Booster Accelerator

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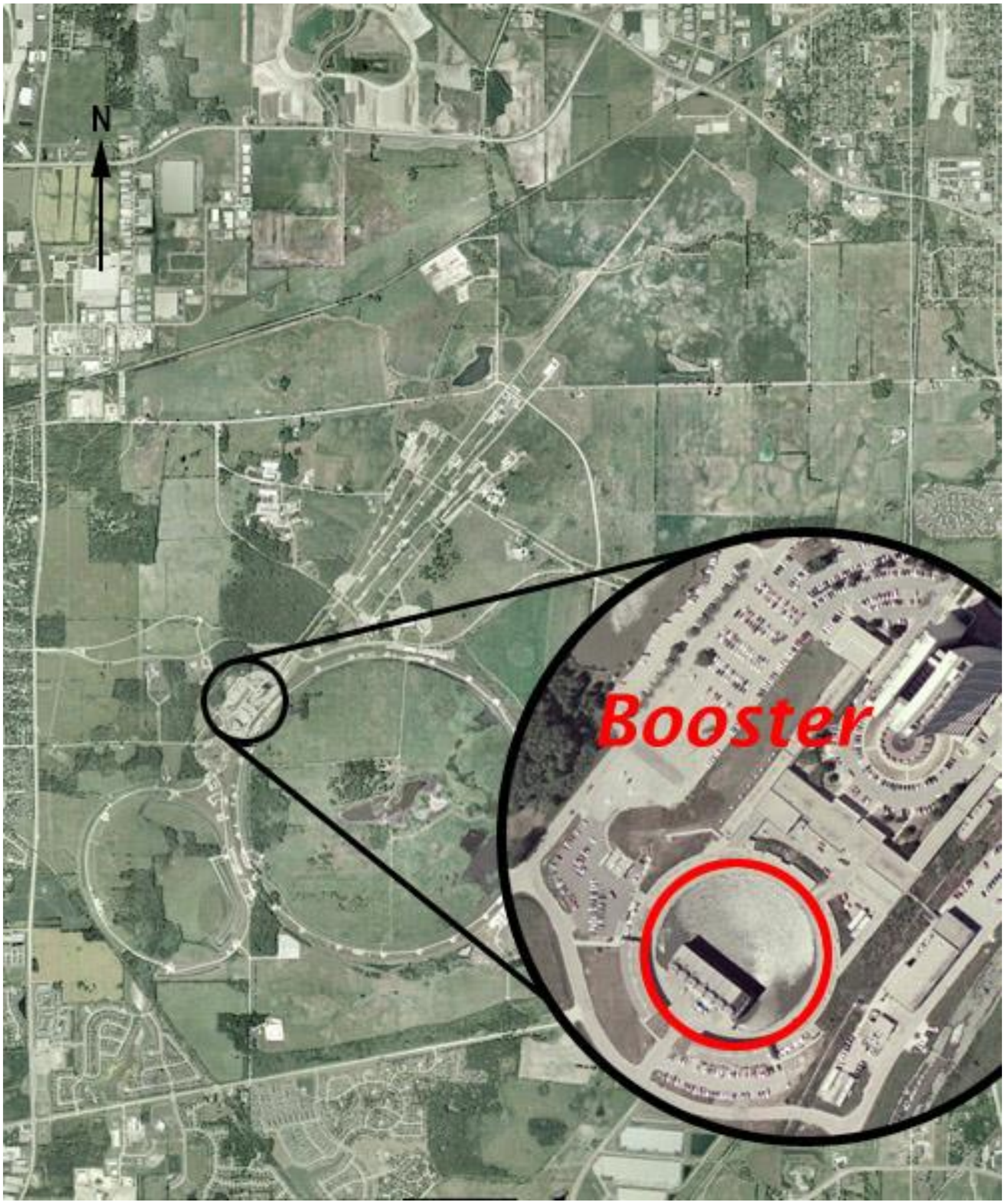

II - 3.2 Inventory of Hazards

The following table lists the identified hazards found in the Booster accelerator enclosure and support buildings. 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 Residual activation Ground water activation Surface water activation Air activation Radioactive waste Lasers	**Kinetic Energy** Power tools * Pumps and motors *
Toxic Materials Lead shielding * Beryllium components *	**Potential Energy** Crane operations * Compressed gases * Vacuum / pressure vessels * Vacuum pumps *
Flammable & Combustible Materials Cables *	**Magnetic Fields** Fringe fields *
Electrical Energy Stored energy exposure * High voltage exposure * Low voltage, high current exposure *	**Gaseous Hazards** Confined spaces *

II - 3.3 Introduction

This Section II, Chapter 3 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Booster accelerator area located southeast of the 400 MeV end of the Linac accelerator.

