Total Loss Monitors (TLM) and other Radiation Detectors as Credited Controls for the Fermilab Booster

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L. Prost

Contents

I. Maximum Credible Incident

As indicated in the Booster SAD Chapter, Section III-4.3.1, the Maximum Credible Incident is defined with the assumption that the upstream section of the accelerator chain, namely Linac, provides a beam of "reasonable intensity" and not the Linac MCI beam intensity. Thus, a "reasonable intensity" is characterized as:

- A beam current of 35 mA
  - This corresponds to the best output from the Linac since the installation of the RFQ Injection Line (RIL)
- A pulse length of 60 μs
  - This is the maximum pulse width possible, which is limited by both the Linac hardware and the components of the Booster that allow injection into the Booster (a.k.a. ORBUMP)

Consequently, to calculate the MCI intensity, defined for the top energy of 8 GeV (i.e. at extraction), we assume that 1.3e13 protons per pulse could be injected into the Booster at 15 Hz at 400 MeV, or 7.1e17 protons per hour.

However, simulations of the beam capture, based on the ***maximum*** RF power available, in an ideal case [1] indicate that the possible maximum intensity for beam circulating at injection energy (400 MeV) is limited to 1.0e13 protons per pulse, corresponding to 5.5e17 protons per hour. Without considering various practical inefficiencies during acceleration from 400 MeV to 8 GeV, the most restrictive physical limitation for the number of particles reaching the top energy is the so-called Robinson instability, due to beam loading, which develops from 2 GeV onwards. This instability effectively limits the efficiency of the acceleration process to 60-70% (depending on the actual beam intensity at injection).

During short study periods, the Booster delivered up to 6.5e12 protons per pulse at 8 GeV to downstream machines. Being conservative, the <u>MCI intensity is determined to be 7.0e12 protons per pulse at 8 GeV</u>, or 3.8e17 protons per hour (at 8 GeV).

II. Dose rate estimations

With the MCI intensity estimated in the previous Section, calculations show that, unmitigated (i.e. without passive shielding or other engineered controls) one could be exposed to a dose rate of > $8\text{x}10^6$ **rem**/hr (at 8 GeV). At a minimum, the Booster is surrounded by 13.5 e.f.d. of passive shielding, although ***only 10.3 e.f.d. are assumed*** and credited for the dose rate calculations (and trip limits) discussed below. The remaining 3.2 e.f.d. are considered "defense-in-depth" (Booster SAD Chapter, Section III-4.4.2).

For the energy of 8 GeV, dose rates at the surface can be estimated using the Incremental Shielding Assessment (ISA) scaling sheets [2] for single point losses. For 3.8e17 protons per hour, the estimated dose rate is 4.54×10^5 mrem/hr. This is several orders of magnitude larger than the SAD limit of 500 mrem/hr outside the buildings. Therefore, engineered controls must be used.

III. Radiation detectors' locations, operation, and trip limits

The analyses of the dose rates that may be expected for MCI conditions show that interlocked radiation detectors are necessary to ensure radiation doses anyone would be susceptible to experience never exceed regulatory limits.

III.1. Locations

Prior to 2017 (1998 Booster Shielding Assessment [3]), it was determined that a system of accredited radiation safety detectors (a.k.a. chipmunks) were sufficient to actively protect areas outside of the Booster enclosure. Locations of these detectors are indicated on Figure 1. These detectors may be outside buildings (i.e. on the berm), inside buildings (i.e. galleries) or buried. Of note for the discussions that follow are the two chipmunks labeled “For 8 GeV Extraction Losses” in the figure. Following several significant changes to the Booster between 1998 and 2017, the shielding assessment [4] was revised. It was then found that additional/alternate measures were necessary to provide adequate protection.

