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MuCOOL Facility Shielding Assessment

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The MuCOOL Beamline and Experimental Hall

Description of Facility

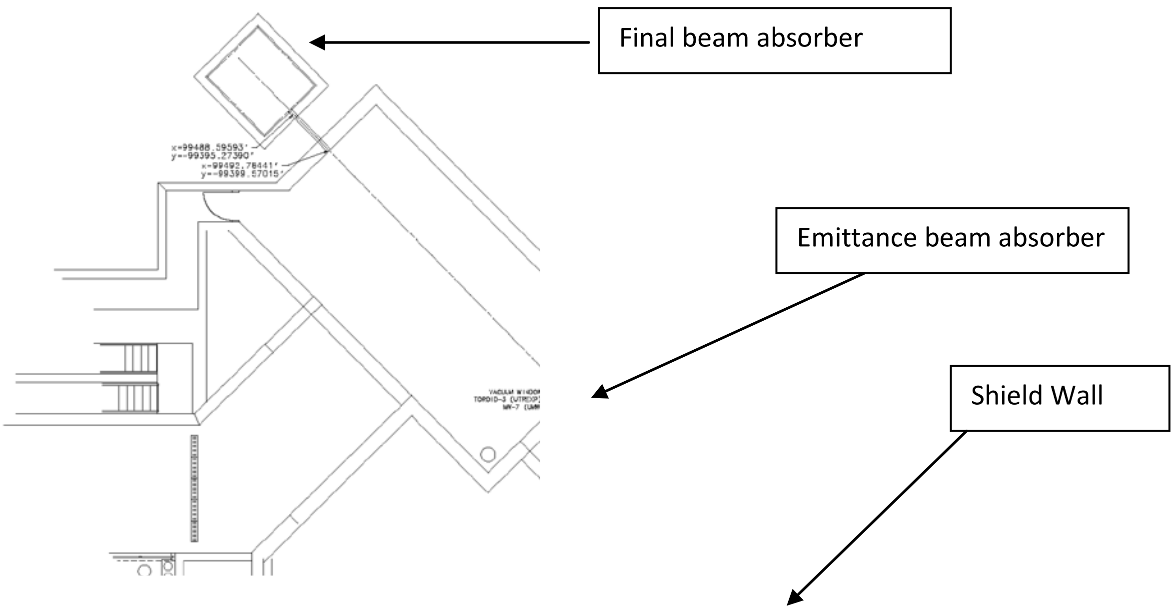
The MuCOOL Beamline extracts, transports, and delivers 400-MeV H^- beam directly from the Linac and Linac enclosure to a test facility, the MuCOOL Test Area (MTA) experimental hall. This experimental facility, located southwest of Wilson Hall, between the Linac berm and parking lot, will be used initially to support the MuCOOL R&D program and is designed to accept the full Linac beam pulse. The design concept for the MuCOOL facility is taken from an earlier proposal [1], but modifications were necessary to accommodate high-intensity Linac beam, cryogenics, and the increased scale of the cooling experiments. The MTA is one of the few such facilities in the world where a primary beam is available for experiments.

Most of the upstream MuCOOL beamline is housed in an enclosure contiguous with the Linac. The remaining downstream section of the beamline resides in a 30’ beamline “stub” that opens into the experimental hall. A shield wall, located beneath the access hatch, separates the upstream section of the beamline from the downstream beamline stub and experimental hall. This wall effectively isolates the Linac primary beam enclosure from all downstream enclosures, preventing personnel access and exposure to radiation from Linac operation. Upstream of the shield wall, the beamline is installed in a pre-existing section of the Linac enclosure and on an inclined ramp which raises the beamline from the Linac elevation to the elevation of the stub. The layout of the beamline starting from the extraction point in the Linac up to the entrance of the experimental hall is given in Figure 1.

The facility will support two modes of operation. One mode is delivering beam to experiments. In addition, the beamline design incorporates a specialized insertion for beam diagnostics. This specialized insertion allows another mode of operation, or beamline tune, to be established which will provide detailed measurements of Linac beam properties such as emittance, greatly enhancing the functionality of this line, and supplying valuable information about accelerator operation. The two modes of operation are: 600 pulses/hour for an emittance measurement, and 60 pulses/hour to the experiments. These modes will be referred to as the Emittance mode and Experiment mode, respectively. Two critical devices upstream of the shield wall, a 4-magnet dipole bend string, UHB03 (to give its control system name), and a beamstop, UBS01, service both modes, as described in the MuCOOL Critical Device Justification (Attachment 18). (This attachment contains details of the beamstop construction.)

Assessment Boundaries

The boundary of the radiological area covered by this assessment starts at extraction from the Linac, which begins in the first pulsed C magnet (UHB01A) just upstream of the 400-MeV Chopper. (The 2nd C magnet, which completes the extraction process, is downstream of the Chopper.) Stationing begins at the upstream face of the first pulsed C magnet, defined as station Z=0. The endpoint of the assessment is defined by the mode of operation. For the Emittance mode, described below, the assessment endpoint is the emittance beam absorber (described in Attachment 14); for the Experiment mode it is the final high-intensity beam absorber, which is buried in berm downstream of the experimental hall. Final absorber details are given in Figure 2 and in Attachment 4.



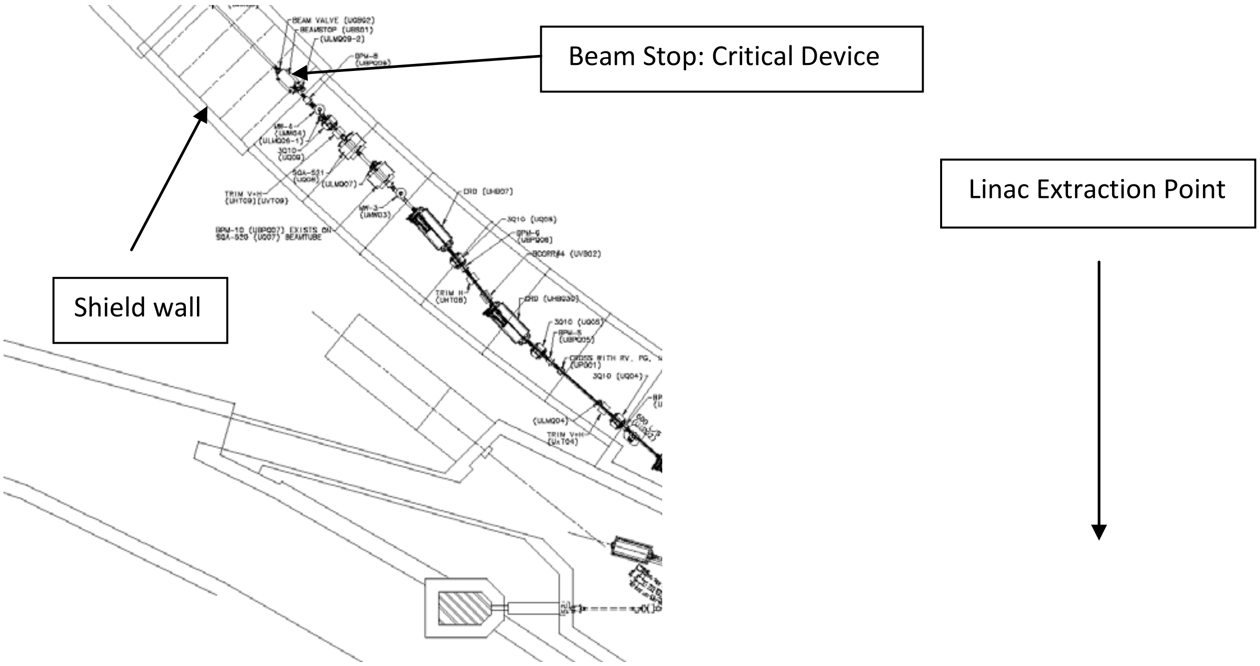


Figure 1. The layout of the MTA beamline: downstream (top) and upstream of shield wall (bottom).

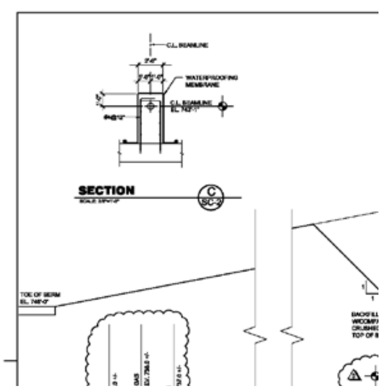


Figure 2. The downstream end of the MTA experimental hall, 6' section of buried beam pipe and beam absorber.

