BOOSTER

SECTION III CHAPTER 04 OF THE FERMILAB SAD

Revision 1 January 3, 2024

This Chapter of the Fermilab Safety Assessment Document (SAD) contains a summary of the results of the Safety Analysis for the Booster of the Fermi Main Accelerator that are pertinent to understanding the risks to the workers, the public, and the environment due to its operation.

SAD Chapter Review

This Section III Chapter 04 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD), *Booster*, was prepared and reviewed by the staff of the AD/BD/PS in conjunction with the Environment, Safety & Health Division (ESH) Accelerator Safety Department.

Signatures below indicate review of this Chapter, and recommendation that it be approved and incorporated into the Fermilab SAD.

☐ ____
Line Organization Owner

☐ ____
Accelerator Safety Department Head

☐ ____
SAD Review Subcommittee Chair

Revision History

Printed versions of this Chapter of the Fermilab Safety Assessment Document (SAD) may not be the currently approved revision. The current revision of this Chapter can be found on ESH DocDB #1066 along with all other current revisions of all Chapters of the Fermilab SAD.

Author	Rev. No.	Date	Description of Change
Salah Chaurize	1	December 19,2023	Updated for MCI and continued updated SAD format
CY Tan Salah Chaurize Mike Wesley	1	August 7, 2023	• Updated to include new SAD layout Incorporation of Risk Matrix and hazard discussion
William Pellico	0	January 18, 2017	Initial release of the Booster Accelerator Chapter for the Fermi National Accelerator Safety Assessment Document (SAD)

Table of Contents

Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ACNET	Accelerator Control Network System
AD	Accelerator Directorate
AHJ	Authority Having Jurisdiction
ALARA	As Low As Reasonably Achievable
ANSI	American National Standards Institute
APS-TD	Applied Physics and Superconducting Technology Directorate
ARA	Airborne Radioactivity Area
ASE	Accelerator Safety Envelope
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASO	Accelerator Safety Order, referring to DOE O 420.2D *Safety of Accelerators*
^{7}Be	Beryllium-7
BLM	Beam Loss Monitor
BNB	Booster Neutrino Beam
BPM	Beam Position Monitor
BY	Boneyard
CA	Controlled Area
CA	Contamination Area
CAS	Contractor Assurance System
CC	Credited Control
CCL	Coupled Cavity Linac
CDC	Critical Device Controller
CERN	European Organization for Nuclear Research
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations (United States)
Ci	Curie
CLW	Co-Located Worker (the worker in the vicinity of the work but not actively participating)
cm	centimeter
CPB	Cryogenics Plant Building
CSO	Chief Safety Officer
CUB	Central Utility Building
CW	Continuous Wave
CX	Categorically Excluded
D&D	Decontamination and Decommissioning
DA	Diagnostic Absorber
DAE	Department of Atomic Energy India
DCS	Derived Concentration Standard
DocDB	Document Database
DOE	Department of Energy
DOT	Department of Transportation
DR	Delivery Ring

DSO	Division Safety Officer
DSS	Division Safety Specialist
DTL	Drift Tube Linac
DUNE	Deep Underground Neutrino Experiment
EA	Environmental Assessment
EA	Exclusion Area
EAV	Exhaust Air Vent
EENF	Environmental Evaluation Notification Form
EMS	Environmental Management System
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
ES&H	Environment, Safety and Health
Fermilab	Fermi National Accelerator Laboratory, see also FNAL
FESHCom	Fermilab ES&H Committee
FESHM	Fermilab Environment, Safety and Health Manual
FHS	Fire Hazard Subcommittee
FIRUS	Fire Incident Reporting Utility System
FNAL	Fermi National Accelerator Laboratory, see also Fermilab
FODO	Focus-Defocus
FONSI	Finding of No Significant Impact
FQAM	Fermilab Quality Assurance Manual
FRA	Fermi Research Alliance
FRCM	Fermilab Radiological Control Manual
FSO	Fermilab Site Office
FW	Facility Worker (the worker actively performing the work)
GERT	General Employee Radiation Training
GeV	Giga-electron Volt
^3H	Tritium
HA	Hazard Analysis
HAR	Hazard Analysis Report
HCA	High Contamination Area
HCTT	Hazard Control Technology Team
HEP	High Energy Physics
HFD	Hold for Decay
HLCF	High Level Calibration Facility
HPR	Highly Protected Risk
Hr	Hour
HRA	High Radiation Area
HSSD	High Sensitivity Air Sampling Detection
HVAC	Heating, Ventilation, and Air Conditioning
HWSF	Hazardous Waste Storage Facility
Hz	Hertz
IB	Industrial Building
IBC	International Building Code
ICW	Industrial Cooling Water

