton Source facilities which are to be repurposed for the mu2e experiment and the new M4 beam line. The Production Solenoid Room, Transport Solenoid Room, Detector Solenoid Room and the mu2e service building are reviewed in a separate, stand-alone document.

Contents

1 Introduction

It is intended that the existing Antiproton Source facilities will be repurposed to deliver an 8 kW, 8 GeV proton beam[1] through the M4 line, a new beam enclosure, to a new mu2e target station where it will strike a tungsten target located within the Production Solenoid (PS) [1]. The un-interacted primary proton beam and secondary beam shower travel through an air gap and finally to a new beam absorber. A secondary muon beam is transported in the direction opposite the primary proton beam through a Transport Solenoid (TS) and finally toward a Detector Solenoid (DS) which are all to be located in new facilities. The layout of the mu2e experiment is shown in Figure 1.

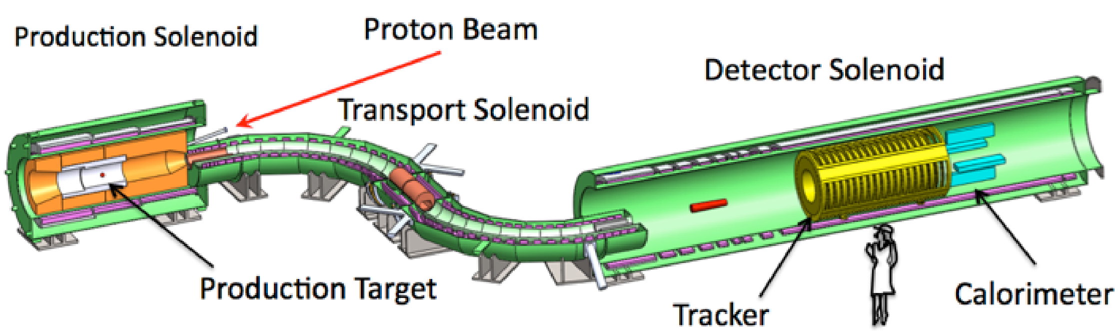

Figure 1 The Mu2e apparatus.

The existing Antiproton Source facilities consist of:

- M1 line (formerly the AP1 line located in the PreTarget/PreVault enclosure)
- M3 line (formerly the AP3 line located in the PreVault/PreTarget enclosure, beneath AP0 target building, the Transport enclosure, and the Rings enclosure)
- Delivery Ring (formerly the Debuncher Ring in the Rings enclosure)

The existing Anti-proton Source facilities downstream of the AP0 Service Building were chiefly intended for low power secondary beams, nominally up to about 13 watts and were built with no reserve capacity for additional shielding. The challenge in designing a radiation safety plan for these facilities is the development of a protection scheme which relies upon active protection and which meets all FRCM requirements. Shield drawings for the existing Antiproton Source facilities are included with this preliminary assessment [28].

New facilities for the mu2e experiment include:

- the M4 beam line
- the experimental area consisting of:

[1] An 8 GeV, 8 kW proton beam is equivalent to 6.25E12 protons/second with kinetic energy of 8 GeV

- Production Solenoid enclosure
- Transport Solenoid enclosure
- Detector Solenoid enclosure
- mu2e service building
- primary beam absorber
- extinction monitor room
- target replacement robotics staging room

The 8 kW primary beam interacts in and is stopped at the experimental area. Consequently, the facility must be designed for this normal condition. The shielding assessment for the experimental areas listed above is covered in a separate document. The scope of this assessment includes the former Anti-proton Source facilities plus the M4 beam line.

Preliminary construction drawings for the beam line connecting the Delivery Ring to the experimental area and for the experimental area have been prepared [29][30].

2 Radiation Safety Plan Design Approach

2.1 Requirements

Radiation Safety Plan design comes from the consideration of the mu2e project physics goal and the FRCM [2] requirements. The mu2e project physics goal is to deliver an 8 kW proton beam by 1/3 integer, slow resonant extraction to the Production Solenoid [1]. The various FRCM requirements for controlling prompt effective dose rate are introduced in this section while their applications for the M4 beam line and existing Anti-proton Source facilities are discussed below in the Technical Design section.

2.1.1 Prompt Effective Dose Control

The FRCM requirement to control the prompt effective dose rate outside of accelerator and beam lines tunnels fall into two broad categories: the normal condition and the accident condition. The permitted effective dose rates for the conditions cover a wide range of values depending upon the controls which can be implemented on a location by location basis. Table 1 and Table 2 containing the range of limits are reproduced from the FRCM for convenience.

Table 1: Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions (from Table 2-6 of FRCM)

Dose Rate (DR) Under Normal Operating Conditions	**Controls**
DR < 0.05 mrem/hr	No precautions needed.
0.05 ≤ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
0.25 ≤ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy (occupancy duration of less than 1 hr).
5 ≤ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
100 ≤ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 2: Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions When It is Likely that the Maximum Dose Can Be Delivered (From Table 2-7 of FRCM)

Maximum Dose (D) Expected in 1 hour	**Controls**
D < 1 mrem	No precautions needed.
1 < D ≤ 10 mrem	Minimal occupancy only (duration of credible occupancy < 1 hr) no posting
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed. Radiological Worker Training required.
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy (duration of occupancy of less than1 hr). The Division/Section/Center RSO has the option of imposing additional controls in accordance with Article 231 to ensure personnel entry control is maintained. Radiological Worker Training required.
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.

2.1.2 Interlocked Radiation Detectors

A partial set of laboratory standard shielding requirements [3] for an 8 kW, 8 GeV proton beam is given in Table 3. The Categories 1A through 5A provide an upper limit of effective dose delivered for an 8 kW continuous beam loss if the given shield thickness is present. For example, a location where a 20.6 foot shield is present while an 8 kW, 8 GeV proton beam is continuously lost at a single point, would result in an effective dose rate of up to 5 mrem/hr. Application of Categories 1A through 5A are for situations in which sufficient passive shielding exists to provide adequate protection.

Categories 6A through 10A relate the effective dose which could be received for a single pulse of 6.25E12 protons delivered at a location given a particular shield thickness. Categories 6A through 10A are applied in conjunction with interlocked radiation detectors. For example, a single beam pulse of 6.25E12 protons lost at a location where the shield is 11.4 feet thick would result in a delivered effective dose of up to 1 mrem. Interlocked radiation detectors are used for Categories 6A through 10A to limit the duration and severity of beam loss conditions when insufficient passive shielding exists.

Table 3 Partial list of shield criteria for 8 kW, 8 GeV proton beam derived from Reference 3

Magnet in Enclosure		
	Category	Shield Thickness (ft)
D < 1mrem	1A	**23.0**
1 ≤ D ≤ 5 mrem	2A	**20.6**
5 ≤ D ≤ 100 mrem	3A	**16.2**
100 ≤ D ≤ 500 mrem	4A	**13.8**
500 ≤ D ≤ 1000 mrem	5A	**12.8**
1 pulse – 6.25E12 protons		
D < 1mrem	6A	**11.4**
1 ≤ D ≤ 5 mrem	7A	**9.0**
5 ≤ D ≤ 100 mrem	8A	**4.6**
100 ≤ D ≤ 500 mrem	9A	**3.0**
500 ≤ D ≤ 1000 mrem	10A	**3.0**

A summary of the radiation shielding thicknesses for the existing Anti-proton Source facilities is given in Table 4. The basis for the Radiation Safety Plan springs from a comparison of Table 3 and Table 4. It would be possible to operate most of the existing Anti-proton Source facilities with passive shielding if, as required by Table 1 and Table 2, four or eight foot fences were to be installed around the entire facility. In addition, interlocked radiation detectors would be required for the Transport Enclosure at the AP0 Service Building and at all Delivery Ring Service Buildings because those locations have less than 12.8 feet of shielding. However, Indian Road, the major thoroughfare between the Main Injector and the remainder of Fermilab would need to be closed off with fences. Since both closing Indian Road and adding shielding to the entire complex are impractical options, the use of interlocked radiation detectors is imperative. The shielding plan for existing Anti-proton Source facilities is based solely upon the Categories 6A through 10A in Table 3.

For practical considerations, the design of the shield for the M4 beamline (discussed below) includes the use of interlocked radiation detectors.

Table 4 List of Anti-proton Source accelerator and beam line facilities along with the nominal shield

Location	Nominal shield (ft)
Pre-Vault Enclosure at AP0 Service Building – M1 line	13
Transport Enclosure at AP0 Service Building – M3 line	12.5
Transport Enclosure Shielded Tunnel – M3 line	14
Transport Enclosure under Indian Road – M3 line	13
Transport Enclosure to Delivery Ring – M3 line	13
Delivery Ring at Arcs	13
Delivery Ring at Service Buildings	10
Beam Transport from Delivery Ring to Target Hall – M4 line	16

The nominal interlocked radiation detector currently approved for use as a credited safety system is the Chipmunk ion chamber; it has a nominal detector length of less than one foot. In order to adequately cover the shielded locations listed in Table 4, and assuming15 foot spacing is sufficient; a total of about 235 Chipmunk ion chambers would be required. About 45 Chipmunks are presently installed at the locations, primarily at the Service Buildings. Consequently, about 190 additional chipmunks would be required.

The cost to develop, to build, to install, and to maintain such a number of Chipmunks was considered extraordinary. As a result, the mu2e Project received a suggestion to consider the development of an alternative long detector from the ESH&Q Section in May of 2011.

The development of the long detector ion chamber, referred to as Total Loss Monitor (TLM) shown in Figure 2, has been ongoing since May 2011. The TLM system consists of two main parts: the detector [12] and the electrometer [13][14]. The detector response has been characterized utilizing the TLM electrometer for proton beam loss under a variety of conditions [5] [6] [7]. The TLM electrometer has been developed by Accelerator Division.

