Radiation Detectors as Credited Controls for the Fermilab Linac

Version 1.1

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Revision	Date	Author (s)	Description
1.0	1/10/24	L. Prost	Initial release
1.1	2/27/24	L. Prost	Added Section II.1 discussing Linac beam inhibiting devices.

Contents

I. Dose rate estimations

I.1. High Energy end (> 116 MeV)

For the purpose of evaluating the upper limit for the dose rates that could be experienced by an individual near the Linac and its galleries, a combination of measurements and MARS[1] simulations were used. MARS simulations were carried out with the following parameters and assumptions:

- MCI conditions (2.58e18 H^- per hour)
- 400 MeV (highest energy achievable at Linac)
- Entire beam incident on an iron cylinder (at least 2 radiation lengths thick)
- Updated shielding profile

MARS simulations are used to substantiate the methodology of extrapolating measurements performed at low intensity to MCI intensities.

Figure 1 shows a cross section of the model used in MARS for the dose rate calculations. In the image, grey is concrete, cyan is air, green is soil and magenta is CA-7 backfill. Detector volumes are indicated by the small rectangles on top of the berm and on the wall of the higher and lower galleries (left side of the image).

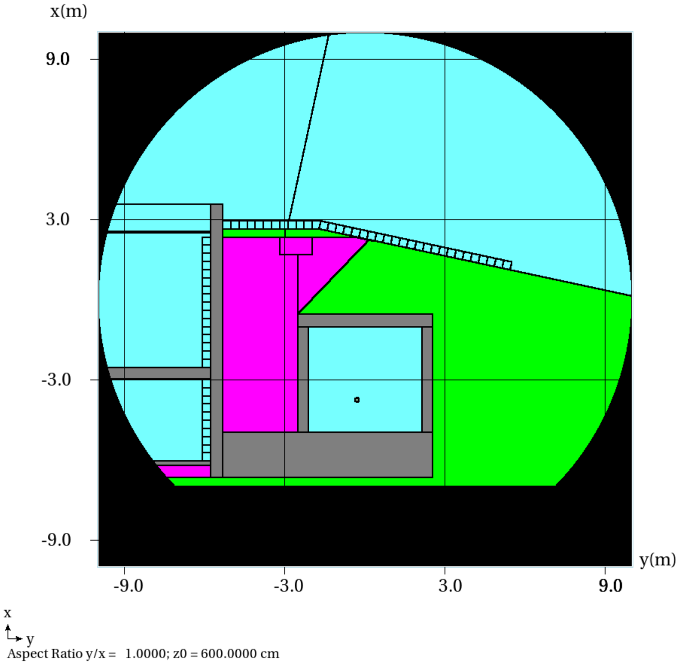

Figure 1: MARS model of the linac enclosure and shielding (cross section)

Shielding assessments for the Low Energy (LE) end of the linac (<116 MeV) and High Energy (HE) end (up to 400 MeV) were conducted/revised in 1991 and 1993, respectively. These shielding assessments were based on actual and thorough measurements of dose rates from losses made intentionally at low intensity at various locations along the beamline and extrapolated to the ***administratively controlled*** maximum beam operating parameters of the Linac. Data from the original report "*Radiation Shielding Assessment of the Linac High Energy Enclosure Following the 1993 Upgrade Installation and Low Intensity*

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[1] *The MARS code system is a set of Monte-Carlo programs for detailed simulation of coupled hadronic and electromagnetic cascades, with heavy ion, muon and neutrino production and interactions, in an arbitrary geometry of shielding, accelerator, detector and spacecraft components.*

Commissioning" [1] have been compiled into the attached Excel spreadsheet [2]. The spreadsheet also presents the results from extrapolating the 1993 measurements to MCI intensities.

For the **HE linac**, the berm (above and to the west of the linac enclosure) and a 12'-thick wall (concrete and CA-7 backfill on the east side of the linac enclosure) provide the first barrier to radiation propagation. Because the dose rate depends on the actual amount of shielding and because of the nature of the berm (soil/dirt), topographical surveys of the Linac enclosure and its surroundings have been carried out regularly. They show that, **on average**, the thickness of the berm above the enclosure has been eroding slowly. The topographical survey conducted in October 2023 [3] shows that, **at its minimum**, the amount of shielding between the inside surface of the enclosure ceiling and the top of the berm is 10.5' (down from a nominal of 12.1' in 1992). Thus, in order to characterize the worst-case scenario, the shielding profile used in the MARS simulations was taken to be 10.5' where the beam interacts with the iron.