IEPA	Illinois Environmental Protection Agency
IEEE	Institute of Electrical and Electronics Engineers
INFN	Istituto Nazionale di Fisica Nucleare
IMPACT	Integrated Management Planning and Control Tool
IPCB	Illinois Pollution Control Board
IQA	Integrated Quality Assurance
ISD	Infrastructure Services Division
ISM	Integrated Safety Management
ITNA	Individual Training Needs Assessment
KeV	kilo-electron volt
kg	kilo-grams
kW	kilo-watt
LBNF	Long Baseline Neutrino Facility
LCW	Low Conductivity Water
LHC	Large Hadron Collider
LLCF	Low Level Calibration Facility
LLWCP	Low Level Waste Certification Program
LLWHF	Low Level Waste Handling Facility
LOTO	Lockout/Tagout
LPM	Laser Profile Monitor
LSND	Liquid Scintillator Neutrino Detector
LSO	Laser Safety Officer
m	meter
mA	milli-amp
MABAS	Mutual Aid Box Alarm System
MARS	Monte Carlo Shielding Computer Code
MC	Meson Center
MCI	Maximum Credible Incident
MC&A	Materials Control and Accountability
MCR	Main Control Room
MEBT	Medium Energy Beam Transport
MEI	Maximally Exposed Individual
MeV	Mega-electron volt
MI	Main Injector
MINOS	Main Injector Neutrino Oscillation Search
MMR	Material Move Request
MOI	Maximally-Exposed Offsite Individual *(Note: due to the Fermilab Batavia Site being open to the public, the location of the MOI is taken to be the location closest to the accelerator that is accessible to members of the public.)*
MP	Meson Polarized
mrad	milli-radian
mrem	milli-rem
mrem/hr	milli-rem per hour
MT	Meson Test
MTA	400 MeV Test Area

MTF	Magnet Test Facility
^{22}Na	Sodium-22
NC	Neutrino Center
NE	Neutrino East
NEC	National Electrical Code
NEPA	National Environmental Policy Act
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NFPA	National Fire Protection Association
NM	Neutrino Muon
NMR	Nuclear Material Representative
NOvA	Neutrino Off-axis Electron Neutrino (ve) Appearance
NPH	Natural Phenomena Hazard
NRTL	Nationally Recognized Testing Laboratory
NIF	Neutron Irradiation Facility
NTSB	Neutrino Target Service Building, see also TSB
NuMI	Neutrinos at the Main Injector
NW	Neutrino West
ODH	Oxygen Deficiency Hazard
ORC	Operational Readiness Clearance
OSHA	Occupational Safety and Health Administration
pCi	pico-Curie
pCi/mL	pico-Curie per milliliter
PE	Professional Engineer
PIN	Personal Identification Number
PIP	Proton Improvement Plan
PIP-II	Proton Improvement Plan - II
PHAR	Preliminary Hazards Analysis Report
PPD	Particle Physics Directorate
PPE	Personnel Protective Equipment
QA	Quality Assurance
QAM	Quality Assurance Manual
RA	Radiation Area
RAF	Radionuclide Analysis Facility
RAW	Radioactive Water
RCT	Radiological Control Technician
RF	Radio-Frequency
RFQ	Radio-Frequency Quadrupole
RIL	RFQ Injector Line
RMA	Radioactive Material Area
RMS	Root Mean Square
RPCF	Radiation Physics Calibration Facility
RPE	Radiation Physics Engineering Department
RPO	Radiation Physics Operations Department
RRM	Repetition Rate Monitor
RSI	Reviewed Safety Issue

