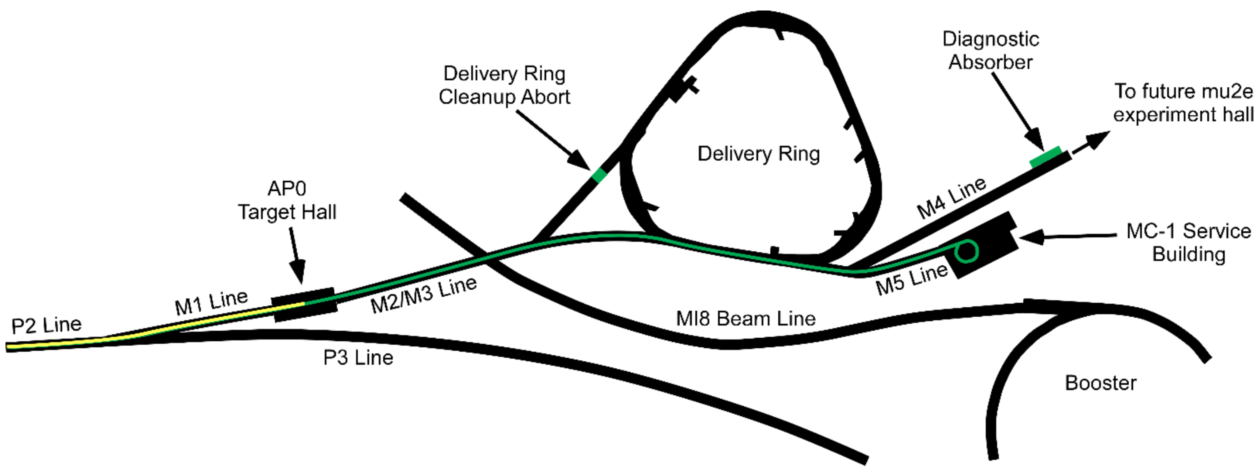


MUON G-2 SHIELDING ASSESSMENT

Extraction Enclosure and MC-1 Service Building

February 7, 2017

Abstract

A Muon Campus Shielding Assessment is required before initiation of beam operations following the reconfiguration of the Anti-Proton Source for muon g-2 operation. This shielding assessment covers the various operational modes required to commission and operate the Muon Campus for beam delivery to the muon g-2 experiment located at the MC-1 building.

Contents

1. Introduction

The Muon Campus is scheduled to begin beam operations to support the Muon g-2 experiment beginning in the spring of 2017. Consequently, a shielding assessment is required.

Recently, the Antiproton Source 2000 Shielding Assessment (AS2000SA) [1] was reviewed [2] to determine its continuing application to the Muon g-2 experiment. The review, which demonstrated the AS2000SA is still valid for the legacy facilities, was subsequently approved [2]. New facilities including the Delivery Ring Cleanup Abort, the M4/M5 shared extraction beam line, the Extraction Enclosure, and the MC-1 Experimental Hall were not included in the review; the assessment of these new facilities is the subject of this shielding assessment.

2. Muon Campus Operating Modes

A general description of Muon Campus operating modes is given in Reference 10. ***Only the specific modes germane to this assessment are described here.*** In the following figures, the primary, 8 GeV beam path is indicated by yellow lines/arrows while the secondary, 3.09 GeV/c beam path is indicated by green lines/arrows.

A. 8 GeV beam to Delivery Ring Cleanup Abort

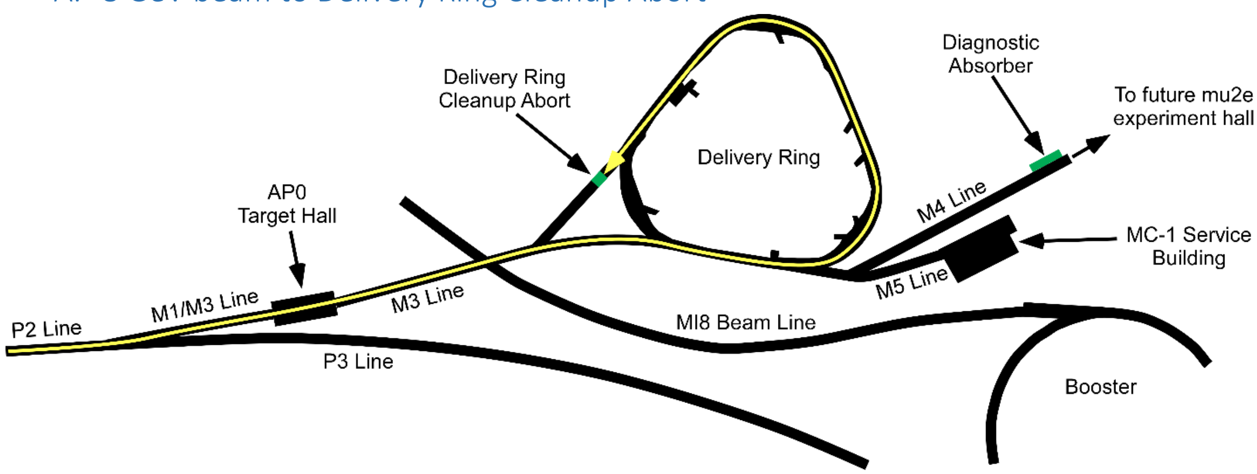


Figure 1

The Booster provides a reliable primary beam source of 8.89 GeV/c protons to the Muon Campus to commission and periodically tune beam line and Delivery Ring optics and orbits. The Delivery Ring Cleanup Abort absorber is to be used to remove primary protons after a partial turn or multiple turns in the Delivery Ring. M1 line, M3 line, Delivery Ring injection, Delivery Ring circulating, and Delivery Ring Cleanup Abort orbits can be established with this mode. Once the orbits are established, beam line and Delivery Ring magnet currents can be reduced/scaled to transport the nominal momentum secondary beam required for the Muon g-2 experiment.