II - 3.3.1 Purpose of the Booster Accelerator

The purpose of the Booster accelerator is to provide 8 GeV proton beam to the Fermilab high energy physics (HEP) program.

II - 3.3.2 Description of the Booster Accelerator Area

The Booster accelerator is located just south of Wilson Hall and consists of a beamline that extends from the end of the Linac (400 MeV Line), a 150 meter diameter 15 Hz proton synchrotron and a 8 GeV extraction line which houses the 8 GeV beam absorber. (See figure 1 below). The Booster tunnel is a concrete tunnel 8 feet high and about 10 feet wide, covered by at least 9 feet of earth shielding (with additional steel and concrete in some areas).

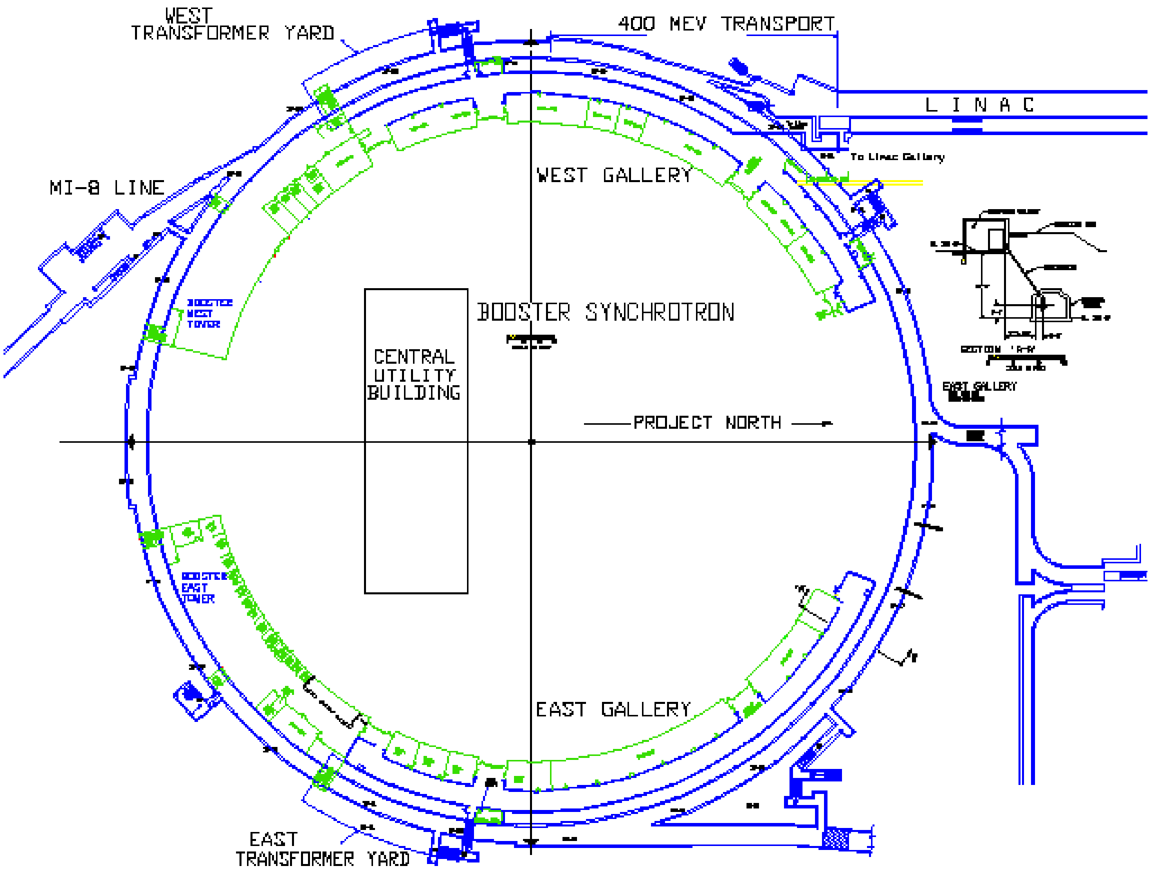

Figure 1. Booster Accelerator Layout

The 400 MeV beam line is used to extract beam from the Linac to Booster accelerator and is part of both the Linac and Booster enclosures. The beam extraction is done using a pulsed electrostatic chopper located at the end of the Linac Radio Frequency (RF) cavities. The length of the chopper pulse determines the amount of beam to be extracted into the Booster accelerator. The 400 MeV beam line has a vertical down bend of 15 feet to reach the Booster accelerator.

