Muon Campus

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Revision History

Author	Description of Change	Revision No. & Date
Jerry Annala John E Anderson Jr	Initial release of the Muon Campus and g-2 Chapter for the Fermi National Accelerator Laboratory Safety Assessment Document (SAD).	Revision 0 February, 2017
Jerry Annala Maddie Schoell	Update of Muon Campus chapter for addition of operating mode to transport beam to the Diagnostic Absorber in the M4 beamline Update references.	Revision 1 February 11, 2020

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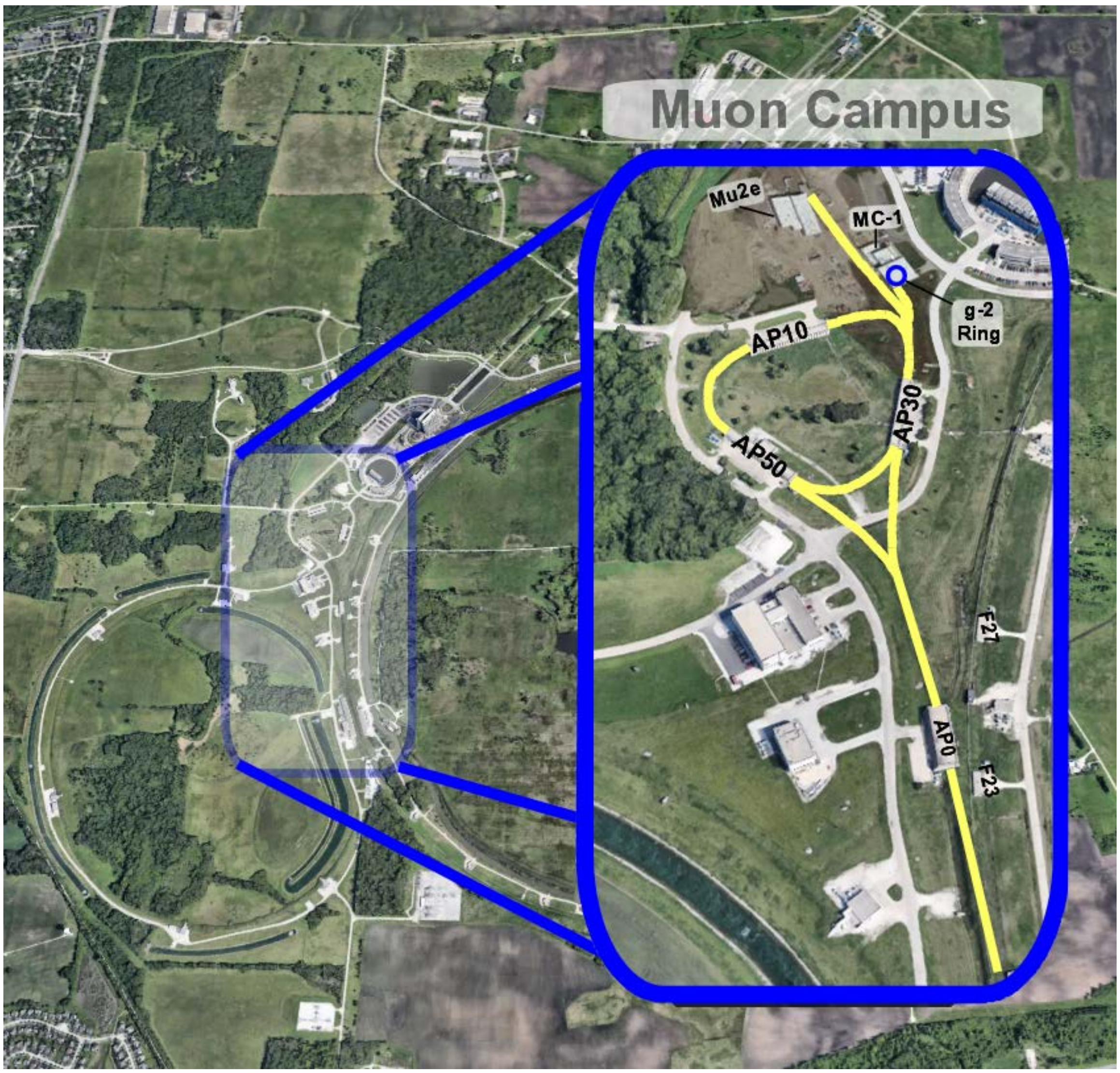
II - 11.1 Muon Campus Location on Fermi National Accelerator Laboratory (Fermilab) Site

The following aerial photograph shows the location of the Muon Campus in relationship to the Fermilab site.



II - 11.2 Inventory of Hazards

Table 1 lists the identified hazards found in the Muon Campus enclosure and support buildings. All hazards with an asterisk (*) have been addressed in Chapters 1-10 of the Fermilab Safety Assessment Document (SAD) and are not addressed in this section of the SAD.

Radiation Ionizing radiation Residual activation Groundwater activation Surface water activation Air activation Radioactive waste	**Kinetic Energy** Power tools * Pumps and motors *
Hazardous Materials Lead shielding * Beryllium components * Lithium *	**Potential Energy** Crane operations * Compressed gases * Vacuum / pressure vessels * Vacuum Pumps *
Flammable & Combustible Materials Cables *	**Magnetic Fields** Fringe fields *
Electrical Energy Stored energy exposure * High voltage exposure * Low voltage, high current exposure *	**Gaseous Hazards** Confined spaces *
Thermal Energy	**Access / Egress** Life Safety Egress *

Table 1

II - 11.3 Introduction

This Section II, Chapter 11 of the Fermi National Accelerator Laboratory (Fermilab) SAD covers the Muon Campus Accelerator area as configured to operate g-2 and for commissioning with 8 GeV protons to the M4 beamline Diagnostic Absorber (DA). Operating with beam to the Mu2e experiment will be addressed at a later time, therefore this version of the SAD does not cover the final Mu2e configuration. The staff of the Fermilab Accelerator Division (AD) Muon Department prepared this chapter.

II - 11.3.1 *Purpose of the Muon Campus Area*

The Muon Campus Area provides 3.1 GeV muons to the g-2 experimental apparatus, as well as 8 GeV protons to the Mu2e experiment. The accelerator is not capable of operating both experiments simultaneously, so the complex, described in the next sections, will be configured in one mode or the other. Although operating of g-2 calls for sending protons from the Recycler Ring to the AP-0 target where only 3.1 GeV secondary particles are captured, it is possible to bypass the target with the primary protons for commissioning and periodic tuning of the beamline and Delivery Ring (DR). For this reason, it is possible to operate with 8 GeV protons in a portion of the Muon Campus while in the g-2 configuration.

In the g-2 mode of operation, the AP-0 target accepts a pulsed primary proton beam of 8 GeV consisting of 1 x 10^{12} protons/pulse at an average repetition rate of 12 pulses per second. The pulse trains are structured in bursts of 8 pulses separated by 10 milliseconds. Two groups of 8 pulses strike the target every 1.4 seconds. 3.1 GeV secondary particles from the target are transported to and captured in the DR. After proton removal, 3.1 GeV muons are delivered to the g-2 experimental hall.