Figure 2 displays an output from MARS, which shows the distribution of the dose rates to be expected in the galleries, right behind the wall (for orientation, Figure 2 is a view from the side (beam going from left to right), looking from the left side in Figure 1). Maxima are pointed out both in the upper and lower galleries. Not shown on Figure 2 is the dose rate at the top of the berm, which is 8144 mrem/hour. Clearly, these dose rates are incompatible with any occupational classification. Thus, as indicated in Section III-1.4.1.2.1 of the Linac SAD chapter, radiation detectors are used as credited controls.

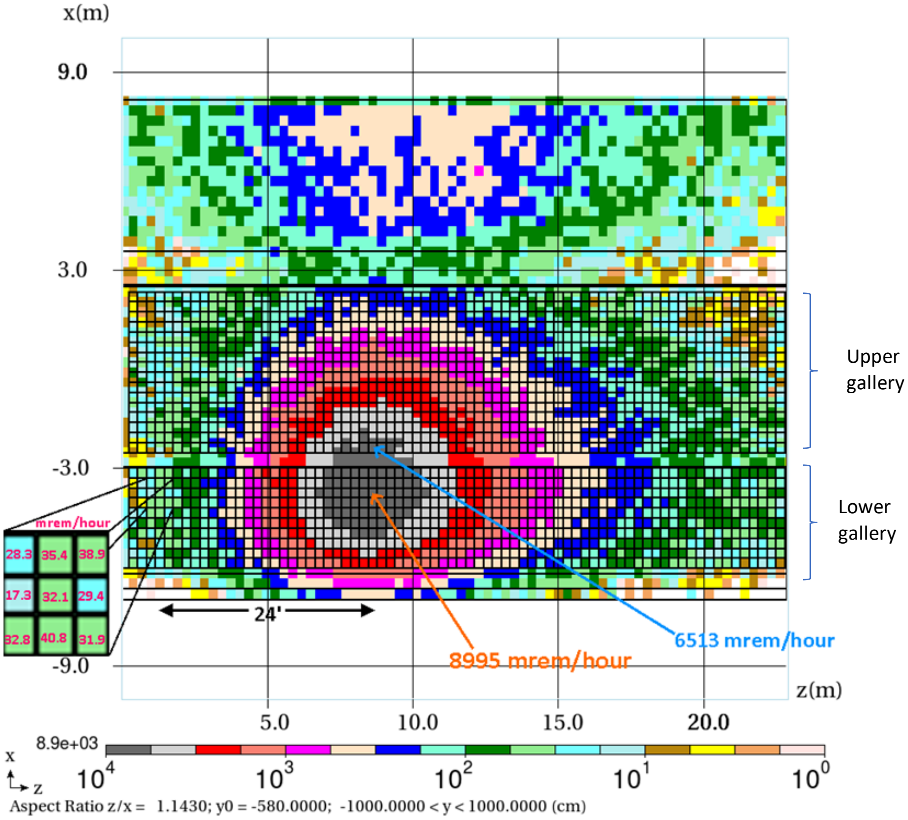

Figure 2: MARS histogram showing the dose rate distribution in the galleries.

The measurements performed at the High Energy end of the Linac for the 1993 Linac Shielding Assessment revision show a maximum dose rate of ~20,000 mrem/hour at the entrance door to the 400 MeV labyrinth, **when extrapolated to the MCI intensity**. However, for dose rates measured in a location of the machine that resembles better the geometry simulated, the MCI intensity extrapolation gives only ~4,200 mrem/hour (Tab "Module7" in [2]). Both the lower and higher numbers are within a factor of 2-3 to what has been simulated in MARS. Given the simplistic nature of the simulation, these numbers give confidence in the chosen approach of extrapolating the results from the measurements to MCI intensities in order to determine Credited Controls (CC) trip limits for the radiation detectors. Note that this extrapolation method was used, reviewed, and documented since its application for both the 1991 and 1993 Linac Shielding Assessments (e.g. [4]). It should also be noted that the measurements show that the Booster tunnel is one of the areas with the highest extrapolated dose rates. Also note that for the measurements conducted in 1993, all the HE linac penetrations were filled as they are today.

The next step to eventually determine the CC trip limits was, for each set of measurements, to extrapolate the highest measured dose rate to 500 mrem/hr and scale (down) the values measured at the other detectors accordingly. There are 9 sets of measurements, which cover losses at locations where it is the most likely to lose beam as well as when sending beam to the dumps.