B. 3 GeV secondary beam through AP30 to MC-1

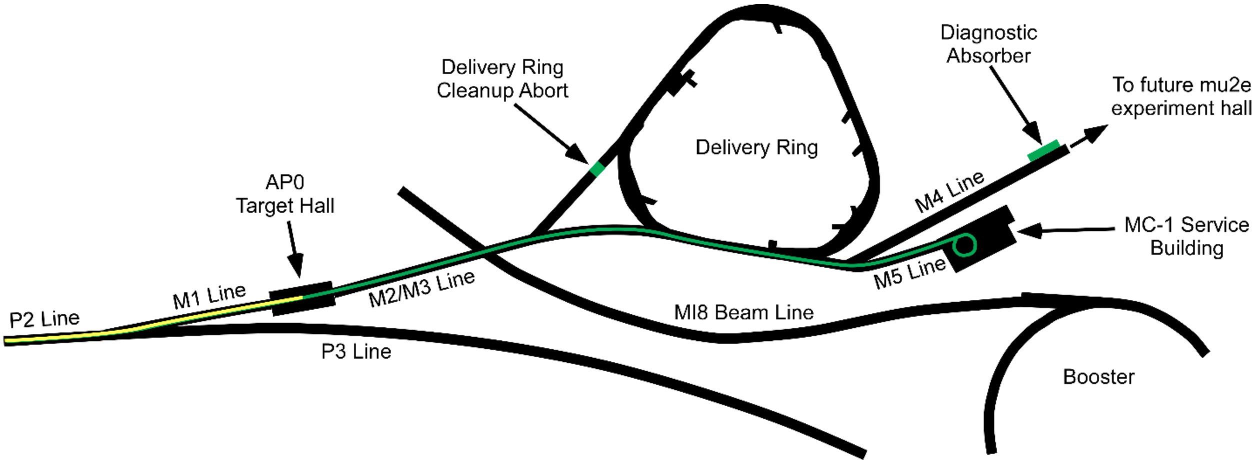


Figure 2

It may be necessary and/or desirable to direct the 3.09 GeV/c secondary beam produced in the target vault to the Muon g-2 storage ring, especially early in the commissioning phase of the Muon g-2 experiment. In this mode there is no attempt to optimize pion decay or proton removal from the beam. This mode will be useful for shared M4/M5 beam line tune-up or MC-1 storage ring circulation studies, as well as to produce a signal for Muon g-2 detector systems. The cycle time for this mode will be limited by an interlocked radiation detector positioned in the MC-1 storage ring room [20].

C. 3 GeV secondary beam through Delivery Ring to MC-1

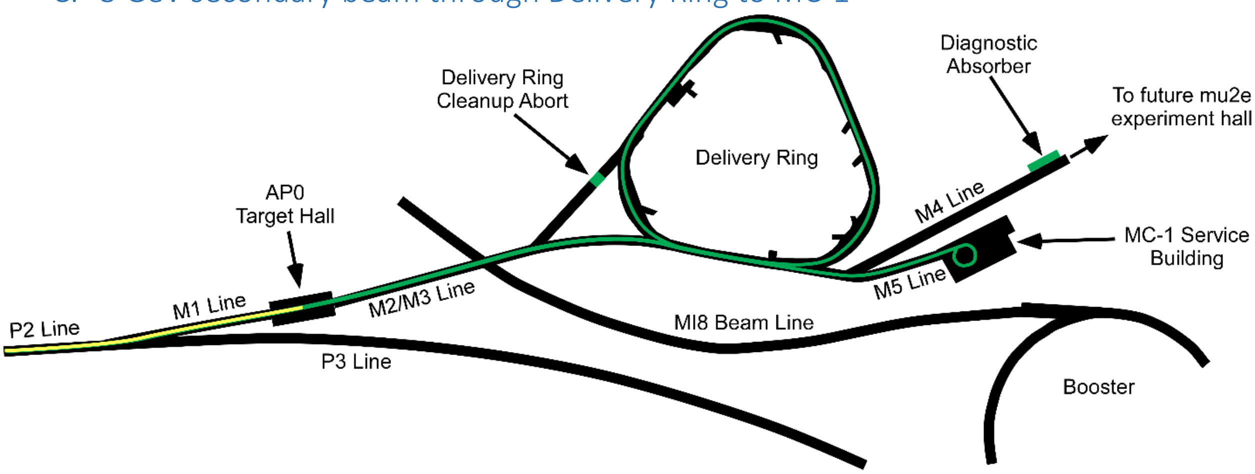


Figure 3

This is the nominal operating mode for the Muon g-2 experiment which is designed for an average operating frequency of 12 Hz. The secondary beam is circulated for 3 to 4 turns to allow pions to decay and the proton secondary beam to slip away from the muon beam, making it possible to kick the proton beam out of the Delivery Ring while extracting the remaining secondary beam (primarily muons) to the Muon g-2 ring. The secondary protons (not shown) are to be kicked out of the Delivery Ring into the Cleanup Abort.

D. 8 GeV primary beam through Delivery Ring Extraction System

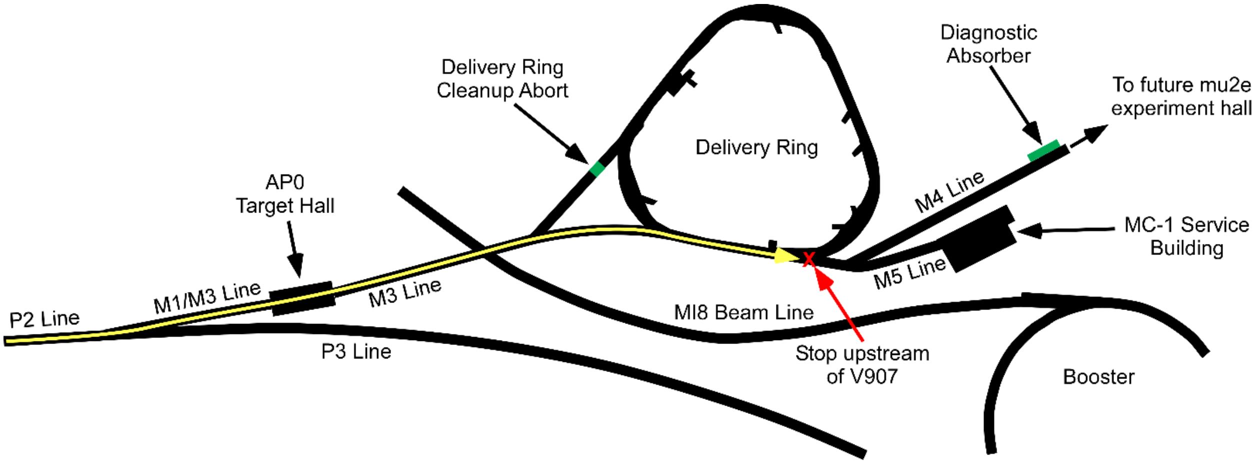


Figure 4

It may be necessary or desirable to extract 8 GeV primary protons from the Delivery Ring, either directly as shown in Figure 4 or after circulation in the Delivery Ring, in order to commission the extraction beam line. In this event, magnet power supplies beginning with V906 would be locked off. The low power beam would be lost in the trim magnet HT906 and the quadrupole Q906 as illustrated in Figure 6 and Figure 7. While no primary beam would enter the Extraction Enclosure, the secondary beam shower would be directed into the Extraction Enclosure. The consequences of this type of beam loss for the shielding berm were considered in Reference 2. The consequences for this beam loss for the Extraction Enclosure are considered below in Section 7D.