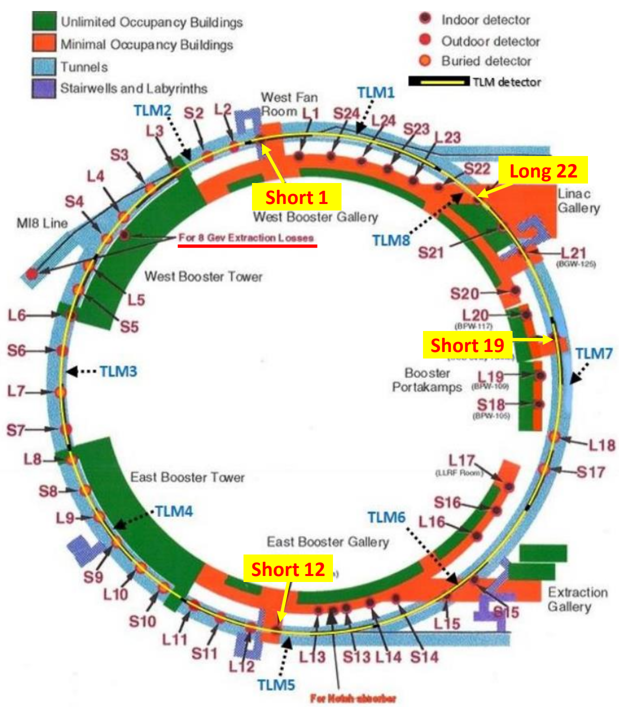

Figure 1: Location of detectors around the Booster ring at the time of the 2017 Booster Shielding Assessment [4]

The number of chipmunks that would be needed to cover the entire Booster ring is prohibitive. Instead, a Total Loss Monitor (TLM) system was installed. It allows continuous coverage of the Booster ring. Nevertheless, further beam studies [5] and data collected over 1 year of normal operation [6] indicated that there were a few specific areas where a chipmunk was more sensitive to losses than the corresponding TLM section. Those locations are Short 1, Long 22, Short 19 [5] and Short 12 [6] (see Figure 1). In addition, the 2017 Booster Shielding Assessment concludes that the two detectors associated with extraction need to be retained (labeled “For 8 GeV Extraction Losses” on Figure 1), referring to the configuration of chipmunks adopted in 1998 and current at the time.

III.2. Radiation detectors operation

A discussion of the operation of the chipmunks (in the context of the Safety Assessment Document) can be found in Ref. [7].

a. TLM

The output of the TLMs is the collected charge due to ionization of the gas contained within an Andrew Heliax® cable, the detector’s active volume, by the radiation field produced from beam losses. “Loss rates” are given in nC/min. The TLMs are used in the “integrated” mode of operation for which a trip limit is set by the RISS. However, they also have a built-in feature that inhibits the beam for large loss rates (e.g. MCI), the so-called “excessive charge” trip/feature. A trip occurs when the signal starts saturating and the response to beam loss deviates from linear, which is dictated by the choice of the capacitors and resistors for the integration circuit. As fabricated, the excessive charge trip occurs when the integrating capacitor voltage is 2.5V, which corresponds to a charge of 10,000 nC (with a 4 μF capacitor).

Figure 2 shows an example of the TLM's calculated "integrated signal" (left) and "excessive charge signal[1]" (right) [8], using a model of the detector, which includes a 20-second time constant for the discharge of the integrating capacitor and a background signal of 5 nC/min. The integration card integrates the signal over 15 minutes (RSS Sum signal). The model assumes 'normal' losses of 100 nC/min, 'accident' losses of 6000 nC/min and a trip level of 3000 nC/min. The beam is on for 3 minutes before accident conditions are applied (and when the beam is turned back on after a trip, the accident conditions persist).