Figure 3 shows an example of a map obtained following that methodology in the case where the beam was lost above the Booster chute (yellow star in the Figure). Figure 3 shows the extrapolated dose rates for both the MCI intensity (green numbers in orange boxes) and for the 500 mrem/hr limiting case (black numbers in yellow boxes). From this, one can see that the highest dose rate was measured to be in the Booster tunnel below the Linac's straight-ahead dump (red circle).

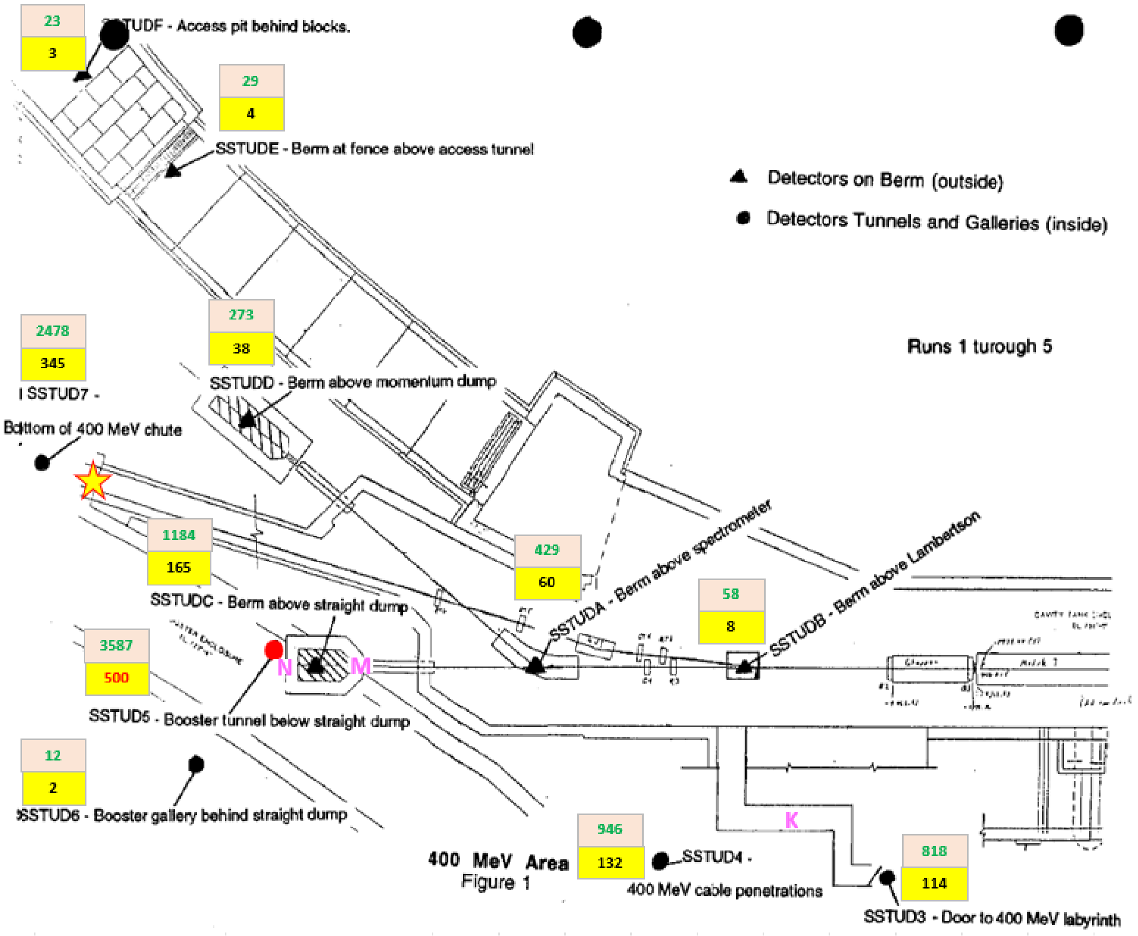

Figure 3: Extrapolated dose rates (in mrem/hr) at the end of the Linac based on the measurements taken for the 1993 Linac Shielding Assessment where the beam was lost above the Booster chute. Pink letters indicate present day radiation detector locations (K is in Leg 2 of the 400 MeV labyrinth, N & M are on the berm).

Figure 4 and Figure 5 summarize the maximum dose rates that would be measured by all the radiation detectors, for all 9 runs, would their trip limit be set to 500 mrem/hr. Note that only dose rates larger than 100 mrem/hr are shown.