RSIS	Radiation Safety Interlock System
RSO	Radiation Safety Officer
RWP	Radiological Work Permit
SA	Shielding Assessment
SAA	Satellite Accumulation Areas
SAD	Safety Assessment Document
SCF	Standard Cubic Feet
SCFH	Standard Cubic Feet per Hour
SEWS	Site-Wide Emergency Warning System
SNS	Spallation Neutron Source
SR	Survey Riser
SRF	Superconducting Radio-Frequency
SRSO	Senior Radiation Safety Officer
SSB	Switchyard Service Building
SSP	Site Security Plan
SWIC	Segmented Wire Ionization Chambers
TLM	Total Loss Monitor
TLVs	Threshold Limit Values
TPC	Time Projection Chamber
TPES	Target Pile Evaporator Stack
TPL	Tagged Photon Lab
TSB	Target Service Building, see also NTSB
TSCA	Toxic Substances Control Act
TSW	Technical Scope of Work
T&I	Test and Instrumentation
UPB	Utility Plant Building
UPS	Uninterruptible Power Supply
USI	Unreviewed Safety Issue
VCTF	Vertical Cavity Test Facility
VHRA	Very High Radiation Area
VMS	Village Machine Shop
VMTF	Vertical Magnet Test Facility
VTS	Vertical Test Stand
WSHP	Worker Safety and Health Program
µs	micro-second

III-4. Booster

III-4.1. Introduction

This Section III Chapter 4 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Booster segment of the Fermilab Main Accelerator.

III-4.1.1 Purpose/Function

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

III-4.1.2 Current Status

The Booster segment of the Fermilab Main Accelerator is currently: **operational.**

