Maximum Credible Incident Analysis for the Muon Campus Beam Lines and Enclosures

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1 Introduction

This document presents an analysis of the current Muon Campus shielding and credited device configuration under the newly established Maximum Credible Incident (MCI) intensity defined below. The mitigation approach, described here, implements additional credited devices in order to comply with the 500 mrem in and hour ASE accident condition at all accessible locations, and 5000 mrem in an hour in locked (controlled) locations.

The Muon Campus beamlines start at F17 in the Tevatron enclosure where the F17B3 switch magnet directs the beam up and away from the P2/P3 lines and into the M1 line. The M1 line enters the first Muon Campus enclosure through a buried pipe between the two enclosures. The actual Muon Enclosures are named Pre-Target, Pre-Vault, Vault, Transport, Delivery Ring, Extraction, and M4. The 3 destinations for Muon Campus beam are the AP0 target area, the Delivery Ring beam absorber, and the M4 line Diagnostic Absorber (DA). A fourth destination is the g-2 experiment but that operation is currently inactive and disabled. A diagram showing the beam lines is included as figure 1 below.

Figure 1 - Muon Campus layout

The Muon Campus accepts beam from the Recycler when the F17B3 switch magnet is energized. The beam destine for the Muon Campus is prepared by the Recycler RF system which redistributes two Booster batches of 81 bunches (53 MHz bunches) into eight 2.5 MHz bunches. The 8 bunches are then individually sent to the Muon Campus when the clock system triggers a Recycler kicker to pulse. The Muon Campus injection system is pulsed on the same clock events to accept the Recycler beam. This beam transfer process is designed to transfer 8 bunches of 1 e12 (8 GeV protons) every 1.33 seconds, but the Muon Campus presently operates at a much lower beam power limit for commissioning. The operating limit is 3.65 e13 protons/hr.

Figure 2 - Representation of bunches formed in the Recycler to be sent to Muon Campus

2 Boundaries

The MCI in the Muon Campus is evaluated beginning from the point where beam leaves the Tevatron enclosure near F17 through a buried pipe. The analysis includes the M1, M2, M3, M4, m5 beamlines as well as the Delivery Ring and abort line. The MCI is evaluated in the M4 line all the way to the end of the beam pipe at the Diagnostic Absorber. The analysis for the M5 line ends at the point where the beamline enters the g-2 experimental hall.

3 Beam Parameters

This section describes the underlying beam parameters used to determine the ASE and compliance with the 500 mrem limit on potential exposure from a MCI in accessible locations, and 5000 mrem in locked locations.

3.1 Normal and Accident Conditions

The Muon Campus is designed to deliver 8 pulses of 8 GeV protons at an intensity of 1 e12 every 1.33 seconds. This is a proton deliver rate of 2.17 e16 protons/hr. The g-2 experiment operated at twice that proton delivery rate, by doubling the cycle frequency, up to the AP0 target. But only low intensity secondary particles were transported downstream of the target.

Possible accident conditions could result in greater beam intensity, but the actual intensity that could possibly be delivered depends on what part of the Muon Campus we consider. Figure 2 below indicates the area of the Muon Campus where different MCI intensities are possible.