The Booster accelerator is a 15 Hz synchrotron that uses a resonant power system to excite 96 combined function magnets arranged in a FOFDOOD lattice repeated 24 times. The

FOFDOOD lattice consists of 2 (F) focusing gradient magnets, 2 (D) defocusing gradient magnets, (O) short strait section, and (OO) long straight section. The Booster accelerates the 400 MeV beam to 8 GeV in 33 msec using 18 RF cavities. Extraction of the beam to either the beam absorber (located at the up-stream end of the MI-8 enclosure) or to the MI-8 extraction line requires four pulsed magnetic kicker magnets.

The MI-8 extraction line has four enclosure areas: the Booster MI-8 area which includes the 8 GeV beam absorber shown in figure 2; the MI-8 transport area, the MI-8 to Main Injector (MI) accelerator injection region; and the MI-8 line to the Booster Neutrino target area. Only the up-stream area of the MI-8 line, up to MI-8 803/804, is part of the Booster accelerator enclosure.

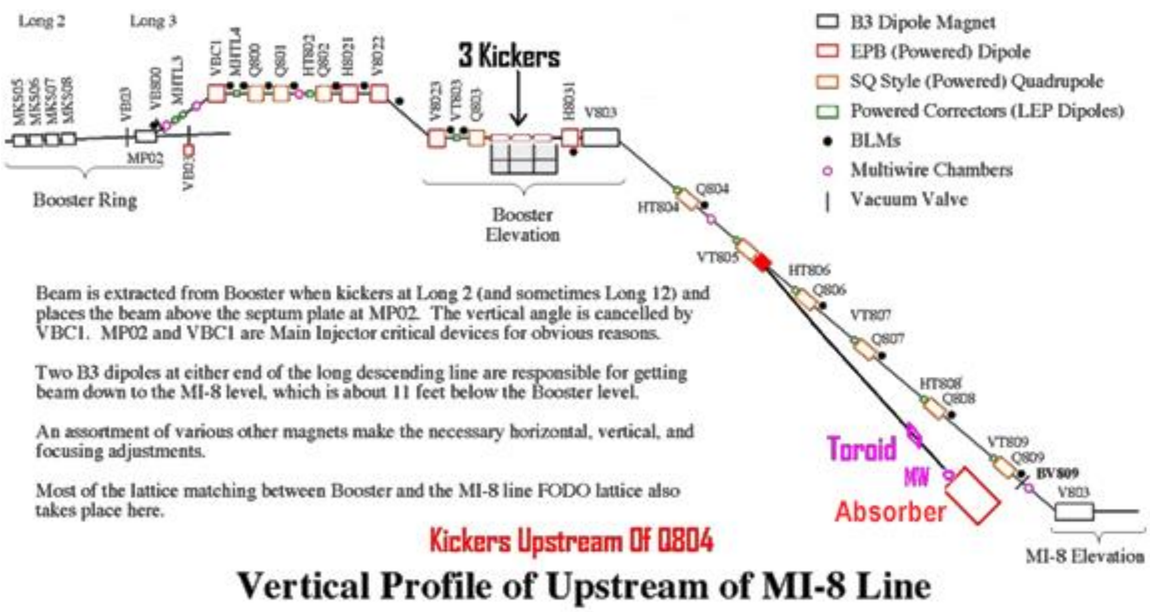

Figure 2. Booster Side of MI-8 line showing beam absorber

II - 3.3.3 Operating Modes

There are two operating modes with the main operating mode being for the Fermilab HEP program. The HEP mode is mainly the Neutrino program with occasional cycles used for Booster studies, Fermilab 120 GeV Fixed Target HEP, or to the Muon area (formally the Antiproton Source). The other operational mode is called the Absorber mode. The absorber mode is typically used only during long MI shutdown periods or after a long shutdown to do Booster studies or commissioning of Booster operations.

Using a multi-turn injection scheme, the Booster accelerator can accelerate from 1E11 up to 6.5E12 protons per Booster cycle with typically 4 to 5 E12 protons/pulse for the Neutrino program. The other users, Fermilab 120 GeV Fixed Target operations, beam to the Muon area, and Booster studies have historically used less than 5% of the beam cycles and at reduced root mean square (RMS) power levels.

The primary Booster operational mode is supplying 8 GeV protons for the Booster Neutrino users and beam to MI for 120 GeV Neutrino program. In this mode, Booster beam cycles are also used for Fermilab 120 GeV Fixed Target operations out of the MI and for the Muon area. The Booster Shielding Assessment[1] limits the Booster 8 GeV flux at 2.7E17 protons/hour up to the absorber. The beam absorber limits are discussed in the subsequent Absorber mode operation below. The intensity limit is monitored by the AD Operations Department through the Beam Permits and Running Conditions.

The Booster has Beam Loss Monitors (BLM) located at all high beta and high loss areas in the enclosure. These BLMs are not part of the Radiation Safety Interlock System (RSIS) however are used as operational controls to limit tunnel activation. In addition to the BLM system, the Booster also has a toroid system that calculates energy loss in the Booster in real-time. These systems are tied to the beam abort system and help to maintain acceptable loss levels and to prevent unnecessary tunnel activation. Tunnel surveys are done periodically to confirm and calibrate the BLM and toroid systems.