The Mu2e mode of operation will be commissioned in stages. The first stage has begun with 13 watts of 8 GeV protons (3.60 x 10^{13} protons/hr). The proton beam bypasses the AP-0 target and is transported through the DR to the DR abort absorber. The next phase will be to extract the 8 GeV beam and transport it through the M4 beamline to the DA. In the future, electrostatic septa will be installed, and resonant extraction will be commissioned to the DA. The magnet circuit that steers beam around the target is disabled when g-2 cycles are detected to prevent the higher beam power cycles from entering the downstream beam lines. The Mu2e cycles are repetition rate limited in the Time Line Generator hardware to ensure the frequency of commissioning cycles remains low.

The radiation protection throughout the Muon Campus will be upgraded in the future allowing up to 8 kW of beam, although only 170 watts will be allowed to be directed to the DA. When the Muon Campus is configured for beam to the Mu2e experiment, the primary proton delivery will consist of 8 pulses every 1.4 seconds at 8 GeV. This beam will be resonantly extracted from the DR and transported to the Mu2e target station. This version of the Safety Assessment Document only covers the initial stage of commissioning with 13 watts of beam delivered only as far as the DA in the M4 line. Until the beam power upgrades are complete and approved, safeguards will remain in place to limit the beam power of the 8 GeV beam cycles.

II - 11.3.2 *Description of the Muon Campus Area*

The Muon Campus is located west of the Tevatron enclosure between the Booster and Main Injector. The Muon Campus area consists of: 5 beamlines (named M1, M2, M3, M4 and M5) originating in the Tevatron tunnel at F17, a target station at AP-0, DR (the former Antiproton Source Debuncher), six service buildings (named F23, AP-0, F27, AP-10, AP-30, and AP-50) and the two Muon Campus experimental areas (MC-1 and Mu2e Detector Hall). Figure 1 shows the location of these beamlines and buildings. The MC-1 building and Mu2e building are experimental halls but do contain some accelerator equipment.

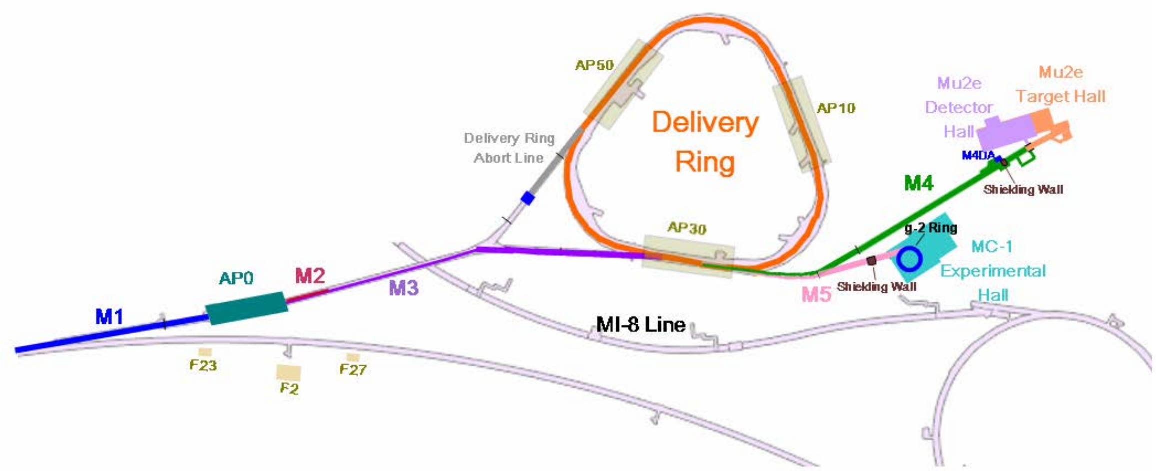


Figure 1: Muon Campus Layout and Associated Beamlines for g-2 and Mu2e Diagnostic Absorber operation

The M1 beamline begins in the Tevatron enclosure at F17 and runs through the Pre-Target and Pre-Vault enclosures to the AP-0 target. The M3 line splits from the M1 line just upstream of the AP-0 target. It runs around the target vault and meets the DR under the AP-30 service building. This beamline is 309 meters in length and is comprised of 100 magnets. The M2 beamline begins downstream of the AP-0 target and runs 50 meters where it merges with the M3 beamline.

The DR is essentially the repurposed Debuncher ring formerly used for the Tevatron Collider. The DR is 500 meters in circumference and has beam transfer inserts for injection, extraction, and the abort. The end of the old AP-2 injection line is used to transport beam from the DR to the DR abort. The physical enclosures for all beamlines mentioned to this point are unchanged from the former Tevatron Collider Antiproton Source operation.

The Extraction Enclosure and M4 Enclosure are new beam enclosures that house the M4 beamline, and most of the M5 beamline. The M4 line exits the DR under the AP-30 service building and runs through these two enclosures to the Mu2e experiment enclosure.

The M4 line has a branch point just 30 meters downstream of the DR. At that point the M5 line splits from the M4 line and runs to the g-2 storage ring in the MC-1 Enclosure. The MC-1 building is covered in Section III Chapter 8 of the Fermilab SAD.

50 meters upstream of the Mu2e enclosure, there is a horizontal dipole that can direct beam into a 22 meter long beamline that terminates at the DA. Beam is prevented from being transported to the Mu2e enclosure during the DA commissioning phase by two beam stops upstream of the shield wall in the M4 beamline that will remain closed. The Mu2e Experimental Hall SAD Chapter will be developed before beam commissioning to the Mu2e experiment.

II - 11.3.3 *Operating Modes*

The Muon Campus configured for g-2 operation allows several variations that can be implemented for commissioning and accelerator diagnostic analysis. The normal mode of operations will be described followed by variations used for commissioning and can be used for accelerator improvement studies and experiments.

II - 11.3.3.1 g-2 Operations

Single bunches of protons are delivered to the Muon Campus from the Recycler Ring in an irregular pattern. 16 bunches are sent to the Muon Campus every 1.4 second cycle with the individual bunches separated by 10 msec. The intensity of each bunch is 1 x 10^{12}, with a bunch length of 120 nsec. When the idle time between cycles is included, the average pulse rate is 11.4 Hz.

Protons are delivered to the Muon Campus from the Recycler Ring via the P1 and P2 beamlines that were used for the Tevatron Collider operations. These two beamlines together provide a path from the MI/Recycler all the way to the beginning of the M1, shown in figure 1. Conversion of the beamlines from Collider operation to the Muon Campus operation includes an extraction insert in the Recycler and a short beamline connecting the Recycler to the P1 line. Several magnets were replaced in the existing transfer line to improve the aperture for Muon Campus operation. The beamline transported both 8 GeV and 120 GeV protons during collider operations. Transfers to the Muon Campus will be limited to the lower energy, so limiting aperture magnets were replaced trading reduced field capability for better beam transmission.

Beam is introduced in the Muon Campus at F17 in the Tevatron enclosure and travels through the M1 line to the AP-0 target. The only significant change to the M1 line is the final focus for the target which was altered to form a more compact triplet closer to the target.

The 8 GeV protons strike the target in the AP-0 target vault. The focus and momentum selection magnets downstream of the target direct 3.1 GeV, positively charged particles into the M2 line. The M2 line merges with the M3 line 50 meters downstream of the target by energizing a switch magnet named D:H812. The beamline then continues on to the DR injection area. Along the entire path, pions decay into muons and neutrinos. The optics of the beamlines are designed to capture the maximum number of decayed muons at 3.094 GeV/c.