3. Beam Power Specifications

Beam power for the Delivery Ring Cleanup Abort, Extraction Enclosure, and MC-1 Experimental Hall are derived from two sources:

1. There is an 8 GeV, 12.8-watt primary proton beam (3.6E13 protons/hr), which originates from the Booster and is transmitted from the MI or RR through the P1/P2/M1/M3 lines to the Delivery Ring. This primary beam can be circulated in the Delivery Ring and/or directed to the Delivery Ring Cleanup Abort.
2. There is a 15.4 kW, 8 GeV primary proton beam (1.2E13 protons/sec or 1E12 protons per pulse at an average operating frequency of 12 Hz) incident on the AP0 target station, which produces a low-power, 3.09 GeV/c secondary beam. The secondary beam yield has been the subject of a number of simulation efforts, most recently documented in Reference 4. Table 1 summarizes the estimated secondary beam power by particle type transmitted through the M2/M3 beam line to the Delivery Ring.

Secondary Beam Power				
Protons on Target:	1.2E+13	Protons per second		
secondary particle	particles per POT [4]	yield (sec^{-1})	energy (GeV)	watts
protons	1.37E-04	1.64E+09	2.295	0.604
pions	1.87E-05	2.24E+08	2.958	0.106
muons	2.62E-06	3.14E+07	2.99	0.015

Table 1: Secondary beam yield and power summary after transmission through the M3 line and just prior to Delivery Ring injection is derived from Reference 4. Note that the proton secondary yield intensity estimate has increased by a factor of nearly 7 since the Preliminary Shielding Assessment was written in June 2012.

For this shielding assessment, the estimated partial secondary beam powers listed in Table 1 are the beam powers used to evaluate the efficacy of shielding in the Extraction Enclosure, M5 line, and MC-1 Experimental Hall. Under normal conditions, while the Muon g-2 experiment is operational, only the muons are intended to be transferred to the MC-1 storage ring. However, during initial commissioning and when beam line tune-up is required, the entire secondary target station yield could be transmitted to the MC-1 storage ring at a reduced operating frequency. (NOTE: The muon yield used for MC-1 storage ring injection under normal condition is lower than that reported in Table 1 due to transmission losses and muon decay. Muon yield for this condition is addressed in Reference 20.)

4. Critical Devices and the Muon Campus Beam Mode Key Switch

Five Critical Device Controllers have been defined to permit and control beam delivery to Muon Campus facilities and the Muon g-2 experiment. While the review and approval process for the use of Critical Device Controllers is outside the scope of the shielding assessment process, the Critical Device Controller reference documents are included as supplemental material at the request of shielding assessment review panel:

- M1 CDC – Reference 21
- Delivery Ring CDC – Reference 22
- Coasting Beam CDC – Reference 23
- Extraction CDC – Reference 24
- MC-1 CDC – Reference 25

In addition to the critical device controllers, a Muon Campus Beam Mode key switch, located in the Main Control Room will be used to configure the Muon Campus beam operating modes. The modes are 8 GeV beam to the AP0 target station and 8 GeV beam to the M3 line. The two main functions of the Muon Campus Beam Mode key switch are:

- Select whether 8 GeV primary beam is directed to the AP0 target station for Muon g-2 or to the M3 beam line
- Permit energizing MC-1 critical devices only when the AP0 target station mode is selected

When switching between Muon Campus modes, the Coasting Beam CDC acts to insert the Delivery Ring coasting beam valves to remove any residual circulating beam in the Delivery Ring not associated with the newly selected mode. This feature prevents the unintended transfer of 8 GeV primary beam to the MC-1 Experiment Hall.

5. Reference Drawings

Construction drawings for the Extraction Enclosure are available for reference at beams doc.db 5067-v1. Construction drawings for the MC-1 building are available for reference at mu2e doc.db 7671-v1. Radiation shielding drawings for the entire Muon Campus are documented in FESS drawing set 9-6-10-2 [12].

6. Delivery Ring Cleanup Abort Shielding

The Cleanup Abort was designed [3] to accommodate a 400 watt, 8 GeV primary proton beam associated with Mu2e operation while meeting or exceeding requirements for groundwater and surface water activation, prompt effective dose rate shielding, and residual dose rates following beam operation. The maximum beam power to be sent to the cleanup abort during Muon g-2 operation is 12.8 watts or about 3.2% of the full cleanup abort design power. The peak prompt effective dose rate calculated for the shielding berm as a result of 400-watt beam operation is 0.15 mrem/hr [3]. With 12.8-watt beam operation, the effective dose rate on the shielding berm is estimated at 4.8 μrem/hr. No radiological posting or controls should be required on the shielding berm above the Cleanup Abort during Muon g-2 operation. The design of the Delivery Ring Cleanup Abort is completely adequate for intended Muon g-2 operations.

7. Extraction Enclosure Shielding

The Extraction Enclosure receives beam from the Delivery Ring extraction system located in the AP30 straight section. The beam extraction line is a shared M4/M5 beam line. Beam is diverted to the M4 and M5 lines by the action of the V907 bending magnet. In the final design for this magnet, both a moveable magnet stand to change the pitch of the V907 magnet and a current window are employed to direct primary 8 GeV beam or secondary 3.09 GeV/c beam to the M4 and M5 lines, respectively. For the interim design, and for the purposes of this shielding assessment, the V907 magnet will be installed with a fixed pitch, oriented for M5 beam line operation; a current window is not required since 8 GeV beam transmission to the M4 line is prevented by the Extraction critical devices. The Extraction Enclosure shielding requires consideration of the following conditions:

- Secondary beam transmission through the shared M4/M5 beam line region
- Secondary beam transmission through the M5 beam line region
- M4 beam line labyrinth shielding requirement at Extraction Enclosure/M4A Enclosure boundary during secondary beam transmission to the MC-1 Experimental Hall
- M5 beam line shielding requirement for personnel access in the MC-1 Experimental Hall during beam operations in the Delivery Ring

A. Shared M4/M5 beam line shielding

As illustrated in Reference 12, sheets C-6 and C-8, the Extraction Enclosure earth equivalent shielding (station 0+00 to 0+200) is typically 16 feet over the shared M4/M5 beam line. From Reference 13, the requirement for 0.604 watt, 2.295 GeV proton beam loss on a “Magnet in Enclosure” for the Category 1A accident condition is 9.4 earth equivalent feet. To meet the requirement for Category 1A (Beam on Magnet in Enclosure) in this region, a beam power loss on a magnet of up to 53.7 watts could be tolerated. Consequently, the shielding for the shared M4/M5 beam line requires no further consideration.

B. M5 beam line shielding

As illustrated in Reference 12, sheets C-6 and C-8, there is a change in the Extraction Enclosure shielding beginning near M5 line station 2+00 and extending to the junction of the MC-1 service building. In this M5 beam line region, the shielding thickness is reduced from 16 feet to 7 feet. Under normal operating conditions, pions have decayed, while secondary protons have been removed from the secondary beam prior to transmission through the M5 beam line. Consequently, under normal conditions, effective dose rates on this section of berm would be due to the secondary muon beam and would be << 50 μrem/hr.