The Absorber mode operation is the ability to establish Booster beam when the MI beam permit is down. The Absorber mode is typically used when there is an extended period of no MI beam or dedicated Booster only studies. Beam is accelerated to 8 GeV and then extracted at Long 3 just as in the primary mode. The beam then exits Booster and heads down the MI-8 line. As the beam passes Q803, three Booster style kickers produce a vertical down bend of 32 mrad. Next, the beam passes through off center in Q804 and receives an additional vertical deflection of 12 mrad. The next element is the vertically focusing quad Q805, just upstream of the septum magnet; it reduces the deflection angle slightly. The beam is vertically displaced by ~33 mm as it enters the field region of the septa. The septa, with a vertical bend angle of 62 mrad, also has a slight horizontal roll of 6.73 degrees, giving the extracted beam a small 0.55 degree horizontal bend. After the septa, two small vertical trim magnets provide small vertical corrections in the absorber line. A beam stop located between Q809 and B3 magnet V809 prevents beam transport down the MI-8 line. The maximum hourly beam power transmitted to the Booster MI-8 absorber is limited to that provided by 12,000 pulses of 6E12 protons per pulse or 36,000 pulses of 5E12 protons per pulse. This operational limit is based on ANSYS (2-D) heating analysis of the absorber core[2]. The maximum yearly beam intensity transmitted to the Booster MI-8 absorber is 6.8E18 protons per year.

II - 3.4 Safety Assessment

The unique beam line specific hazards for the Booster accelerator area are analyzed in this section. The radiological hazards 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 Booster accelerator has unique laser and electrical hazards that are addressed.

II - 3.4.1 Radiological Hazards

The Booster Accelerator presents radiological hazards in the form of prompt and residual ionizing radiation from particle beams, potential non-ionizing radiation from high power RF systems, residual radiation due to activation of beam line components, and environmental radioactivity in the form of potential ground water, surface water, and air activation resulting from the operation of the beam transport systems.

A detailed shielding assessment and post assessment documents of the Booster accelerator has been compiled and reviewed by the Fermilab Radiation Safety Subcommittee Shielding Assessment Review Panel to address these hazards. The assessment provides a detailed analysis of the Booster accelerator, demonstrating the required shielding, use of approved ES&H signs, and active interlocks to comply with the Fermilab Radiological Control Manual[3] (FRCM).

The assessment considers ground water and surface water activation, lists surface water discharge points and monitoring locations, 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.

Residual activation of components makes a substantial impact on the ability to operate the Booster accelerator. The operational maintenance needs of the Booster requires that additional operating limits be in place. These operating limits use the BLM and active software analysis to alarm and if necessary remove the beam permit. The shielding assessment for the Booster is summarized in Sections 3.4.1.1 through 3.4.1.6 below.

II - 3.4.1.1 Ionizing Radiation

Prompt ionizing radiation is the principle radiation hazard when beam is accelerated and transported through the Booster accelerator. In order to protect workers and the general public, the enclosures and beam pipes are surrounded either by sufficient amounts of shielding (soil, concrete, or iron), and/or networks of interlocked detectors to keep any prompt radiation exposure within acceptable levels.

The Booster Shielding Assessment provides a detailed analysis of the beam line, demonstrating 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 Booster accelerator includes analyses of injection, Booster ring, and extraction areas. The Booster Shielding Assessment requires that:

- *Certain penetrations are filled with shielding as specified;*
- *All movable shielding blocks are installed as specified;*
- *All interlocked detectors are installed as specified; and*
- *The radiation safety interlock system is certified as working.*

The Booster Shielding Assessment concludes:

- *The facility is in conformance with all FRCM requirements and can be operated safely with the following beam parameters:*
    - *Maximum operating intensity is 2.7E17 protons per hour;*
    - *Maximum energy is 8 GeV.*

II - 3.4.1.2 Non-Ionizing Radiation

The Booster accelerator does not have any hazardous levels of RF electromagnetic energy. The RF cavities in the Booster enclosure contain electromagnetic fields; however the fields are not of sufficient magnitude to accelerate ‘dark-current’ electrons to energies capable of producing x-ray radiation. The cavities thereby remain on, unless locked out for maintenance. The ESH&Q Section Industrial Hygiene Group periodically monitors for stray RF fields in the work areas.