A pulsed septa and kicker magnet combination are used for injection into the DR. The beam circles the DR 4 times before the muons are extracted. By this time, all of the pions have decayed so the beam consists mainly of muons and protons. Because the relativistic beta of the protons and muons differ, the revolution time of the two particle types differ by 70 nsec. After 4 revolutions in the DR, there is enough separation for a kicker to rise between the particles. On the 4th revolution, the extraction kicker and abort kicker are both fired such that the protons are sent to the DR cleanup abort, and the muons are extracted into the M4 line. The muon beam continues in the M4 line for 30 meters where a switch magnet named D:V907 directs the beam up into the M5 line for transport to the g-2 storage ring in the MC-1 building.

II - 11.3.3.2 8 GeV Protons through the Delivery Ring for Commissioning

Variations on these normal operations have been used for commissioning and for accelerator improvement efforts. One such variation is to bypass the target with the 8 GeV protons by powering the D:H700 switch magnet just upstream of the AP-0 target. This directs the protons into the M3 line for transport to the DR. The M3 beamline and the DR can be powered to a higher current to transport 8 GeV protons in this mode. Beam can be stored in the DR for diagnostic work for an arbitrary length of time. Running in this mode is done at a much-reduced repetition rate consistent with the Accelerator Safety Envelope[14] and the Antiproton Source 2000 Shielding Assessment[1]. This mode is used for commissioning Mu2e operations as well as g-2 operations.

II - 11.3.3.3 3.1 GeV Secondary Beam for g-2 Commissioning

Another variation of the g-2 operating mode that is used for commissioning and diagnostics is to alter the number of DR revolutions of the 3.1 GeV secondary beam. The number of revolutions can vary from zero to storage for an indefinite time. If less than 4 revolutions are made in the DR, both protons and muons are sent to the g-2 storage ring as there is not enough time separation to direct the two beams into separate beamlines. The Muon g-2 Shielding Assessment [3] includes this operation.

II - 11.3.3.4 Mu2e Operations

The Muon Campus can also be configured in support of Mu2e operation. The normal HEP mode of operation will be described followed by variations used for commissioning and machine development studies. The approval of this version of the Safety Assessment Document will allow only a limited subset of the commissioning variations, and not allow for beam delivery to the Mu2e experiment.

In the final Mu2e configuration of the Muon Campus, eight 8 GeV proton bunches will be delivered to the Muon Campus from the Recycler every 1.4 seconds. The train of 8 bunches will be separated in time by 48 msec followed by a 1 second wait for the cycle to repeat. The proton bunches will bypass the AP-0 target station and be injected into the DR. The beam will then be resonantly extracted over the span of 43 msec. The extraction point is just downstream of the injection point, where beam enters the M4 line. The first 30 meters of the M4 line is common to both g-2 and Mu2e beam delivery.

30 meters into the M4 beamline, the V907 switch magnet is configured to direct beam to the Mu2e experiment. The downstream end of the magnet is oriented in alignment with the M4 beam line when configured in Mu2e mode. The magnet polarity and operating strength is also set for transport to Mu2e. In the future, the M4 beam line will end at the production solenoid which contains the Mu2e target. The particles surviving beyond the Mu2e target terminate in a dedicated proton absorber, which is designed for the full Mu2e beam power.

II - 11.3.3.5 Commissioning the M4 Line to the Diagnostic Absorber

The initial stages of commissioning the beamline to Mu2e will be done while the experimental apparatus is being installed. This commissioning activity will take advantage of the DA placed upstream of the experiment during civil construction. This absorber is shielded sufficiently to allow access into the experimental area for installation during beam operation.

II - 11.3.3.5.1 Single Turn Extraction

Before the resonant extraction system is installed in the DR, the g-2 extraction kicker will be used to commission the first 70% of the M4 beamline. Single turn extraction will be used to transport beam through 175 meters of the beamline up to a switch magnet that will be energized to send the beam the remaining 22 meters to the DA. Only low power beam (13 watts), consistent with the Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber[12], will be used for this commissioning activity. Downstream of this switch magnet are two beam stops, locked in the closed position, and a 15 foot thick shield wall to prevent radiation exposure downstream of the M4 enclosure while operating in this mode. These beam stops will serve as critical devices for Mu2e once the experiment is installed and ready to accept beam.

II - 11.3.3.5.2 Resonant Extraction

Once the resonant extraction system is installed, the same beamline configuration will be used to commission resonant extraction at low beam power. Eventually, once the shielding and safety systems in the Muon Campus are upgraded, up to 170 watts of beam will be allowed to go to the DA for beam commissioning. A new shielding assessment and an updated SAD will be required before increasing the beam power above 13 watts.

II - 11.3.3.6 Configuring the Operational Modes

A Muon Campus Beam Mode key switch located in the Main Control Room will be used to configure the Muon Campus beam operating mode. The modes are 8 GeV beam to the AP-0 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 AP-0 target station, or to the M3 beamline.
- Permit energizing the MC-1 critical devices for beam to the g-2 storage ring only when the AP-0 target station mode is selected

When switching between Muon Campus modes, the Coasting Beam Critical Device Controller (CDC) acts to insert the DR coasting beam valves to remove any residual circulating beam in the DR not associated with the newly selected mode. When the key switch is in the position to bypass the AP-0 target, the critical devices that allow beam to the g-2 experiment are disabled. These features prevent the unintended transfer of 8 GeV primary beam to the MC-1 Enclosure.

II - 11.4 Safety Assessment

The unique beamline specific hazards for the Muon Campus area are analyzed in this section. The radiological hazards include ionizing radiation, residual activation, groundwater and surface water activation, air activation, and radioactive waste.

II - 11.4.1 *Radiological Hazards*

The Muon Campus beamlines present radiological hazards in the form of prompt and residual ionizing radiation from particle beams, residual radiation due to activation of beamline components, and environmental radioactivity in the form of potential groundwater, surface water, and air activation resulting from the operation of the beam transport systems.

Detailed shielding assessments and post assessment documents address these hazards [1, 2, 3, 12]. The assessments provide a detailed analysis of the Muon Campus as configured for g-2 operation, and 13 watt operation to the DA, demonstrating the required shielding, controls and interlocks comply with the Fermilab Radiological Control Manual (FRCM) [4].

The shielding assessments[1, 2, 3,12] for the Muon Campus begin at the switch dipole located at the end of the P2 line at F-17. The Antiproton Source Assessment from the year 2000[1] includes the beamlines from F-17 to the DR, and the DR itself. The Muon g-2 Shielding Assessment[3] includes the external beamline where it exits the DR at the 30 straight section, through the MC-1 Enclosure. The Muon g-2 Assessment[3] also includes the DR cleanup abort. The Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber [12] includes the M4 beamline through the Extraction Enclosure and M4 Enclosure up to the DA only. The assessments[1, 2, 3,12] do not consider Mu2e operation which will allow primary beam intensities several orders of magnitude higher, and the operation of the Mu2e beamline downstream of the Extraction Enclosure.

The assessments[1, 2, 3,12] consider groundwater and surface water activation; calculates air activation; estimates annual release, and release points; considers muon production; considers bulk shielding requirements; summarizes labyrinth and penetration calculations; calculates residual dose rates when significant; and specify active shielding controls and monitoring.

II - 11.4.1.1 Ionizing Radiation

Prompt ionizing radiation is the principle radiation hazard when beam is transported through the Muon Campus beamlines. In order to protect workers and the general public, the enclosures and beam pipes are surrounded either by sufficient amounts of shielding (soil, concrete, or iron), and/or networks of interlocked detectors to keep any prompt radiation exposure within acceptable levels.