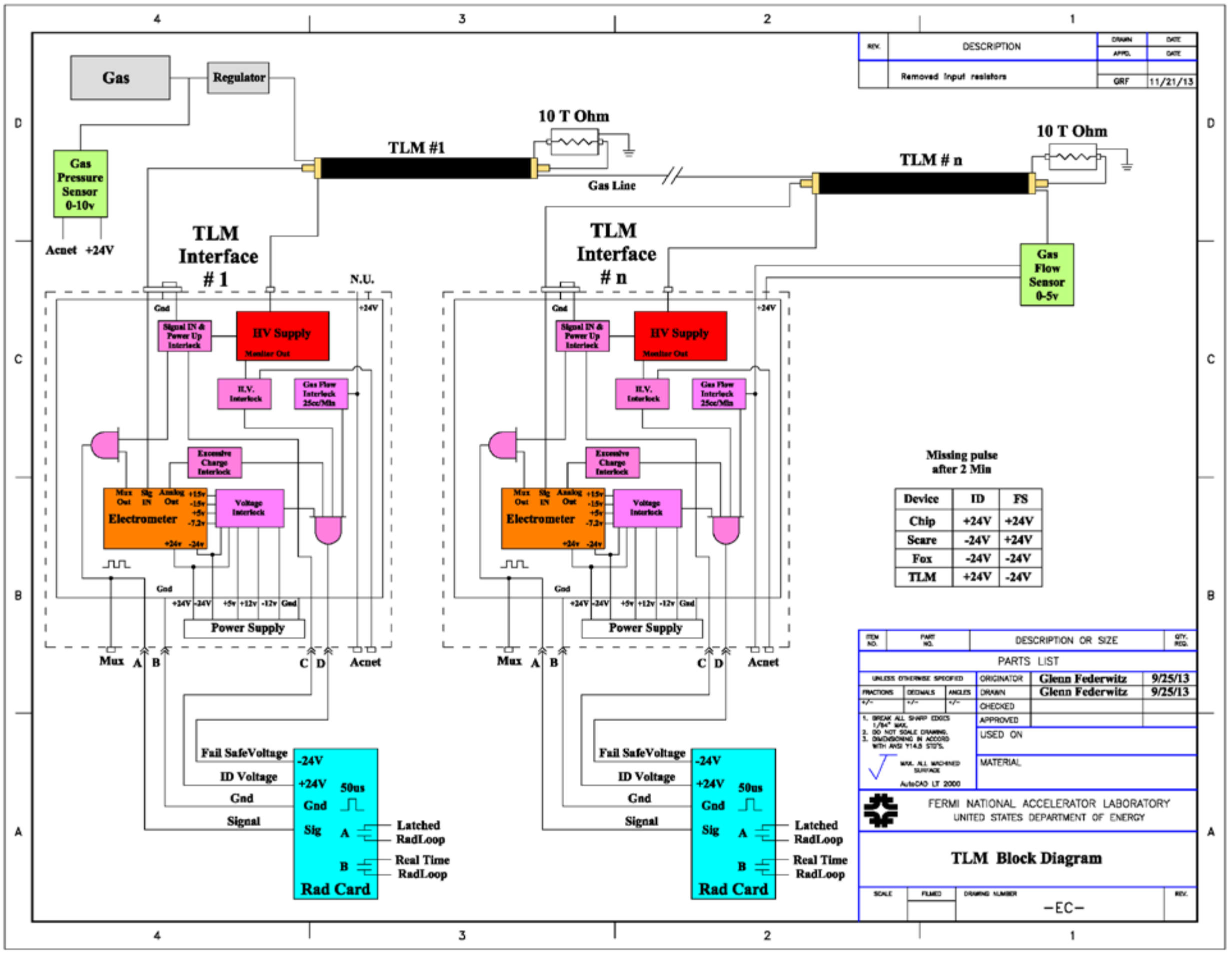

Figure 2 TLM System Schematic. The TLM detector gas volumes may be connected in series to share detector gas systems. However, each detector is connected to an individual TLM electrometer.

The ESH&Q Section granted preliminary approval to use the TLM system as a credited safety system in May 2014[18]. The mu2e project, having identified the risk that the TLM system may not receive approval as a credited safety system, provided a corrective action in the event the risk is realized [24]. Since preliminary approval has been granted, it appears likely that the TLM solution can be adopted.

The trip level for an integrating style interlocked radiation detector (either Chipmunk or TLM) becomes the nominal upper limit of the normal operating condition. Since the time-weighted average effective dose is limited by the RSS system, a trip level must be chosen which is high enough to permit normal operating losses with some reasonable margin without exceeding the normal effective dose rate limits established in Table 1.

2.2 Technical Design

2.2.1 Delivery Ring Extraction Losses

As can be gathered from Table 4, the most challenging shield design for the mu2e project is at the AP service buildings. In particular, the slow resonant extraction process occurs at the AP30 service building. Previous controlled beam loss measurements and shield calculations have been made to characterize the situation without a complete understanding of beam loss mechanisms [8] [9] [10]. In more recent work, a model of the slow resonant extraction system including the electrostatic septa, extraction Lambertson, C-magnet, quadrupole magnets and a subset of extraction line magnets has been developed to more accurately assess the nature of beam losses in the AP30 straight section [11]. As shown in Figure 3, the model includes the AP30 service building and the nearby Type 2 exit stairway. An in-tunnel shielding system [16], as shown in Figure 4, has been developed to supplement the existing 10 foot service building shield. The complete in-tunnel shielding system, incorporated in the MARS simulation model is shown in Figure 5. A sample of the 8 GeV extracted proton beam tracks is shown in Figure 6.

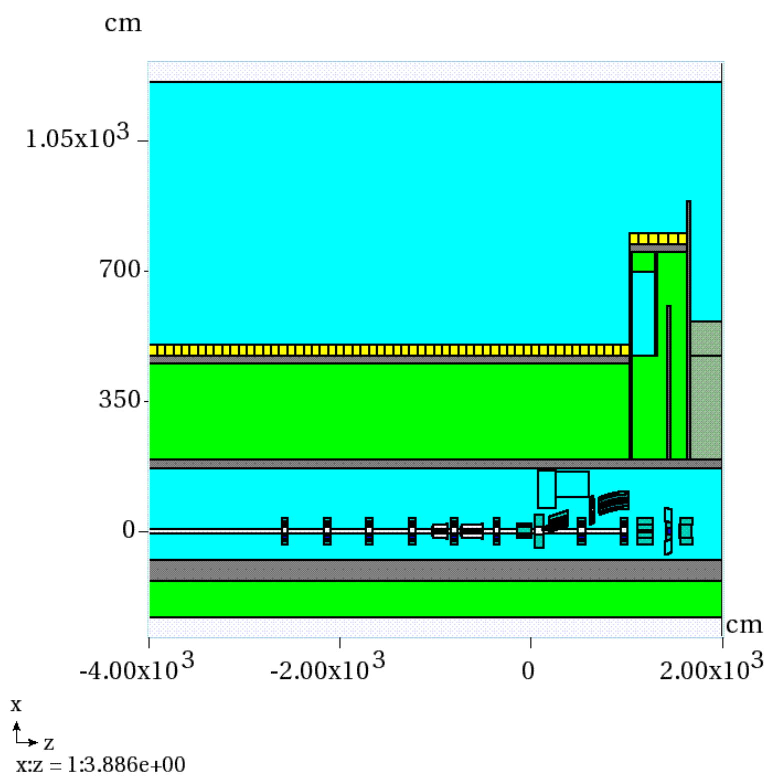

Figure 3 Elevation view depicting MARS model of AP30 service building, including the exit stairway and the slow resonant extraction system

Beam transport into the extraction channel is based upon resonant extraction models being considered for the mu2e experiment. Particle tracking surfaces were included in the beam aperture of the MARS model at the first vertical down bend magnet (EDWA) and a circulating aperture quadrupole (D2Q7) to determine the percentage beam loss; these are depicted in Figure 6. The percentage of beam loss determined in the simulation is 1.25%.

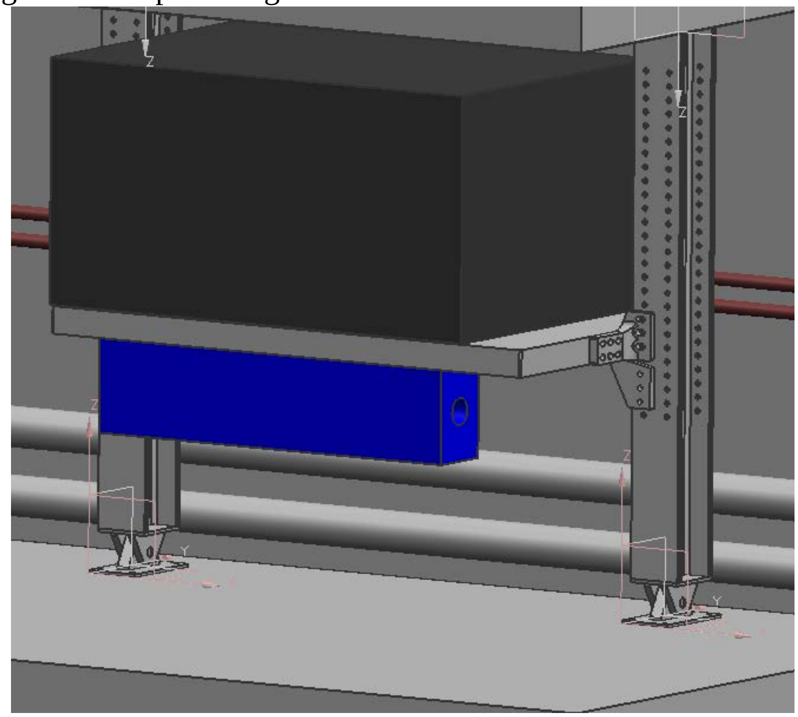

Figure 4 Example of in-tunnel shield design at the extraction Lambertson location