As established in the Beam Power Specifications section above, the most significant beam power for the M5 beam line is associated with the 2.295 GeV, secondary proton beam. The intentional transmission of secondary beam containing protons is limited to the occasionally-required tune-up of the M5 beam line and the MC-1 storage ring. In Reference 20, it is determined that the cycle time for proton injection must be limited to about 120 seconds. (NOTE: the actual limit is imposed by the protective action of an interlocked radiation detector). In the event of a beam steering error leading to the complete loss of secondary protons under the normal condition, the effective dose rate on the M5 shield berm is estimated to be ~0.001 mrem/hr. No additional controls would be required for the normal proton injection under either normal or accident conditions.

From Reference 13, an accident condition with the complete loss of 0.604 watts of 2.295 GeV protons on a "Magnet in Enclosure" with a 7-foot shield would just meet the requirement of Category 2A, i.e., ≤5 mrem/hr. As a cross check, a MARS simulation [14] was made to determine the effective dose rate on the M5 shielding berm for accidental beam loss on a typical M5 element, a 4Q24 quadrupole. The effective dose rate, normalized to 1.64E9 protons per second was 1.9 mrem/hr. The simultaneous failure of the proton removal system and a beam line steering error during nominal 12 Hz operation would be required for this condition. Since the duration of credible occupancy on the M5 shielding berm during this accident condition thought to be less than one hour, Table 2-7 of the FRCM would require no additional controls or posting.

C. M4 beam line labyrinth shielding requirement at Extraction Enclosure/M4A Enclosure boundary

A temporary labyrinth shield wall was conceived to permit beam line construction in the M4A Enclosure during Muon g-2 operation. MARS simulations were completed to study the effectiveness of various shield configurations; these are documented in Reference 5. The result of the MARS simulation from Reference 5 for the worst case accident condition is included in Table 2.

Accident condition	Incident beam parameters	Detector 1 [mrem/hr] (error)
Beam pipe scraping loss	1.64E9 protons/s	5.49 (6.4%)

Table 2: The peak effective dose rate resulting from the worst case accident condition studied in Reference 5 is provided in the table. Statistical error for the MARS simulation is reported in parentheses. An interlocked radiation detector located on the Extraction Enclosure/M4A line junction gate should be used to limit the magnitude and duration of the accident condition.

It was recommended [5] that an interlocked radiation detector be employed on the Extraction Enclosure gate just downstream of the M4 labyrinth to limit the effective dose rate potential. Since the full, continuous secondary beam loss on an element of the M5 line is unlikely, a low trip level, for example, 1 mrem/hr in the integrate mode would provide ample protection for the occupants of the M4A line.

D. M5 line shield wall

A 12-foot concrete shield wall has been installed in the M5 beam line enclosure approximately 10 feet from the 6-foot elevation change step as shown in Figure 5. The purpose of the shield wall is to permit personnel access to the MC-1 Experiment Hall (storage ring room) at the junction of the Extraction Enclosure while 8 GeV beam is circulated in the Delivery Ring.

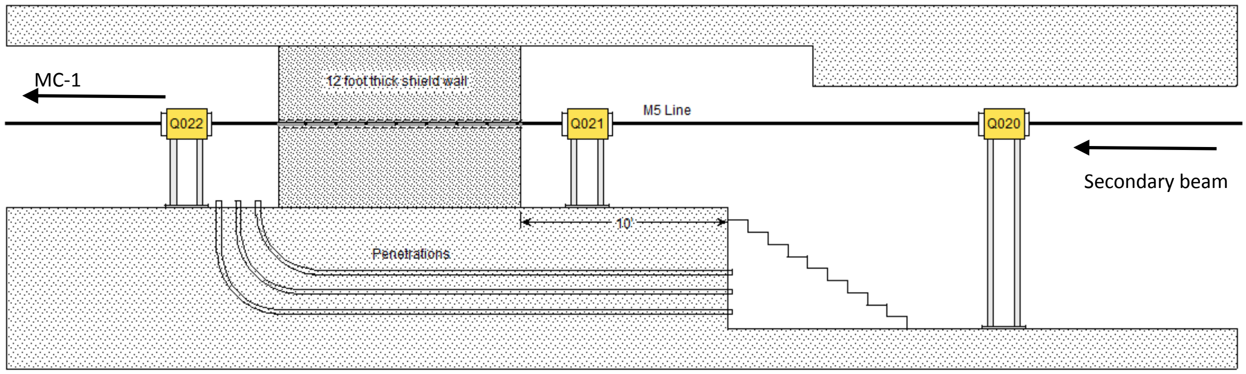


Figure 5

During the early development phase of the Muon Campus, it was envisioned that it would be possible to transport 8 GeV primary protons through the M4 line while personnel access was permitted in the MC-1 Experimental Hall. A series of simulations documented in Reference 6 considered various shield wall positions, compositions, beam loss locations, beam powers, and protective measures. At this time, the schedule to transport 8 GeV beam through the M4 line has been delayed until the Fall of 2021. While 8 GeV primary beam transport into the Extraction Enclosure is not considered at this time, it may be desirable to extract and transport the beam from the Delivery Ring up to, but not beyond, Q907 in the shared M4/M5 beam line as illustrated in Figure 6 and Figure 7. Similarly, the deliberate or accidental primary beam loss in the Delivery Ring near the Extraction Enclosure boundary as illustrated in Figure 8 is possible. The shielding effectiveness of the M5 shield wall for these cases requires consideration.

