Muon g-2 Storage Ring

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Author	Description of Change	Revision No. & Date
Brendan Casey	Initial release of the Muon g-2 Storage Ring Chapter for the Fermi National Accelerator Safety Assessment Document	Revision 0 March 2, 2017

Table of Contents

III - 8 Muon g-2 Storage Ring

III - 8.1 Muon g-2 Storage Ring Area Location on Fermilab Site

III - 8.2 Inventory of Hazards

The following table lists the identified hazards found in the Muon g-2 Storage Ring enclosure. All hazards with an * have been discussed in Chapters 1-10 of the Fermilab Safety Assessment Document and are not covered further in this section.

Radiation Ionizing radiation X-ray producing devices Radioactive waste Lasers	**Kinetic Energy** Power tools * Pumps and motors *
Toxic Materials Lead shielding *	**Potential Energy** Crane operations * Compressed gases * Vacuum / pressure vessels * Vacuum pumps *
Flammable & Combustible Materials Cables * Flammable gas*	**Magnetic Fields** Fringe fields *
Electrical Energy Stored energy exposure * High voltage exposure * Low voltage, high current exposure *	**Gaseous Hazards** Confined spaces * Flammable gas * Cryogenics

III - 8.3 Introduction

This Section III, Chapter 8 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Muon g-2 Storage Ring located North West of the delivery ring in the Muon Campus. This document updates the Hazard Analysis Report for the Muon g-2 Project[1]. The remainder of the Muon Campus is covered under Section II Chapter 11, Muon Campus/g-2, of the Fermilab SAD.

III - 8.3.1 Purpose of the Muon g-2 Storage Ring

The purpose of the Muon g-2 Storage Ring is to store 3.09 Giga-electron volts (GeV) muon beam for the Muon g-2 experiment. The Muon g-2 experimenters will examine the precession (change in the orientation of the rotational axis of a rotating body) of muons that are subjected to a magnetic field.

III - 8.3.2 Description of the Muon g-2 Storage Ring

The Muon g-2 Storage Ring is located south of Wilson Hall across the street from the Booster area. It connects to the M5 beamline of the Muon Campus. The g-2 Storage Ring is a 1.45 Tesla C magnet with four 24-turn superconducting coils designed to store 3.09 GeV muons. It is located in the high bay of the first Muon Campus Building, MC-1. The enclosure is 80 feet by 80 feet by 50 feet high. The walls are 2-foot-thick concrete up to 29 feet above the floor. See figure one below.

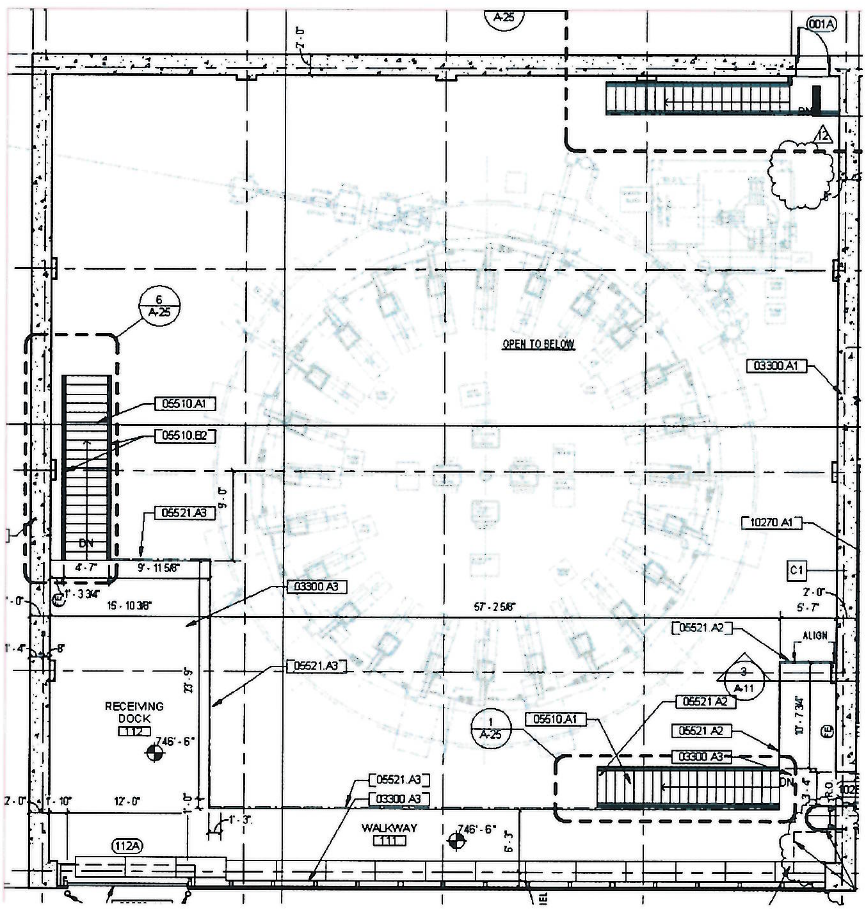

Figure 1. Muon g-2 Storage Ring layout.