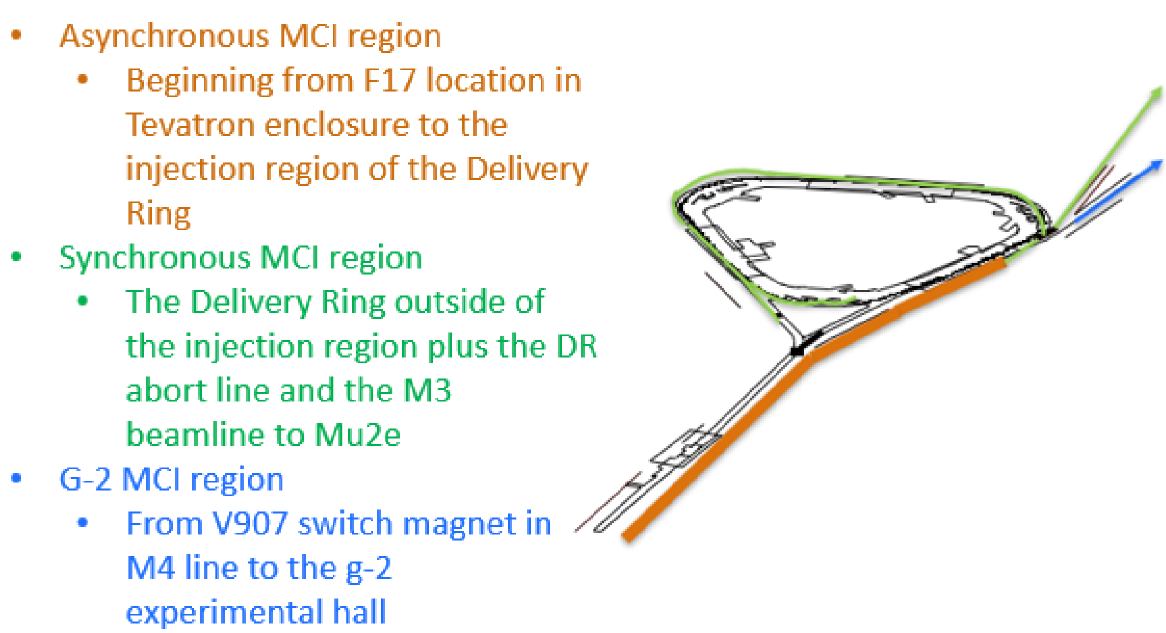

Figure 3 - areas of the Muon Campus where different MCI intensities are possible

The MCI accident could result from a large orbit distortion in the Recycler that could be caused by one or more correction elements being energized incorrectly. If the orbit was distorted such that the first turn of beam injected into the Recycler was steered into the extraction channel of the Lambertson at MI-52, all the beam getting to the Recycler could be sent to the Muon Campus. Under this condition, the bunch forming mentioned in section 1 of this document would not occur, and the beam going toward the Muon Campus would not be synchronized to events that trigger the normal beam transfer devices. This scenario could result in 7 e12 protons being delivered at 15 Hz, or 3.78 e17 protons/hr. These protons would arrive in trains of 81 bunches with a 53 MHz structure. Since beam in this scenario is not synchronized with the beam transfer devices designed for injection into the Delivery Ring, the beam would survive no further than the injection area under the AP30 service building. This scenario will be referred to as the asynchronous MCI scenario throughout this analysis and is applicable only between the buried pipe near F17 in the Tevatron to the injection area of the Delivery Ring.

For beam to survive past the injection area in the DR, the injection devices must fire synchronous with the arrival of the beam from the Recycler. For efficient transfer of beam between the Recycler and DR, the bunch forming process must play out in the Recycler. It would be possible to develop a timeline that would deliver beam at a rate of 5.54 e16 protons/hr. To accomplish this, 100 msec are required to inject 2 Booster batches into the Recycler. 90 msec are then needed to form the bunches by the rf system. Transferring the bunches to the DR requires another 336 msec. The maximum rate the process can repeat is once every .53 seconds or every 8 Booster cycles. This scenario will be referred to as the synchronous MCI scenario throughout this analysis. This MCI intensity applies to all the Delivery Ring other than the injection area, the abort line, and the entire M4 beamline up to the Diagnostic Absorber.

A third MCI condition applies to the g-2 operating mode. This mode is presently inactive through configuration control, but it could be activated again with some effort. In considering this mode, it should be noted that the M5 beam line is incapable of transporting 8 GeV beam. Since all Muon Campus beam comes via the Recycler at 8 GeV, the only beam that could be transported by the M5 line is a beam of secondary particles that originate from the AP0 target station. The only reasonable energy to consider is that of the g-2 experiment which is 3.1 GeV. Extensive simulations show that the maximum number of secondary particles that can survive from the AP0 target to the M5 line is 1.5 e-4 times the number of protons on target. The maximum number of protons that could be focused on target in the g-2 mode of operation would be 3.1 e13 protons/sec. This rate would be as fast as the beam transfer systems and the rf could operate and be 5 times faster than any scenario proposed. This would be the limit of the possible rate of beam transfers to the AP0 target. Reaching this particle flux would require the following conditions. It would take 100 msec to inject two Booster batches into the Recycler, 90 msec to form the bunch structure for transfer, and then 70 msec to transfer the 8 bunches that are prepared. Since the Booster is limited in its operation to 15 Hz, this scenario would use 4 full Booster cycles and so this process could repeat every .268 seconds allowing 3.1 e13 protons/sec on target. The number of 3.1 GeV secondary particles that could reach the M5 line would be 4.5 e9 particles/sec.