Detailed shielding assessments have been compiled and reviewed by the Fermilab Shielding Review Panel to address these concerns. The assessments provide a detailed analysis of the beamline, demonstrating the required overburden or soil shielding, use of signs, fences, and active interlocks to maintain any prompt radiation within acceptable levels.

Shielding assessments [1, 2, 3,12] for the Muon Campus beamlines have included analyses of the AP-0 target station, injection, circulation, extraction, absorption areas, the MC-1 Enclosure and DA, as well as the transport lines between. These shielding assessments and FRCM require that:

- *All movable shielding blocks must be installed as specified.*
- *The average beam intensity to the AP-0 target shall not exceed* 4.32×10^{16} *protons/hr.*
- *The beam intensity to bypass the target shall not exceed* 3.6×10^{13} *protons/hr.*
- *The radiation safety interlock system must undergo initial and periodic testing by the ES&H Section to ensure correct functioning.*
- *Radiation detectors around the Muon Campus enclosures are installed and interlocked to the radiation safety interlock system.*

II - 11.4.1.2 Residual Activation

Since the Muon Campus beamlines downstream of the AP-0 target will either transport low intensity secondary beams, or a less frequent 8 GeV proton commissioning cycles, the residual radiation dose will be minimal. The beamlines upstream of the AP-0 target have the potential for higher residual activity. The area in and around the AP-0 target vault will have the highest levels of residual radioactivity.

The AP-0 target station utilizes a closed loop cooling water system commonly denoted as "RAW" (radioactive water) system for target station components. The predominant isotopes in the activated water have half-lives between 2 and 20 minutes. A chipmunk radiation monitor located in the water cage monitors the radiation levels due to the activated water. Access to the water cage is controlled by the assigned Radiation Safety Officer (RSO) and is not generally permitted until sufficient radiation cooling time has elapsed following beam operation.

As documented in the Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber[12], the residual dose rate on the upstream face of the DA itself is estimated to be 76 mrem/hr following 30 days of continuous 13 watt operation followed by one day of cooldown.

When the Muon Campus is not in operation, personnel access to beamline enclosures are administratively controlled by an entry control system consisting of access control procedures, key entry systems, and Radiological Work Permits (RWPs). The control measures include training and training verification, and centralized access authorization.

In most situations, general RWPs for accesses will suffice. A job-specific RWP and an as-low-as-reasonably-achievable (ALARA) plan will be required for work on any highly activated equipment with a potential individual exposure greater than 200 mrem or potential job exposure greater than 1000 person mrem. Members of the ES&H Section Radiation Physics Operations Department will supervise these tasks under the direction of the assigned RSO.

II - 11.4.1.3 Groundwater and Surface Water Activation

Operation of the Muon Campus beamlines will activate ground and surface water primarily in the vicinity of the AP-0 target and the DR clean up absorber, which is downstream of the AP-50 straight section. Most of the activation occurs within 1 to 2 meters of the tunnel walls.

Primary beam power on the AP-0 target for g-2 operation is a factor of 4 lower than the operating beam power during Tevatron Collider Operation. The secondary beam power to g-2, and the primary beam power used for early commissioning of the Muon Campus, are both very low by comparison.

By scaling groundwater concentration estimates from collider era operation[5], potential groundwater activation levels near the AP-0 target during Muon g-2 operations after 10 years of operation are estimated to be approximately 1.7 E-7 pCi/ml-yr for tritium and 3.4 E-12 pCi/ml-yr for sodium-22, or less than 0.01% of the combined United States Environmental Protection Agency and Derived Concentration Standard release limit. Similarly, by scaling enclosure sump sampling measurements, potential surface water tritium activation levels are estimated to be less than 40 pCi/ml, or approximately 2% of the Derived Concentration Standard release limit.

The DR clean up abort and the DA are the only other areas of the Muon Campus to consider for ground and surface water activation. Estimates for groundwater activation levels [3] after 10 years of operation to the DR Abort would be approximately 5.0 E-6 pCi/ml-yr for tritium and 9.9 E-11 pCi/ml-yr for sodium-22, or less than 0.01% of the combined limit. Potential surface water tritium activation levels are estimated to be less than 50 pCi/ml-yr for tritium and 4.42 pCi/ml-yr for sodium-22, or less than 1% of the Derived Concentration Standard release limit if enclosure sump discharge were to occur once per week.

Groundwater zones are regularly monitored as part of the Fermilab Environmental Monitoring Program [6]. Sump discharges to surface waters are sampled at certain locations and frequencies

[7]. The assigned RSO is responsible for acting on these results. Initial 13 watt beam to the DA during occasional commissioning periods will result in ground water activation levels that are 1.2e-8 of the activation limit, even after 20 years of running at much higher than anticipated hours per year[12].

II - 11.4.1.4 Air Activation

Illinois state regulations and the Fermilab registration in Registration of Smaller Sources (ROSS) program, administered by the Illinois Environmental Protection Agency (IEPA), govern releases of airborne radionuclides. The regulations limit the effective dose equivalent delivered to a member of the public to 10 mrem/year [8, 9]. Fermilab has established a secondary goal of keeping the maximum effective dose equivalent at the site boundary due to air emissions under 0.1 mrem/yr.

The principal radionuclides of concern to air activation are carbon-11 (which has a 20 minute half-life), nitrogen-13 (which has about a 10 minute half-life), oxygen-15 (which has about a 2 minute half-life), tritium (which has a 4500 day half-life), and argon-41 (with a 1.83 hour half-life). The Muon Campus primary proton beam for g-2 operation is transported in a vacuum with the exception of the beam exiting the beam pipe, through a vacuum window at the AP-0 target station. The secondary beam likewise is transported in vacuum with the exception of the exit at a vacuum window at the abort absorber and at the vacuum window between the accelerator beamline and the muon storage ring. During 13 W beam commissioning to the DA, the primary proton beam will exit the vacuum pipe through a window and travel through 3 meters of air before reaching the DA.

The release of activated air from the AP-0 target station has been monitored during collider operation [10]. The design beam power on target for g-2 operation is 22% of the actual beam power delivered during collider operation. Air activation near the target will scale with the beam power, so will also be 22% of the activation of the air during collider operation.

Air activation due to operating the DR clean up abort from 2.29 GeV protons has been calculated [3]; the summary of the calculation is shown in Table 2.

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 2: Summary of annual air activity released calculation for the Delivery Ring abort in support of the g-2 experiment.

Beam delivered to the DA is expected to result in a total release of 0.13 Ci/yr based on an estimate of 100 hours of operation per year at 13 W[12].

II - 11.4.1.5 Muon Radiation Shielding

Muons may be produced due to the loss of up to 8 GeV protons during Muon Campus operations. Muons are to be routinely produced at the AP-0 target station and at the DR cleanup abort. These muons travel in the horizontal plane and never emerge from any shielding berm surface. There are several locations at which the protons (and pions or muons) are traveling with an upward velocity component. The failure of a down bending magnet could result in the transmission of muons in an upward direction. Muon Campus locations where this could occur include the magnets HV100 in F-Sector of the Tevatron, HV102 in the Pre-Target enclosure, V901 in the DR, V907 and V003 in the Extraction Enclosure, and VHA03 in the DR cleanup abort line [3]. The range of 8 GeV muons in soil with a density of 2.24 g/cc is approximately 60 feet [11]. Radiation Shielding drawings prepared for the muon campus indicate that in all cases, muons will be ranged out before emerging from ground surfaces.