The 3.1 GeV muon beam enters the MC-1 building through the end of the M5 line. The final four magnets of the M5 line are in the MC-1 building. The muon beam enters the Storage Ring through a hole in the back yoke. The beam passes through a superconducting inflector magnet that cancels the field from the main magnet in the hole through the yoke. A pulsed kicker magnet kicks the beam onto the central orbit. Muons are stored using weak vertically focusing

electrostatic quadrupoles in the Storage Ring. A cross-section of the Storage Ring magnet and a plan view of the vacuum chamber and beam elements are shown in Figures two and three below.

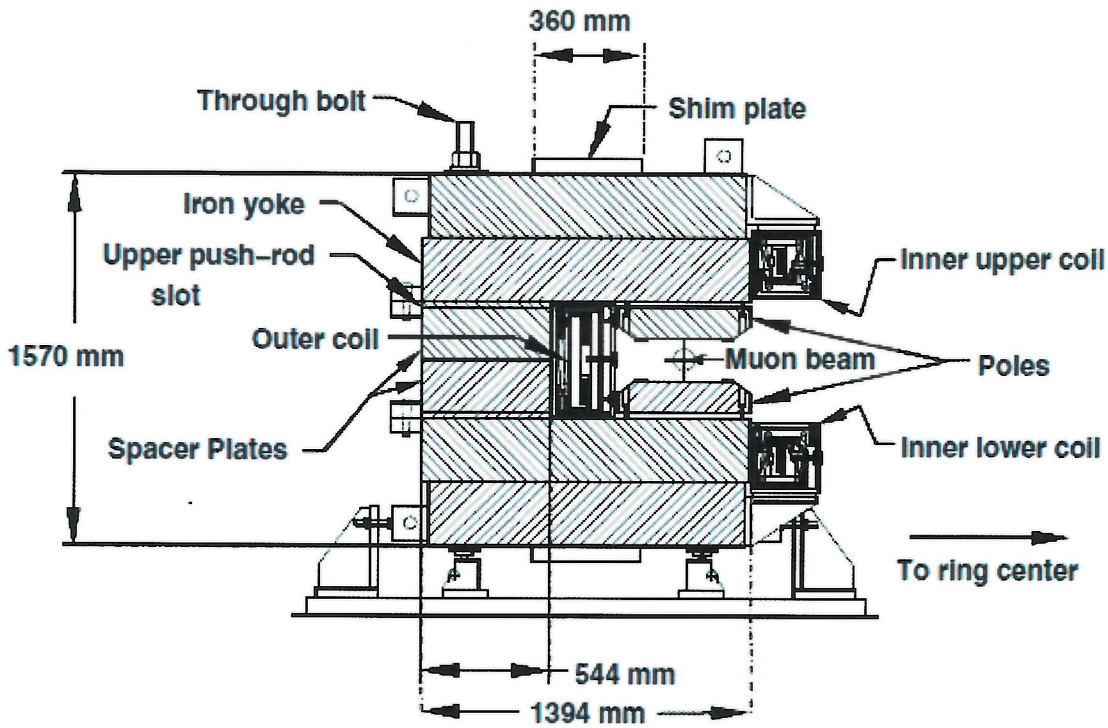

Figure 2: Cross-section of the Muon g-2 Storage Ring.