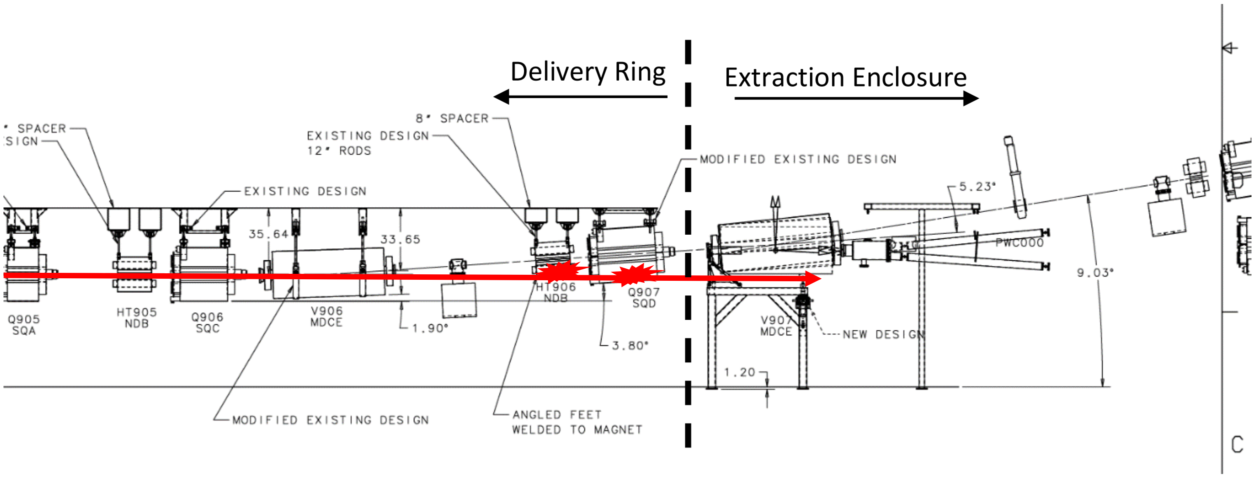


Figure 6: The trajectory of low power, 8 GeV proton beam which may be necessary to commission and tune the first few elements of the shared M4/M5 extraction beam line is shown in this elevation view of the Delivery Ring/Extraction Enclosure junction. The main extraction elements including the extraction Lambertson, C-magnet, V901, and related quadrupoles (not shown at left) direct beam into this section of the M4/M5 shared beam line. The intention is to test primary beam extraction through Q906. V906 and downstream elements would be deenergized. Primary beam loss would occur in HT906 and Q907 as indicated by the star elements. The resulting beam shower would be directed toward the Extraction Enclosure.

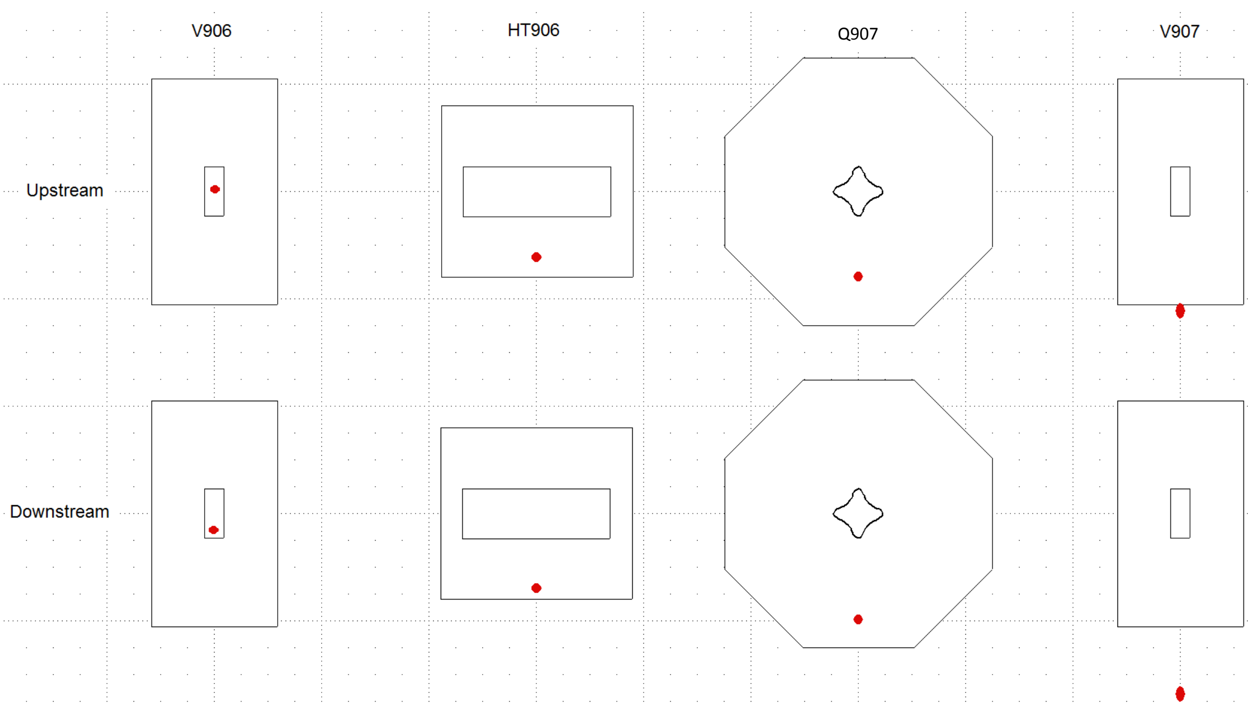


Figure 7: The beam position at the upstream and downstream surfaces of elements shown in Figure 6 are indicated in these beam line element cross sections. The primary beam trajectory passes just beneath V907. The total steel lamination length of the HT906 and Q906 magnets through which the beam would pass is 1.26 meters.

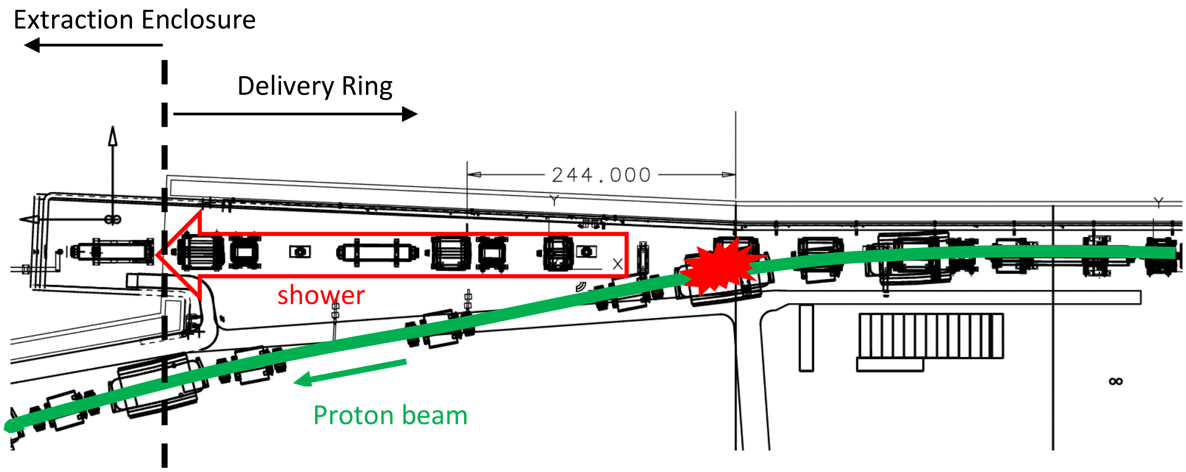


Figure 8: An example of beam scraping loss (star figure) in the Delivery Ring in the vicinity of the Delivery Ring/Extraction Enclosure junction is shown in this plan view of the Delivery Ring/Extraction Enclosure junction. The green line indicates the path of circulating beam in the Delivery Ring. The red arrow shows the direction of concern for the resulting particle shower.