Muons will be produced at the DA during single turn M4 line commissioning studies. These muons will be on axis with areas that may be occupied during beam operations. A MARS simulation [13] was made to address the exposure potential to occupants of the Mu2e experiment area. The result of the simulation concludes that there is no significant exposure to muons even at the DA design beam power limit of 170 watts. No further consideration of muons from the DA is necessary.

II - 11.4.1.6 Radioactive Waste

Muon Campus radioactive waste and waste disposal are managed within the program established for the Fermilab accelerator complex and as prescribed in the FRCM. Waste minimization is an objective of the equipment design and operational procedures. Although production of radioactive material is not an operational function of the Muon Campus beamlines, beam loss and, in the case of some beam diagnostics devices, intentional interception of the beam will result in activation of beamline elements. Reuse of activated items will be carried out when feasible. Activated items that cannot be reused will be disposed of as radioactive waste in accordance with the FRCM requirements.

II - 11.5 Credited Controls

II - 11.5.1 *Passive Controls*

Passive controls are accelerator elements that are part of the physical design of the facility that require no action to function properly. Passive controls are fixed elements of the beamline that take direct human intervention to remove. The Muon Campus enclosures are designed to optimize the effect of these passive controls with permanent concrete and earth-covered radiation shields that use a combination of permanent shielding, movable shielding, and penetration shielding to protect personnel from radiological exposure during beamline operation.

II - 11.5.1.1 Permanent Shielding

The permanent shielding encompasses the structural elements surrounding the Muon Campus beamlines. The Muon Campus shielding includes the following areas:

1. The M1 line beginning at the F17 extraction point in the Tevatron tunnel;
2. The AP-0 target vault;
3. The M2 and M3 injection lines;
4. The DR and abort absorber;
5. The extraction area containing the shared M4 line and the M5 line;
6. The MC-1 Enclosure containing the end of the M5 line and the g-2 storage ring shown in Figure 2
7. The M4 beamline including the DA and adjacent shield wall shown in Figure 3 below.

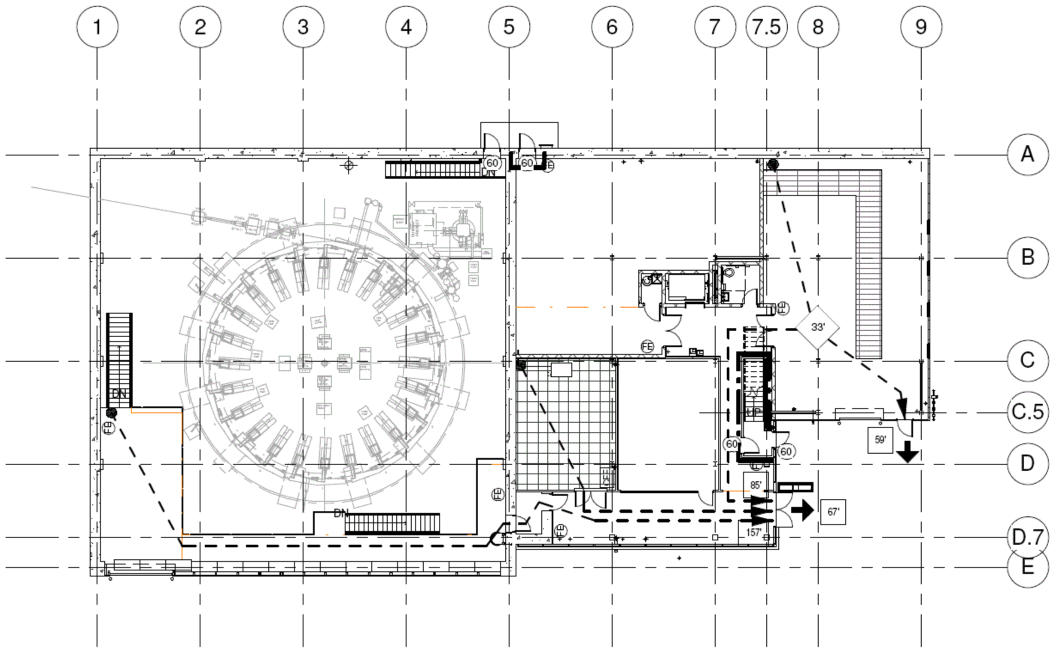


Figure 2: MC-1 building layout

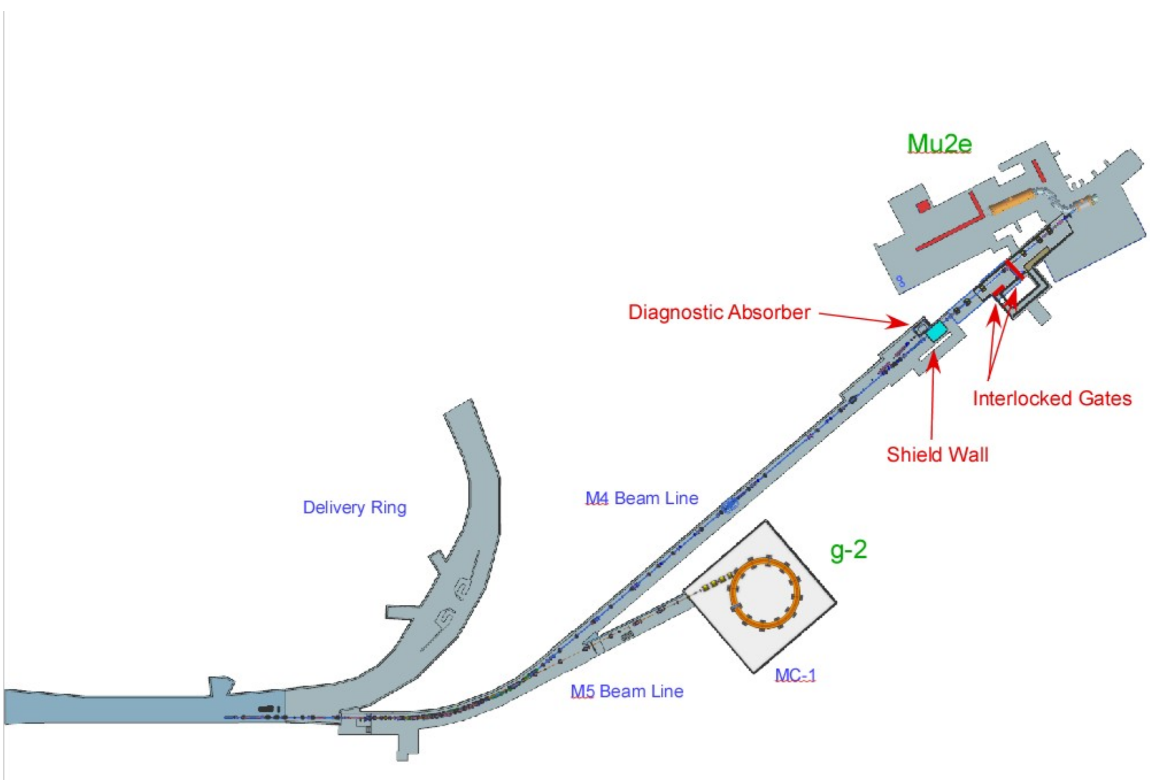


Figure 3: M4 beamline details

The permanent shielding for the enclosures is documented in References [1, 2, 3, 12]. In some cases, the earth overburden must be supplemented by active controls such as interlocked radiation detectors to maintain compliance with the posting requirements of the FRCM under the assessed beam conditions.