II - 3.4.1.3 Residual Activation

The shielding assessment estimates residual activation of materials inside the Booster enclosure. The residual dose rates have been calculated and verified with radiation surveys. The residual dose rate differences measured 10 years apart are shown in Figure 3. The plot shows that for nearly every location, the activation has decreased even though beam intensity has increased. In most cases, the activation reduction has been significant. The decrease in activation is due to the reduction of beam losses from the Proton Plan and the Proton Improvement Plan (PIP) upgrades.

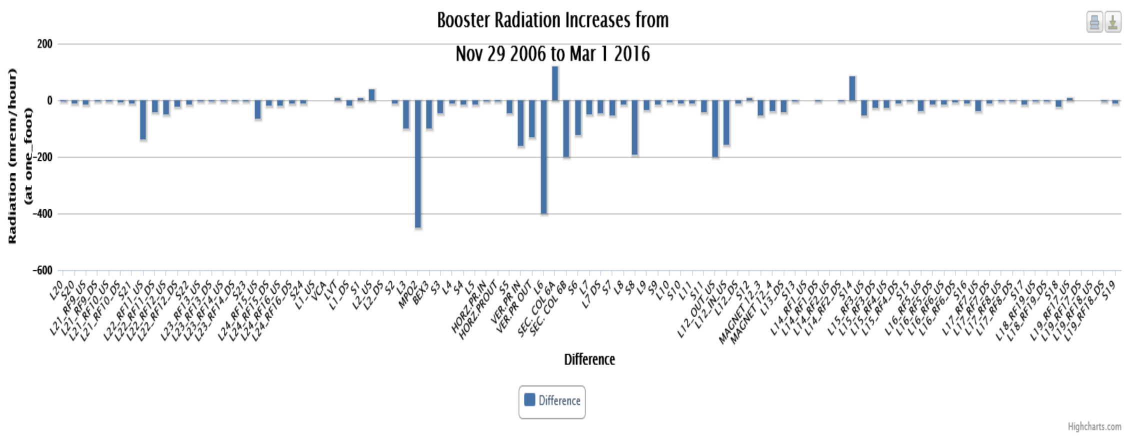

Figure 3. Booster Radiation Increases from Nov 2006 to March 2016.

When the Booster accelerator is not in operation, the enclosure area remains a radiological area and access to these components is tightly controlled with the level of control dependent on the level of residual radiation. The control measures include training and training verification, centralized access authorization, and key entry. Controls required for different levels of residual radiation are specified in the FRCM, and are detailed in the Radiological Work Permit (RWP) for the work to be performed.

The Booster enclosure elements are mainly composed of steel and copper. A decay analysis at several locations helped to develop guidance in job planning and activation analysis (for example see, Figure 4). High initial rates, due to short lived activation, requires a cool down of up to 1 hour for most Booster access maintenance.

In most situations, general RWPs for accesses will suffice and include the 1 hour cool down. A job-specific RWP and an as-low-as-reasonably-achievable (ALARA) plan will be required for work on any highly activated equipment with a potential individual exposure greater than 200 mrem or potential job exposure greater than 1000 person-mrem. These tasks will be supervised by members of the Environment, Safety, Health, and Quality (ESH&Q) Section Radiation Physics Engineering (RPE) Group under the direction of the AD Radiation Safety Officer (RSO).