Assessment Beam Parameters

Two modes of operation will be supported in the MuCOOL beamline: one mode for emittance measurements (and beamline studies) and a second mode for MTA experiments. Maximum beam intensity for these two modes is given below.

The maximum number of protons/year that may be delivered to the MTA Experimental Hall is based on air activation in the present configuration with ODH air-exchange requirements of 1200 cfm, and corresponds to a maximum of 2.35 x 10^{18} protons per year (based on criteria described in the section on air activation and release and in Attachment 15). If cryogens are not used in future experiments and a lower air exchange rate is implemented, potentially this limit can be increased as is indicated in the section on air release and activation.)

Emittance Mode:

1) 9.6 x 10^{15} protons/hour – 600 beam pulses/hour of full Linac beam pulse intensity (1.6 x 10^{13} protons/pulse) to the emittance beam absorber (see Figure 1)

In the Emittance mode, beam is always deposited in the emittance beam absorber (Attachment 14). A thermal analysis of the emittance beam absorber (Attachment 19) shows the absorber is capable of absorbing full linac beam at 15 Hz up to the 600 pulses/hour allowed in this mode.

Experiment Mode:

2) 9.6 x 10^{14} protons/hour – 60 beam pulses/hour of full Linac beam pulse intensity (1.6 x 10^{13} protons/pulse) to experiments in the MTA experimental hall.

In the Experiment mode, two configurations are supported as follows and depicted in Figure 3.

a) Beam is cleanly transported to the final high-intensity beam absorber through vacuum as shown in Figure 3 (top, left).

b) The proton beam is fully interacted by the experimental apparatus and the final beam absorber is not used. No downstream magnetic components are required for this configuration as in Figure 3 (bottom).

All experimental configurations will be handled operationally through Beam Permits and Running Conditions. Each experimental configuration will be individually evaluated based on its MOU and ORC, for compliance with the approved shielding assessment criteria.

Any proposed experiment must fall within the two analyzed configurations. Experiments, for example, that utilize experimental apparatus with minimal rather than total beam interaction, will need to demonstrate that uninteracted beam is cleanly transported to the final beam absorber, or, alternatively, provide a local beam absorber and shielding to satisfy configuration b). Downstream components, such as quadrupoles, collimators, and steering magnets, may be required to transport to and deposit beam cleanly in the final absorber (Attachment 12) as shown in Figure 3 (top, right). Under configuration b), experiments must main maintain the same beam trajectory as in configuration a). No alternative beam path is supported by this assessment.

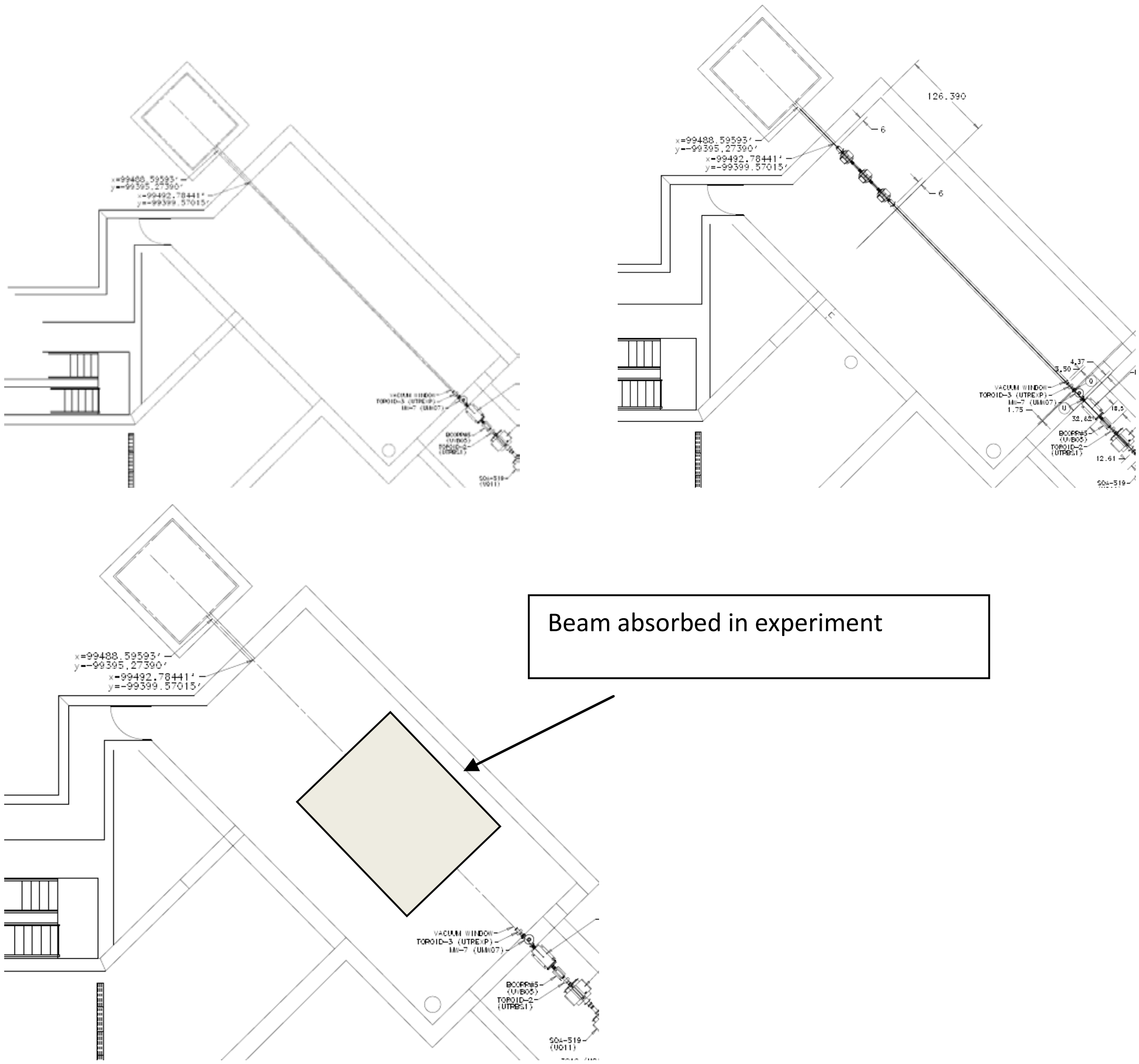


Figure 3. The experimental hall showing Experiment mode configuration a (top, left), b (top, right) and c (bottom).

Shielding Requirements

Attachment 1 contains the shielding requirements tables for the Emittance and Experiment modes described above. Attachment 16 (TM 2248) addresses the scaling of the Cossairt shielding requirements from 1000 GeV to 400 MeV. In this document, a MARS14 simulation produces a difference of only a few percent in the amount of compacted dirt shielding compared to the scaled results.

EMITTANCE MODE

Longitudinal Shielding Summary

The longitudinal shielding part of the Emittance-mode assessment crosses six areas described as the Main Linac enclosure, a section of the Linac enclosure with an elevated (high) ceiling, a "ramp" which connects the main Linac enclosure to the MTA "stub" elevation wise , an alcove section embedded in the primary shield wall which houses the beam stop (a critical device, Attachment 18), the primary shield wall below the access hatch, and, finally, the part of the MTA beamline contained in a ~10'x 10' prefabricated concrete stub. The MuCOOL Radiation Safety Drawings, 9-4-1-35 C-2 and C-3 (Attachment 17), show these six areas with the exception of the alcove and the beam absorber.

The first three sections, from Z=0 to Z=103 (up to the shield wall) are either partially or entirely installed on a slightly inclined floor (about 1.5 degrees upward). Additionally there is a 2.5' step down from the MuCOOL beamline stub into the experimental hall. Table I gives the stationing of the six regions, in addition to three areas that are a part of the Experiment mode, relative to the defined start point at the upstream face of the 1st C magnet. The sections of the beamline which lie in the different longitudinal-shielding areas have been outlined in Attachment 2. Attachment 3 shows the details of the shield wall, including beam stop alcove and penetrations. Attachment 4 contains the full civil engineering drawings of the final beam absorber.

Z=0-41 ' <u>Main Linac Enclosure</u>: The MuCOOL beamline starts in the Linac enclosure at the upstream end of the first pulsed C magnet. This magnet kicks the beam about 3 degrees to the west, achieving separation from the 400 MeV transfer line at the downstream end of the 400 MeV electrostatic chopper. A 2nd pulsed C magnet just downstream of the Chopper enhances the separation, to allow MTA beam to be steered into a separate and distinct magnetic channel. Downstream of the 2nd C magnet, all elements are unique to the MTA beamline and independent of the Linac and the 400-MeV line.