II - 11.5.1.2 Moveable Shielding

The Muon Campus has several areas with removable shielding. There are two drop hatches in the AP-0 building with crane coverage to the tunnel below. There are also 4 drop hatches into the DR enclosure from the outside. There is a drop hatch near the DA in the M4 enclosure. These hatches are filled with concrete shielding blocks. The assigned RSO controls locks for the shielding to these drop hatches and ensures that they are properly filled and secured before permitting beam.

The AP-0 target station consists of several beamline elements suspended from steel modules that provide shielding. Above the steel module are concrete shielding blocks. Surrounding the target vault area is a wall constructed of concrete blocks that allow occupancy of the building during beam operation. The assigned RSO controls access to the area within the concrete block wall; access is not permitted while beam is operable.

There are stackable shield walls in the Extraction Enclosure and the M4 Enclosure. The Extraction Enclosure contains a shield wall at the downstream end of the M5 line that protects the MC-1 Enclosure from beam showers originating from the DR or the M4 line. The shield wall in the M4 enclosure protects the Mu2e area from radiation produced transporting beam to g-2 or to the DA.

The MC-1 enclosure and service building has concrete blocks placed along the north wall and in front of the roll up truck door while beam is permitted. The Muon g-2 Storage Ring chapter in Section 3 of this SAD describes this removable shielding.

The assigned RSO specifies the configuration management measures to be taken to insure the placement of all moveable shielding structures.

II - 11.5.1.3 Penetrations

The Muon Campus contains many penetrations and labyrinths. Table 3 lists by area the number of such penetrations by type in each section of the Muon Campus.

Beamline Enclosure	Penetration count by type
Pre- Target/Pre-Vault	• Stair well (2) • Cable penetration (20) to F23 • Cable penetration (4) to AP-0 • Ventilation stack (1)
Vault	• Cable penetration (32) to AP-0
Transport	• Stair well (1) • Cable penetration (20) to F27 • Cable penetration (25) to AP-0 • 24” air duct into AP-0 (1) • Water pipe penetrations (4)
Delivery Ring	• Emergency exit trunks (3) • Air shafts (3) • Elevator shafts (3) • Stair wells (6) • Cable penetrations (440) • 18 inch stub room penetrations (5)
Extraction	• Stair well (1) • Ventilation stack (1)
M4	• Cable penetrations to MC-1 (32) • Cable penetrations to Mu2e (38) • Stairwell (1) • Gated entrance to experimental hall (1)

Table 3: List of Penetrations

The Muon g-2 shielding assessment [3], the 2000 Pbar Source Shielding Assessment [1, 2], and the Muon Campus Shielding Assessment for 8 GeV Beam Transmission to the Diagnostic Absorber [12] address all of the listed penetrations.

II - 11.5.2 *Active Controls*

Active engineered controls are systems designed to reduce the risks from accelerator operations to an acceptable level. These automatic systems limit operations, shutdown operations, or provide warning alarms when operating parameters are exceeded. The active controls in place for Muon g-2 operations are discussed below.

II - 11.5.2.1 Radiation Safety Interlock System

The Muon Campus enclosures employ a Radiation Safety Interlock System (RSIS). The characteristics of the system are described in Chapter I, Section 4.3.2.1 of the Fermilab SAD.

The Muon Campus beamlines are enclosed in 9 distinct enclosures, each with their own RSIS. There are interlocked access points, emergency egress exits, and interlocked gates between enclosures in each area. Each RSIS inhibits critical devices upstream of its own enclosure to prevent transport of beam when the enclosure is not ready for beam operation.

The Transport US/DS enclosure has chipmunk radiation monitors that are active when access is permitted. These chipmunks are located at each end of the Transport Mid enclosure. The chipmunks monitor the radiation levels coming from the MI-8 line below and will inhibit Booster beam if unacceptable radiation levels are approached.

The production solenoid area of Mu2e is monitored by a chipmunk radiation monitor near the beam pipe at the end of the M4 enclosure. A chipmunk radiation detector monitors the MC-1 Enclosure, where the beamline enters the hall, when access is permitted in the enclosure.

The Muon Campus service buildings employ a series of chipmunks that monitor radiation levels to assure compliance with the FRCM posting requirements. The south end of the AP-0 service building also is protected by a Total Loss Monitor (TLM) that is installed along the ceiling of the Pre-Vault enclosure between the M1 and M3 lines.

Critical devices are used for protecting each of the Muon Campus enclosures. Table 4 below lists the critical devices necessary to allow each beam operating scenario along with other pertinent information.

Muon Campus Enclosure Boundaries and ESS and RSS scenarios with Mode Switch				R.M.Zifko
Scenario	CDC Inputs	Critical Devices to get beam to area in scenario of column A		Comments UPDATED 1/17/2020
M1 CDC Beam to AP0 Target Dump CDC Located in AP0	Pre-Target ESS PreVault ESS AP0 Vault ESS Transport ESS AP0 Rads Delivery Ring CDC FM	I:F17B3 (contactor) Located In F2	M:HV100 (contactor) Located In F23	Chimpmunks ready (or TLM) Radiations monitors move to M2 CDC (RMZ 2-27-15)
Delivery Ring CDC g-2 Beam / Mu2e beam to Delivery Ring Abort CDC Located in AP0	Delivery Ring ESS Extraction ESS Delivery Ring Rads BS707 Pressure Switch Extraction CDC FM Coasting Beam CDC FM Mode Switch	Mu2e Mode SW And D:H812 (D:H704) or G-2 Mode SW And D:H700 (Contactor) Located In AP0	D:BS707 Located In AP0 Will not permit power supplies (CD1)until Beam Stop is fully opened.	D:BSC700 move to new location. (After beam lines come together) New name D:BS707 D:BSC925 no longer needed g-2/Mu2e Current Window on Switcher Power Supply (D:V907) no longer needed. If Coasting Beam CDC Failed, do not bring in more beam Delivery Rings Rad move to this CDC Change Name of CDC from M2 CDC to Delivery Ring CDC Change PS name from D:H926 to D:H700 Mode switch added to input for beam abort reasons
Coasting Beam CDC Coasting beam in the Delivery Ring CDC Located in AP10	Transport ESS Delivery Ring ESS Extraction ESS Extraction CDC FM B:V605A Pressure Switch B:V605B Pressure Switch Mode SW Mu2e Operation or Mode SW g-2 Operation	D:BV605A Located in AP10	D:BV605B Located in AP10	MC-1 Beam or Mu2e Coasting Beam in the Delivery Ring. D:V907 Current Window is an "or" of the Switcher magnet with the correct current for g-2 or Mu2e operations. Added pressure switches. Mode Switch replaced Current Window RMZ 5-4-16
Extraction CDC Beam to MC-1 or Beam to Diagnostic Absorber CDC Located in AP30	Extraction ESS M4 ESS Extract Rad Mon MC-1 CDC FM MC-1 CDC Permit 1 or M4 CDC Permit 1	D:ELAM (Contactor) Located in AP30	D:V901 (Contactor) Located in AP30	MC-1 CDC Permit or Mu2e CDC Permit are inputs to insure one of the two areas are ready for beam. *Depends on which mode you're in (Beam to MC-1 or Mu2e) **Depends if beam is going to the Diagnostic Aborber or to the Detector Hall. Mode Switch added, current window removed from MC1 CDC and M4 CDC and put into Extraction CDC RMZ 5-4-16 Removed Current Intlk. Removed Mode Sw, changed M4A Gate Rad Mon to Extract Rad Mon, removed M4 CDC FM. 1/15/20
MC-1 CDC Beam to MC-1 CDC Located in MC-1	MC-1 ESS MC-1 Rad. Mon. Mode Sw g-2 Oper. D:V907 g-2 Pol.	D:V003 Located in MC-1	D:H005 Located in MC-1	Changed D:H006 to D:H005 Added Mode Sw g-2 Oper. To CDC Inputs Added D:V907 g-2 Pol. To CDC Inputs
M4 CDC Beam to M4 Enc. Diagnostic Absorber or Mu2e Detector Hall CDC Located in AP30	MC1 Stub Chipmunk / TLM Mode Sw Mu2e Oper D:V907 Mu2e Pol Mu2e CDC FM D:HDA01 Current Window Mu2e CDC FM M4 Shielding Wall Chipmunk or Mu2e BS1 Open Mu2e BS2 Open	D:H910 Located in AP30		Beam to Diagnostic Absorber. Added D:V907 Polarity. Removed RHR Rad , and added M4 Rad Mon. Renamed M4B Chipmunk to M4 Shielding Wall Chipmunk. Removed Mu2e CDC Permit. Added Mode Sw Mu2e Oper Removed Extinction ESS Renamed Mu2e to RHR (remote handling room) and removed it from M4 CDC and put it in Mu2e CDC
Mu2e CDC Beam to Mu2e Target Hall CDC Located in Mu2e	RHR ESS Extinction ESS Mu2e Det. Hall ESS Mu2e Rad. Mon. BS 1 & BS 2 Air Pres Switches	Mu2e Beam Stop #1	Mu2e Beam Stop #2	Beam to Mu2e experiment