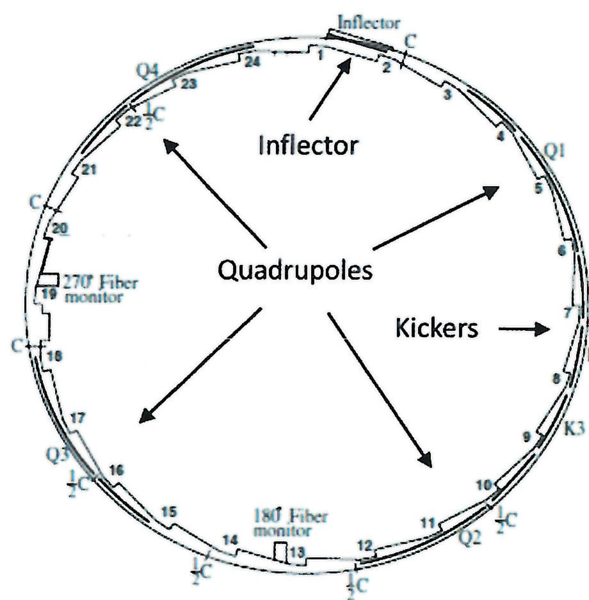

Figure 3: Storage Ring vacuum chamber with beam elements.

III - 8.3.3 Operating Modes

There are two operational modes for accepting and storing positively charged particles in the g-2 Storage Ring. In the first mode used for initial commissioning, the beam consists mainly of 3.1 GeV protons. In normal operations, protons will be removed in the upstream Delivery Ring and the beam will be pure 3.09 GeV/c muons. A signal received from the upstream accelerator indicates upstream muon bunch preparation is beginning. At this point, the kicker magnets charge and the quadrupole High Voltage (HV) ramps up. Once the beam arrives, the kicker fires and steers the beam onto the central orbit. g-2 operators adjust the quadruple HV to steer the beam vertically into a series of collimators to scrape and focus the beam. This all occurs within the first 15 microseconds of the fill. At 20 microseconds, data taking begins. Muons are **stored** for 680 microseconds or approximately 10 muon lifetimes. g-2 operators turn off the quadrupole HV at 700 micro seconds, and the remaining muons spiral vertically into the magnet yoke.

The Shielding Assessment dated February 2017[2] concludes that at nominal running conditions with muons, the effective dose rate does not exceed 0.05 milli-Roentgen equivalent man /hour (mrem/hr) in accessible spaces in MC-1. During commissioning using protons, effective dose rates within MC-1 can exceed 0.050 mrem/hr under normal conditions. Interlocked radiation detectors placed in the hall limit the effective dose rates from normal operations to less than 0.050 mrem/hr and accident conditions to less than 1 mrem/hr in accessible spaces.

III - 8.4 Safety Assessment

The unique beam line specific hazards for the Muon g-2 Storage Ring are analyzed in this section. The radiological hazards analyzed include ionizing radiation, non-ionizing radiation, residual activation, ground water and surface water activation, air activation, and radioactive waste. In addition to the radiological hazards, the Muon g-2 Storage Ring and MC-1 enclosure have unique laser, electrical and magnetic, flammable gas, and cryogenic hazards that are addressed.

III - 8.4.1 Radiological Hazards

The Muon g-2 Storage Ring presents radiological hazards in the form of prompt and residual ionizing radiation from particle beams, potential non-ionizing radiation from high power pulsed HV systems, and residual radiation due to activation of beam line components.

A detailed shielding assessment[2] of the Muon g-2 Storage Ring has been compiled and reviewed by the Fermilab Shielding Assessment Review Panel (SARP) of the Fermilab Radiation

Safety Subcommittee to address these concerns. The assessment provides a detailed analysis of the Muon g-2 Storage Ring operations demonstrating the required shielding, controls and interlocks comply with the Fermilab Radiation Control Manual[3] (FRCM)).

The shielding assessment considers ground water and surface water activation; calculates air activation; considers muon production; considers longitudinal and transverse shielding requirements; summarizes labyrinth and penetration calculations; calculates residual dose rates; and specifies active shielding controls and monitoring.

III - 8.4.1.1 Ionizing Radiation

Prompt ionizing radiation is the principle radiation hazard presented by injecting and storing beam in the Muon g-2 Storage Ring. In order to protect workers, general public, and the environment, the enclosures and beam pipes are surrounded either by shielding (soil, concrete, or iron), and/or networks of interlocked detectors to keep any prompt radiation exposure within acceptable levels.

A detailed shielding assessment[2] has been compiled and reviewed by the Fermilab Radiation Safety Subcommittee Shielding Review Panel to address these concerns. The assessment provides a detailed analysis of the beam line and demonstrates the required overburden or soil shielding, use of signs, fences, and active interlocks to maintain any prompt radiation within acceptable levels.