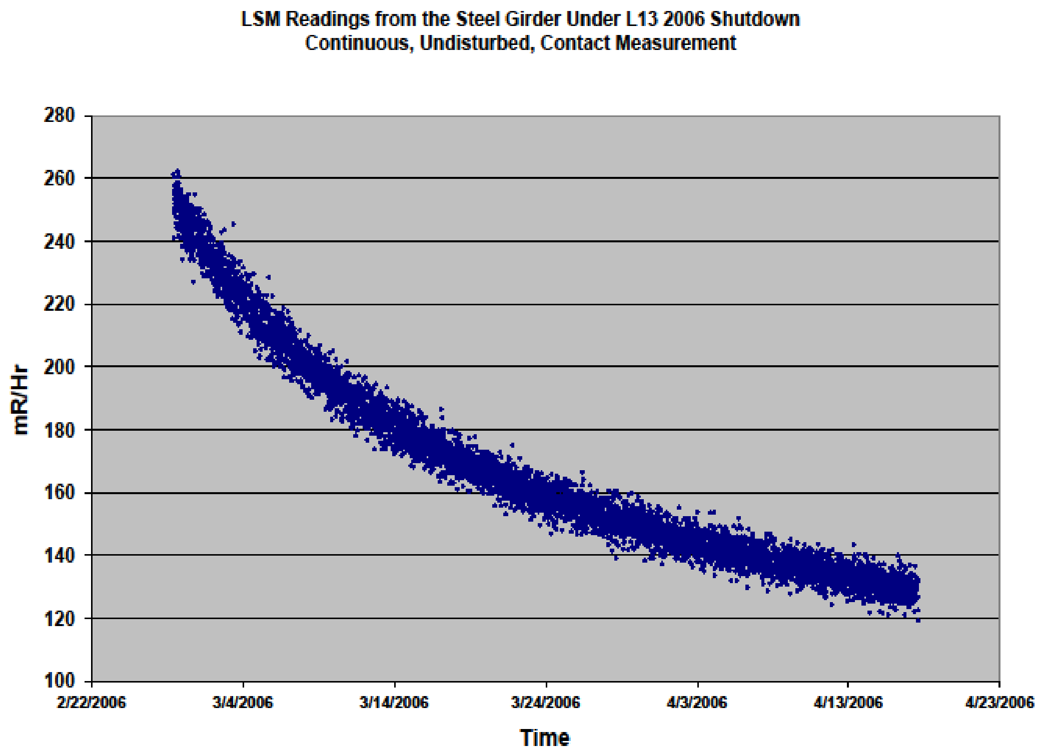

Figure 4. Measured decay rate at L13 over a 1-month period.

II - 3.4.1.4 Ground Water and Surface Water Activation

Operation of the Booster accelerator activates ground and surface water in the vicinity of the beamline enclosure. The majority of the activation occurs within a few meters of the beam line tunnel wall, primarily near the proton absorber and collimators.

The production of tritium and sodium-22 poses the greatest concern, since the product of the production rate, leachability into the water flowing through the soil, and decay half-lives of these nuclides may be large. Fermilab standards pertaining to ground water activation are provided in the FRCM, and the methodology for estimating ground water activation are given in Fermilab Environmental Protection Notes Numbers 8 and 17. The methodology is designed to achieve a conservative estimate of ground water activation. Additionally, the annual integrated intensity used in the calculations is estimated well above the practical beam delivery limits.

As discussed in the Booster Shielding Assessment and the Radiation Shielding of the Booster Beam Absorber[4] document, the simulation program MARS[5], has been used to estimate the surface water and ground water activation concentrations in the vicinity of the primary beam absorber. The limit of the 6.8E18 protons to the absorber annually would result in 80% of the surface water annual activation limit of 1900 pico Curie (pCi)/millilitre (ml) ^{3}H and 10 pci/ml ^{22}Na. Ground water activation was found to be negligible.

The measured beam loss on the collimators[6] has been used to scale previous simulations of star density production rate[7]. The scaled star density production rate has been used for calculation of water activation[8]. The surface water activation was found to be 4.6% of the total limit and the ground water activation was found to be negligible.

MARS simulations of the Booster notcher absorber determined the maximum star density production rate[9] used to calculate a surface water of 9.2% of the total limit and negligible ground water activation[10]. The ESH&Q Section RPE Group periodically samples the water at designated areas and Booster sumps to confirm safe operation.

II - 3.4.1.5 Air Activation

Federal regulations and the Fermilab Lifetime Operating Air Pollution permit issued by the Illinois Environmental Protection Agency (IEPA) govern releases of airborne radionuclides. The regulations limit the equivalent dose delivered to a member of the public to 10 mrem/year [11, 12]. Fermilab has established a secondary goal of keeping the maximum effective dose at the site boundary due to air emissions to under 0.1 mrem/yr.

The principal radionuclides of concern for air activation are carbon-11 (which has a 20 minute half-life), nitrogen-13 (which has about a 10 minute half-life), oxygen-15 (which has about a 2 minute half-life), tritium (which has 4500 day half-life), and argon-41 (with a 269 year half-life, which is produced by thermal neutron capture on argon-40). The beam for the Booster Accelerator is transported in a vacuum with the exception of the beam exiting out of the beam pipe, through a vacuum window, transiting through air before impinging upon the Booster absorber in the MI-8 beam line. The Booster Shielding Assessment calculates the air activation from the limited use of the Booster absorber to be negligible[13].

II - 3.4.1.6 Radioactive Waste

Booster accelerator 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 Booster area, beam loss and, in the case of some beam diagnostics devices, intentional interception of the beam will result in activation of beam line elements. Activated items will be reused when feasible. Activated items that cannot be reused will be disposed of as radioactive waste according to FRCM requirements.

II - 3.4.2 Lasers

There is a Class IV Nd:YAG (neodymium-doped yttrium aluminium garnet) laser operating in the downstream end of the 400 MeV line. The laser is part of the Laser Profile Monitor (LPM), a concept that utilizes a narrow beam of photons to photo detach the outer electron from an H- ion beam in an accelerator system to measure the H- density. Scanning the photon beam across the transverse (or longitudinal) extent allows the construction of a transverse (or longitudinal) beam profile.