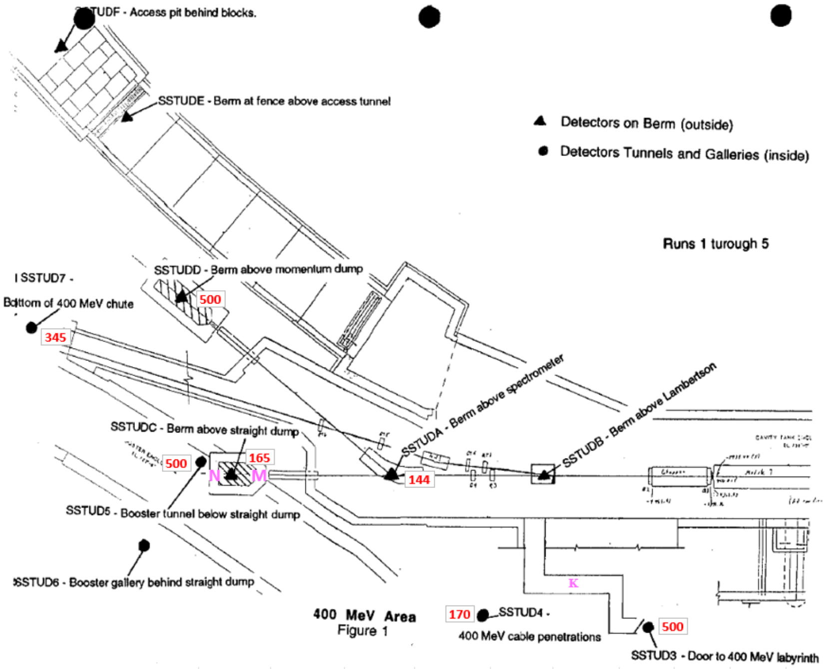

Figure 4: Maximum scaled dose rates (in mrem/hr) in the 400 MeV area based on the 1993 shielding assessment measurements assuming a 500 mrem/hr trip limit.

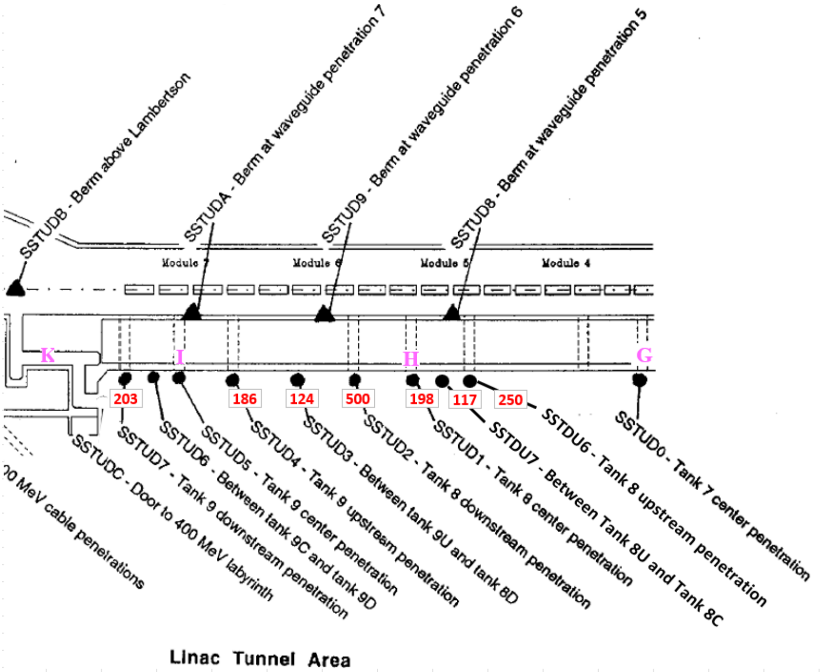

Figure 5: Maximum scaled dose rates (in mrem/hr) in the Linac tunnel area based on the 1993 shielding assessment measurements assuming a 500 mrem/hr trip limit.

I.2. Low Energy end (750 keV- 116 MeV)

For the LE linac, the berm properties remain the same as for the high energy portion. However, on the east side of the linac enclosure, the wall thickness varies from 3' (Tanks #1-2), to 7' (Tanks #3-4), to 12' (Tank #5 and beyond). There is also no shielding at the entrance of the interlocked portion of the linac enclosure. As a result, it is not obvious how to simulate a single meaningful 'worst case' scenario (in MARS).