Z=41-55 ' <u>Linac High Ceiling</u>: About 40' from the start of the beamline, the enclosure ceiling height increases with a corresponding decrease in longitudinal shielding as shown in the MuCOOL Radiation Safety Drawings (Attachment 17).

Z=55-103 ' <u>Linac Ramp</u>: The next section represents the pre-existing Linac access ramp, which ends at the upstream face of the shield wall.

Z=103-106 ' <u>Alcove</u>: A 5' high, 4' wide, and 3' long alcove inset in the shield wall houses the downstream part of the MTA beam stop. This alcove begins at the upstream face of the shield wall, as shown in Attachment 3.

Z=106-115 ' <u>Hatch Shield Wall</u>: Details of the shield wall are given in Attachment 4 including penetrations.

Z=115-147 ' <u>Beamline Stub</u>: The ~10x 10' beam stub between the shield wall and the experimental hall. This stub ends with a 2.5' step down into the experimental hall.

Attachment 5 contains the longitudinal shielding spreadsheets for all six areas for the Emittance and Experiment modes. The sections from Z=0 to 103' are protected by interlocked detectors for both the Emittance and Experiment modes. In the rest of the nine areas, the shielding meets or exceeds the radiological requirements for the stated beam conditions for both modes, as indicated in Attachment 5.

Table 1: The nine longitudinal shielding sections.

Description	Stationing	Northing	Easting
Start	0	99511.30274'	99617.141898'
Main Linac Enclosure	41.4'	99503.14412'	99596.90133'
Linac High Ceiling	54.7'	99494.50715	99585.16936
Linac Access Ramp	102.6'	99459.95440	99551.65122
Beamstop alcove	105.6'		
Shield Wall	114.6'	99451.36564	99543.27872
Beamline stub	146.9'	99428.21164	99520.70773
Experimental Hall	186.9'	99399.56864	99492.78594
Absorber beam pipe	193.4'		
Absorber	202.9'		

Transverse Shielding Summary

The areas remain defined as in the longitudinal shielding section. Attachment 6 contains the transverse shielding spreadsheets for the Emittance and the Experiment modes. The first three sections, Z=0-103', have transverse shielding radial distributions given in the MuCOOL Radiation Safety Drawings (sections B - D and F-G, Attachment 17). The shield wall has transverse shielding distributions as shown in Attachment 3. Again, the first three sections (Z=0-103') are protected by interlocked detectors for both modes. The radial distribution of shielding along the beamline in the downstream areas and through the absorber is sufficient in all cases, as indicated in reference Attachment 6.

Labyrinth and Penetration Summary and Calculations

The penetrations and labyrinths for the MuCOOL facility are listed and described below. Either MARS or labyrinth and penetration calculations were used for this assessment. The penetrations and labyrinths are listed in order from upstream to downstream below. When a penetration or labyrinth being assessed was of a "typical" geometry the standard Labs & Pens spreadsheet was used, when the penetration or labyrinth being assessed was atypical, modeling with MARS was performed. This decision as to which method to use was made by the AD/RSO.

Hatch Shield Wall: Two penetrations were established in the shield wall extending from the RF trench at the top of the berm through the beamline stub and into the experimental hall to accommodate two RF waveguides, a coaxial and a rectangular one. The shield wall engineering drawings in Attachment 3 contain cross sectional slices of these penetrations at different longitudinal positions.

A 3.25" diameter penetration through the shield wall connects the Linac enclosure beamline to the MuCool stub beamline and contains only beam pipe. Since this penetration connects two beam enclosures it is not included in the labyrinth and penetrations spreadsheets. A beamstop (UBS01, described in Attachment 18) blocks radiation from Linac operation during access to the experimental hall or stub. Prompt dose in the hall under access conditions for a worst-case Linac accident has been modeled using MARS and is reported in the subsection General.

Although Cabling has been routed through the shield wall from the RF trench and into the beamline stub, it is tightly packed with sandbags to eliminate any potential for prompt dose and is therefore not considered further. The same is true for cabling routed through the shield wall between the Linac enclosure and the downstream beamline stub.

The entrance for the two Hatch Shield Wall penetrations (RF trench on top of the berm) is located in an assessment category 4 area which is enclosed by a 4' fence that is posted and locked during MuCOOL operation.

<u>Ceiling Vent</u>: A 20" diameter penetration in the experimental wall ceiling provides a vent for gases to the top of the berm (see Attachment 8 for drawings of the experimental hall). The Ceiling Vent penetration exits into an assessment category 4 area enclosed by a 4' fence which is posted and locked during MuCOOL operation.

<u>Gas Manifold Room</u>: Three 3"-diameter, single-leg penetrations run from the experimental hall to the hydrogen gas manifold room. The Gas Manifold Room penetrations exit into an assessment category 4 area enclosed by a 4' fence which is posted and locked during MuCOOL operation.

<u>Refrigerator Room Cryo Penetrations</u>: Six straight penetrations, one 10", one 8", and four 4" diameter openings, run from the experimental hall to the refrigerator room. The penetrations and their contents are detailed in Attachment 7. The Refrigerator Room penetrations exit into a minimally occupied area (category 2).

<u>Refrigerator Room Utility Penetrations</u>: Another set of eight 5" diameter penetrations from the experimental hall enter the refrigerator room at ceiling height. The Refrigerator Room penetrations exit into a minimally occupied area (category 2).

<u>Pit Labyrinth</u>: One personnel labyrinth opens into the pit and remains at the pit floor elevation. The Pit Labyrinth exits into an assessment category 4 area enclosed by a 4' fence which is posted and locked during MuCOOL operation.

<u>Ventilation Ducts</u>: One supply, 14.3" in diameter and one return duct, 18.1" enter and exit at the top of the service building. The Ventilation Ducts exit into an assessment category 4 area enclosed by a 4' fence which is posted and locked during MuCOOL operation.

<u>Stairway Labyrinth</u>: The second personnel labyrinth leads from the experimental hall upstairs to the service building parking lot. The Stairway Labyrinth exits into a minimally occupied area (category 2).

General

The penetration in the shield wall containing beam pipe is shielded by a beamstop (critical device, UBS01) located at the upstream end of the shield wall. Exposure during access to the MuCOOL experimental hall or beamline stub from losses in the Linac has been calculated using MARS to be less than 0.01 mrem/pulse as shown in Figure 4 for a worst-case accident condition. The area is protected by an interlocked detector during access to the experimental enclosure.

Given the large number of labyrinths and penetrations to consider for the MuCOOL experimental hall and beamline, identifying a unique worst-case loss scenario for each case and in both the Emittance and the Experiment mode would represent an extensive body of work. Instead, a mode-independent approach was taken where the worst-case loss location and condition were determined for each individual labyrinth and penetration geometry – the location that produced the largest prompt dose per pulse at their respective exit. First a location is chosen for proximity and line-of-sight to the entrance of the labyrinth or penetration. Upstream and downstream beam-loss locations were then checked to confirm or adjust this location to obtain the largest possible prompt dose. The highest dose per pulse is then scaled to 600 pulses/hour or 60 pulses/hour to assess the Emittance and Experiment mode, respectively. If the dose rate exceeds or is close to the acceptable limit, then a specific MARS model is invoked.

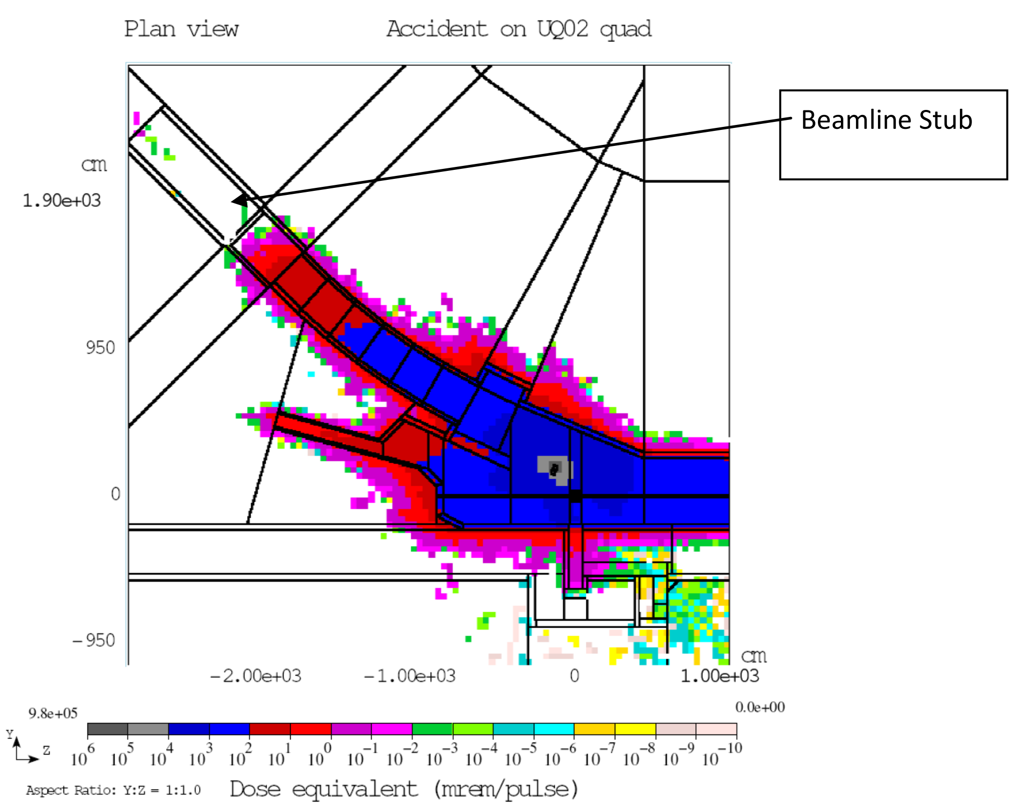


Figure 4. Prompt dose in experimental hall enclosure from worst-case loss in Linac for 1.6 x 10^{13} protons/pulse.