The laser beam is totally enclosed between the laser and the entrance viewport of the vacuum system. The laser beam passes through the enclosed viewport to an exit viewport into a laser beam absorber. All of the enclosures which could potentially allow access to the laser light are interlocked or require special tools to access. Any access to the laser enclosures will prohibit the operation of the laser while the system is in an uncontrolled condition. The normal operational procedure is to allow the operation of the laser only when the Linac and Booster Electrical Safety Systems are permitted, thereby excluding access to either the Linac or Booster enclosures.

II - 3.4.3 Unique Electrical or Magnetic Field Hazards

The Booster 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 the beamline magnetic components and the modulators for the high power RF sources. These hazards are mitigated by containing this equipment in interlocked cabinets, using ES&H approved shielding and by following division or department written Lock Out / Tag Out procedures for access to the cabinets and equipment maintenance.

The Booster reference magnet, used by the gradient magnet power supply control system to regulate the current in the magnets, is the only posted magnetic field hazard in the Booster galleries. The magnetic field could also be a hazard to those with cardiac pacemakers or other medical implants. The Booster enclosures contain no unique or high magnetic hazards. Should such a system be added, the provisions of the FESHM will be implemented.

II - 3.5 Credited Controls

II - 3.5.1 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 Booster enclosure is designed to optimize the effect of these passive controls with permanent concrete and earth-covered radiation shields that use a combination of permanent shielding, movable shielding, and penetration shielding to protect personnel from radiological exposure during beam line operations.

II - 3.5.1.1 Permanent Shielding Including Labyrinths

The permanent shielding encompasses the structural elements surrounding the Booster ring and parts of the associated injection and extraction beam lines. The Linac shielding assessment ends at the 400 MeV chute. The MI-8 beam line assessment starts at the buried steel in the vicinity of the MI-8 location 803/804. The Booster shielding includes the following:

1. Injection Beam Line downstream of the 400 MeV chute;
2. Booster Ring (twenty-four periods);
3. Extraction Beam Line up to the MI-8 803/804 location;
4. Transfer Beam Line to, and including, the Booster 8 GeV Beam Absorber; and
5. Five access labyrinths, one emergency exit, interface gate to the MI-8 beamline at 810, and utility penetrations.

The enclosure areas are shown in blue on the map shown in Figure 1.

The permanent shielding for the enclosure is documented in the Booster Shielding Assessment and consists of sufficient earth overburden and active radiation monitoring interlocks to maintain compliance with the posting requirements of the FRCM under the assessed beam conditions.

II - 3.5.1.2 Movable Shielding

The Booster has no outside areas with movable shielding. However, there are three regions internal to Booster with movable shielding. The 400 MeV chute between Linac and Booster has movable shielding stacked around the beamline elements that creates a shield wall between the Linac and Booster enclosures. The second region once used for Booster to Main

Ring beam transfer has been filled with 20 feet of concrete blocks. This shield wall fills the enclosure section between Booster and Transfer Hall. The third area uses hand stacked shielding for the first leg at the entrance to the abandoned access labyrinth at Short 9.

II - 3.5.1.3 Penetration Shielding

The Booster enclosure has 192 penetrations. 172 of the penetrations are square 6.5”x6.5”x20’ straight leg penetrations from the gallery into the Booster enclosure at 45 degrees. Each of the straight leg penetrations is filled with at least twelve feet of polyethylene beads. The remaining penetrations have either three or four legs; these have been shown to attenuate radiation much more than the single leg penetrations and do not require any additional shielding. Table 1 gives the location and number of penetrations around the Booster enclosure.

Table 1 Booster Accelerator Penetration List (Period and Penetration Count)

P1	**P2**	**P4**	**P5**	**P11**	**P12**	**P13**	**P14**	**P15**	**P16**	**P17**	**P20**	**P21**	**P22**	**P23**	**P24**
8	18	4	8	11	11	10	18	12	14	14	8	14	10	12	20

The Booster enclosure has 6 ventilation ducts, 3 air supplies and 3 air returns. They enter and exit at the top of the entrance way stair wells to supply and return air from the enclosure. The prompt dose rates at the exits of the penetrations and air ducts are within the limits established in the FRCM.

II - 3.5.2 Active Controls

Active engineered controls are systems designed to reduce the risks from accelerator operations to an acceptable level. These are automatic systems that limit operations, shutdown operations, or provide warning alarms when operating parameters are exceeded. The active controls in place for Booster operations are discussed below.

II - 3.5.2.1 Radiation Safety Interlock System

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

There are 4 interlocked entrance doors, one interlocked emergency exit, and two interlocked gates: one gate at the magnet drop staging area and another internal to the MI-8 line. Internal to the Booster enclosure is an interlocked emergency scram system. The RSIS inhibits transport of beam beyond the Linac absorber when the Booster enclosure is not ready for beam operations.

The Booster has a chipmunk detector located at the end of the 400 MeV chute that monitors radiation levels while Booster is open to access. This chipmunk will inhibit Linac beam should an unacceptable level be detected in the Booster.