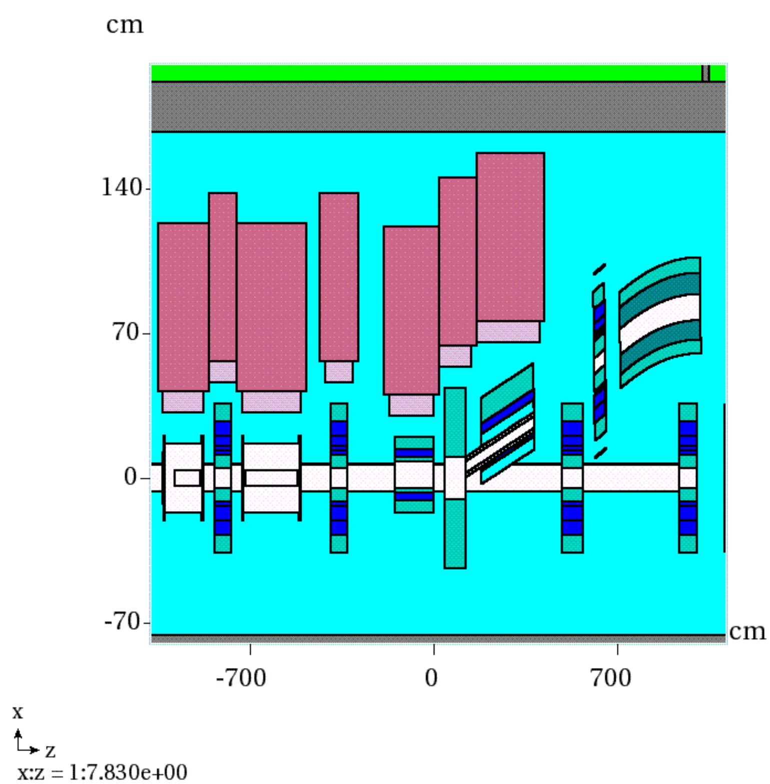

Figure 5 Extraction region shown with 3 foot thick in-tunnel steel shielding

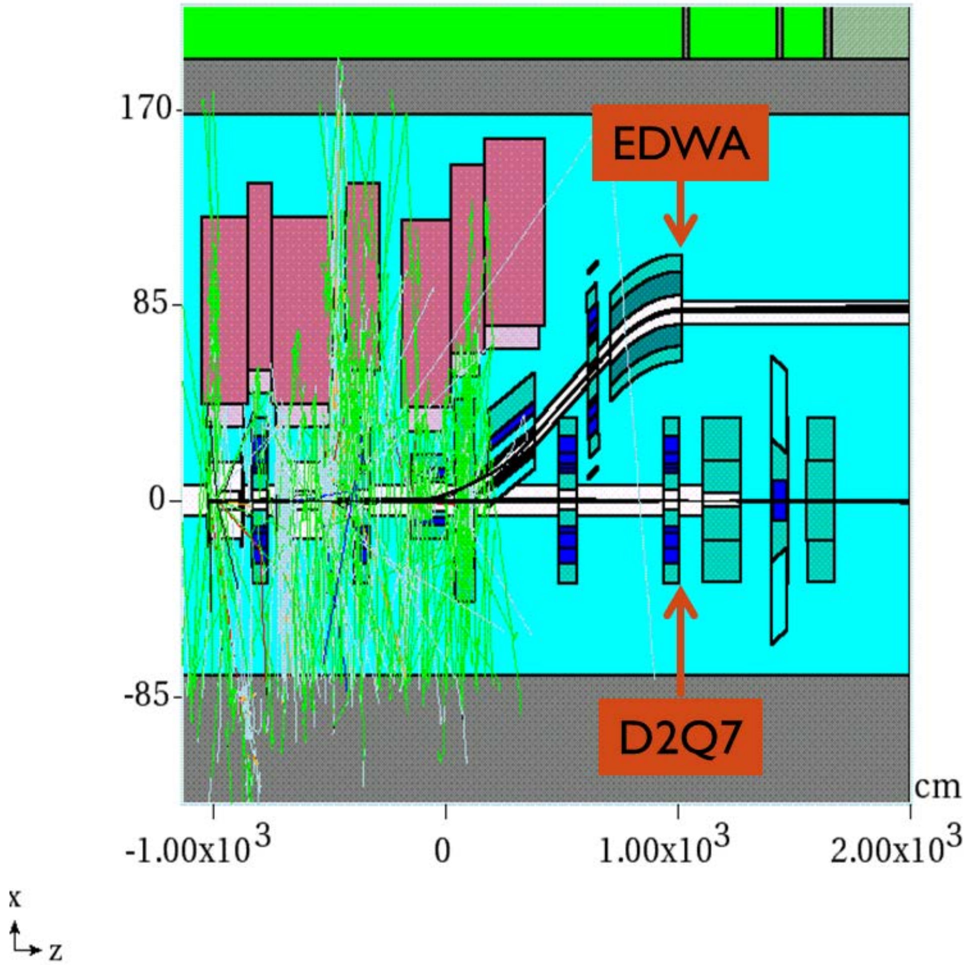

Figure 6 Tracks of 8 GeV proton beam sample directed at the upstream electrostatic septum wires are directed to the extraction channel. Part of the beam is redirected to the circulating orbit of the Delivery Ring. The percentage of beam loss determined by particle surfaces at EDWA and D2Q7 is 1.25%.

A comparison of the results of MARS simulations with and without in-tunnel shielding is shown in Figure 7. The peak normal effective dose rate in the AP30 service building with in-tunnel shielding is just under 40 mrem per hour. From Table 1 it can be seen that this is within the allowable operating range for normal beam loss. The building would be posted as a Radiation Area and access would be restricted through the entry control program to authorized personnel during beam operations.

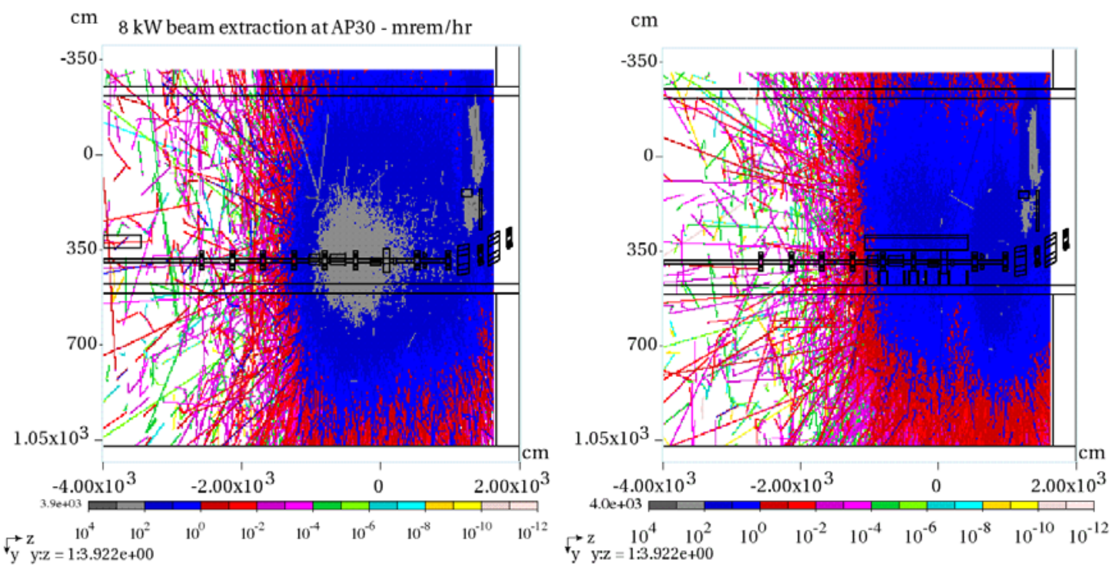

Figure 7 Plan views of MARS histogram results at the elevation of the AP30 service building floor are shown. At left shows the effective dose rate without in-tunnel shielding. At right, the in-tunnel shielding reduces the effective dose rate to acceptable levels. The elevated levels shown at the upper right side of the figures is within the exit stairway which is inaccessible during beam on operation. The lower black lines at Y = 508 cm indicates the tunnel concrete shield wall. The parking lot adjacent to the AP30 service building begins at Y = 750cm.

An additional MARS simulation was made to determine effective dose rates in the parking lot adjacent to the AP30 service building, along Indian Road which passes by the AP30 service building, and at greater distances due to radiation skyshine. The result of the calculation for the parking lot and Indian Road is shown in Figure 8.

The peak effective dose rate in the parking lot is generally less than 1 mrem/hr, though at the perimeter of the service building, rates are several mrem/hr. The MARS model did not include the building wall panels which are 8” thick and so this result is conservative. Effective dose rate at the imbedded steel panels, however, may require supplemental shielding. Some additional shielding could be installed at the building perimeter if necessary or a section of the parking lot along the building perimeter could be fenced to preclude personnel access.

The calculated effective dose rate at Indian Road is found to be less than 0.05 mrem/hr. The occupancy of the roadway would not require personnel access restrictions or radiological postings.

