Fermi National Accelerator Laboratory

Switchyard Fixed-Target Areas Maximum Credible Incident (MCI)

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Scope

The following document describes the Maximum Credible Incident (MCI) for the Switchyard Fixed-target Areas.

Basis of Analysis

The MCI for the Switchyard Fixed-target Areas must include the following segments:

- The P1 Beamline (also known as the P150 Beamline) from the 520 cell of the Main Injector, at Lambertson magnet I:LAM52, to F11 of the Main Ring/Tevatron in the F-Sector Enclosure.
- The P2 Beamline from F11 to F17 of the Main Ring/Tevatron in the F-Sector Enclosure.
- The Muon Campus M1 Beamline from F17 of the Main Ring/Tevatron in the F-Sector Enclosure, at switch magnet F17B3, to the buried beam pipe at the wall of the F18 cell.
- The P3 Beamline from F17 of the Main Ring/Tevatron, downstream of the F17B3 switch magnet, in the F-Sector Enclosure to F49 of the Main Ring/Tevatron in the Transfer Hall Enclosure.
- Continental Switchyard from F49 in the Transfer Hall Enclosure to up to three (3) possible destinations:
    - The Meson Primary Beamline, starting at Lambertson magnet MLAM1, in Enclosure C to the downstream vacuum isolation window in the F3-Manhole.
        - This includes the F1-Manhole Enclosure, F2-Manhole Enclosure, and F3-Manhole Enclosure.
    - The Switchyard Absorber, in Enclosure C.
    - The Neutrino Muon Beamline, starting at the S:V100 Switch Magnet, to the berm pipe in the upstream segment of the N01 Enclosure.
        - This includes Enclosure C, Enclosure G2, and the beamline subsegment known as the G1 Stub in Enclosure C.

These segments are evaluated under separate shielding assessments; therefore, these segments will be referred to by their respective shielding assessment. The downstream boundaries chosen are based on historical areas of responsibility managed by the then named Research Division and Beams Division.

The “P1 & P2 Beamline” segments are responsible for beam delivery to the “P3 Beamline” for the Switchyard Fixed-target Areas (120GeV) and the “M1 Beamline” for Muon Campus (8GeV). The geographic boundaries assessed for the “P1 & P2 Beamlines” are from I:LAM52 at the 520 cell of the Main Injector to the 16” buried beam pipe in the wall at F18 to the Muon Campus “Pre-Target” Enclosure and the first magnet in the P3 Beamline at F17-5. Since this segment will transmit more beam per hour than the P3 segment of the beamline, the MCI will be based on this analysis of the P1 & P2 Beamlines.

An equivalent intensity and repetition rate must be defined to account for the operation of multiple beam destinations with two different energy beams, 8GeV and 120GeV, with different repetition rates. A comparison of beam power is more useful for this analysis.

Six (6) scenarios are identified for beam delivery:

1. 7E12 protons per 15Hz cycle at 8GeV (134.6kW).
2. 3.57E13 protons per 5.2 seconds at 120GeV (134.6kW)
3. 4.2E13 protons per 5.2 seconds at 120GeV (155.1 kW)
4. 4.2E13 protons per 55 seconds at 120GeV (14.66 kW)
5. A combination of 8GeV and 120GeV beam delivery (155.1 kW to 134.6kW)
    a. Switchyard events with a repetition rate of 5.2 seconds at 120GeV, 4.2E13 protons per event.
    b. Muon events with a repetition rate of 15Hz at 8GeV, 7E12 protons per event.
6. 8.4E13 protons per 1.0667 seconds at 120GeV (1.5 MW)

Scenario 1 assumes the Booster MCI intensity of 7E12 protons per 15Hz cycle delivered to the "P1/P2 Beamline" segment (134.6kW beam power). This scenario is credible since it has been found that the Recycler has the trim dipole strength to divert 8GeV beam into the aperture of the "Recycler to P1 Beamline" Lambertson magnet, R:LAM52, with one to two trim magnet "failures". Based on this finding, it is credible to assume that 8GeV, 15Hz beam from Booster could enter the P1 Beamline. The P1 and P2 Beamlines are designed to transport 8GeV beam to the Muon Campus "M1 Beamline". The nominal resting energy of these beamlines is 8GeV, therefore it is credible to assume that 8GeV, 15Hz beam from Booster could enter the P2 and M1 Beamlines.