Emittance Mode:

Hatch Shield Wall: Two RF penetrations in the shield wall contain a 5” x 10” rectangular waveguide, and a 9” coaxial transmission line, both running from the top of the berm, through the hatch shielding, into the beamline stub. These RF penetrations were modeled using MARS for the worst case: losing the entire beam on a component about 7’ downstream of the shield wall (Attachment 7 and Attachment 8, TM2457). The dose rate at the top of the berm is calculated to be 1.38 mrem/hr from the two RF waveguide penetrations combined. The Linac and MuCOOL berms are entirely enclosed by a 4’ fence which is locked and posted during MuCOOL operation (category 4).

Ceiling Vent: The voids in the 20” ceiling vent are filled with polyethylene beads. However, even with the beads, the dose rate exceeds 100mr/hr at 600 pulses/hour (the category 4 operational limit) when beam is fully deposited in a device downstream of the emittance absorber (experimental category c). Therefore a detailed MARS simulation was performed for the Emittance mode. Beam loss on the emittance absorber, which is the loss closest to the ceiling vent in the Emittance mode, plus a component with a smaller radial physical dimension, were modeled to determine the maximum possible dose rate. This MARS simulation, which is described in Attachment 8, TM2457, indicates that the dose is less than 0.1 mrem/pulse, or 60 mrem/hr for beam lost on the emittance beam absorber. Beam loss on the emittance absorber was determined to represent the worst case due to location, since the emittance absorber is the component closest to the ceiling vent (for the Emittance mode), and since smaller transverse dimensions produced lower prompt dose (see Attachment 8).

Gas Manifold Room: The three penetrations to the gas manifold room are filled with polyethylene beads and cabling except for two 0.25” copper lines that feed gas to the experimental hall. Independent of the mode, the worst case for prompt dose in the gas manifold room is generated by a loss directly across from the penetrations as described in Attachment 8, TM2457. Such a loss delivers a combined dose of no more than 1.51×10^{-3} mrem/pulse in the gas manifold room. Therefore, the Emittance mode, where beam is deposited further upstream on the emittance absorber (at a rate of 600 pulses/hour), is, for worst case, 0.906 millirem/hour. This level is acceptable since the gas manifold room is inside a 4’ fenced, posted area (category 4). The gas manifold room is protected by an interlocked detector.

Refrigerator Room Cryo Penetrations: A cage and a 2’ shield wall in the refrigerator room surrounds and blocks the area around the exit of all six of these penetrations, preventing access by personnel. The MARS simulation gives the largest prompt dose at a point accessible by personnel to be 1.51×10^{-3} mrem/pulse (outside of the cage and downstream of the 2’ shield wall) based on the worst case described in Attachment 8, TM 2457, independent of mode. The worst case for beam lost on the emittance absorber, which is further upstream, is this value scaled to 600 pulses/hour, or 9.06×10^{-1} mrem/hour. The dose at the exit of the penetrations is monitored by an interlocked detector.

Refrigerator Room Utility Penetrations: The total dose from all eight utility penetrations in the refrigerator room , which are grouped together by geometry, was calculated using labyrinth spreadsheets, which is the standard methodology. This gives a summed dose of 5.42×10^{-14} mrem/pulse in the refrigerator room at the exit of the penetrations (Attachment 7). Beam deposited on the emittance absorber, which is further upstream and designed to stop forward-directed loss particles, is, at worst, 3.25×10^{-11} mrem/hour (for 600 pulses/hour).

Pit labyrinth: The pit is a posted radiation area. Using the standard methodology of labyrinth spreadsheets, the maximum prompt dose at the exit of the pit labyrinth door is calculated to be 2.00×10^{-2} mrem/pulse (Attachment 7). For 600 pulses/hour in the emittance mode, the prompt dose from beam deposited on the emittance absorber, which is much further upstream, is then, in the worst case, 12 mrem/hour at the pit labyrinth exit door.

Ventilation ducts: Using labyrinth spreadsheets, the supply vent on the roof of the service building delivers a prompt dose of 3.54×10^{-8} mrem/pulse (Attachment 7). The dose from beam deposited on the emittance absorber at 600 pulses/hour will therefore be, at worst, 2.12×10^{-5} mrem/hour. The maximum prompt dose delivered at the exit of the return vent is 4.35×10^{-8} mrem/pulse (Attachment 7). The prompt dose from beam on the emittance absorber is, at worst, 2.61×10^{-5} mrem/hour for 600 pulses/hour.

Stairway Labyrinth: The worst-case dose at the labyrinth exit door leading outside (parking lot level) as calculated using labyrinth spreadsheets is 4.38×10^{-6}mrem/pulse (Attachment 7). For beam deposited on the emittance absorber at 600 pulses/hour, the dose is, at worst, 2.63×10^{-3} mrem/hour at the labyrinth exit door.

Air Activation Calculations, Estimate of Annual Release, and Air Release Points

Figure 5 shows the air intake and exhaust vents located at the top of the service building and experimental hall. The exhaust ducts for both the experimental hall and service buildings are then extended through piping into the tank farm area.

The EPA/IEPA has limited the annual dose to a Maximally Exposed Off-site Individual (MEOI) from the radioactive air emissions for a facility/source to 10 mrem (Attachment15). However, if this annual dose is more than 0.1 mrem, the source(s) of emissions will require EPA approved continuous monitoring. Fermilab has declared the whole site as one source. Fermilab's policy has been to keep the annual dose to MEOI less than 100 micro-rem. Based on releases expected from the accelerators, and the current and near future experiments it is determined that annual air releases from the operation of the MuCool beam line should be kept below 30 Curies. Detailed calculations of potential activated air releases from MTA are given in Attachment 15.

The release of 30 Ci in a year from the MuCOOL Facility was determined by the ES&H Section to be a reasonable addition to the overall integrated Fermilab yearly allowable site discharge. The maximum number of protons/year that may be delivered to the MTA Experimental Hall, based on air activation in the existing configuration with ODH requirements of **1200** cfm, corresponds to a maximum of **2.35E18** protons per year. If cryogens are not needed in future experiments, Table 2 can be used to assist in determining the appropriate yearly proton limit. Experimental changes are handled operationally via. MOUs and ORCs.

Table 2: The maximum number of protons/year to the MTA facility based on air flow rate.