The shielding assessment for the Muon g-2 Storage Ring has included analyses of injection and muon storage. The Muon g-2 Storage Ring shielding assessment requires that:

- *All movable shielding blocks must be installed as specified;*
- *Interlocked radiation detectors shall be installed in MC-1 as specified; and*
- *The radiation safety interlock system is certified as working.*

The Muon g-2 Storage Ring Shielding Assessment concludes:

- *The facility is in conformance with all FRCM requirements and can be operated safely with a 3.09 GeV/c secondary beam.*

III - 8.4.1.2 Non-Ionizing Radiation

The quadrupoles in the Muon Storage Ring have the potential to emit x-rays when they spark. The x-rays do not have the ability to penetrate the Storage Ring vacuum chamber when all

detectors are installed. When testing the quadrupoles without the detectors installed, lead shielding is used to absorb any x-rays under the direction of the Radiation Safety Officer (RSO).

III - 8.4.1.3 Residual, Air, and Water Activation

The shielding assessment[2] concludes that the secondary beam powers utilized for the Muon g-2 experiment are quite low, less than 0.7 watts. Expected losses will produce no residual, air, ground water, or surface water activation concerns.

III - 8.4.1.4 Radioactive Waste

Muon g-2 Storage Ring radioactive waste hazards 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 MC-1 area, beam loss and, in the case of some beam diagnostics devices, intentional interception of the beam may result in activation of beam line elements. When feasible, activated items will be reused. Activated items that cannot be reused will be managed as radioactive waste according to FRCM requirements.

III - 8.4.2 Lasers

There is a Class 3b laser system located in an interlocked enclosure in the high bay of MC-1 underneath the loading dock on the North East corner of the building. The laser system complies with Fermilab Environment, Safety and Health Manual[4] (FESHM) Chapter 4260, "Lasers". The laser energy is distributed to the 24 detector stations in the center of the Storage Ring using enclosed fiber optics. All of the enclosures which could potentially allow access to the laser light are interlocked. Any access to the laser enclosure prohibits the operation of the laser while the system is in an uncontrolled condition. The laser energy transmitted outside the safety enclosure to the detectors through encased fiber optics falls below the Maximum Permissible Energy (MPE) for this pulsed laser system. The normal operational procedure has the laser pulsing at random intervals during both beam on and beam off conditions to monitor detector gain stability.

III - 8.4.3 Unique Electrical or Magnetic Field Hazards

The Muon g-2 Storage Ring electrical hazards fall within the scope described in the "Electrical Hazards" paragraph of Section 1, Chapter 4 of the Fermilab SAD. The notable accelerator-specific electrical hazards are the power supplies for storage ring magnet, the

inflector, the kickers, and the quadrupoles. Using shielding and following applicable written Lock Out / Tag Out procedures for cabinet access and equipment maintenance mitigate these hazards.

The Muon g-2 superconducting coils produce a field of 1.45 Tesla (14,500 gauss). A concern with all these devices is the strength and extent of the fringe fields and how they may affect persons and equipment in their vicinity. Fringe fields in excess of five gauss are of particular concern because they could affect medical electronic devices (pacemakers), and fields over 600 gauss could impact ferromagnetic implants (artificial joints) and other material (tools).

Residual magnetic fields will be present in the Muon g-2 detector enclosure when the superconducting coils are powered. The magnetic field is at most 200 gauss at ~130 centimeters (cm) from the maximum region, falling off to less than five gauss at ~190 cm from the maximum region. In accordance with FESHM Chapter 4270, "Static Magnetic Fields", access will be restricted when the coils are powered and warnings will be posted for people with pacemakers and implants. Ferrous tools and objects will be restricted within zones to be determined by measuring the fields.

III - 8.4.4 Flammable Gas

Tracking detectors for the experiment use a flammable mixture of argon and ethane. A gas shed is located outside the building along the east wall. The gas is vented to atmosphere on top of the fenced in berm behind MC-1. Flow rate is monitored by the experiment's programmable logic controls system on the supply and return. Any loss of flow indicative of a leak will cause an alarm in the g-2 control room and an automatic shutdown of gas flow using solenoids controlled by the experiment's programmable logic controls system. The system is designed to maintain 'Class 0' classification in accordance with FESHM Chapter 6020.3 "Storage and Use of Flammable Gases."