Table 4: Critical Device list, inputs, and scenarios

Each Muon Campus enclosure is protected by upstream critical devices, which need to be positively activated to allow beam into the next enclosure. To allow beam in any Muon Campus enclosure, beam must be permitted in all upstream enclosures as well, meaning that access to those areas is not allowed. The following describes how each of the Muon Campus enclosures is protected from beam exposure to personnel. In the Muon Campus, disabling a magnet is done by opening a contactor to a power supply that energizes the magnet. This contactor is controlled by the RSIS. The enclosures are illustrated in Figure 4 below, and a description of what devices protect personnel during permitted access is given in beam order beginning with the M1 line.

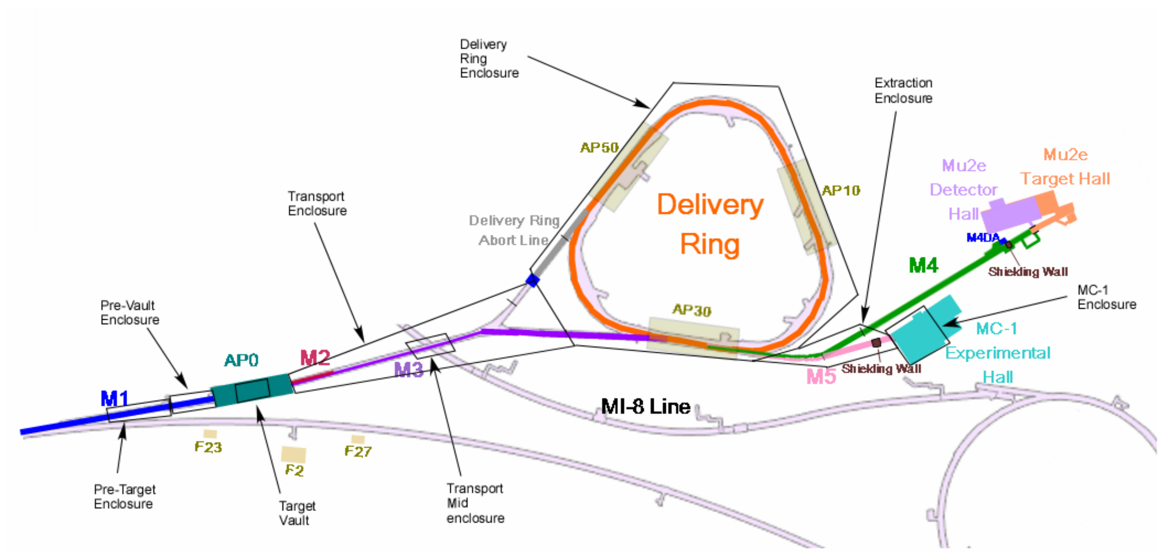


Figure 4: Muon Campus enclosure map

The Pre-Target enclosure is where the M1 line enters the Muon Campus as the beam exits the Tevatron enclosure. If access is permitted in the Pre-Target enclosure, two pairs of critical devices inhibit the transfer of beam from the Main Injector and Recycler into the P1 line. The Recycler extraction Lambertson, I:LAM52, bends the beam down away from the Recycler by 21 mrad. Without current in the I:LAM52 magnet string, beam is lost in the region just downstream. A vertical dipole, R:V703, is a second critical device that bends beam back up 24 mrad onto the P1 line trajectory. Without the R:V703 24 mrad bend, the beam is lost within the R:V703 dipole.

A similar critical device pair prevents beam from transferring from the Main Injector into the P1 line when access is allowed into Pre-Target enclosure. I:LAM52 and I:V701 are bending dipole strings required to bend the beam out of the Main Injector and into the P1 beamline. Turning either of these devices off prevents beam from being transported through F-Sector in the

Tevatron enclosure toward either the Muon Campus or the 120 GeV Fixed Target experimental program.

The M1 line continues through the Pre-Vault enclosure. Two critical devices in the very upstream portion of the M1 line, I:F17B3 and M:HV100, have their contactors disabled when access is allowed to the Pre-Vault enclosure. The first of these devices, I:F17B3, is a dipole string in the P2 line that needs to be energized for beam to be bent away from the P2 line trajectory. With I:F17B3 at zero current, the beam passes cleanly into the P3 line and on to the 120 GeV Fixed Target experimental area. The second device, M:HV100, is a dipole string that bends beam horizontally away from the P2 line trajectory toward the target station. With M:HV100 off, nearly all of the beam is lost within the second HV100 magnet, and the beam is 100% extinguished on the next quadrupole downstream which is still within the Tevatron F-Sector enclosure. It is not possible for beam to leave the Tevatron enclosure without both I:F17B3 and M:HV100 magnet strings energized.

When access into the AP-0 target vault area is permitted, the same two critical devices protecting the Pre-Vault area (I:F17B3 and M:HV100) are disabled. There are interlocks associated with access into the vault area, as well as a specific written procedure for entry. Access to the Target Vault is under the control of the assigned RSO.

When access is permitted in the Transport enclosure, which is immediately downstream of the AP-0 target, beam is not permitted in the M1 line. The same two critical devices (I:F17B3 and M:HV100) are disabled as are for permitting access to the Pre-Target enclosure and Target Vault.

In the middle of the Transport enclosure is embedded another enclosure called the Transport Mid enclosure. Being within the Transport enclosure it utilizes the same critical devices (I:F17B3 and M:HV100). In addition, when access is permitted in this enclosure, beam is disabled in the MI-8 beamline, that passes beneath, by disabling B:LAM and B:MH1 by turning off the magnet power supplies through the CDC controller and removing an Enclosure Enter key. Both critical devices are discussed in the Booster Chapter of this SAD.