Protons/year	FlowRate(cfm)
6.20E+20	50
3.21E+20	60
1.24E+20	80
6.49E+19	100
4.08E+19	120
2.86E+19	140
2.16E+19	160
1.72E+19	180
1.48E+19	196
1.43E+19	200
1.22E+19	220
7.69E+18	300
3.69E+18	600
2.76E+18	900
2.35E+18	**1200**

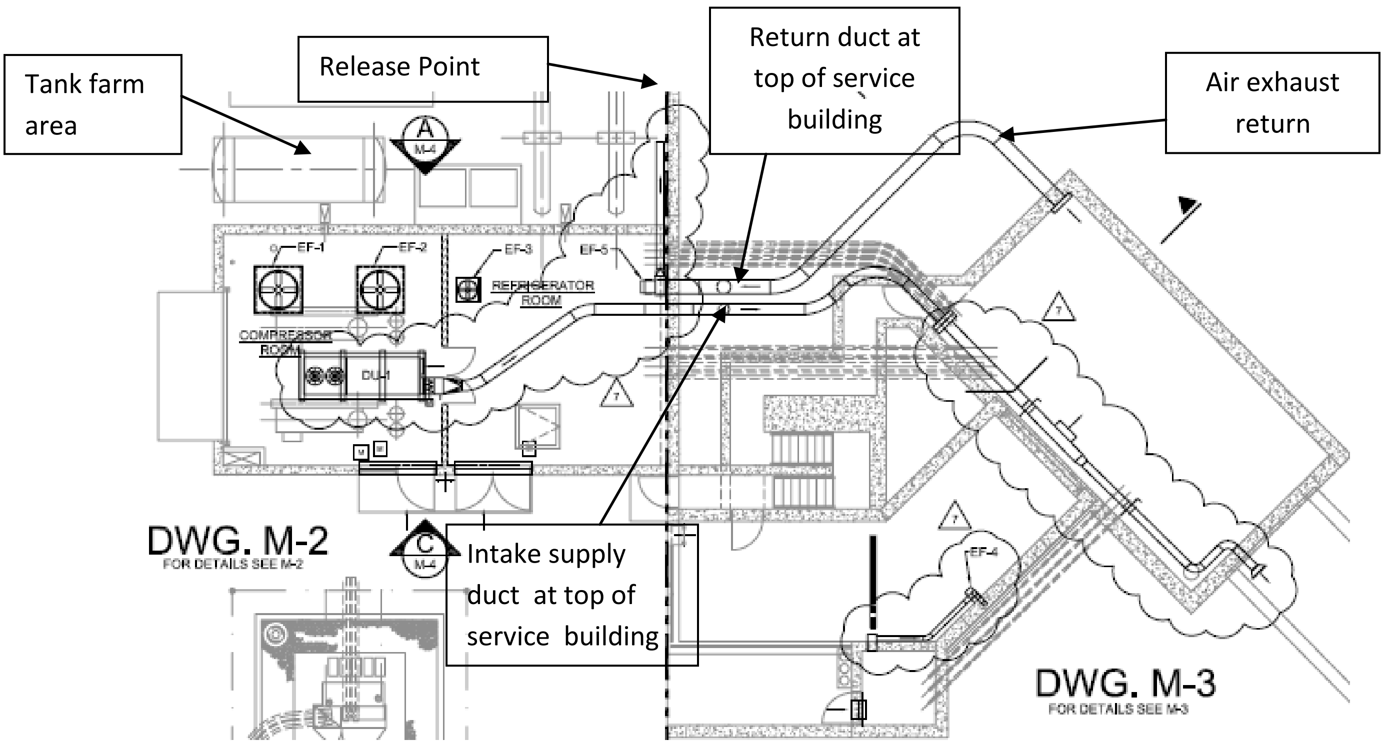


Figure 5. Air exhaust vent for the experimental hall and service buildings.

Ground and Surface Water Activation Calculations and Surface Water Discharge Points and Monitoring Locations

The estimates for ground and surface water are given in Attachment 9, for both the Emittance mode (Appendices 1 and 2 of Attachment 9) and the Experiment mode (Appendices 3 and 4). The limit for tritium, ^{3}H, in surface water is 2000 pCi/ml and for sodium-22, ^{22}Na, it is 10 pCi/ml. For ground water the tritium limit is 20 pCi/ml and for sodium-22, it is 0.4 pCi/ml.

The calculation of the star density associated with the emittance absorber is listed in the MARS compilation of Attachment 10. For Emittance mode operation, Attachment 9 examines the hypothetical annual number of protons which would be necessary to reach limits for surface water and for groundwater.

Beneath the experimental hall are drain tiles to collect surface water. A sump pump located in the northeast corner of the pit area collects surface water from around the experimental hall and discharges to a trench along Booster Road as shown in Figure 6. The beamline enclosure on the Linac side, upstream of the shield wall, is tied into the Booster sump system and discharges into the Booster Pond.

Booster sump concentrations and the MTA sump concentrations are regularly sampled as part of the AD/Routine Monitoring Program, procedure ADDP-SH-1003, and the Booster Pond is sampled as part of the ES&H Section's Environmental Monitoring Program.

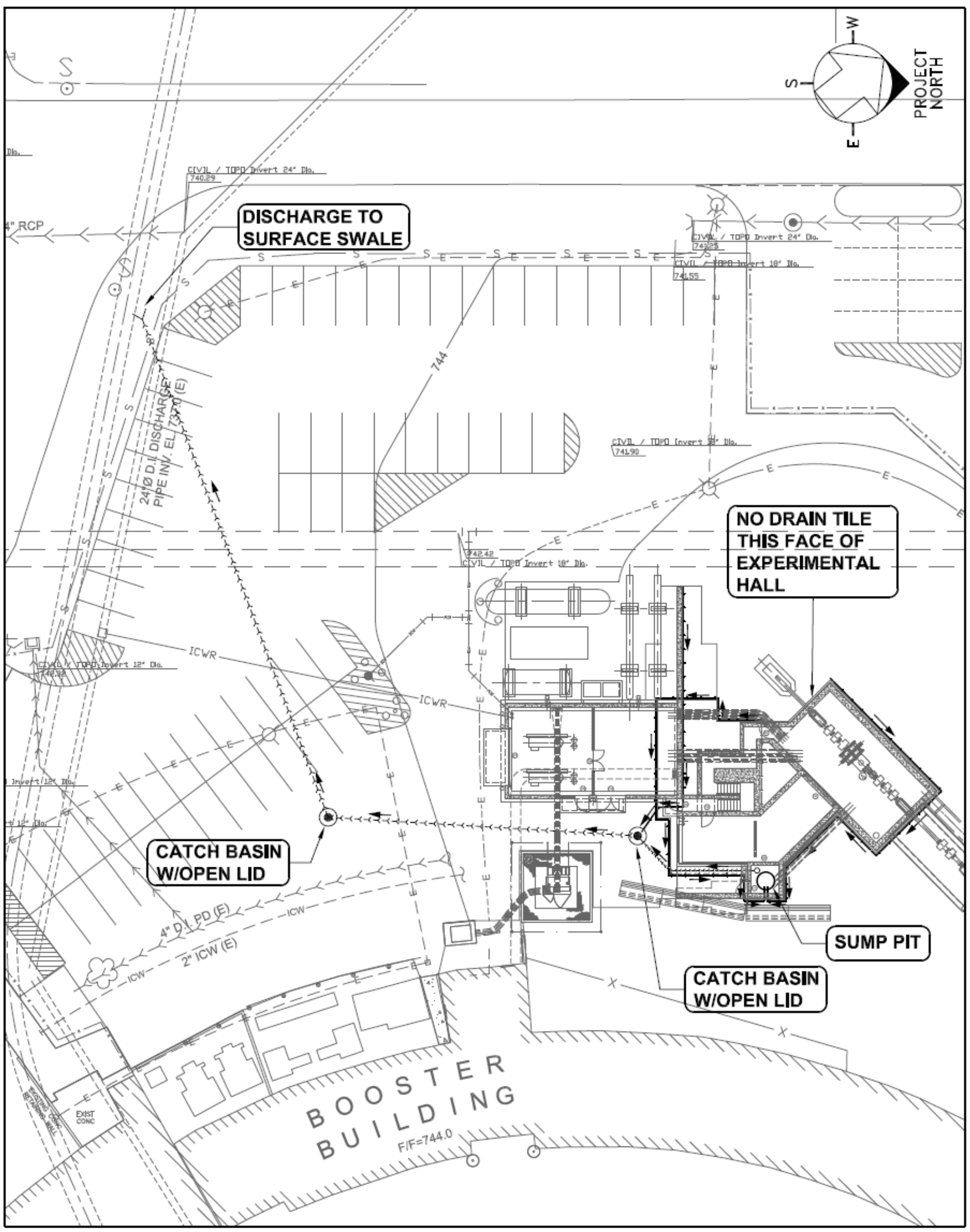


Figure 6. Surface water collection and discharge points.

Muon Production

Muons are produced through pion decay, and the number of pions in the hadronic cascade increases with proton kinetic energy. Pion production becomes energetically possible only when the proton kinetic energy is higher than the rest mass of the pion, 139 MeV, as is just the case with 400-MeV protons. The maximum energy of the secondary muons is therefore less than 260 MeV. From Reference 2 the muon range at 300 MeV for graphite (1.700 g/cm2) and carbon (compact, 2.265 g/cm2) is 3' and 2', respectively. Since concrete and berm exceed the density of graphite, and more than 10' combined (1.5' and 9' of concrete enclosure and berm, respectively) exists in all directions per the MuCOOL Radiation Safety Drawings (Attachment 17), there is adequate shielding in place to range out the muons.