A MARS simulation was made in which a 12.8 watt, 8 GeV proton beam is lost on a 1 m long, 22 cm diameter steel cylinder located at the V907 position in the Extraction Enclosure [6]. This simulation is a conservative representation of the loss points illustrated in Figure 6, Figure 7 and Figure 8. The Extraction Enclosure model is shown in Figure 9. The simulation was made without the 12-foot concrete M5 shield wall. A tissue equivalent detector was placed in the model at the junction of the Extraction Enclosure/MC-1 Experiment Hall. The results of the MARS simulation are shown in Figure 10. The peak effective dose rate for this condition was 5.1 mrem/hr. From inspection of Reference 13, the addition of the 12 foot M5 shield wall would reduce the effective dose rate at the MC-1/Extraction Enclosure junction by at least 3 orders of magnitude or an effective dose rate of <0.05 mrem/hr.

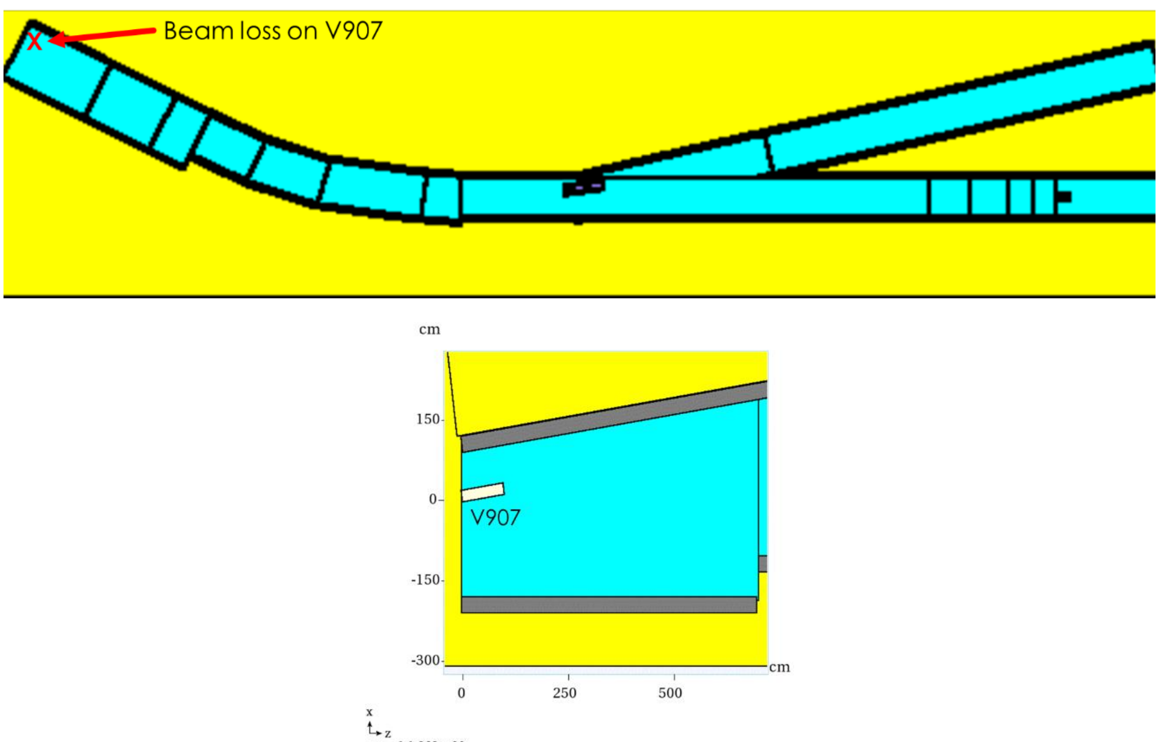
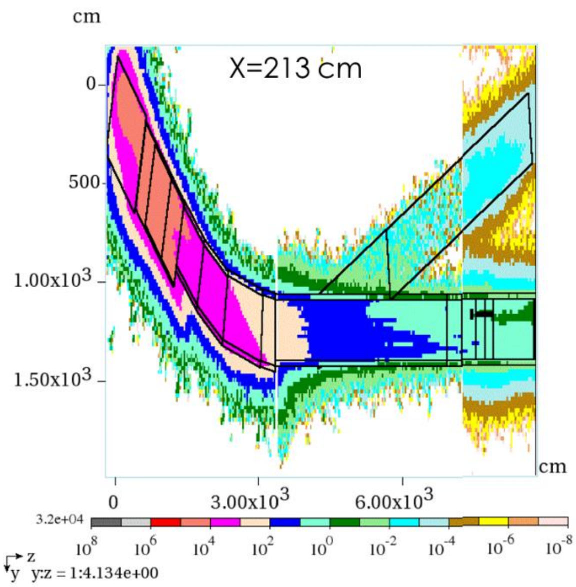


Figure 9: At top in the figure is a plan view of the Extraction Enclosure model used in the MARS simulation [6]. At bottom is a longitudinal elevation view of the 1 m x 22 cm steel cylinder used to initiate the beam shower.



1.7	0.9	1.5	1.9	2.7
0.6	0.8	2.7	5.1	3.3
1.3	0.7	2.2	2.5	1.5
0.5	0.8	1.8	2.3	2.0

mrem/hr – 12.8 watt loss on V907

0.2%	0.3%	0.3%	0.2%	0.2%
0.3%	0.2%	0.2%	0.1%	0.2%
0.3%	0.3%	0.2%	0.2%	0.2%
0.3%	0.2%	0.2%	0.2%	0.2%

Statistical errors

Figure 10: The result of a three stage MARS simulation is shown at left. The units are in mrem/hr normalized to 12.8 watt, 8 GeV proton beam incident on the 1 m x 22 cm steel cylinder located at the upstream end of the Extraction Enclosure. At top right, the effective dose rate is shown in a 4 x 5 array of tissue equivalent detectors located at the M5/MC-1 Experiment Hall junction. The statistical errors from the simulation for the each of the 20 tissue equivalent detectors are shown at bottom right.

8. Muon Shielding at Vertical Bend Locations

The secondary beam, en route from the Delivery Ring extraction system to the MC-1 Experimental Hall, receives vertical kicks at the major bend locations indicated in Table 3. As part of the extraction line design, there are other, smaller vertical kicks to achieve desirable quadrupole steering. If a major down-bending supply is off while beam is present, muons could travel on some upward trajectory through the shielding berm. Earth berm shielding for muons on upward trajectories are considered here at the two major down-bending locations, i.e., V901 and V003. Failure of an upward-bending magnet would result in a smaller or no vertical upward kick and are not considered further.

Device	Bend angle milliradian/degrees	Direction (up/down)	Muon shield thickness (feet)
Extraction Lambertson	40/2.29	up	-
C magnet	57/3.26	up	-
V901	112/6.42	down	> 200
V906	66/3.78	up	-
V907	91/5.21	up	-
V003	157/8.99	down	> 100

Table 3: Major vertical-bending magnets between the Delivery Ring extraction region and the MC-1 Experimental Hall.