Scenario 2 assumes 134.6kW of protons delivered at 120GeV. This is equivalent to 3.57E13 protons per 5.2 seconds. In this scenario beam is delivered to the P1/P2 Beamline segment at 120GeV, therefore it is assumed that it takes a finite amount of time to ramp the Main Injector from 8GeV to 120GeV then back to 8GeV. The repetition rate selected for this scenario is 5.2 seconds, 4.2 second spill plus 1 second to ramp the Main Injector. The beam intensity described in this scenario corresponds to six (6) Booster Batches of 5.95E12 protons per 15Hz cycle. This per batch intensity is less than the Booster MCI intensity, therefore this scenario is not the MCI.

Scenario 3 assumes six (6) Booster Batches of 7E12 protons, 4.2E13 protons per event to Switchyard, are delivered at 120GeV. In this scenario beam is delivered to the P1/P2 Beamline segment at 120GeV, therefore it is assumed that it takes a finite amount of time to ramp the Main Injector from 8GeV to 120GeV then back to 8GeV. The repetition rate selected for this scenario is 5.2 seconds, 4.2 second spill plus 1 second to ramp the Main Injector. This scenario results in 155.1kW of beam power delivered. While the beam power delivered in this scenario is greater than that in Scenario 1, Scenario 3 would require more than two failures to occur simultaneously for this event to occur. Therefore, this scenario is not credible.

Scenario 4 assumes six (6) Booster Batches of 7E12 protons, 4.2E13 protons per event to Switchyard, are delivered at 120GeV, once every fifty-five (55) seconds. This scenario assumes that the Repetition Rate Limiter in the P3 Beamline is a credited control device, set for a period of sixty (55) fifty-five between ramps. While it is possible to place multiple Switchyard events in the timeline, based on the timing of the beamlines relative to the accelerators, no beam would be transported on the subsequent events because of the Switchyard Critical Device Controller (CDC) being tripped by the repetition rate limiter. Operational history has shown that the beam on that second event would be inhibited prior to the pulse shift of the beam destined for Switchyard. This scenario is credible.

Scenario 5 is a combination of 8GeV 15Hz events and 120GeV 5.2 second repetition rate events. Because this scenario requires multiple failures across two separate accelerators for this event to occur, it is not considered as the MCI.

Scenario 6 is the beam scenario described in the *NuMI MCI*, but now the 8.6E13 protons at 120GeV every 1.0667s (1.5MW) are delivered to the P1 & P2 Beamline segment. This scenario is not credible as there is no full machine, fast extraction device to deliver beam to the P1 Line from Main Injector. The Main Injector single-batch extraction kicker at the 520 period was removed from the accelerator in May 2018. While the possibility of the beam from Recycler that was originally destoned for NuMI is extracted at 8GeV from Recycler, this scenario would be a subset of Scenario 1 and is not considered further.

No credited control device exists that prevents extraction of Recycler beam at 8GeV with a 15Hz repetition rate to the P1 & P2 Beamlines. Since multiple failures are required to ramp the Main Injector and the P1 & P2 Beamlines to 120GeV in 5.2 seconds, the P1 & P2 MCI is Scenario 1.

The MCI scenario evaluated for the P1 & P2 beamlines is 134.6 kW beam power delivered, 3.78E17 protons per hour, 7E12 protons per pulse, 15Hz repetition rate, 8GeV beam energy.