Residual Dose Rate Estimates

The residual dose rates on copper (Cu) and steel have been calculated for long and short (1 hour) beam periods. As shown in the Figure 7, the Emittance mode has been calculated for steel at 10 pulses/min. An emittance measurement will typically take less than an hour. For 600 pulses in one hour, the maximum expected residual activation of the emittance absorber is 1-2 rem/hr based on Figure 7 (since Cu activation is comparable to steel). This and other potential residual activation hazards will be handled operationally as in all other Accelerator Division primary beam enclosures.

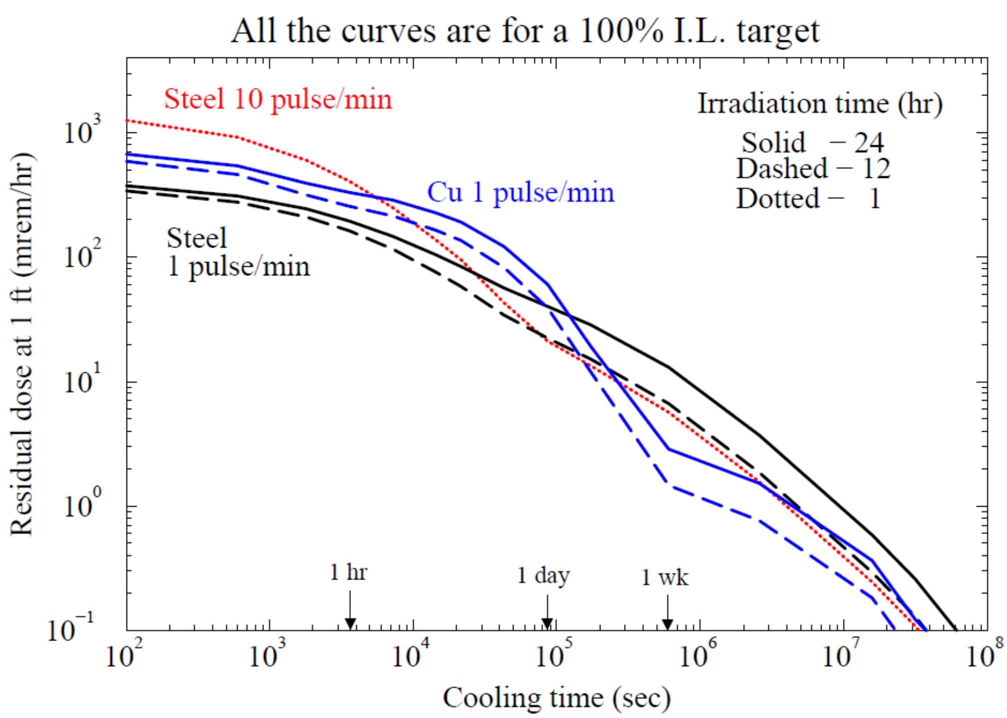


Figure 7. The calculated potential residual dose at one foot for Emittance and Experiment mode, and 1.6×10^{13} p/pulse, on 100% interaction length Cu and steel targets for 12, 24, and 1 hour periods of beam followed by a cooling period. A 100% interaction length target represents the worst case.

Intended Active Shielding Controls and Monitoring

An interlocked rate limiter actively counts Linac pulses delivered to the MuCOOL beamline. If the number of pulses allowed in Running Conditions is exceeded, beam is disabled through the critical devices. The Repetition Rate Monitor interlock is a safety class component that has been reviewed, Interlock Review 103, and approved by the ESH Section for use within the Fermilab Radiation Safety Systems. For the Emittance mode, the number is 600 pulses/hour. Attachment 11 is a description of the rate limiter.

Interlocked detectors in the Linac High Ceiling area, Linac ramp (Z=55-103'), the hatch shield wall (Z=106-115'), the Gas Manifold Room, and the Refrigerator Room Cryo Penetrations, limit dose rates appropriate to the area postings as needed.

EXPERIMENT MODE

Longitudinal Shielding Summary

The longitudinal shielding part of the assessment crosses the six areas described previously under Emittance Mode Longitudinal Shielding, continuing through three additional areas downstream of the beamline stub, also shown in the MuCool Radiation Drawings (Attachment 17). These are the 20' x 40' MTA experimental hall, the region occupied by a 6' long beam pipe that connects the MTA hall to the absorber, and the final beam absorber. Table I gives the stationing of all nine areas.

Z=147-187 ' Experimental Hall: A 20'x40' enclosure housing the experimental apparatus.

Z=187-193 ' Beam pipe to Absorber: A 6.5' long beam pipe is installed starting from the downstream wall of the experimental hall to upstream face of the beam absorber, Attachment 4.

Z=193-203 ' Final beam absorber: Engineering drawings are given in Attachment 4. Attachment 12 gives a full description of the absorber design and ANSYS calculations used.

Attachment 5 contains the longitudinal shielding spreadsheets for all nine areas for the Experiment mode. The sections from Z=0 to 103' are protected by interlocked detectors for both the Emittance and Experiment mode. In the rest of the nine areas, the shielding meets or exceeds the radiological requirements for the stated beam conditions for both modes.

Transverse Shielding Summary

The areas remain defined as in the longitudinal shielding section. Attachment 6 contains the transverse shielding spreadsheets for the Emittance (Attachment 6A) and the Experiment (6B) modes. The first three sections, Z=0-103', have transverse shielding radial distributions shown in the MuCOOL Radiation Safety Drawings (sections B - D and F-G, Attachment 17). The shield wall has transverse shielding distributions as shown in Attachment 3. Again, the first three sections (Z=0-103') are protected by interlocked detectors for both modes. The radial distribution of shielding along the beamline in the downstream areas and through the absorber is sufficient in all cases, as indicated in Attachment 6 for the Experiment mode.

Labyrinth and Penetration Summary and Calculations

The penetrations and labyrinths for the MuCOOL facility were listed under this section for the Emittance mode. Either MARS or labyrinth and penetration calculations were used for this assessment (Attachment 7 and 8). When a penetration or labyrinth being assessed was of a "typical" geometry the standard Labs & Pens spreadsheet was used, when the penetration or labyrinth being assessed was atypical, modeling with MARS was performed. This decision as to which method to use was made by the AD/RSO.

Experiment Mode:

Hatch Shield Wall: Two RF penetrations in the shield wall contain a 5" x 10" rectangular waveguide, and a 9" coaxial transmission line, both running from the top of the berm, through the hatch shielding, into the beamline stub. These RF penetrations were modeled using MARS for the worst case: losing the entire beam on a component about 7' downstream of the shield wall (Attachment 7 and Attachment 8, TM2457). The dose rate at the top of the berm is calculated to be 0.138 mrem/hr from the two RF waveguide penetrations combined. The Linac and MuCOOL berms are entirely enclosed by a 4' fence which is locked and posted during MuCOOL operation (category 4) as shown on the Radiation Safety Drawings (Attachment 17).

The penetration which feeds cabling between the Linac enclosure and the experimental hall is tightly packed with sandbags and there is no prompt dose in the hall from Linac operation. The beampipe through the shield wall is protected by beamstop which is one of the critical devices for the experimental area.

Ceiling Vent: With voids filled with polyethylene beads, the MARS simulation described in Attachment 8, TM2457 indicates that the dose is less than or equal to 0.3 mrem/pulse, or 6 mrem/hour for a beam loss nearest the ceiling vent (which represents the worst-case beam loss).

Gas Manifold Room: The three penetrations to the gas manifold room are filled with polyethylene beads and cabling except for 0.25" copper lines that feed gas to the experimental hall. The copper lines do not provide a direct path for neutrons. Independent of the mode, the worst case for prompt dose in the gas manifold room is generated by a loss directly across from the penetrations as described in Attachment 8, TM2457. Such a loss delivers a combined dose of no more than 1.51×10^{-3} mrem/pulse in the gas manifold room. For the Experiment mode, where beam is delivered at a rate of 60 pulses/hour, the worst case is 0.0906 mrem/hour. This level is acceptable since the gas manifold room is inside a 4' fenced, posted area (category 4). The gas manifold room is protected by an interlocked detector.

Refrigerator Room Cryo Penetrations: A cage and a 2' shield wall in the refrigerator room surrounds and blocks the area around the exit of all six of these penetrations, preventing access by personnel. The MARS simulation gives the largest prompt dose at a point accessible by personnel to be 1.51×10^{-3} mrem/pulse (outside of the cage and downstream of the 2' shield wall) based on the worst case described in Attachment 8, TM 2457 independent of mode. The worst case beam loss, when this value scaled to 60 pulses/hour, is 9.06×10^{-2} mrem/hour. The dose at the exit of the penetrations is monitored by an interlocked detector.