From Reference 15, Figure 1.9, the range of 3 GeV muons in earth is about 27 feet (8 meters). The sketch in Figure 11 shows the positions of V901 and V003 within the Delivery Ring and Extraction Enclosure, respectively. In the event either of these major downward-bending magnet power supplies fail, the earth shielding along the resulting muon trajectories greatly exceeds the range of 3 GeV muons, the nominal secondary muon beam energy.

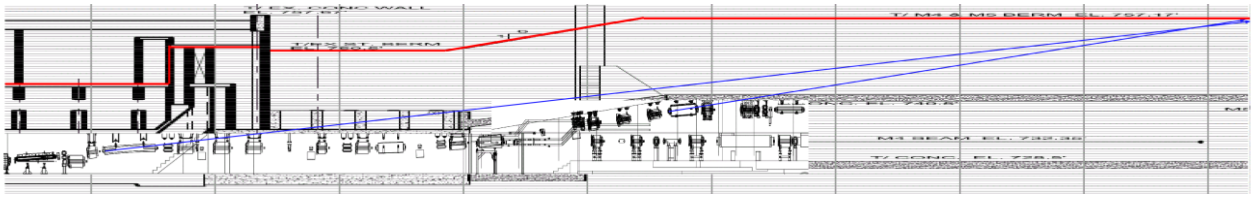


Figure 11: This is a composite drawing assembled from References 12 and 16. V901 is the vertical down bending magnet at left located in the Delivery Ring enclosure. V003 is the vertical down bending magnet at right located in the Extraction Enclosure. The red line indicates the earth equivalent shielding boundaries. The blue vectors at each of the major down bending magnets indicate the muon trajectory in the event the respective power supplies fail to an off state. The horizontal distance between vertical lines is 25 feet. The muon shielding is > 200 feet for V901 and > 100 feet for V003. The muon range for 3 GeV muons is approximately 27 feet.

The g-2 secondary muon beam is more than adequately shielded in the event of failure of any major down-bending supply.

9. MC-1 Experimental Hall Shielding Assessment

MARS simulations for normal and accident beam loss conditions have been completed [20]. The summary from Reference 20 is repeated here:

Radiation effective dose rates have been determined for normal and accident conditions for the MC-1 building based upon estimates of secondary beam yield due to the 15.4 kW, 8 GeV beam incident on the AP0 target station.

The hourly effective dose rate during normal operation, i.e., proton-free, muon beam injection, is less than 50 µrem/hr at MC-1 storage ring room surfaces. The annual effective dose rate at the West Booster Tower and Wilson Hall for normal proton-free muon injection due to skyshine are < 1 mrem/year and <0.1 mrem/year, respectively.

The hourly effective dose rate due to complete muon beam scraping losses on the injection line (accident condition) are ≤ 1 mrem/hr. Assuming a normal 1% muon scraping loss on the injection line, effective dose rates for all spaces would be less than 50 µrem/hr.

The MC-1 service building should be posted as a Controlled Area since effective dose rates at spaces within it can exceed 50 µrem/hour under normal conditions (proton injection).

The radiological consequences of proton beam in the injection line and storage ring are significant. It appears to be impracticable to add shielding to the MC-1 service building for protection against proton injection. Consequently, interlocked radiation detectors must be used to limit the magnitude and duration of proton beam injection under both normal and accident conditions.

The hourly effective dose rate during the accident condition, i.e., during the failure of the proton removal kicker system resulting in proton injection into the storage ring, ranges from tens to a hundreds of mrem/hr on outside surfaces of the MC-1 storage ring room roof, perimeter walls, and normally occupied spaces in the MC-1 service building without interlock radiation detector protection. The hourly effective dose rate due to proton scraping loss on the injection line is the most severe accident condition found for the MC-1 service building. An interlocked radiation detector placed at the 746.5-foot elevation between the downstream end of Q023 and the *upstream end of Q024 with a trip level of 2.5 mrem/hr in integrate mode would limit the effective dose rate for the accident condition in all spaces to less than 1 mrem/hr.*

The most restrictive normal condition is one in which the 2nd floor conference room effective dose rates are limited to 50 µrem/hr while protons are intentionally injected into the storage ring. An interlocked radiation detector placed at the center of the storage ring at elevation 746.5 feet with a trip setting of 0.4 mrem/hr in integrate mode should limit effective dose rates in the 2nd floor conference room to 50 µrem/hr. If unlimited occupancy of the second floor conference room is prohibited by administrative controls during normal proton injection, then the trip level for the storage ring center interlocked radiation detector could be raised to 0.9 mrem/hr. In this case, the limiting effective dose rate control of 50 µrem/hr would apply to unposted outdoor areas at the south, east and north perimeter walls.

A third radiation detector could be positioned at the 746.5-foot elevation on the west wall as shown in Figure 12*. While the large angle muon beam loss result shown in the histogram is not considered feasible, a temporary radiation detector positioned there would provide additional interim injection line monitoring.*