Thus, the approach to estimate dose rates at the locations of the radiation detectors in the low-energy end of the Linac was similar to the one used for the HE linac portion but relied only on measurements (from measurements carried out for the 1991 Linac Radiation Shielding Assessment [5]). Two sets of studies were performed in February and April 1991. For the first study (reported in "*Radiation Studies of the Linac Enclosure*" [6] for which data were taken on February 19-22, 1991, and have been compiled into the attached Excel spreadsheet [7]) penetrations through the shielding wall were left open (i.e. no shielding material present). The second study (April 23-24, 1991) focused on the areas which were found to have insufficient shielding at the conclusion of the first study period and were mitigated. In particular, all penetrations were filled with concrete and/or poly beads to attenuate the radiation field measured in the galleries as best as possible. There are 3 penetrations for each tank. The center penetration is used for the RF transmission line. The upstream and downstream penetrations are used for water lines and cable trays. This is the current configuration to this day.

It is important to note that because the beam is not accelerated through the SCL, to determine the MCI intensity, the pulse length limitation is increased from 60 μs to **116 μs**, where the latter is determined by the capabilities of the RFQ RF power generation equipment. Thus, for the extrapolated numbers presented next, the MCI intensity is ***5.08e18 H^- ions per hour*** (i.e. 1.933 higher than for the HE linac estimates).

Similar to Figure 3, Figure 6 is a map of the LE Linac, which shows the extrapolated dose rates for the MCI intensity. In the example of Figure 6, the beam was lost at the entrance of Tank 3 (at 37.5 MeV). Dose rates reported on that figure are those for radiation detectors located in the upper linac gallery (red in yellow boxes), lower gallery (red, no background) and near the entrance gate to the linac tunnel (red in blue-grey boxes). Note that the extrapolated dose rates are based on the February 19-22, 1991, measurements, for which the penetrations were not shielded or filled.

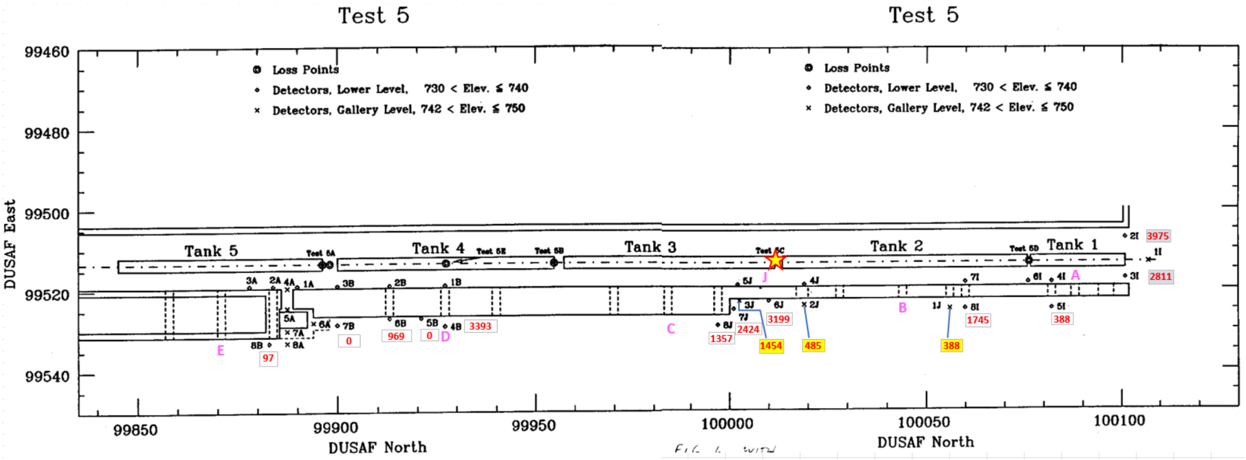

Figure 6: Extrapolated dose rates (in mrem/hr) along the Linac based on the measurements taken for the 1991 Linac Shielding Assessment (February data) where the beam was lost at the entrance of Tank 3. Pink letters indicate present day radiation detector locations in the lower Linac gallery (except for A and J, which are located inside the Linac tunnel).

While the extrapolated dose rates are generally much lower than those obtained for the HE Linac, they remain beyond any acceptable limits. Depending on the location (but outside of the linac enclosure), the maximum extrapolated dose rate ranges from ~1600 mrem/hr in the upper gallery, to ~4500 mrem/hr at the gates to the entrance of the Linac enclosure to >10^4 mrem/hr in the lower gallery.

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

The analyses of the dose rates that may be expected for MCI conditions, both for the HE linac and the LE linac, show that interlocked radiation detectors are necessary to ensure radiation doses anyone would be susceptible to experience never exceed regulatory limits. Trip limits need to be set based on the location of these detectors along the beam line, considering the uncertainties on the estimates and the constraints of the buildings/equipment.