Refrigerator Room Utility Penetrations: The total dose from all eight utility penetrations in the refrigerator room, which are grouped together by geometry, was calculated using labyrinth spreadsheets which is the standard methodology. This gives a summed dose of 5.42×10^{-14} mrem/pulse in the refrigerator room at the exit of the penetrations (Attachment 7). The worst case loss is 3.25×10^{-12} mrem/hour for 60 pulses/hour.

Pit labyrinth: Using the standard methodology of labyrinth spreadsheets, the maximum prompt dose at the exit of the pit labyrinth door is calculated to be 2.00×10^{-2} mrem/pulse (Attachment 7). For 60 pulses/hour in the Emittance mode, the prompt dose from beam deposited on the emittance absorber, which is much further upstream, is then, in the worst case, 1.2 mrem/hour at the pit labyrinth exit door.

Ventilation ducts: Using labyrinth spreadsheets, the supply vent on the roof of the service building delivers a prompt dose of 3.54×10^{-8} mrem/pulse (Attachment 7). The dose from beam deposited at 60 pulses/hour will be, at worst, 2.12×10^{-6} mrem/hour. The maximum prompt dose delivered at the exit of the return vent is 4.35×10^{-8} mrem/pulse (Attachment 7). The prompt dose is, at worst, 2.61×10^{-6} mrem/hour for 60 pulses/hour.

Stairway Labyrinth: The worst-case dose at the labyrinth exit door leading outside (parking lot level) as calculated using labyrinth spreadsheets is 4.38×10^{-6} mrem/pulse. For 60 pulses/hour, the dose is, at worst, 2.63×10^{-4} mrem/hour at the labyrinth exit door.

Air Activation Calculations, Estimate of Annual Release, and Air Release Points

The air activation and release estimates and points for the Experiment mode are discussed in the corresponding Emittance mode section above.

Ground and Surface Water Activation Calculations and Surface Water Discharge Points and Monitoring Locations

The estimates for surface water and ground water are given in Attachment 9 for the Experiment mode (Appendices 3 and 4). The limit for tritium, ^{3}H, in surface water is 2000 pCi/ml and for sodium-22, ^{22}Na, it is 10 pCi/ml. For ground water the tritium limit is 20 pCi/ml and for sodium-22, it is 0.4 pCi/ml. Both the description and the calculation of the star density associated with the final beam absorber are given in Attachment 13.

Surface water concentrations will need to be evaluated in detail for any particular configuration of experimental apparatus. Attachment 9 examines an example of a "thick" experiment which may be typical. It consists of a high-pressure RF cavity followed by an absorber, not enclosed in the MTA solenoid magnet. For Experiment mode operation, Attachment 9 presents the hypothetical annual number of protons which would be necessary to reach limits for surface water and for ground water .

This calculation is intended only to offer a typical example; any new experiment must be analyzed separately. This includes "thin" apparatus, where a substantial fraction of the incident beam does not interact.

Beneath the experimental hall are drain tiles to collect surface water. A sump pump located in the northeast corner of the pit area collects surface water from around the experimental hall and discharges to a trench along Booster Road as shown in Figure 6. The beamline enclosure on the Linac side, upstream of the shield wall, is tied into the Booster sump system and discharges into the Booster Pond.

Booster sump concentrations and the MTA sump concentrations are regularly sampled as part of the AD/Routine Monitoring Program, procedure ADDP-SH-1003 , and the Booster Pond is sampled as part of the ES&H Section's Environmental Monitoring Program.

In the experiment mode, beam can be transported to the final absorber which is buried in the berm beyond the downstream wall of the MTA enclosure. This absorber is designed to handle high intensities. There was no granular underdrainage installed in this region. Instead water percolates into the soil around and below the absorber. Therefore surface water limits are not relevant.

Groundwater limits would be reached with 2.01 X 10^{20} protons per year incident on the final absorber, or about 1430 pulses per hour in continuous operation at full Linac intensity (Attachments 9 and 13).

Activity generated by continuous beam in the Experiment mode, at 60 pulses per hour, would therefore not exceed this level.

Muon Production

The background considerations for muon production, the threshold, maximum, and range energy of secondary muons, are discussed in the Emittance mode section and apply to the Experiment mode as well.

As in the Emittance mode, since concrete and berm exceed the density of graphite and more than 10' combined (1.5' and 9' of concrete enclosure and berm, respectively) exists in all directions per MuCOOL Radiation Safety Drawings (Attachment 17), the shielding in place is more than needed to range out the muons at all locations in the experiment hall.

The following is a general example where neutron and muon fluxes were calculated for a gas-filled RF test cell located in the experimental hall along with an energy spectrum of the generated muons, Figure 8. The average energy of the muons is 15 MeV and, as shown in Figure 9, muons lose all their energy in the concrete walls of the enclosure. Muon production and flux calculations are required and must be addressed in each experimental assessment.

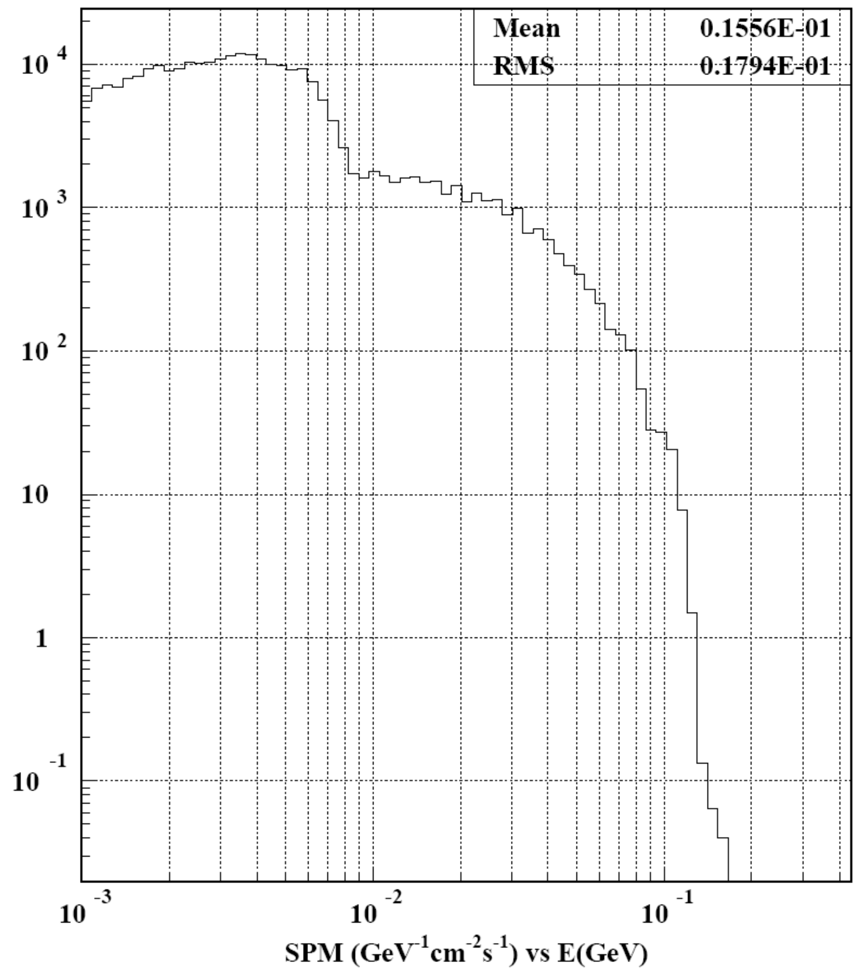


Figure 8. Muon energy spectrum from 400-MeV protons incident on a gas-filled RF test cell in the experimental hall for 2.67 x 10^{11} p/sec (1.6 x 10^{13} p/pulse and 1 pulse/minute in Experiment mode), equivalent. The flux for the Emittance mode is a factor of 10 higher.