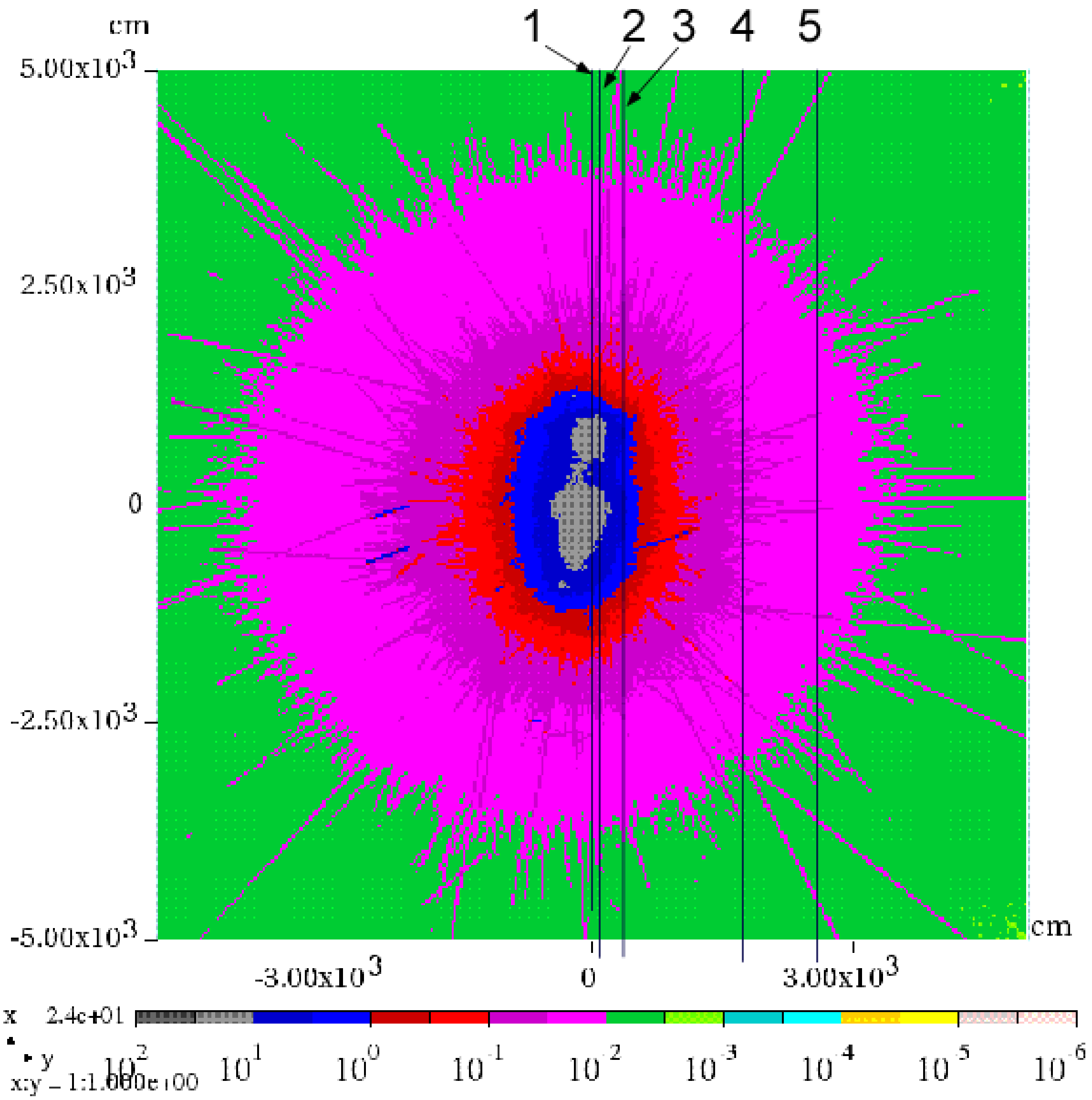

Figure 8 This image shows the result of a MARS skyshine simulation for the in-tunnel shielding case. The effective dose rate (mrem/hr) at ground level includes contributions from all particle fluences, both direct and reflected from the atmosphere. Line 1: Delivery Ring centerline; Line 2: Tunnel outer concrete surface; Line 3: AP30 service building outer edge; Region 3 to 4: AP30 Parking Lot; Line 5: edge of Indian Road.

The result of the skyshine calculation is shown in Figure 9. In this calculation, the effective dose rate at ground level is due solely to skyshine radiation. The average effective dose rate at 500 meters, the nominal distance to Wilson Hall, is < 0.2 mrem/year.

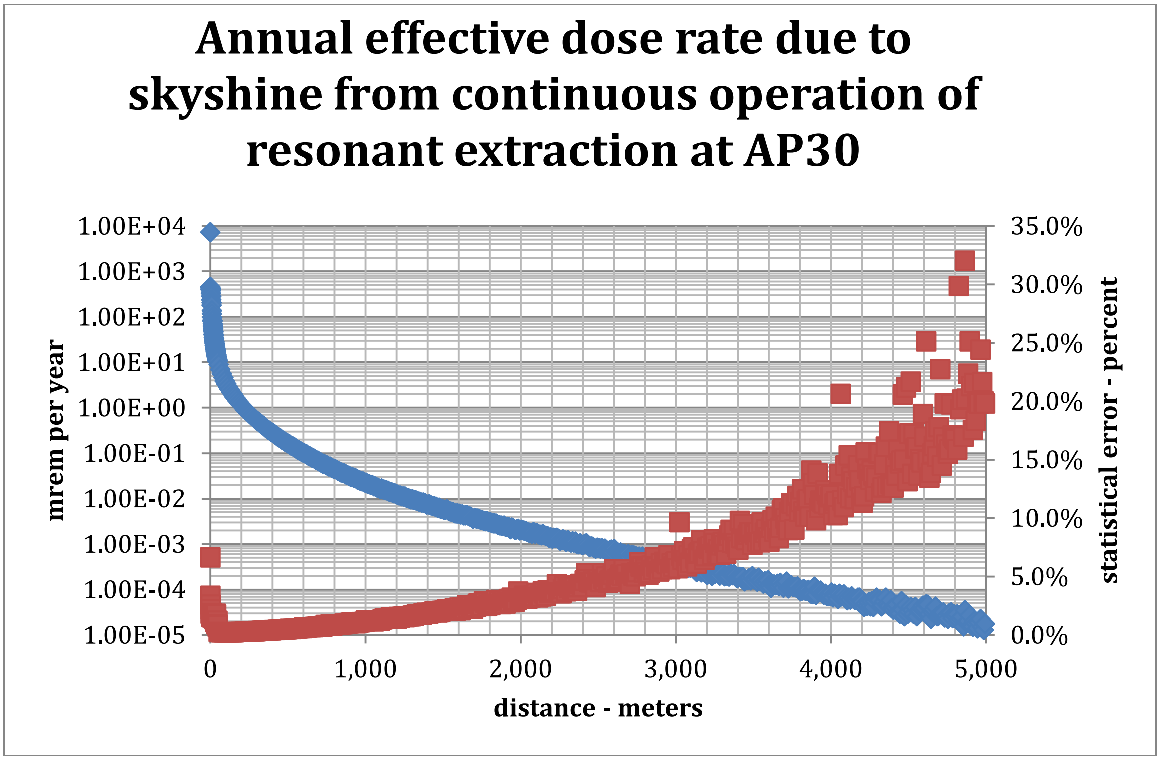

Figure 9 The effective dose (blue points) due to skyshine as a function of distance from the AP30 service building is shown in the figure. The statistical errors (red points) are shown as a function of distance. The effective annual dose rate at 500 meters, the nominal distance to Wilson Hall, for continuous occupancy is < 0.2 mrem/year.

The final concern for the normal extraction losses at AP30 is the direct radiation exposure to occupants of Wilson Hall. A MARS simulation was made in which a detector cylinder 0.3 meters thick, 70 meters high, and with a radius of 500 meters is established to predict the annual effective dose rate as a function of floor elevation. The relationship of Wilson Hall with respect to AP30 service building is shown in Figure 10; Wilson Hall is approximately 23 degrees clockwise relative to the incident beam direction. The result of the simulation is shown in Figure 11; the annual effective dose rate for all floors at Wilson Hall is <1 mrem/yr at the azimuthal angle of 23 degrees.

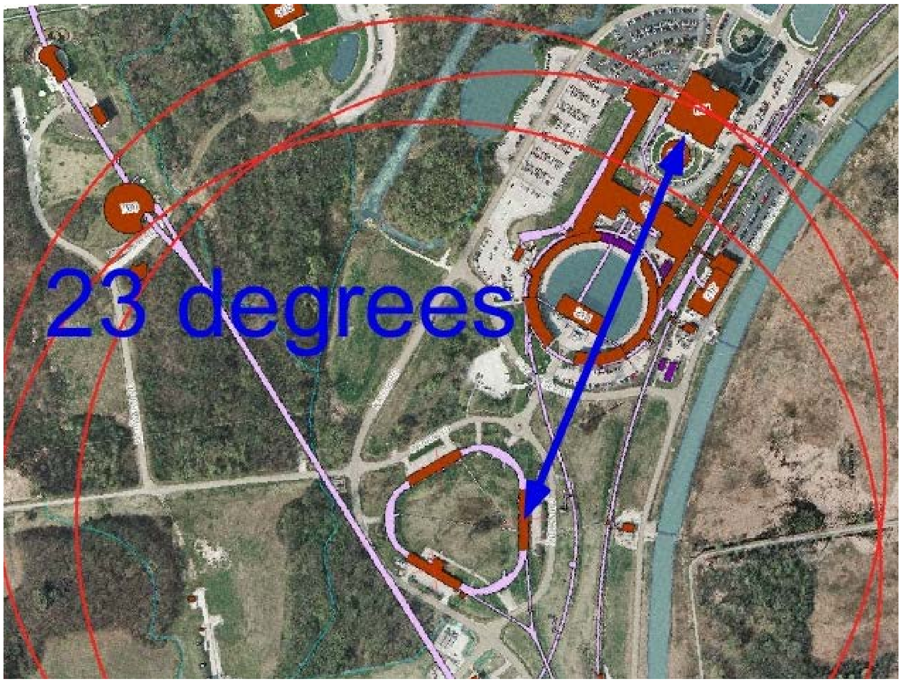

Figure 10 The red circles have a radius of 500 m; each one is centered at one of the service building footprints. The azimuthal angle between the z axis of the MARS simulation (parallel with the major axis of the AP30 service building) and the center of Wilson Hall is indicated by the blue line.

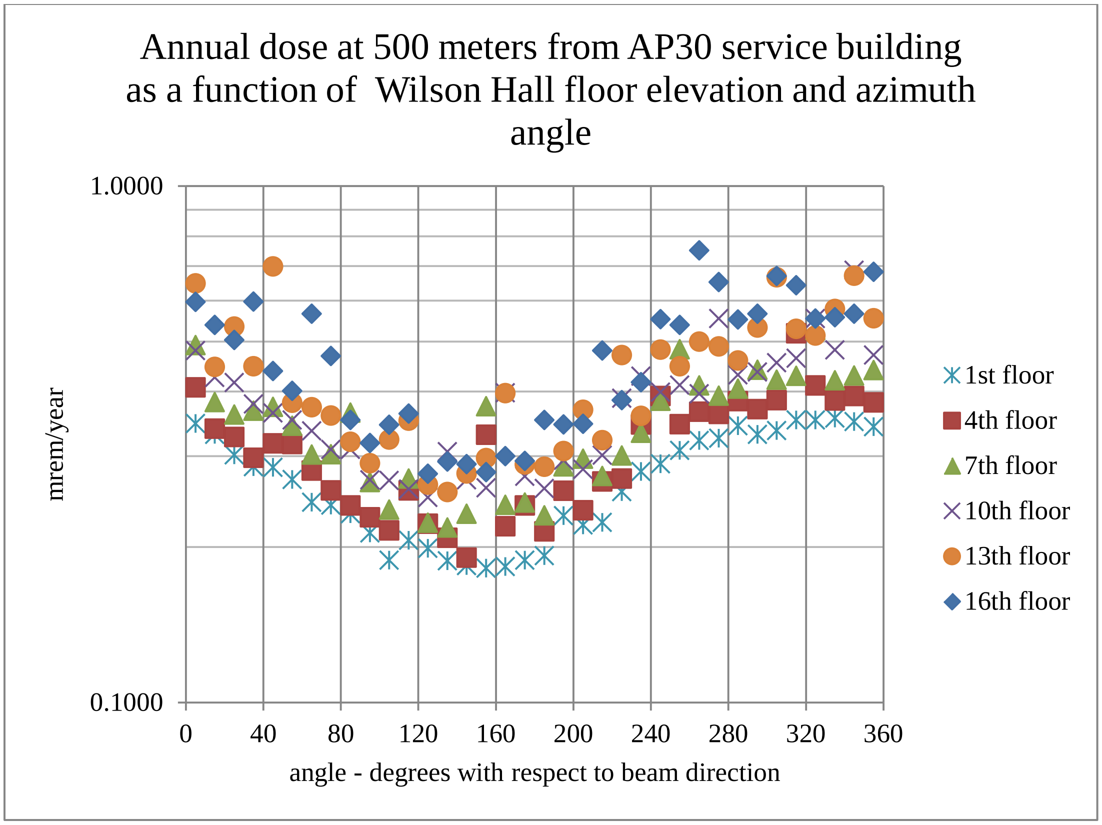

Figure 11 The MARS simulation result for the total effective annual dose rate as a function of floor elevation in Wilson Hall from direct radiation exposure originating from the AP30 service building plus skyshine is shown here. Wilson Hall lies at angle of 23 degrees relative to the incident proton beam direction.