The “P3 Beamline to Switchyard Absorber” segment is not designed to transport 8GeV beam. The P3 Beamline is what remains of the Main Ring accelerator. This line is powered by two Main Ring style power supplies for the dipole strings HP3US & HP3DS, and one Main Ring style power supply to power the quadrupoles, QP3. Due to available voltage limitations from the yard transformers, the P3 Beamline must idle at 400A to reach the flattop current in time with the Main Injector for 120GeV operation. 400A on the Main Ring bus is equivalent to 35.5GeV operation of the Main Ring. [7]

The first magnet of the HP3US dipole string is a “2X Turn Dipole B-2”, also known as a “Double B2” style magnet. At 400A, this magnet provides a 64.52 mrad deflection to an 8GeV particle. The horizontal aperture is 4”, therefore the beam would be extinguished by the first magnet somewhere between 0.768m and 1.57m of the 6.096m long magnet. By geometry it is not possible for the P3 Beamline to transport 8GeV beam while S:HP3US are operating at 400A. The P3 Beamline cannot operate at 8GeV (99A) and support the 120 GeV Fixed-Target Program due to the voltage requirements of the power supplies.

At 120GeV operational values, 1358A, the magnet in the above example will provide a 219 mrad deflection to an 8GeV particle. The beam strikes the aperture of the magnet between 0.228m and 0.457m of the 6.096m long magnet. Therefore, 8GeV beam entering the first magnet of the HP3US dipole string cannot be transported further than the first magnet of the dipole string.

When the Switchyard CDC is disabled, HP3US & HP3DS are de-energized. In this case, a particle would impinge on the aperture between 3.08m to 6.32m from the front of the first magnet of the HP3US magnet string. Therefore, beam cannot be transported further than the second magnet of the HP3US dipole string.

The first magnet of the HP3DS dipole string is a “B2” style dipole magnet. Since this magnet is half the strength of the dipole magnet in the HP3US example, at 400A, an 8GeV particle will be deflected 32.26 mrad. The horizontal aperture is 4”, therefore the beam would be extinguished by the first magnet somewhere between 1.57m and 3.15m of the 6.096m long magnet. By geometry it is not possible for the P3 Beamline to transport 8GeV beam while S:HP3DS is operating at 400A.

At 120GeV operational values, 1358A, the magnet in the above example will provide a 110 mrad deflection to an 8GeV particle. The beam strikes the aperture of the magnet between 0.48m and 0.92m of the 6.096m long magnet. Therefore, 8GeV beam entering the first magnet of the HP3DS dipole string cannot be transported further than the first magnet of the dipole string.

When the Switchyard CDC is disabled, HP3US & HP3DS are de-energized. In this case, a particle would impinge on the aperture between 3.08m to 6.32m from the front of the first magnet of the HP3DS magnet string. Therefore, beam cannot be transported further than the second magnet of the HP3DS dipole string.

A repetition rate limiter is used to protect against the delivery of 120GeV beam more than once a minute. This device has been used for many years and has been refined by the AD PESD and the ES&H Interlocks Group. This device is a Credited Control. The following scenarios will disable the Switchyard CDC by turning off S:HP3US & S:HP3DS, inhibiting beam transport:

- If the magnet power supply S:VH94 is excited for more than seven seconds in a sixty second period.
- If the magnet power supply S:VH94 is excited more than once in a 60 second period.
- If a fault occurs with the Repetition Rate Limiter Hardware Input Module, Output Module, or Analog monitoring Module.

In the event two Switchyard events are placed within a sixty second window, the Switchyard CDC will be disabled by the repetition rate limiter for the length of time set in the PLC for the “Rate Time Period” at minimum. This period will be set for sixty seconds. As previously stated, operational history has shown that the beam on that second event would be aborted in the Main Injector prior to the beginning of slow spill (also known as resonant extraction), we must assume that all beam on the second cycle in the sixty second period is delivered. Therefore, only two Switchyard cycles with beam entering the P3 Line are possible in a sixty second period.

Because 8GeV beam transport is not supported by the operation of the P3 Beamline, and a repetition rate limiter is used in this segment, Scenario 1 is not credible. The credible scenario is then Scenario 4: 120GeV beam, 4.2E13 protons per event, at a repetition rate of once every 30 seconds.

<u>The MCI scenario evaluated for the “P3 Beamline to Switchyard Absorber” and all areas downstream is 14.66kW beam power delivered, 2.75E15 protons per hour, 4.2E13 protons per event, at 120GeV, once every fifty-five (55) seconds.</u>