II.1. Beam inhibiting devices

When a fault condition is detected (e.g. radiation dose rate limit), the Linac RSIS shuts off the gate valve located just upstream of the RFQ entrance as well as the RFQ RF system, thus preventing beam from propagating downstream. With a maximum beam energy of 35 keV at this location, and even at the MCI intensity (130 mA extracted from the ion source), the level of radiation generated outside the vacuum chamber/beam pipe when the beam interacts with the gate valve (and its surroundings) is negligible. Therefore, a dose rate that a co-worker might experience in case of an MCI is orders of magnitudes smaller than regulatory limits.

II.2. Locations

For both the 1991 "Radiation Studies of the Linac Enclosure" and the "Radiation Shielding Assessment of the Linac High Energy Enclosure Following the 1993 Upgrade Installation and Low Intensity Commissioning", temporary radiation detectors were used. From these measurements, and as suggested by the analyses summarized in this document (and references), the locations of the radiation detectors were chosen as follows:

- In Leg #2 of the 400 MeV access labyrinth
- Outside of the enclosure at the entrance of the RF transmission line penetrations (in the Linac Lower Gallery)
- On the berm above the straight-ahead absorber
- In the Booster Chute area
- In the area where the Linac beam is injected into the Booster accelerator

for a total of 12 detectors (11 chipmunks and 1 scarecrow - the difference between chipmunks and scarecrows is in the details of their electronics and applicable range). In addition, there are two (2) detectors located in the Linac tunnel in the Low Energy end (discussed further below). Those locations are shown in Section III-1.4.1.2.1 of the Linac SAD (as well as in some of the figures in the preceding chapter).

Pages 2-4 of the 1991 "Radiation Studies of the Linac Enclosure" contain the detailed explanation of the measurements carried out to evaluate the efficacy of placing chipmunks at the so-called "center" penetrations (to each tank in the tunnel correspond 3 penetrations from the lower gallery: upstream, center, and downstream) for the purpose of minimizing the dose rate outside of the tunnel, without the need for additional detectors in between. This assessment was revisited in [4], using data logged between 1996 and 1999, in addition to the original data (page 3 of Ref. [4]).

II.3. Radiation detectors operation

The radiation detectors have two modes of operation: a "rate" mode and a "integration" mode. Any chipmunk can be set in either mode. The "rate" mode detects when dose rates exceed some threshold, while the "integration" mode accumulates data over longer period of time (thus measure actual doses rather than just a rate). Generally speaking, "integration" mode chipmunks are located where dose rates are expected to be relatively slow but could be sustained for long periods of time. On the other hand, the chipmunks set to the "rate" mode are located where large doses could be generated over short periods of time, thus requiring the beam to be turned off rapidly.

All the Chipmunks/Scarecrows in the Linac are set to the "rate" mode. In that mode of operation, the detector trips when the dose ***rate*** is larger than the trip limit for 10 consecutive pulses. Thus, assuming that all 15 Hz pulses lead to dose rates higher than the detector's threshold, then the detector would 'trip' (i.e. issue a fault condition to the controls system) in 10/15 = 0.667 s. Taking into account various latencies in the electronics and devices that inhibit the beam, the beam is interrupted in ~1 second.

For instance, let's assume that an accidental loss induces a dose rate of 5000 mrem/hr (for more than 10 consecutive pulses). Whatever may the trip limit of the chipmunk be, it will trip in 0.667 s and the beam will be shutoff within 1s. The dose that someone would then get in this scenario is 1.39 mrem. Alternatively, in the "integration" mode, assuming a purely linear integration process (a better model may assume some background, time constant…) and a trip limit of 100 mrem/hr, it would take 72 seconds for the chipmunk to trip and, the received dose would be 100 mrem (as long as the beam remains off for the remaining of that hour when the trip occurred). Figure 7 shows an example of that better model [7] where real parameters have been chosen: the time constant of the integrating card is 20s, the chipmunk background (noise) is 0.6 mrem/hr and normal losses amount to 0.5 mrem/hr. In the calculation, the accident condition (5000 mrem/hr) starts after 60s of normal losses and remains so each time the beam is being turned back on (hence, it trips again a few tens of seconds later). The first trip occurs 34s after the accident condition is applied and the beam is briefly turned back on 3 times over that hour. The overall dose received by an individual over one hour turns out to be 113.9 mrem in this case.