4 Shielding Requirements

The shielding requirements for the Muon Campus are specified in a set of Shielding Assessments developed over time. The Muon Campus was developed by converting the Tevatron Collider Antiproton Source into the Delivery Ring along with the beamlines used for injection. The Antiproton Sources used the AP0 target with protons incident on target at a much greater beam power. The beamline upstream of the target was assessed for normal targeting operations with 8 e12 protons on target every 2.2 seconds at 120 GeV. The Antiproton Source was also assessed to operate with protons at 13 watts or 3.6 e13 protons/hr throughout the facility which did not include the M4 or M5 beamlines. The Antiproton Source Shielding Assessment was used and referenced in developing the SA for the Muon Campus. The SA for operating g-2 with a secondary muon beam was approved at that time. Later the M4 beamline was assessed to operate with 8 GeV protons to the diagnostic absorber at the same 3.6 e13 protons per hours as approved in the Delivery Ring. Mars simulations were used in these assessments to verify that the shielding and active engineered controls installed were sufficient to operate at these intensities while meeting the posting requirements specified in the FRCM.

Shielding in the upstream Muon Campus, between F17 in the Tevatron and the AP0 target station, have enough passive shielding to protect against the MCI loss condition in satisfying conditions in the ASE. The same is true for areas downstream of the Delivery Ring enclosure. However, the Transport enclosure and the Delivery Ring enclosure require active engineered controls to limit losses under the MCI intensities to the doses permitted in the ASE. Determination of radiation detectors and their trip limits to satisfy the condition of the ASE are documented in the Muon Campus portion of the SAD (section III-10).

4.1 Prompt Dose Rates

Prompt dose rates are calculated using MARS for the broad prompt dose distributions outside the enclosure shielding and the ISA spreadsheets for prompt doses at the exit of labyrinths and penetrations; the latter nominally represents the least attenuated position and therefore the highest dose point for accident conditions. These data are then compared to FRCM Table 2-6, *Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions* [6] to establish radiological categories, operational intensity limits and any required radiological controls for occupancy during beam operation.

5 Labyrinths and Penetrations

Within the Muon Campus, there are 615 penetrations for cables and water lines, 11 stairwells with associated labyrinths, and 13 miscellaneous shafts for emergency egress, ventilation, and elevators. There are 23 survey risers that are all filled with either sand or poly beads. Beam measurements have been made on some unfilled penetration to verify the conclusion that filling with shielding material is not required.

6 Intended Active Shielding Controls and Monitoring

6.1 Enclosure Interlocks

All beamline enclosures are interlocked to the Radiation Safety Interlock System (RSIS). This system is routinely tested and certified to turn off critical device(s) for the beamline within one second of detecting an out-of-range or absent input signal.

6.2 Radiation Detectors

Interlocked radiation detectors are placed at specified locations in the AP-10, AP-30 and AP50 service buildings and throughout the Delivery Ring and Transport enclosures. These detectors are credited controls located where the passive shielding alone is not sufficient to protect against the MCI accident condition as documented in the ASE. Additional radiation detectors are placed in various locations to provide additional monitoring for defense in depth and compliance with posting requirements in the FRCM. This system is routinely tested and certified to turn off critical devices in the upstream beamline to stop the transmission of beam.

Locations and trip levels of radiation detectors interlocked to the RSIS will be set by the Radiation Safety Officer to ensure all radiation posting limits are satisfied as well as satisfying the ASE limits. To satisfy the ASE limits, all Chipmunks listed in Table 1 must be set to trip at 500 mrem/hr or less and set in the integrate mode. The qualify factor for the Chipmunks is set to 5, and a trip will open the CDC electrical contactor for two power supplies in the upstream end of the M3 line (D:H700 and D:H812) as well as close a beam stop in the upstream M3 beamline. These fail safe actions prevent beam from nearing the Delivery Ring.

Radiation detectors (chipmunks and TLMs) are capable of disabling beam within a maximum of 3 seconds of reaching the trip setting. The trip settings are calculated to keep the dose delivered to areas outside of the shielding below ASE limits even with the 3 extra seconds for the disabling of the beam. Below is a table of locations and identifiers of the credited Chipmunk detectors and TLM detectors.

Table 1: Credited Chipmunk radiation monitor locations and their associated MUX channel number.