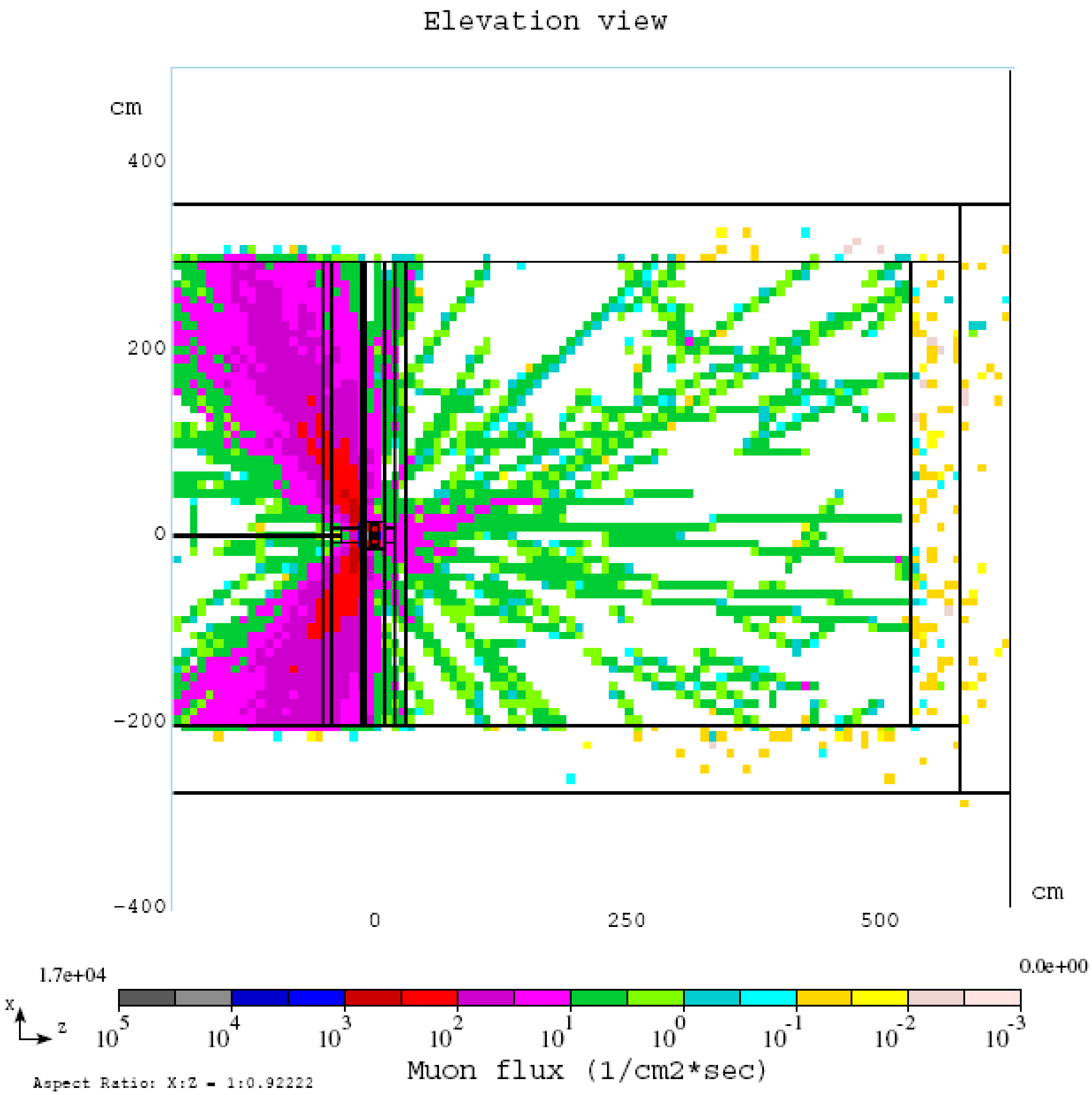


Figure 9. Muon flux in the experimental hall for 2.67 x 10^{11} p/sec (1.6 x 10^{13} p/pulse and 1 pulse/minute in Experiment mode) on a gas-filled RF test cell with thick (>100% Interaction length) walls. The flux for the Emittance mode is a factor of 10 higher.

Residual Dose Rate Estimates

The residual dose rates on copper and steel have been calculated for long and short (1 hour) beam periods as shown in the Figure 7 for the Experiment mode (1 pulse/min). Potential residual activation hazards, as in the Emittance mode, may be considerable and will be handled operationally, as in all other Accelerator Division primary beam enclosures.

Intended Active Shielding Controls and Monitoring

An interlocked rate limiter actively counts Linac pulses delivered to the MuCOOL beamline. If the number of pulses allowed in Running Conditions is exceeded, beam is disabled through the critical devices. For the Experiment mode, the number is 60 pulses/hour. Attachment 11 is a description of the rate limiter.

Interlocked detectors in the Linac High Ceiling area and Linac ramp (Z=55-103’), the hatch shield wall (Z=106-115’), the Refrigerator Room Cryo Penetrations, and the Gas Manifold Room, will limit dose rates appropriate to the area postings as necessary.

Summary and Conclusions

Table 3 is a summary of the prompt dose associated with each labyrinth and penetration. All above ground areas associated with the MuCOOL Facility are category 4 fenced, posted, and locked areas except for the adjacent parking lot and the support buildings which are considered to have no occupancy limits.

Table 3: Labyrinth and Penetration Dose Summary

Description	Dose in the Emmitance Mode 600 pulses/hour	Dose in the Experiment Mode 60 pulses/hour	
Hatch Shield Wall	1.38 mrem/hr	0.14 mrem/hr	
Ceiling Vent	60 mrem/hr	6 mrem/hr	
Gas Manifold Room Penetration	0.906 mrem/hr	0.09 mrem/hr	
Refrigerator Room Cryo Penetrations	9×10^{-1} mrem/hr	9.06×10^{-2} mrem/hr	
Refrigerator Room Utility Penetrations	3.25×10^{-11} mrem/hr	3.25×10^{-12} mrem/hr	
Pit Labyrinth	12 mrem/hr	1.2 mrem/hr	
Ventilation Duct Supply	2.12×10^{-5} mrem/hr	2.12×10^{-6} mrem/hr	
Ventilation Duct Return	2.61×10^{-5} mrem/hr	2.61×10^{-6} mrem/hr	
Stairway Labyrinth	2.63×10^{-3} mrem/hr	2.63×10^{-4} mrem/hr	

Note: The allowed dose per hour under DC conditions is 100 mrem in a fenced, posted, and locked area.
The allowed dose per hour under Accident Conditions is 500 mrem in a fenced, posted, and locked area.

Table 4 summarizes the yearly MuCOOL Facility proton limits based on Surface Water and Groundwater activation as well as from Air activation.

Table 4: Surface Water and Groundwater summary

Description	Yearly Proton Limit for Surface Water	Yearly Proton Limit for Groundwater	Yearly Proton Limit Due to Air Activation
Emittance Mode	2.93×10^{20}	7.75×10^{19}	
Experiment Mode	6.7×10^{20}	1.77×10^{20}	
Final Beam Absorber	NA	2.01×10^{20}	
MuCOOL Facility	NA	NA	2.35×10^{18}

The maximum number of protons/year that may be delivered to the MuCOOL Facility is based on air activation in the present configuration with the ODH air-exchange requirements of 1200 cfm, which corresponds to a maximum of 2.35×10^{18} protons per year as monitored by the Accelerator Division BBM (Beam Budget Monitor), system.

References

[1] Ankenbrandt, C. et al, "Design report: Linac Experimental Area,"FERMILAB-PUB-95-078 (Mar 1995).
[2] Groom, Donald E.; Mokhov, Nikolai V.; Striganov, Sergei, “Muon Stopping Power and Range Tables 10 MeV-100 TeV”, pp. 218-219.
<http://www.physics.princeton.edu/~mcdonald/examples/detectors/groom_adnat_78_183_01.pdf>

Attachments

1) MuCOOL Shielding Requirements
   1A) Emittance Mode
   1B) Experiment Mode
2) The MuCOOL Beamline
3) MuCOOL Hatch Shielding Complete Assembly, 2130.000-ME-391334
4) MTA Absorber Installation Drawings, 4-1-35A
5) MuCOOL Muon Test Area Longitudinal Shielding
   5A) Emittance Mode
   5B) Experiment Mode
6) MuCOOL Transverse Shielding
   6A) Emittance Mode
   6B) Experiment Mode
7) Summary of Labyrinths and Penetrations in the Muon Test Area (MTA) Enclosure
8) TM-2457: Beam Loss Scenarios for MuCOOL Test Area
9) Groundwater and Surface Water Activity in MuCOOL Beam Operations
10) The Emittance Absorber for the MuCOOL Beamline
11) MuCOOL Rep Rate Monitor Interlocks
12) MuCOOL Test Facility Beam Absorber
13) Surface and Groundwater Calculations for the MuCOOL Beam Absorber
14) MuCOOL Emittance Absorber
15) Air Activation Levels in the Muon Test Area Target Hall
16) TM 2248: Radiation Shielding Calculations for MuCOOL Test Area at Fermilab
17) MuCool Radiation Safety Drawings
18) Critical Device Justification
19) MuCOOL Beam Stop Thermal Analysis,
   19 A) Appendix A Result Based on Current Design
   19 B) The temperature Study for Beam Dump Used in Muon Cooling