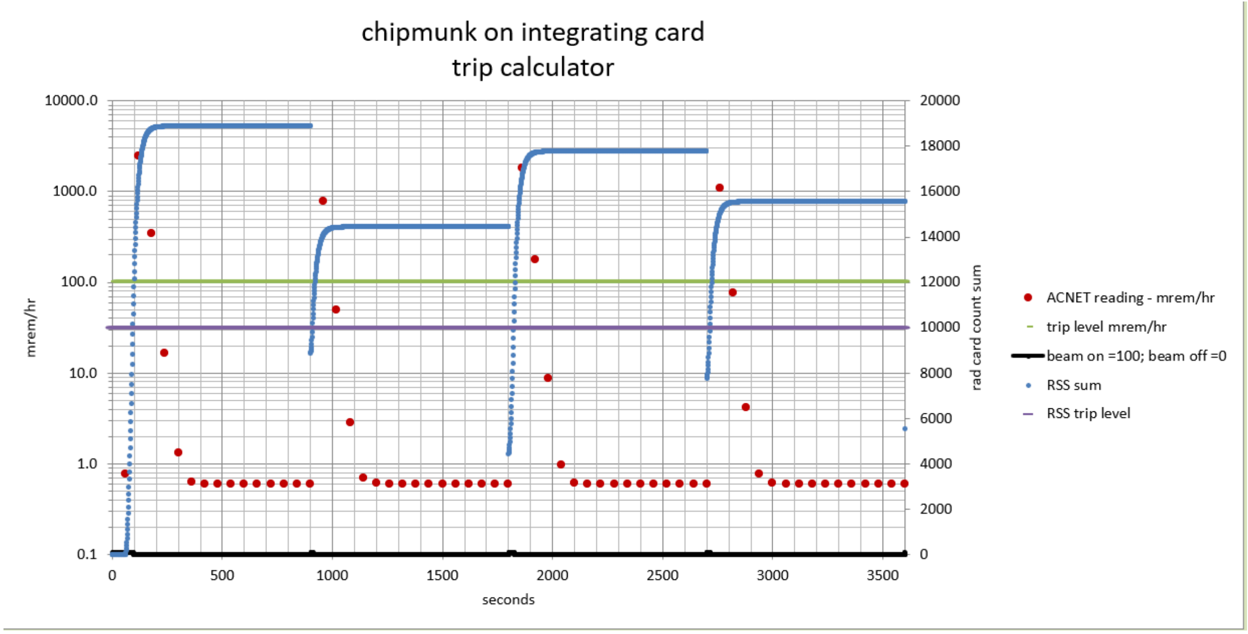

Figure 7: Response of a chipmunk in "integration" mode

Unfortunately, it is not possible to have point-like instruments cover the entirety of the Linac beam line.

II.4. Credited Controls (CC) trip limits

a. HE Linac

If a chipmunk is located at z = 6m in Figure 2, it will trip in 1s at any (reasonable) trip limit. However, if the chipmunk is 24' away from the maximum dose rate (i.e. the maximum distance between chipmunks in the HE linac is currently 48’, hence any beam loss is within ~24’ of a radiation detector), it measures only 31.2 mrem/hr (average of the values in the 3x3 matrix in Figure 2, on the left). In that case, if the trip limit is 50 mrem/hr, the chipmunk will never trip (assuming a steady state loss) but an individual located at the maximum dose rate location would receive close to 9000 mrem in an hour! Therefore, the trip limits for the chipmunk would have to be set relatively low to account for the distinct coverage. On the other hand, setting the chipmunk trip limits *too* low will impair normal operation and tuning of the beam line. This reasoning, however, assumes solid shielding at all points between the chipmunk locations, which is not the actual layout of the Linac.

While the Linac Lower Gallery is not a public area, because the public is invited to the Linac Upper Gallery for tours and to account for uncertainties and differences between the exact locations of the detectors during the studies and their final locations for normal configuration/operation of the Linac, the chipmunks CC trip limit should be set to 90 mrem/hr or less. The only exception is the detector located in Leg #2 of the 400 MeV access labyrinth. Extensive MARS simulation studies [8] have shown that the attenuation between Leg #2 and the access gate is at least 100, only due to the geometry, independently of the beam energy considered. Since the original measurements were carried out with the detector placed *outside* that access labyrinth, to limit the dose of an individual in the gallery near the enclosure entrance gate to <100 mrem/hr, it is sufficient to set the trip limit to 10,000 mrem/hr.

b. LE Linac

Like for the HE linac, the current shielding configuration in the low energy part of the linac is insufficient to limit the dose to 100 mrem for an MCI event and interlocked radiation detectors are located at the entrance of each center penetration. However, two areas require additional detectors: the RIL (35 keV-750 keV) and a room in the upper gallery just before the wall thickness increases from 3’ to 7’.