III - 8.4.5 Cryogenics

The Muon g-2 Storage Ring and inflector require a continuous supply of cryogenic helium. Three recycled Tevatron "satellite" refrigerators reside in the Muon Campus Cryo Facility (MCCF) attached to the MC-1 building. Existing compressors used until recently for the Tevatron and located at the F0 Service Building drive compressed helium gas to the cryo facility. The refrigerators require liquid nitrogen for a pre-cooling stage. One of the Central Helium Liquefier nitrogen dewars was moved to the new MCCF area. Cryogenic helium is piped from the MCCF to the Muon g-2 experimental area within the MC-1 surface building where thermal siphon "feedboxes" distribute the helium to the superconducting ring and inflector. The feedboxes also require liquid nitrogen. Cryogenic systems were designed in conformance with applicable

American Society of Mechanical Engineers (ASME) standards and the FESHM Chapter 5032, "Cryogenic System Review." The potential Oxygen Deficiency Hazard (ODH) is mitigated by the MC-1 Heating Ventilation and Air Conditioning (HVAC) system and by the use of oxygen monitors. Oxygen monitors are installed in the MC-1 high bay and in the MC-1 refrigerator room where cryogenics and large gas volumes are present. When a low level of oxygen is detected, the building heating, ventilation and air conditioning system will bring in fresh air and local audio and visual alarms will be activated. In addition to the local alarms, the ODH alarm is sent to FIRUS to initiate a Fermilab Fire Department Response and alarms in the g-2 control room to alert g-2 operators. All areas in the MC-1 building that contain ODH hazards are regulated in accordance with existing Fermilab policy and in compliance with FESHM Chapter 5032, "Cryogenic System Review", and Chapter 4240, "Oxygen Deficiency Hazards".

III - 8.5 Credited Controls

III - 8.5.1 Passive Controls

Passive controls are accelerator elements that are part of the physical design of the facility that require no action to function properly. These passive controls are fixed elements of the beam line that take direct human intervention to remove. The MC-1 building is designed to optimize the effect of these passive controls with permanent concrete radiation shields that use a combination of permanent shielding, movable shielding, penetration shielding, and the storage ring magnet yoke to protect personnel from radiological exposure during beam line operations.

III - 8.5.1.1 Permanent Shielding Including Labyrinths

The permanent shielding encompasses the structural elements surrounding the storage ring and parts of the associated injection beam line. The MC-1 shielding includes the following:

1. Last nine magnets of the M5 line down-stream of the shielding wall;
2. The Muon g-2 Storage Ring;
3. Utility penetration shielding.

The permanent shielding for the enclosure is documented in the Muon g-2 Shielding Assessment[2] and consists of sufficient concrete and active radiation monitoring interlocks to maintain compliance with the posting requirements of the FRCM under the assessed beam conditions.

III - 8.5.1.2 Movable Shielding

The north wall of the MC-1 enclosure contains movable concrete shielding blocks that allowed the ring to be inserted into the building (mail slot) and shielding blocks placed in front of the loading dock door during beam operations. Hand stacked shielding is used close to the end of the M5 line to isolate the MC-1 building from upstream radiation.

III - 8.5.1.3 Penetration Shielding

MC-1 penetrations include the South wall emergency exit door and exit stairway, eight-inch cable penetrations in West wall, and a 2.5 feet wide x 5 feet high rectangular cable penetration in the west wall. The penetrations are all included in the shielding assessment document.

The MC-1 enclosure has an 8000 cubic feet per minute ODH purge fan. The prompt dose rates at the exits of the penetrations and air ducts are within the limits established in the FRCM.

III - 8.5.2 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 Storage Ring operations are discussed below.

III - 8.5.2.1 Radiation Safety Interlock System

The MC-1 high bay enclosure employs a Radiation Safety Interlock System (RSIS). The characteristics of the system are described in Section I, Chapter 4.3.2.1 of the Fermilab SAD.

There is one interlocked entrance door and one interlocked emergency exit door. The loading dock door is also interlocked and blocked by shielding blocks during beam running. The RSIS inhibits transport of beam into the MC-1 enclosure when it is not ready for beam operations.

The MC-1 enclosure has chipmunk radiation detectors located between Q023/Q024 and at the center of the ring. Both detectors are at the 746.5-foot elevation. The chipmunks will inhibit beam before radiation levels can exceed FRCM posting requirements in occupiable spaces in MC-1.

If the RSIS interlocks are dropped, beam is inhibited from entering the MC-1 enclosure with critical devices D:V003 and D:H005.[5] D:V003 is a power supply connected to a single

vertical bend magnet that bends the beam down approximately 9 degrees. With D:V003 off, beam is lost in the Q004 magnet immediately down stream of D:V003. D:H005 is a power supply connected to three horizontal bending magnets that bends the beam to the left approximately 27 degrees. With D:H005 off, beam is lost in the right side extraction enclosure tunnel wall. The geometry of the M4 and M5 enclosures provide sufficient distance and shielding downstream of D:V003 and D:H005 to allow access into the g-2 Storage Ring enclosure.