A TLM installed in the AP30 straight section would be employed to limit beam losses to those expected at nominal levels. A trip level margin commensurate with limitations for the control level chosen from Table 1 would also apply. As a result, it would not be possible for the time-weighted average effective dose rate delivered under any conditions including accident ones to exceed that permitted under normal conditions.

The remainder of the Delivery Ring is not expected to have significant beam losses with the possible exceptions of the abort kickers in the AP50 straight section and the injection region in the AP30 straight section. Supplemental shield of the same design could be used at those locations if it is found to be necessary. The control of beam losses for the AP10 and AP50 service buildings, assuming no additional in-tunnel shielding will be required, is discussed in the next section.

Detailed results of in-tunnel shielding calculations are provided in Reference [11].

2.2.2 General Protection Scheme for Limiting Prompt Effective Dose Rate

The preceding section covered the in-tunnel shielding, and active control features for the AP30 service building. In this section, remaining Anti-proton Source facilities are considered.

In general, significant beam losses are expected to be minimal and should not require additional control measures such as in-tunnel shielding. As discussed in 2.1.2, interlocked radiation detectors will be required to ensure the effective dose rate limits are observed for all tunnel enclosures. TLMs are to be used for this purpose. Since interlocked radiation detectors are to be used and the trip level setting defines the limiting condition, a control level from Table 1 must be chosen. The intention is to not require fences on roadways or berms. The small region of Indian Road crossing the Transport Enclosure is considered minimal occupancy, less than 1 hour per day. Minimal occupancy limited to 1 hour per day is also reasonable for shielding berms. The controlled area posting for all outdoor areas would be required. There are two categories in Table 1 that cover these parameters and they are identified with a control level ID number in Table 5. Based upon this set of choices, the Categories from Table 5 can be applied to the Anti-proton Source facilities; these are listed in Table 6 .

The TLM response for a controlled beam loss has been determined at the Booster for 6 to 8 GeV proton beam loss using the argon/CO_2 detector system [6]. The value, 2.6 nC/1E10 protons, is used in Table 6 to calculate a TLM charge collection level limit.

Table 5 Control level indices for use in Table 1.7

Control level	Dose range	Required controls
1	0.25 < DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy (occupancy duration of less than 1 hr)
2	5 < DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.

The following is a description of entries in Table 6:

- TLM ID number – included for counting purposes
- Location – The section of tunnel covered by a common TLM detector. The section is uniformly shielded so that the limiting effective dose per lost proton is nominally constant throughout the region

- Control Level – as described in Table 5
- Shield (ft) – the shielding thickness in feet at the TLM installation
- Beam loss scaling factor – the number of protons lost per mrem for the given shielding thickness. The factor is determined from the standard shield scaling criteria of Reference [3].
- Lower hourly dose rate for control level – this is the lower range value for the given control level
- Upper hourly dose rate for control level - this is the upper range value for the given control level
- Project suggested TLM limiting rate – this is the mu2e project suggested trip level which should be achievable while meeting the physics goals for the mu2e experiment
- Extended limit – the product of the beam loss scaling factor and the Project suggested TLM limiting rate
- TLM trip level – the average charge collected in nanocoulombs per minute which would result in a interlocked radiation detector trip.

Table 6 TLM locations and trip levels. TLM 2 is installed across 2 control levels and so the trip level for the lowest control level would apply.

TLM	Location	Control Level	shield (ft)	beam loss scaling factor (protons per mrem	lower hourly dose rate for control level	upper hourly dose rate for control level	Project Suggested TLM limiting rate	extended limit - protons per hour	TLM trip level (nC/min)
1	Pre-Vault Enclosure at AP0 Service Building – M1 line	2	13	1.89E+13	5	100	50	9.43E+14	604
2	Transport Enclosure at AP0 Service Building – M3 line	2	12.5	1.34E+13	5.00	100	50	6.71E+14	430
2	Transport Enclosure Shielded Tunnel – M3 line	1	14	3.73E+13	0.25	5	5	1.86E+14	119
3	Transport Enclosure under Indian Road – M3 line	1	13	1.89E+13	0.25	5	0.25	4.72E+12	3
4	Transport Enclosure to Delivery Ring – M3 line	1	13	1.89E+13	0.25	5	5	9.43E+13	60
5	Delivery Ring 20 Arc	1	13	1.89E+13	0.25	5	5	9.43E+13	60
6	Delivery Ring 40 Arc	1	13	1.89E+13	0.25	5	5	9.43E+13	60
7	Delivery Ring 60 Arc	1	13	1.89E+13	0.25	5	5	9.43E+13	60
8	Delivery Ring at AP10 Service Buildings	2	10	2.44E+12	5.00	100	50	1.22E+14	78
9	Delivery Ring at AP30 Service Buildings	2	10	2.44E+12	5.00	100	50	1.22E+14	78
10	Delivery Ring at AP50 Service Buildings	2	10	2.44E+12	5.00	100	50	1.22E+14	78
11	Upstream Beam Transport from Delivery Ring to Target Hall – M4 line	1	16	1.46E+14	0.25	5	5	7.28E+14	467

12	Downstream Beam Transport from Delivery Ring to Target Hall – M4 line	1	16	1.46E+14	0.25	5	5	7.28E+14	467

The suggested TLM trip levels are based upon a beam loss occurring at a single point which would deliver an effective dose rate up to the Project suggested limit. Since the TLM system cannot distinguish how the collected charge was distributed, the actual effective dose rate at any location along the shielded location will generally be much lower than the Project suggested limit. Consequently, the TLM system is a conservative protection system.

Residual activation can also be considered in setting TLM trip levels. One watt per meter is the accepted nominal level [25] which allows worker access without the need for extraordinary controls. The trip levels given in Table 6 are modified in Table 7 if, instead, it is desirable to limit beam losses to 1 watt per meter. The maximum effective dose rate outside the shield is reduced accordingly where modified trip levels apply.

Table 7 Modified TLM trip levels to limit beam loss to 1 watt per meter. The maximum effective dose rate by location is reduced commensurately with the reduced trip level. The trip level for TLM 9 will be determined by MARS simulation with consideration of the in-tunnel shielding.

TLM	Location	extended limit - protons per hour	TLM length	watts	watts per meter	TLM trip level (nC/min)	modified trip level (nC/min)	maximum effective dose rate
1	Pre-Vault Enclosure at AP0 Service Building – M1 line	9.43E+14	11.6	336	29.0	604	21	1.7
2	Transport Enclosure Shielded Tunnel – M3 line	1.86E+14	138	66	0.5	119	119	5.0
3	Transport Enclosure under Indian Road – M3 line	4.72E+12	10	2	0.2	3	3	0.3
4	Transport Enclosure to Delivery Ring – M3 line	9.43E+13	138	34	0.2	60	60	5.0
5	Delivery Ring 20 Arc	9.43E+13	118	34	0.3	60	60	5.0
6	Delivery Ring 40 Arc	9.43E+13	118	34	0.3	60	60	5.0
7	Delivery Ring 60 Arc	9.43E+13	118	34	0.3	60	60	5.0
8	Delivery Ring at AP10 Service Buildings	1.22E+14	51	44	0.9	78	78	50.0
9	Delivery Ring at AP30 Service Buildings							
10	Delivery Ring at AP50 Service Buildings	1.22E+14	51	44	0.9	78	78	50.0
11	Upstream Beam Transport from Delivery Ring to Target Hall – M4 line	7.28E+14	138	259	1.9	467	248	2.7

12	Downstream Beam Transport from Delivery Ring to Target Hall – M4 line	7.28E+14	138	259	1.9	467	248	2.7

2.2.3 M4 Beam Line Shield Wall and Diagnostic Absorber

A 170 W beam absorber is required in the M4 line for commissioning Delivery Ring fast spill and slow resonant extraction. The commissioning period will take place during the construction phase of the Production, Transport, and Detector Solenoids. Consequently, a shield wall is also required to limit the effective radiation dose rate in the Production Solenoid Hall. MARS simulations were used to iterate the design of the Diagnostic Absorber and shield wall [20]. Figure 12 shows a plan view of the arrangement.