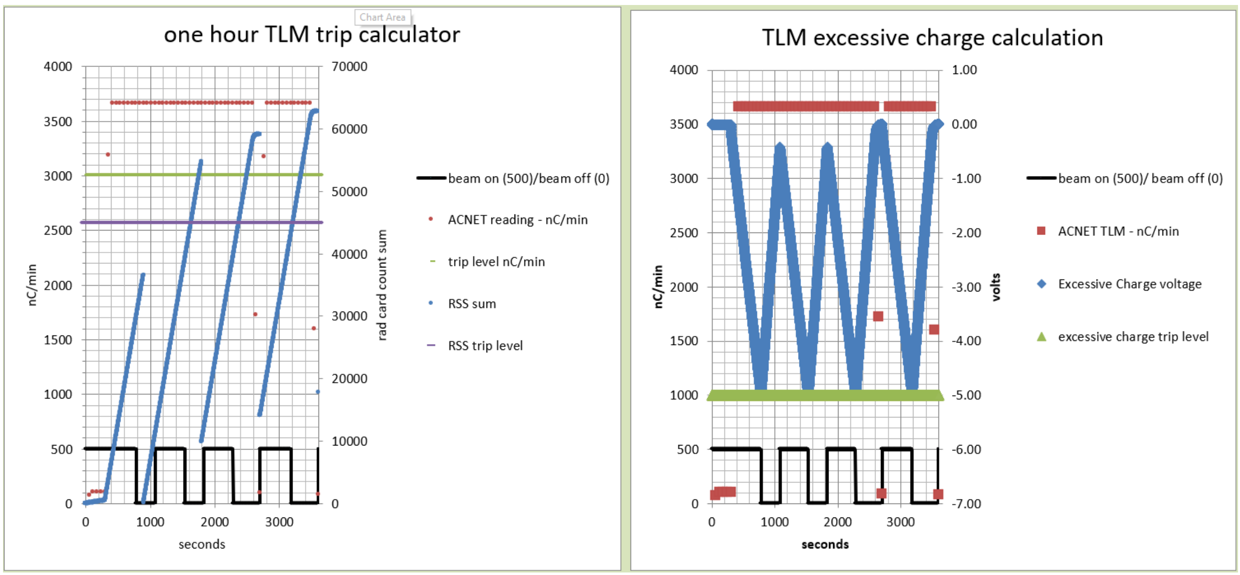

Figure 2: Response of a TLM (illustration) [8]. Left – Integration mode signal; Right: Excessive charge signal.

All trips are initiated by the "excessive charge" signal, before the "RSS sum" (the integrated sum) reaches its threshold value. Note that the beam is turned back on arbitrarily 300 seconds after a trip occurs (this is a manual reset). Also note that, should the RSS sum be beyond its trip limit, such reset would not be allowed by the safety system.

b. TLM maximum signal limit

The TLM system was designed to protect individuals from getting any dose larger than prescribed in FRCM 835 for minimal occupancy (i.e. < 5 mrem/hr). By construction, the TLM operating upper range is limited to 3610 nC/min. This is the maximum trip limit that the TLM system can be set to before the Safety System would inhibit beam due to an "excessive charge" channel fault indication.

III.3. Credited Controls (CC) trip limits

As explained in the preceding section, the TLM system was not designed to prevent possible dose rates exceeding a few mrem/hr. Thus, for MCI conditions, the settable trip limit is irrelevant. Protection against very large beam losses (radiation doses) is built-in and changing that limit requires physically modifying the equipment.

a. Dose estimation **with** an active TLM system

To estimate the dose that one might receive from an MCI, we start from the operational trip limit, 3000 nC/min, which limits the dose rate on the Booster berm to a maximum of 5 mrem/hr [4, 5]. However, this relationship between the TLM measured charge rate and the dose rate reflects the actual thickness of the berm, which, as mentioned previously, is 13.5 e.f.d. but only 10.3 e.f.d. should be considered when determining Credited Controls trip limits.

[1] The "excessive charge signal" is actually twice the actual voltage on the TLM integrating capacitor, hence a trip limit of 5V on the plots.

In the methodology applied within the ISA scaling sheets, a "tenth-value-layer" (TVL) constant is defined as the thickness of shielding material that will reduce a dose rate by a factor of ten (10) and its value is calculated to be 3.38 e.f.d. Since the shielding thickness used for MCI calculations is 3.2' e.f.d., i.e. ~1 TVL, *shorter*, we can assume that the operational trip limit of 3000 nC/min would correspond to a dose rate of 5 x 10 = 50 mrem/hr with 10.3 e.f.d. of shielding. ***If*** the TLM was capable **and** would maintain a linear response over the necessary range, a 500 mrem/hr dose rate at 10.3 e.f.d. would correspond to a 30,000 nC/min reading from the TLM system. At this rate, the TLM would reach the excessive charge trip limit of 10,000 nC in ~20 seconds.

Extrapolating to the estimate obtained in Section II (4.54×10^5 mrem/hr) for an MCI event, the TLM system would return a loss rate of (4.54×10^5 / 500) x 30,000 = 2.7e7 nC/min. Such conditions would inhibit beam in less than a second whatever the trip limit may be (within the applicable range). The total charge collected would then be 2.7e7 / 60 = 4.5e5 nC.

Using the earlier result that a 3000 nC/min measured loss rate corresponds the dose rate of less than or equal to 50 mrem/hr with 10.3 e.f.d. of shielding, by simple linear extrapolation, the total charge that the TLM system would collect over an hour would be 3000 x 60 = 180,000 nC and correspond to a total dose of 50 mrem (over an hour with 10.3 e.f.d. of shielding). This reasoning leads to having a direct conversion between nC and mrem.