Trained and qualified personnel from the Accelerator Division (AD) Operations Department must search and secure the MC-1 hall before permits from the RSIS may be reestablished 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 beam line enclosure, controlled access procedures, personnel training requirements, and procedures for maintenance of interlock systems are in conformance with the FRCM.

III - 8.5.3 Administrative Controls

Administrative controls are procedures that encompass the human interactions and form the foundation for safe accelerator operations. All Muon g-2 Storage Ring 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. The administrative procedures and programs considered necessary to ensure safe accelerator operations are discussed in this section.

The MC-1 building is classified as a property protection area. Access to the building is restricted to personnel who have either passed MC-1 hazard awareness training or to people escorted by trained guides.

III - 8.5.3.1 Beam Permits and Run Conditions

In accordance with AD Administrative Procedure on Beam Permits, Run Conditions, and Startup (ADAP-11-0001), beam will not be transported to the MC-1 enclosure without an approved Beam Permit and Run Condition. The Beam Permit specifies beam power limits as determined and approved by the AD Head in consultation with the ESH&Q Radiation Physics Engineering (RPE) Manager, AD RSO, AD Operations Department Head, and AD Muon Department Head. The run conditions list the operating modes and safety envelope for the Muon g-2 Storage Ring. Run conditions are issued by the AD RSO, and are signed by the AD Operations Department Head, AD Muon Department Head, AD RSO, and AD Head.

III - 8.5.3.2 Operational Readiness Clearance for Experiments

Operational readiness of the g-2 experiment is governed by FESHM Chapter 2005, "Operational Readiness Clearance". An operational readiness review in accordance with FESHM 2005 is conducted prior to operations. The appropriate Environment, Safety and Health (ES&H) review committee(s) reviews the experiment installation for environmental, safety and health issues. Once the committee is satisfied with the installation, the PPD office grants approval for operations.

III - 8.5.3.3 Summary of Beam Operating and Safety Envelope Parameters

The Muon g-2 Storage Ring has been assessed from the standpoint of beam operating and safety envelope parameters. There is a 15.4 kilowatts, 8 GeV primary proton beam (1.2E13 protons/second or 1E12 protons per pulse at an average operating frequency of 12 hertz) incident on the AP0 target station, which produces a low-power, less than 0.7 watts, 3.09 GeV/c secondary beam. The safety envelope parameters have been assessed in Appendix A - Accelerator Safety Envelope.

III - 8.6 Summary & Conclusion

Specific hazards associated with operation of the Muon g-2 Storage Ring are identified and assessed in this chapter of the Fermilab SAD. The designs, controls, and procedures to mitigate Muon Storage Ring specific hazards are identified and described. The Muon g-2 Storage Ring is 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 g-2 Storage Ring operations and the credited controls established to mitigate those hazards demonstrate that the Muon g-2 Storage Ring 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.

III - 8.7 Glossary, Acronyms

AD	Accelerator Division
BLM	Beam Loss Monitor
ES&H	Environment, Safety, and Health
ESH&Q	Environment, Safety, Health, and Quality
FESHM	Fermilab Environment, Safety, and Health Manual
FRCM	Fermilab Radiological Control Manual
GeV	Giga-electronvolt
HV	High Voltage
Hz	Cycles per second
IEPA	Illinois Environmental Protection Agency
MC	Muon Campus
MC-1	Building housing the Muon g-2 Experiment
MCCF	Muon Campus Cryo Facility
mrem	milli-Roentgen equivalent man
ODH	Oxygen Deficiency Hazard
RPE	Radiation Physics Engineering
RSIS	Radiation Safety Interlock System
RSO	Radiation Safety Officer
SAD	Safety Assessment Document

III - 8.8 References

[1] Hazard Analysis Report for the Muon g-2 Project. Version 2.6, August 12, 2015.

[2] Muon g-2 Shielding Assessment, February 2017.

[3] Fermilab Radiological Control Manual. - The current web link is: http://www-esh.fnal.gov/home/esh_home_page.page?this_page=900

[4] Fermilab ES&H Manual. The current web link is: http://esh.fnal.gov/xms/ESHQ-Manuals/FESHM

[5] MC-1 Critical Device Justification, Beams doc.db 5228-v1, A. Leveling, September 13, 2016.