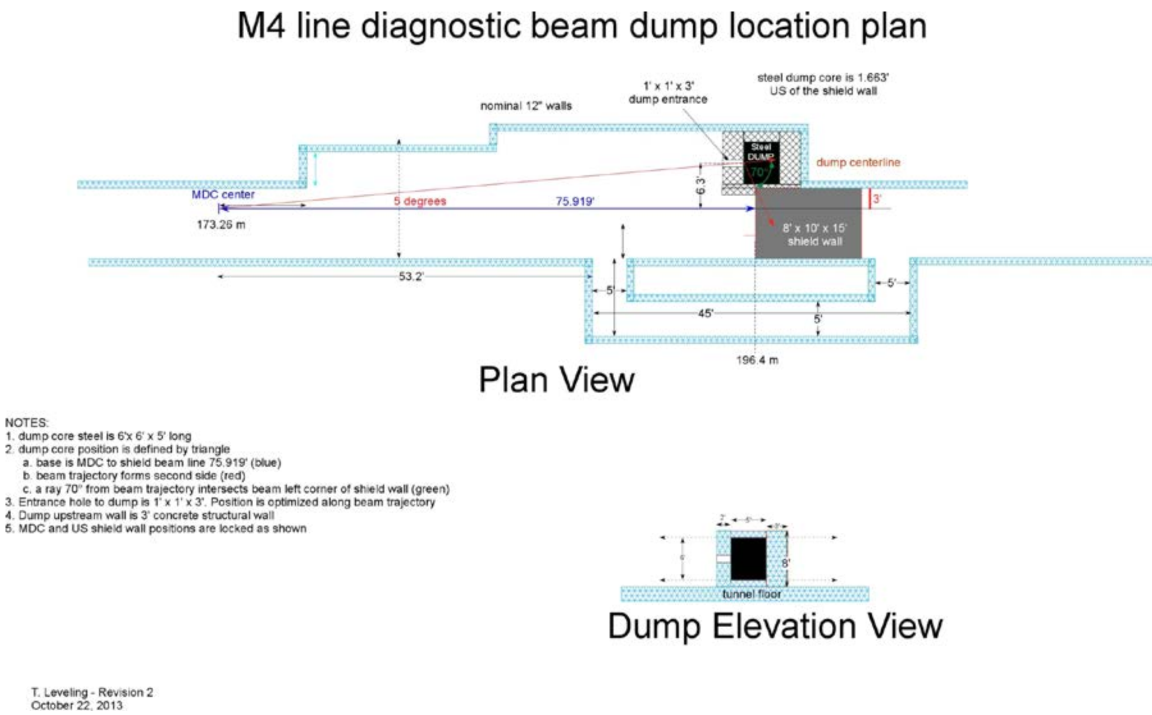

Figure 12 M4 line diagnostic absorber plan and elevation view

The prompt effective dose rate at the Production Solenoid room calculated from MARS simulations is < 0.05 mrem/hr during normal beam operation to the diagnostic absorber. Figure 13 shows prompt effective dose rates generally resulting from this design.

An accident condition in which the 170 watt proton beam is lost on the MDC switching magnet was also considered. The resulting dose rate in the Production Solenoid room was calculated to be about 250 mrem per hour [20]. A TLM located in the M4 line upstream of the M4 line shield wall was discussed in the preceding section. The corresponding TLM response for this accident condition is estimated to be about 2400 nC/min. The trip level for the upstream M4 line TLM during the PS/TS/DS construction phase will have to be reduced from the nominal 248 nC/minute listed in Table 7 to about 6.5 nC/minute in order to limit accident condition prompt effective dose rate to < 1 mrem/hr and, consequently, to permit non-radiation workers unrestricted access to the Production Solenoid room.

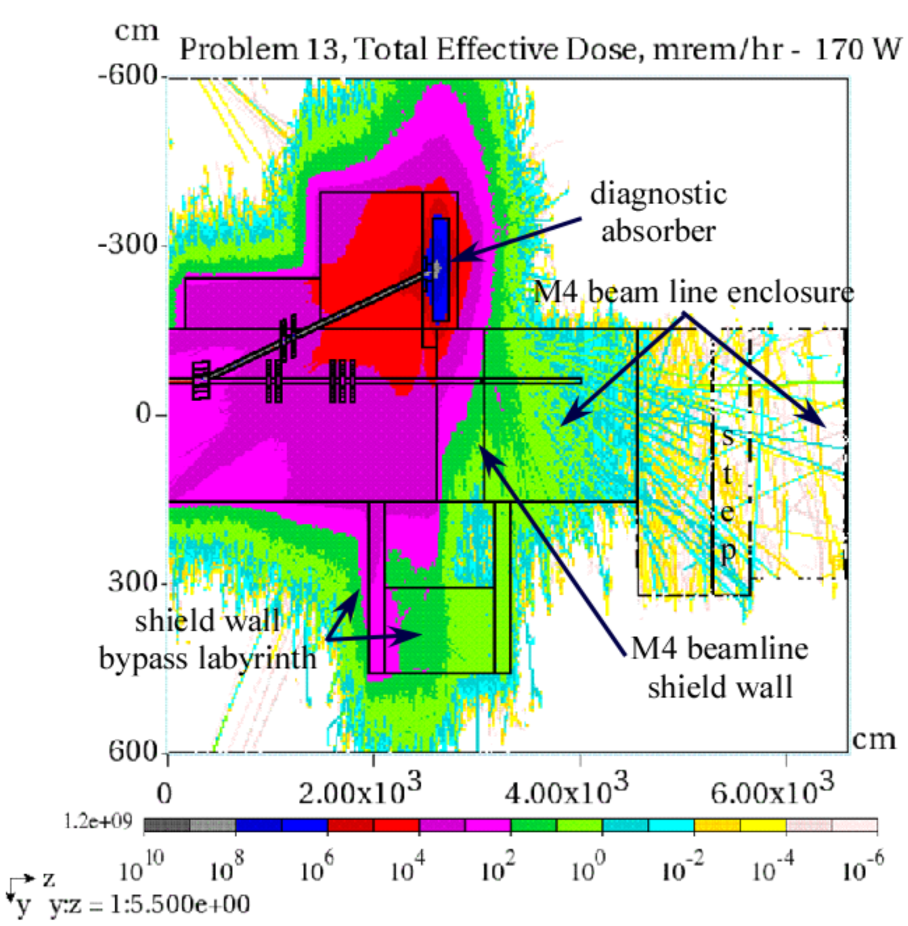

Figure 13 Plan view of MARS simulation showing the diagnostic absorber, shield wall, shield wall bypass labyrinth under the normal operating condition.

The nominal shielding over the M4 beam line and diagnostic absorber is 16 feet (4.88 m). In Figure 12 it can be seen that the prompt radiation effective dose rate adjacent to the beam dump, left side (y = -396 cm), is just under 100 mrem/hr at y = -600 cm, i.e., with about 2 meters of shielding. An additional 2.88 meters of shielding should reduce prompt effective dose rate on the surface of the berm above the diagnostic absorber by about 2.88 orders of magnitude to < 0.25 mrem/hr.

2.2.4 M5 Beam Line Shield Wall

A shield wall, provided by the muon g-2 experiment is required in the M5 beam enclosure to permit personnel access to the MC-1 service building during mu2e beam operation. MARS simulations were used to iterate on the design of the M5 line shield wall [23]. The simulations show that a TLM trip level of 520 nC/min would limit the effective dose rate downstream of the M5 composite shield wall to 0.25 mrem/hr. The limit in Table 7 for the upstream TLM is 248 nC/min, which is well below the specified trip level in the M5 analysis. The combination of composite shield wall and this TLM trip level will be sufficient to permit trained radiation workers unlimited access to the MC-1 service building.

2.2.5 Delivery Ring Cleanup Absorber

A beam abort is required to remove residual beam following each slow resonant extraction cycle. It is estimated that about 5% of the beam for each cycle will remain; consequently, the beam power requirement of the beam dump is nominally 400 watts. A beam dump has been designed and is illustrated in Figure 14 (elevation cross section view), Figure 15 (longitudinal elevation view), and Figure 16 (plan view).