When access is permitted in the DR enclosure, critical devices in both the M2 and M3 line prevent beam from being transported through the Transport Enclosure. Dipole magnet D:H700 is disabled by turning off the magnet power supplies through the CDC controller and removing an Enclosure Enter key, which prevents primary proton beam from being directed out of the M1 line and into the M3 line. With D:H700 at zero current, the M1 line beam continues straight to the AP-0 target vault target. Disabling dipole D:H812 prevents secondary beam from the AP-0 target from entering the M3 line. D:H812 provides a 52.4 mrad bend to put the secondary beam on the trajectory of the M3 line. With D:H812 unpowered, beam is completely lost in the two quadrupoles immediately downstream of H812. Downstream of the point where the M2 and M3 lines merge, is beam stop D:BS707. D:BS707 is the second critical device for both the primary proton beam in the M3 line and the secondary beam from the M2 line. D:BS707 is closed for DR access, preventing any beam transmission beyond the beam stop. The geometry of the Transport enclosure provides sufficient distance and shielding downstream of D:H700, D:H812, and D:BS707 to allow access into the DR enclosure.

When access is permitted in the Extraction Enclosure, the same critical devices that allow access into the DR enclosure (D:H700, D:H812, and D:BS707) are disabled.

When access is permitted in both the MC-1 enclosure or the M4 enclosure, extraction from the DR is not allowed by disabling the extraction Lambertson magnet, D:ELAM, and the dipole, D:V901. If D:ELAM is not energized, the beam kicked into the normal extraction channel stays at the DR elevation and cannot enter the aperture of the C-Magnet in the extraction line. A second critical device is a downward bending dipole, D:V901. With D:V901 not energized, beam travels in a straight line through this sector magnet and is lost on the steel part way through the magnet. It is necessary to energize both D:ELAM and D:V901to transport beam into the Extraction enclosure. The geometry of the Extraction Enclosure provides enough shielding from the DR to allow access into the MC-1 enclosure or the M4 enclosure with D:ELAM and D:V901 disabled. If the Muon Campus is configured for g-2 operation, but access is permitted to the MC-1 Enclosure, extraction from the DR is disabled by the same two critical devices (D:ELAM and D:V901).

If access is permitted to the MC-1 Enclosure, two critical devices in the M5 beamline have their contacts disabled to protect the enclosure if beam is being transported to the DA. D:V003 and D:H005 are both disabled when access is permitted to the MC-1 Enclosure. D:V003 is a 9 degree down bend. With this magnet disabled, beam would continue in an upward direction and exit the vacuum pipe before traversing the next magnetic element. D:H005 is a three-magnet bend string that provides 27 degrees of horizontal bend. With this magnet string disabled, beam would exit the vacuum pipe before it reached the second dipole.

If access is permitted to the M4 enclosure the dipole string critical device named D:H910 is disabled by use of an electrical contactor. This magnet string provides the 41 degrees of horizontal bend required to direct beam toward the M4 beamline and to Mu2e. With this bend string disabled, beam continues in the direction of the beam extracted from the DR toward the extraction enclosure wall. When access to the M4 enclosure is permitted, the status of the D:H910 contactor is monitored to ensure that it is open. If the contactor open status goes away, the Extraction Enclosure Critical Device is disabled as a backup to D:H910.

There is also a coasting beam Critical Device Controller. This safety system device closes two independent beam valves, D:BV605A and D:BV605B, in the DR when access is allowed to the Transport, DR, or Extraction enclosure. The beam valves (D:BV605A and D:BV605B) eliminate the possibility of stored beam being present in the DR.

Trained and qualified personnel from the AD Operations Department are required to search and secure the enclosure before permits from the RSIS may be re-established following any personnel access to the enclosure, except under strictly specified controlled access conditions. The RSIS requirements including requirements for hardware and system testing, inventory of interlock keys, search and secure procedures for the beamline enclosures, controlled access procedures, personnel training requirements, and procedures for maintenance of interlock systems are in conformance with the FRCM.

II - 11.5.3 *Administrative Controls*

All Muon Campus accelerator operations with potential to impact the safety of employees, researchers, or members of the public or to adversely impact the environment are performed using approved laboratory, division or department procedures. These procedures are the administrative controls that encompass the human interactions and form the foundation for safe accelerator operations. The administrative procedures and programs considered necessary to ensure safe accelerator operations are discussed.

II - 11.5.3.1 Beam Permits and Run Conditions

In accordance with AD Administrative Procedure on Beam Permits, Running Conditions, and Startup (ADAP-11-0001), beam will not be transported to the Muon Campus enclosures without an approved Beam Permit and Running Condition. The Beam Permit specifies beam power limits as determined and approved by the AD Head in consultation with the ES&H Radiation Physics Operations (RPO) Department Head, assigned RSO, AD Operations Department Head, and AD Muon Department Head. The Running Conditions list the operating modes and safety envelope for the Muon Campus beamlines. Running conditions are issued by the assigned RSO, and are signed by the AD Operations Department Head, AD Muon Department Head, assigned RSO, and AD Head.

II - 11.5.3.2 Summary of beam operating and safety envelope parameters

The Muon Campus shielding assessments [1, 2, 3,12] have assessed the safe beam operating parameters and have been used to develop the safety envelope parameters in Appendix A, *Accelerator Safety Envelope*. The shielding assessments determined that the Muon Campus enclosures can be safely operated with 8 GeV protons on target at a maximum of 4.32×10^{16} protons/hour, and for 8 GeV protons bypassing the target at a maximum of 3.6×10^{13} protons/hour.

II - 11.6 Summary & Conclusion

Specific hazards associated with operation of the Muon Campus accelerators for Muon g-2 and commissioning 8 GeV protons to the M4 DA are identified and assessed through the shielding assessments[1, 2, 3, 12] and summarized in this chapter of the Fermilab SAD. The designs, controls, and procedures to mitigate Muon Campus specific hazards are identified and described. The Muon Campus accelerators are subject to the global and more generic safety requirements, controls and procedures outlined in Section 1 of the Fermilab SAD.

The preceding discussion of the hazards associated with Muon Campus accelerator operations and the credited controls established to mitigate those hazards demonstrate that the Muon Campus accelerator and beamlines can be operated in a manner that will produce minimal risk to the health and safety of Fermilab workers, researchers, the public, as well as to the environment.

II - 11.7 Glossary, Acronyms

AD	Accelerator Division
ALARA	As Low As Reasonably Achievable
CDC	Critical Device Controller
Ci	Curie
DA	Diagnostic Absorber
DR	Delivery Ring
ES&H	Environment, Safety & Health
Fermilab	Fermi National Accelerator Laboratory
FESHM	Fermilab Environment, Safety, and Health Manual
FRCM	Fermilab Radiological Control Manual
GeV	Giga-electron volt
HEP	High Energy Physics
Hr	Hour
Hz	Hertz
IEPA	Illinois Environmental Protection Agency
LCW	Low Conductivity Water
MI	Main Injector
RPO	Radiation Physics Operations
RAW	Radioactive Water system
RSO	Radiation Safety Officer
RWP	Radiological Work Permit
SA	Shielding Assessment
SAD	Safety Assessment Document
TLM	Total Loss Monitor

II - 11.8 References

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