Now using the total charge collected during an MCI, the estimate of the total dose for that incident is simply 4.5e5 x 50 / 180,000 ≈ 125 mrem assuming 10.3 e.f.d of shielding. Note that in practice, since the Booster shielding thickness is actually ≥13.5 e.f.d., the dose outside the Booster shielding boundaries would be ≤12.5 mrem.

b. Other detectors - Ring

Beam studies carried out in March 2015 [9] both at 400 MeV and 8 GeV, and data analyses from normal operation in 2016 [6] indicated that there were a few specific areas where a chipmunk was more sensitive to losses than the corresponding TLM section. Those locations are Short 1, Long 22, Short 12 and Short 19 (see Figure 1).

Using the data from the March 2015 studies, specific effective conversion factors between nC/min and mrem/hr can be deduced for those chipmunks. For the chipmunks located at Long 22 and Short 19, the conversion factor is of the order of 10 mrem/hr for a 3000 nC/min trip limit of the corresponding TLM section. It is as much as 22 mrem/hr for a 3000 nC/min trip limit of the corresponding TLM section for the chipmunk at Short 1. In other words, for MCI conditions where the TLM system inhibits beam within 1 second, the total dose one might experience at these locations would be (10/5) x 14.5 = 29 mrem at Long 22 and Short 19, and (22/5) x 14.5 = 63.8 mrem at Short 1. These doses remain significantly less than the 500 mrem allowable in an hour in case of an MCI.

At Short 12, the data analyzed in 2016 similarly indicate that the chipmunk is more sensitive to certain losses than the TLM in proportions analogous to those found for the chipmunks at Long 22 and Short 19.

In conclusion, while these chipmunk detectors are indispensable to ensure that occupational radiation limits are not exceeded during normal operation, they do not need to be credited controls in the context of the SAD analysis.

c. Other detectors – Extraction line

There are two chipmunk detectors, labeled "For 8 GeV extraction losses" in Figure 1, that specifically address possible losses during extraction in the portion of the MI8 line, which belongs to the Booster segment. Like the other chipmunks discussed in the preceding section, these detectors are required for complying with occupancy limits defined in FRCM 835. However, the passive shielding thickness over that beam line is >17.7 e.f.d., which is required to limit the dose rate to < 500 mrem/hr for MCI conditions (using the Incremental Shielding Assessment scaling sheets). Thus, both these detectors do not need to be credited controls in the context of the SAD analysis.

IV. Conclusion

Analyses based on an extensive set of measurements show that the Total Loss Monitor (TLM) system installed in the Booster tunnel protects workers, co-located workers, and MOI from an MCI event.

By design, the <u>TLM restricts integrated total beam losses to 10,000 nC</u>; an event resulting in a dose rate of 500 mrem/hr outside the boundaries of the Booster shielding would then correspond to reaching that charge limit in a few seconds.

For an MCI event, taking credit for ***only*** 10.3 e.f.d. of shielding (and scaled according to Section II.3.b. for 4 specific locations), the TLM system would inhibit beam in ~1s (taking into account latencies of the electronics chain), resulting in a **total dose of ≤ 125 mrem**. Note that in practice, since the Booster shielding at its minimum is 13.5 e.f.d., the dose that an individual would experience for an MCI event is actually ≤ 12.5 mrem.

V. References

[1] *Booster Beam Injection Simulations with SC using ESME for Current Operation for SAD*, C. Bhat, November 10, 2023, AD Beams-doc-10058

[2] *Research Division Incremental Shielding Assessment Methodology*, W. Higgins, W. Schmitt and M. Vincent, AD Beams-doc-3843

[3] *1998 Booster Shielding Assessment*

[4] *Booster Shielding Assessment Version 6*, January 17, 2017

[5] *TLM and Chipmunk Response to Controlled Beam Loss at Booster*, A. Leveling and K. Gollwitzer, AD Beams-doc-4914

[6] *Side by Side comparison of Booster TLM and Chipmunk response over a calendar year*, A. Leveling and K. Gollwitzer, AD Beams-doc-5246

[7] *Linac MCI Analysis*, L. R. Prost

[8] *Chipmunk and TLM radiation detector trip calculators,* A. Leveling, AD Beams-doc-4732

[9] *TLM and Chipmunk Response Check for 400 MeV beam loss at Booster*, A. Leveling and K. Gollwitzer, AD Beams-doc-5170