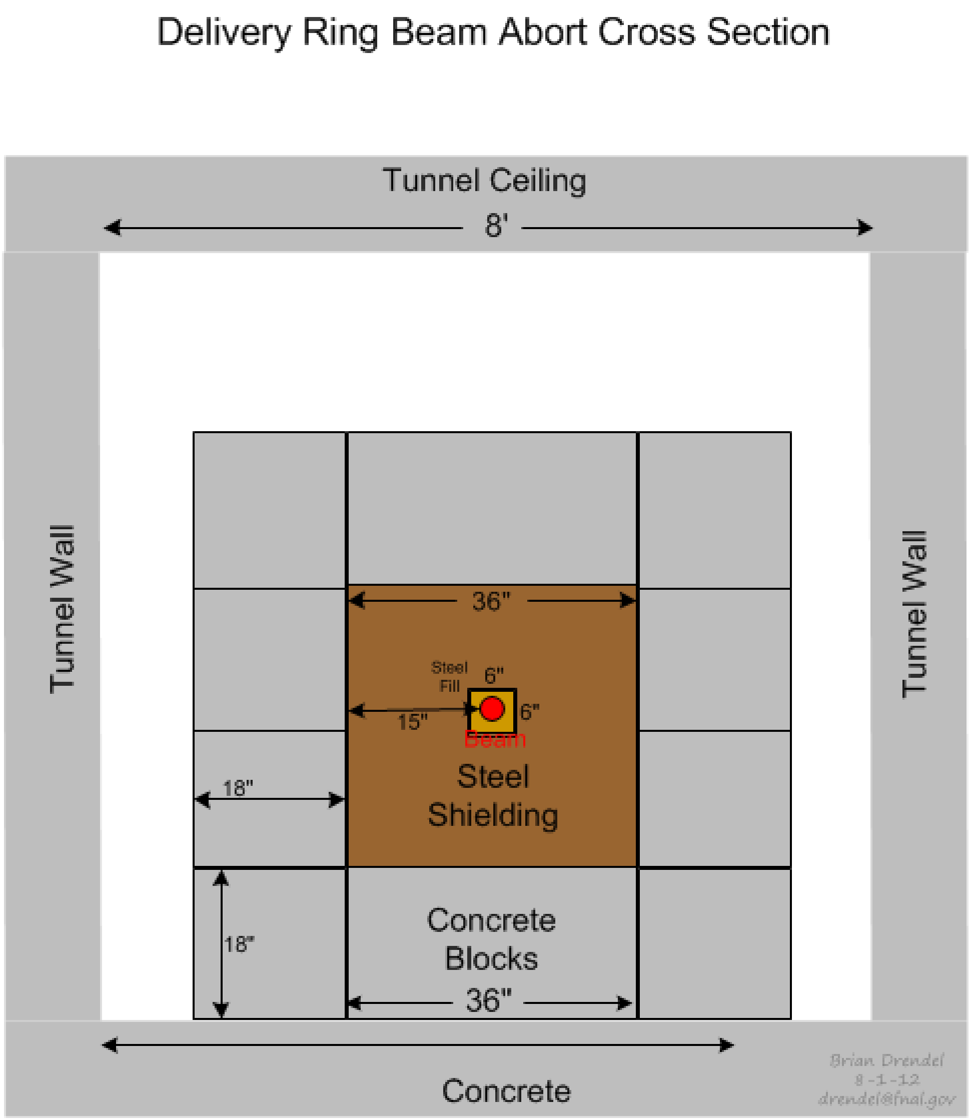

Figure 14 Delivery Ring cleanup dump elevation view

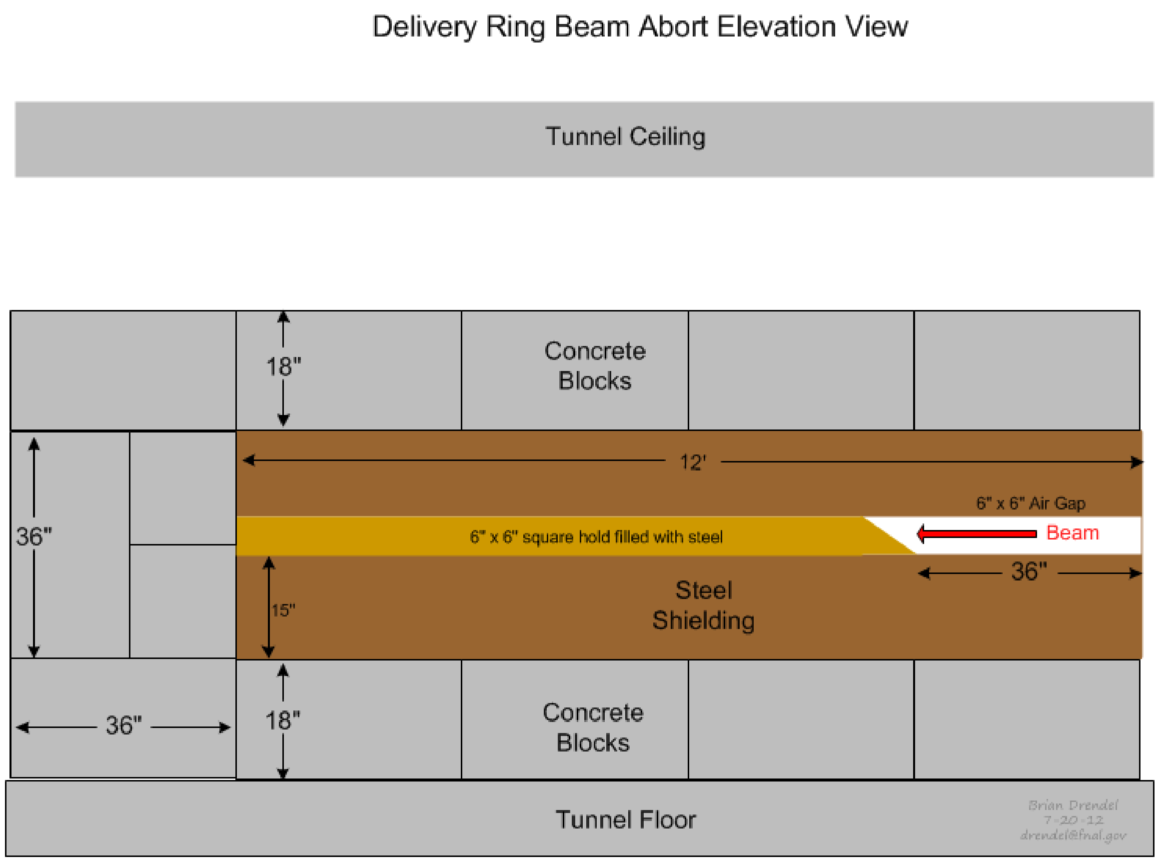

Figure 15 Delivery Ring cleanup dump longitudinal elevation view

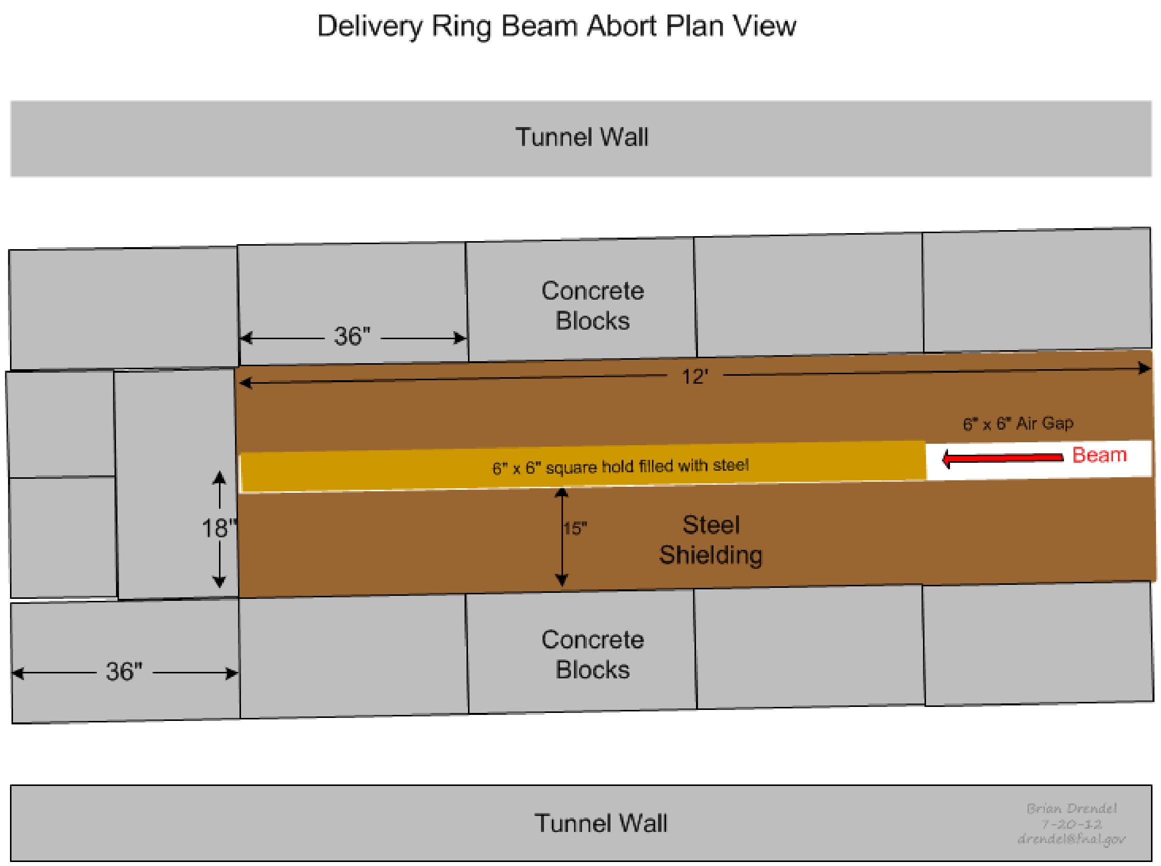

Figure 16 Delivery Ring cleanup dump plan view

A simple cylindrical MARS model of the Delivery Ring clean up dump is shown in Figure 17. The existing AP2 shielding in the vicinity of the dump is 13 feet. A tissue equivalent detector is placed in the model on the berm surface to determine the effective dose rate as a result of 400 watt, normal operation.

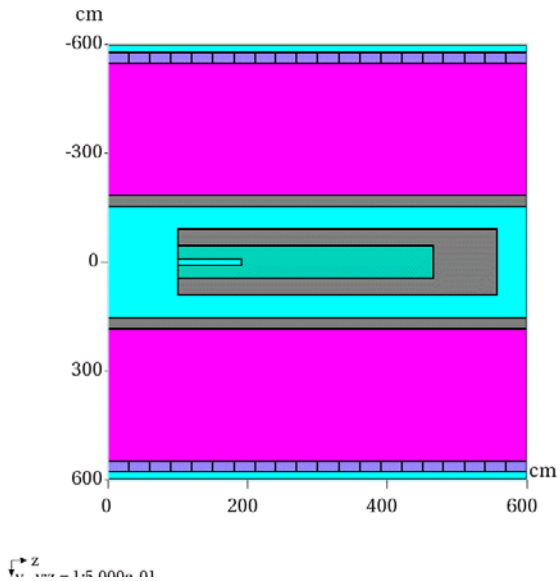

Figure 17 Simple cylindrical MARS model of delivery ring beam dump. The model is representative of a vertical plane along the beam axis, starting at the beam center and moving upward to the AP2 line berm surface.

A 2 stage MARS run was made since this is a thick shielding problem. Figure 18 shows a cross section of the model at z = 300 cm along with particle tracks originating from the outer surface of the concrete tunnel at radius = 182.88 cm

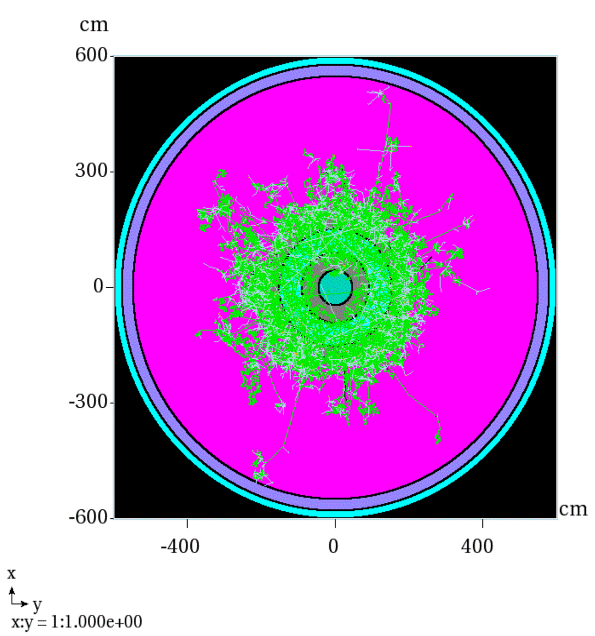

Figure 18 Cross section of the delivery ring simple model at z = 300 cm. The indicated tracks produced in a trial, stage 2 run originate at the outer surface of the tunnel concrete.

The result of the stage 2 run is shown in Figure 19 and Figure 20. The peak effective dose rate is about 85 mrem/hr.