The Booster employs a combination of Total Loss Monitor (TLM), Chipmunk, and Scarecrow radiation monitors both internal and external to the enclosure to assure compliance with the FRCM posting requirements.

The Booster RSIS inhibits beam by controlling redundant critical devices. In this case, the B:LAM and B:MH1 power supplies feed the Linac extraction Lambertson magnet and a dipole magnet, respectively. Both magnets are located at the start of the 400 MeV transfer line in the Linac enclosure immediately downstream of the electrostatic chopper. The B:LAM bends the beam roughly 9 degrees to the west into the Booster injection line and the B:MH1 dipole magnet bends the beam an additional 4.82 degrees to the west. In the event of a critical device failure, the system has a failure mode function that will reach back and inhibit beam to the Linac, thus eliminating the possibility of beam reaching the Booster.

Following any personnel access to the enclosure, trained and qualified personnel from the AD Operations Department are required to search and secure the enclosure before permits from the RSIS may be reestablished, except under strictly specified controlled access conditions. The RSIS requirements including those 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.

II - 3.5.3 Administrative Controls

All Booster accelerator 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. These procedures are the administrative controls that encompass the human interactions and form the foundation for safe accelerator operations. The administrative procedures and programs considered necessary to ensure safe accelerator operations are discussed.

II - 3.5.3.1 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 Booster 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 RPE Manager, AD RSO, AD Operations Department Head, and AD Proton Source Department Head. The run conditions list the operating modes and safety envelope for the Booster accelerator. Run conditions are issued by the AD RSO, and are signed by the AD Operations Department Head, AD Proton Source Department Head, AD RSO, and AD Head.

II - 3.5.3.2 Summary of beam operating and safety envelope parameters

The Booster has been assessed from the standpoint of beam operating and safety envelope parameters. The beam operating parameter was assessed for 8 GeV protons at a maximum of 2.7E17 protons/hour. The safety envelope parameters have been assessed in Appendix A - Accelerator Safety Envelope.

II - 3.6 Summary & Conclusion

Specific hazards associated with operation of the Booster accelerator are identified and described in this chapter of the Fermilab SAD. The designs, controls, and procedures to mitigate Booster-specific hazards also are identified and described. The Booster accelerator is subject to the global and more generic safety requirements, controls and procedures outlined in Section 1 of the Fermilab SAD.

The credited controls identified and established in this chapter allows for Booster accelerator operations to be conducted in a manner that will produce minimal risk to the health and safety of Fermilab workers, researchers, the public, and the environment.

II - 3.7 Glossary, Acronyms

AD	Accelerator Division
ALARA	As Low As Reasonably Achievable
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
HEP	High Energy Physics
Hz	Cycles per second
IEPA	Illinois Environmental Protection Agency
LPM	Laser Profile Monitor
MeV	Million-electronvolt
MI	Main Injector
ml	Milliliter
pCi	pico Curie
PIP	Proton Improvement Plan
RF	Radio Frequency
RMS	Root Mean Square
RPE	Radiation Physics Engineering
RSIS	Radiation Safety Interlock System
RSO	Radiation Safety Officer
RWP	Radiological Work Permit
SAD	Safety Assessment Document
TLM	Total Loss Monitor

II - 3.8 References

[1] Booster Shielding Assessment Version 6, January 17, 2017.

[2] A Thermal Analysis for a Steel Dump used in MI8, Ang Lee, Aug 30, 2005.

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

[4] Radiation Shielding of the Beam Absorber in the MI 8 GeV Beam Line, I. Rakhno, December 30, 2005, Fermilab-TM-2340-AD.

[5] N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628 (1995);N.V. Mokhov, O.E. Krivosheev, "MARS Code Status", Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000).

[6] Beam Loss on Booster Collimators, B. Pellico, March 2016.

[7] Scaling the Star Density Production Rate from a MARS Simulation Using the Measured Beam Loss Intercepted by the Booster Collimation System, K. Gollwitzer, March 2016.

[8] Booster Collimators Groundwater & Surface Water 04-04-16, B. Higgins, April 2016.

[9] MARS Simulation of Proton Beam upon Booster Notcher Absorber, I.Rakhno and K Gollwitzer, October 26, 2016, AD Beams-doc-5259-v1.

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[11] Title 40, Code of Federal Regulations, Part 61, Subpart H, "National emissions standard for hazardous air pollutants (NESHAP) for the emission of radionuclides other than radon from Department of Energy Facilities", 1989.

[12] Illinois Environmental Protection Agency Fermilab Air Permit, March 6, 2006.

[13] Booster Absorber Air Activation, M. Geelhoed, April 4, 2016, AD Beams-doc-5133-v1.