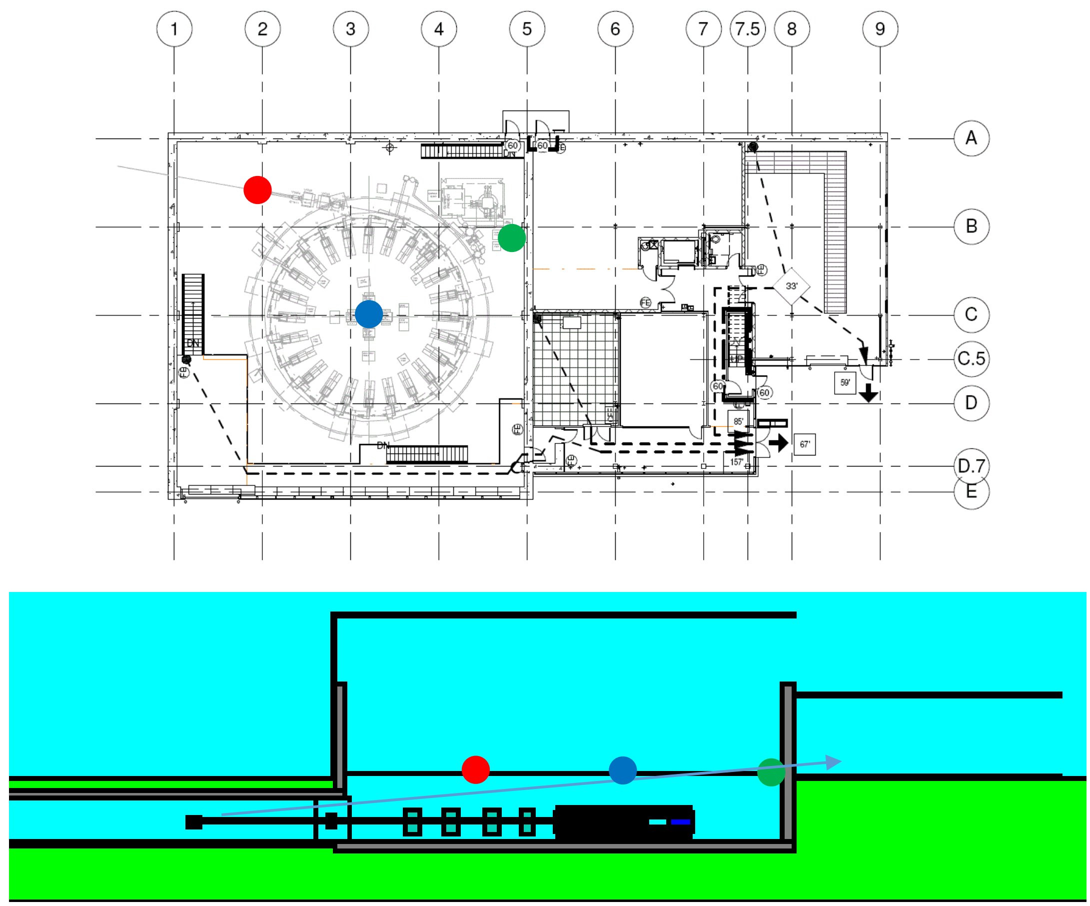


Figure 12: Recommended placement of an interlocked radiation detectors on the trajectory of the injection line (red dot) and at the center of the MC-1 storage ring (blue dot) is shown in the plan view in the top figure and in the elevation view in the lower figure. An optional third detector (green dot) could be placed as shown or as otherwise directed by the Radiation Safety Officer for additional monitoring purposes; no interlocking or trip levels are intended to be specified for the third detector by this shielding assessment document.

10. Labyrinths and Penetrations

Adjacent to the upstream Extraction Enclosure entrance is an M4 line air exhaust ventilation duct, which is required for monitored air emissions for the Mu2e experiment. The beam power used to evaluate shielding effectiveness due to the placement of this duct is based upon the total loss of secondary protons within the extraction enclosure [17]; the estimated effective dose rate for the Muon g-2 worst case accident condition is 4.21E-4 mrem/hr.

There are 8 six-inch conduits located in the six-foot-high step wall of the M5 enclosure as illustrated in Figure 5. The conduits end on the upper level of the M5 branch of the tunnel. These cable penetrations are used to route cables around the twelve-foot concrete shield wall shown in Figure 5. The effective dose rate at the penetration entrance, taken from Figure 10, is < 10 mrem/hr. The effective dose rate at the exit of the penetrations has been evaluated [19]; the effective dose rate is 2.33E-9 mrem/hr.

There is one exit stairway from the Extraction Enclosure that leads to an outdoor location along Indian Road. The beam power used to evaluate shielding effectiveness of this exit stairway is based upon the total loss of secondary protons within the extraction enclosure [18]; the effective dose rate for the Muon g-2 worst case accident is 3.52E-3 mrem/hr.

There is one site riser location in the Extraction Enclosure that leads to the berm surface. The beam power used to evaluate shielding effectiveness of this site riser penetration (no shield material fill required) is based upon the total loss of secondary protons within the extraction enclosure [26]; the effective dose rate for the Muon g-2 worst case accident is 1 mrem/hr.

11. Groundwater, Surface Water, Air Activation, Skyshine

The primary and secondary beam powers utilized for Muon Campus beam line tune up and for the Muon g-2 experiment for all locations covered by this shielding assessment are quite low. Expected losses will produce no groundwater, surface water, or air activation concerns.

The only anticipated, significant, nominal beam loss location is the Delivery Ring Cleanup Abort. Estimates for the production of groundwater activation, surface water activation and air activation are reported in Reference 3; it can be used to quantify expected peak groundwater, surface water and air activation for Muon g-2 operation.

Groundwater activation levels reached after 10 years of Mu2e operation are estimated [3] to be 2.5 ppm of the groundwater limit. The scaling factor for Muon g-2/Mu2e beam power for the Delivery Ring Cleanup Abort is 0.604 watts/400 watts or 0.00151. Consequently, the expected groundwater could reach about 3.8 ppb of the limit after ten years of operation.

Surface water would scale similarly [3]. The surface water estimates for Mu2e operation scaled to Muon g-2 operation would produce surface water activation at <1% of the surface water limit even with very limited pumping frequency, e.g., 1 year.

Release of activated air due to Muon g-2 has been calculated and reported [28]. A summary of the air activation calculation is shown in Table 4.

Energy (GeV)	Power (W)	Duty factor	Absorber entrance port (Ci/yr)	Enclosure air (Ci/yr)	Total (Ci/yr)
2.29	0.6	63.40%	0.0103	0.0084	0.0187
8	12.8	5%	0.1543	0.0512	0.2055
Total Activity released (mCi/yr) =			**224**		
Dose to Maximally Exposed Offsite Individual=				**0.093**	**micro-rem/yr**

Table 4: Summary of annual air activity release calculation due to operation of the Delivery Ring cleanup abort in support of the Muon g-2 experiment

Due to the absence of a shielding mass over the MC-1 storage ring room, radiation skyshine has the potential as a source of radiation exposure at the site boundary. For normal operation, i.e., the proton-free muon injection and circulation at the storage ring, the effective dose rate at a radius of 1 km is <0.0001 mrem/year. Skyshine due to normal and accidental transport and injection of protons to the storage ring is mitigated by interlocked radiation detectors located within the MC-1 storage ring room.

12. Summary

Radiation shielding has been considered for the Delivery Ring Cleanup Abort, the Extraction Enclosure, the MC-1 Experimental Hall and the M4/M5 shared beam line. In order to satisfy FRCM requirements, a number of controls are suggested:

1. Interlocked radiation detector(s) should be placed in the MC-1 Experiment Hall as shown in **Error! Reference source not found.** to limit the magnitude and duration of accidental, c ontinuous injection of secondary protons during muon g-2 operation. The detector is also required to limit effective dose rates during normal proton injection operation.
2. In the event the low power primary proton beam is to be extracted from the Delivery Ring, interim administrative controls (for example, locking out power supplies for V906, HT906, and Q906) should be developed to ensure primary protons are not transported in the Extraction Enclosure. Historically, such controls are under the purview of the AD SSO and/or the AD RSO. Eventually, when the M4 beam line controls and operating procedures become fully functional, the use of the interim procedures could be suspended.
3. An interlocked radiation detector should be deployed at the M4A/Extraction Enclosure gate while the M4 labyrinth shield wall is required. When the M4 labyrinth shield wall is removed, the interlocked radiation detector would no longer be required.

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