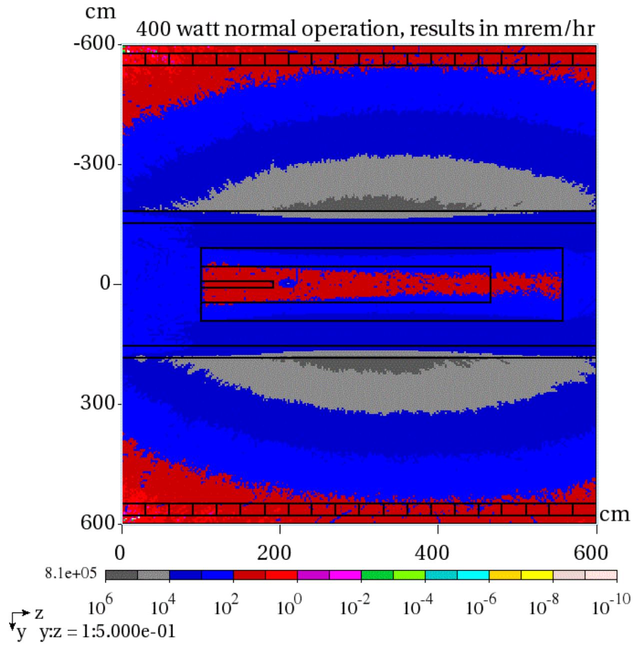

Figure 19 MARS simulation result; stage 2 run with 8 GeV, 400 watt beam power in Delivery Ring Dump. Effective dose rate at the berm surface approaches 100 mrem/hr.

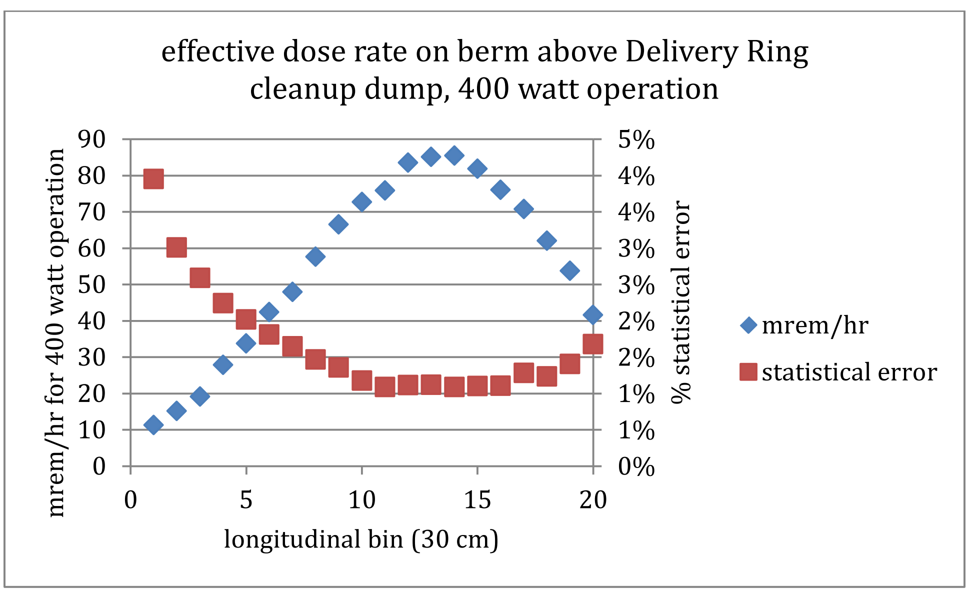

Figure 20 Effective dose rate in 20 tissue equivalent detectors along berm surface over Delivery Ring Dump. Statistical errors for the calculation are shown.

For the purpose of this preliminary shielding assessment, the design meets the criteria of Table 1 if the area around the dump is fenced and posted as a radiation area. The design of the dump can be further iterated to reduce radiation dose rates on the berm surface. For example, the steel could be extended vertically by 1 foot above the dump and another foot of concrete could be placed in the remainder of the 2 foot air gap of the present design. These adjustments could reduce the calculated rates by a factor of about 50 to eliminate the requirement for a fence and reduce the posting level to controlled area.

2.2.6 Exit Stairways and Penetrations

The shielding evaluation of the Delivery Rings and related beam transport lines has been considered in conjunction with discussion on TLM applications. Penetrations through the passive radiation shielding including stairways, various ducts, and cable penetrations are considered in this section. TLMs described above also play a role in limiting the radiation effective dose rate for these penetrations through the radiation shield.

An Excel spreadsheet developed by the ES&H Section [21] was used to calculate the radiation dose rates at the exit of labyrinths and penetrations based upon user input parameters including the source term, aspect ratio, and length of each of the legs of the labyrinth or penetration. The evaluated penetrations are listed in Table 8 along with the resulting dose rate calculated for the 2000 Pbar shielding assessment [22]. The third column of the table shows the resulting dose rate by scaling to the 8 kW beam power required for Mu2e. The fourth column shows the maximum number of protons lost per hour as limited by the TLMs trip levels established in Table 6. The fifth column shows the maximum possible dose rate (single point beam loss) at the exit of facility penetrations based upon the TLM trip levels established in Table 7. As indicated in Table 8, the resulting radiation effective dose rates at the exits of these penetrations are within limits prescribed by the FRCM. No additional remediation is required for the existing facility including the three elevator shafts at the type 1 stairways.

Table 8 2000 Pbar shielding assessment penetration dose calculations (mrem/hr) scaled to proposed TLM trip levels. Radiation dose rates at penetration exits would require no addition mediation if TLMs are used as described above.

Penetration Name	Calculated exit dose rate from 2000 pbar shielding assessment	Scaled to 8 kW, 8 GeV proton beam loss	TLM #	Max protons lost/hour limited by TLMs	Penetration dose rate limited by TLMs
Determined for 3.6E13 8 GeV primary protons per hour					
ACC/DEB airshaft	7.54E-02	47	5,6,7	9.43E+13	0
ACC/DEB stairway type 2	1.85E-03	1	8,9,10	1.22E+14	0.0171
Transport to AP0 penetrations	9.62E-02	60	2	1.86E+14	0
Stub Room Penetrations	2.00E-01	125	8,9,10	1.22E+14	1
AP0 water pipe penetrations	8.21E-01	513	2	1.86E+14	4
Transport air duct vent to AP0	4.01E-03	3	2	1.86E+14	0
Transport to F27 Penetrations	6.32E-14	0	2	1.86E+14	0
ACC/DEB elevator shafts	5.09E-01	318	8,9,10	1.22E+14	2
Transport stairway	4.47E-02	28	2	1.86E+14	0
ACC/DEB stairway type 1	1.41E-05	0	8,9,10	1.22E+14	0
AP50 Pit Vent	7.63E-07	0	10	1.22E+14	0
AP50 Pit Labyrinth	1.78E-02	11	10	1.22E+14	0
Determined for 1.8E16 120 GeV primary protons per hour					
PreVault stairway	1.58E-02	0	1	3.26E+13	0
Sweeping Magnet Penetrations	1.23E+00	0	1	3.26E+13	0
PreVault to F23 Penetrations	5.12E-04	0	1	3.26E+13	0

In addition to the calculations described above, there have been a number of measurements of radiation effective dose rate at exits of penetrations simultaneously with measurements adjacent to radiation shields. In general, there has been no evidence that the radiation effective dose rate through well-designed penetrations is greater than those found through radiation shields. Several examples are given here.

A radiation effective dose rate measurement was made at the AP30 #2 exit stairway in 2011[26]. This measurement was made during the mu2e pre-conceptual design phase when both the Accumulator and Debuncher Rings were to be used for the experiment running at 25 kW. The measurement was made with the 8 GeV proton beam extinguished in the Accumulator Extraction Lambertson (ELAM). The effective dose rate at the stairway exit due to a 25 kW beam loss on ELAM was 4.5 rem/hr [26]. The effective dose rate just above the ELAM beam loss on the AP30 service building floor was determined to be 25 mrem/3.6E13 protons [8]. The ratio of effective dose rate at the exit stairway to the effective dose rate directly above the loss point on the service building floor is 1:10.85.

Two specific penetration/shield measurements were made and documented for the 2000 pbar shielding assessment [22] at AP30 and AP50. In both cases, the effective dose rate through the shield was higher than that measured at the exits of penetrations.

A MARS simulation for a site riser design required for the M4 beam line has been made and documented [27].

2.2.7 Ground water activation

The major sources of groundwater activation for the Mu2e experiment include losses at the following locations:

- Delivery Ring beam absorber
- M4 line Diagnostic Absorber
- Delivery Ring extraction

Detailed groundwater activation calculations for Mu2e operation were completed for the mu2e experiment during the pre-conceptual design phase for a 25 kW beam power scenario [4]. No ground water issues were identified. Since the final design beam power is now 8 kW, no further consideration is warranted for this preliminary shielding assessment.

2.2.8 Surface water activation

The major sources of surface water activation due to beam operations at the Accumulator/Debuncher facility for the Mu2e experiment are the same sources as those listed for ground water activation. Detailed calculations for surface water activation for Mu2e operation of the Accumulator/Debuncher Rings have been completed [4]. No surface water issues were identified.

2.2.9 Airborne radioactivity

The major source of airborne radioactivity due to beam operations at the Accumulator/Debuncher facility for the Mu2e experiment is from primary/secondary beam passing through the air volume between the Production Target Solenoid and the Main Beam Absorber. Other sources to be considered are due to beam losses at locations listed in the ground water section. Local shielding at the extraction region and other beam transfer locations will reduce airborne radioactivity levels significantly. Detailed calculations for airborne radioactivity for Mu2e operation have been completed [4]. Engineered ventilation controls will be used to limit the impact of air emissions for the Mu2e project.

The Production Solenoid Enclosure air system will be continuous with the M4 beam line. The air supply in the Production Solenoid Enclosure will come from a supply duct located adjacent to the Production Solenoid Beam Absorber. This air will pass through the Production Solenoid Enclosure and will be exhausted at an exhaust trunk located near the upstream end of the M4 beam line enclosure. The exhaust flow rate at the normal fan speed will be about 900 cfm. In the event of an ODH alarm in the Production Solenoid Enclosure, a high speed fan will exhaust air at 10,000 cfm from a separate exhaust stack near the PS room.

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