Chipmunk Location	MUX channel
AP-10 North Door	2080
AP-10 Relay Rack A17R05	2081

AP-10 Relay Rack A16R07	2082
AP-10 Relay Rack A16R03	2083
AP-10 D:QS power supply	2084
AP-10 D:QD power supply	2085
AP-10 Relay Rack A14R03	2086
AP-10 Relay Rack A14R0Y	2087
AP-10 Control Room Southwest Door	2088
AP-10 Bay A13 South	2089
AP-10 Bay A12 North	2090
AP-10 Relay Rack A2R01	2091
AP-10 Southwest Rollup Door	2092
AP-10 South Door	2093
AP-30 South Door	2096
AP-30 South Rollup Door	2097
AP-30 D:H744 power supply	2098
AP-30 D:Q303 power supply	2099
AP-30 Relay Rack A35R07	2100
AP-30 Relay Rack A35R01	2101
AP-30 D:ISEP power supply	2102
AP-30 Relay Rack A35R03	2103
AP-30 Relay Rack A33R07	2104
AP-30 Relay Rack A33R01	2105
AP-30 D:ELAM power supply	2106
AP-30 D:V906 power supply	2107
AP-30 NE Rollup Door	2108
AP-30 North Door	2109
AP-50 West Door	2112
AP-50 Relay Rack A57R07	2113
AP-50 Relay Rack A57R01	2114
AP-50 Relay Rack A56R04	2115
AP-50 Relay Rack A55R08	2116
AP-50 Relay Rack A55R02	2117
AP-50 D:SEXV power supply	2118
AP-50 D:VA03 power supply	2119
AP-50 Relay Rack A53R07	2120
AP-50 Relay Rack A53R01	2121
AP-50 Abort Kicker power supply	2122
AP-50 D:ASEP power supply	2123
AP-50 East Rollup Door	2124
AP-50 East Door	2125

TLMs are used in areas of the Muon Campus that require active engineered controls that are not under the Delivery Ring service buildings. Table 2 shows the locations, channel names, and the devices that are disabled to inhibit beam from the area for the credited TLMs.

Table 2: TLM locations, MUX channel numbers and Critical Device Controller Response

TLM Location	MUX channel	CDC (and devices inhibited)
Transport upstream	2077	M1 line CDC (D:F17B3 and D:HV100)
Transport downstream	2056	M1 line CDC (D:F17B3 and D:HV100)
Delivery Ring 20 arc	2059	Deliver Ring CDC (D:H700, D:H812, M3 line Beam Stop closed)
Delivery Ring 40 arc	2060	Deliver Ring CDC (D:H700, D:H812, M3 line Beam Stop closed)
Delivery Ring 60 arc	2095	Deliver Ring CDC (D:H700, D:H812, M3 line Beam Stop closed)
Delivery Ring abort line	2062	Deliver Ring CDC (D:H700, D:H812, M3 line Beam Stop closed)

6.3 Chipmunk Trip Level Setting

The credited Chipmunk radiation monitors are located in the service buildings over the Delivery Ring spaced by 13 feet. Beam loss studies were used to determine the trip level required to mee the requirements of the ASE under the MCI beam loss condition. The beam studies involved setting up conditions where all the beam was lost on a single solid device under the service buildings. A background measurement was made for the Chipmunks for a period with no beam operating. The beam was then turned on and the response of the Chipmunks was measured. The response was normalized to the number of protons lost, so the response could be calculated for the loss of the MCI intensity.

A calculation was then made to determine how long the accident condition would need to persist to result in a Chipmunk trip at various trip settings. 3 seconds was added to that interval to allow for the RSIS to fully disable beam. The total dose was then calculated for an accident condition that persisted for that extended interval. The trip level selected for the ASE was one that resulted in a calculated dose below the ASE allowed limit.

Once that trip setting is selected, the increase in total dose is calculated for an accident if 3 efd of shielding was removed. That calculated dose is still below the ASE limit. From that calculation it is determined that the amount of shielding being credited can be reduced from the 8 existing efd to 5 efd as long as the Chipmunks are credited with a 500 mrem/hr trip setting.

6.4 TLMC Trip Level Setting

The credited TLM trip settings are calculated in much the same way as the Chipmunk trip settings, although additional measurements are needed in the beam loss studies. The studies involve placing temporary Chipmunk detectors on the berm (outside of the shielding) at the location of maximum dose resulting from the generated beam loss.

7 Conclusions

The shielding for the Muon Campus beamlines has been analyzed under normal and accident conditions for the new ASE beam intensities. There are three separate intensities to analyze in different areas of the Muon Campus. The MCI intensities at 8 GeV are: 2.78 e17 protons/hr between F17 in the Tevatron and the 30 straight section of the Delivery Ring; 5.54 e16 protons/hr in the Muon Campus beyond the Delivery Ring 30 straight section; and at 3.1 GeV, 3.1 e13 particles per hour in the M5 line. The analyses and calculations performed for prompt dose rates are all within FRCM requirements based on the installation of radiation detectors and the facility can be operated safely.

8 References

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