The RIL, by itself, does not produce radiation levels in excess of 100 mrem/hr. However, losses downstream can generate unacceptable radiation levels outside the enclosure, near its entrance gate [7]. Measurements (and their analysis, page 4, Section “The 750-keV Area” of Ref. [9]) showed (by extrapolation) that locating a radiation detector near the exit of Tank #1 (***in the enclosure***), with a trip limit of 1000 mrem/hr, will limit the dose rate at the RIL to <500 mrem/hr during an MCI event. The RIL is **not** an area where the public is invited.

The particular location of a room on the upper gallery just before the wall thickness increases from 3’ to 7’, creates a ‘dead-zone’ where both the chipmunk from the center penetration of Tank 2 and the chipmunk from the center penetration of Tank 3 are insufficient in preventing non-acceptable radiation dose levels for certain beam loss conditions (e.g. beam lost at the entrance of Tank #3, tab “37.5MeV” in Ref. [7]). Measurements (and their analysis, pages 4-5, Section “The Three-Foot Wall” of Ref. [9]) determined that the 3-foot wall was providing an attenuation of 3500 in this area. Thus, to limit the exposure to 500 mrem/hr, a radiation detector is placed ***in the linac enclosure*** near the entrance of Tank #3, with a trip limit of no more than 175 **rem**/hr.

For the penetrations (pages 2-3, Section “The Linac Utility Penetrations” of Ref. [9]), measurements (and their analysis) showed (by extrapolation) that radiation detectors set to trip at 250 mrem/hr or less would limit the dose during an MCI event to 500 mrem or less, in the lower gallery, which is an area where the public is **not** invited.

III. Summary

Analyses based on MARS simulations and extensive measurements show that radiation detectors located at the entrance of the linac penetrations, 400 MeV access labyrinth Leg #2, the Booster chute (Booster enclosure), the Booster 400 MeV injection area (Booster enclosure), the berm above the straight-ahead dump, and near Tank #1 and Tank #3 in the tunnel enclosure set to the appropriate Credited Control trip limits (Table below) protect workers, co-located workers and MOI from an MCI event.

Table 1: Credited Controls trip limits for the linac

Detector Location	**CC Limit (mrem/hr)**
A: Linac Enclosure Tank #1	1000
B: Linac Gallery Tank #2	250
C: Linac Gallery Tank #3	250
D: Linac Gallery Tank #4	250
E: Linac Gallery Tank #5	250
F: Linac Gallery Tank #6	90
G: Linac Gallery Tank #7	90
H: Linac Gallery Tank #8	90
I: Linac Gallery Tank #9	90
J: Linac Enclosure Tank #3	175,000
K: Linac Enclosure 400 MeV Labyrinth	10,000
L: Booster Chute	90
M: Linac Dump #1 Berm US	90
N: Linac Dump #1 Berm DS	90
O: Booster Tunnel Dump #1	90

IV. References

[1] *Radiation Shielding Assessment of the Linac High Energy Enclosure Following the 1993 Upgrade Installation and Low Intensity Commissioning*, Charles Schmidt & Thomas Kroc, September 21, 1993 (included in the “1993 Linac shielding assessment” package)

[2] LinacRadiation1993_ExtrapolationAnalysis.xlsx (*attached*)

[3] Revised Linac berm shielding drawings (10/23/23)

[4] *Justification for De-posting the Linac Lower-Level Gallery Radiation Area*, Memo from Matt Ferguson (Radiation Protection Group Leader) to Mike Gerardi (Accelerator Division’s Radiation Safety Officer), March 15, 2000 (included in the “1993 Linac shielding assessment” package)

[5] “1991 Linac Shielding Assessment” package

[6] *Radiation Studies of the Linac Enclosure*, Linac Department, April 25, 1991 (included in the “1991 Linac shielding assessment” package)

[7] LinacRadiation1991_ExtrapolationAnalysis.xlsx (*attached*)

[8] *A Radiation Shielding Study for the Fermilab Linac*, I. Rakhno & C. Johnstone, February 3, 2006, FERMILAB-TM-2306-AD

[9] *Radiation Shielding Assessment of the Linac Enclosure*, Charles Schmidt, Tom Kroc, Larry Allen and Elliott McCrory, April 26, 1991 (included in the “1991 Linac shielding assessment” package)