III-4.1.3 Description

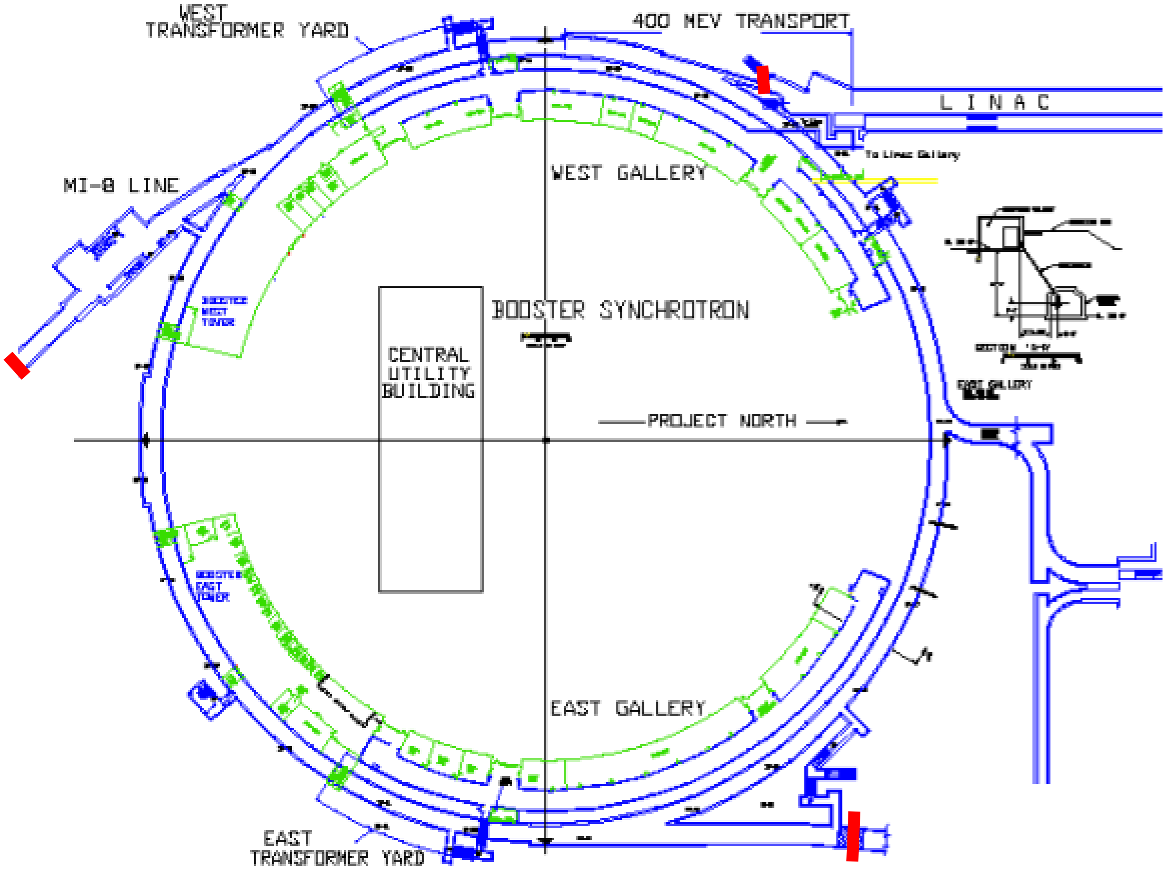


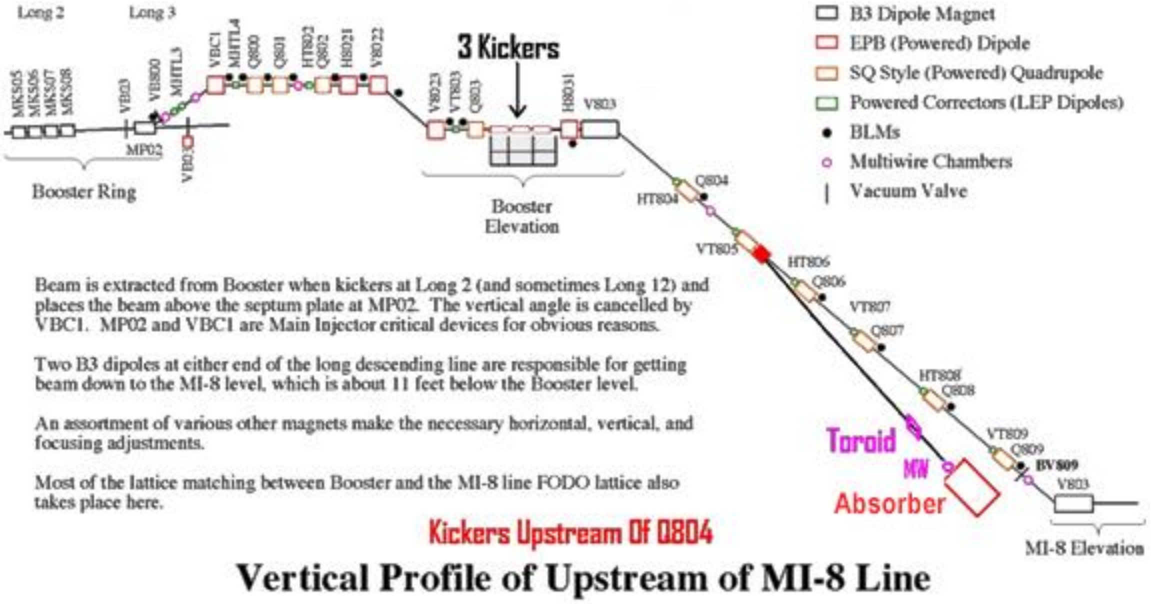
Figure 1: The Booster accelerator layout.

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). 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).

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.



Beam is extracted from Booster when kickers at Long 2 (and sometimes Long 12) and places the beam above the septum plate at MP02. The vertical angle is cancelled by VBC1. MP02 and VBC1 are Main Injector critical devices for obvious reasons.

Two B3 dipoles at either end of the long descending line are responsible for getting beam down to the MI-8 level, which is about 11 feet below the Booster level.

An assortment of various other magnets make the necessary horizontal, vertical, and focusing adjustments.

Most of the lattice matching between Booster and the MI-8 line FODO lattice also takes place here.

Figure 2:Booster side of the MI-8 line showing beam absorber.

III-4.1.4 Location

The Booster of the Fermilab Main Accelerator is located on the Fermilab site in Batavia, IL.

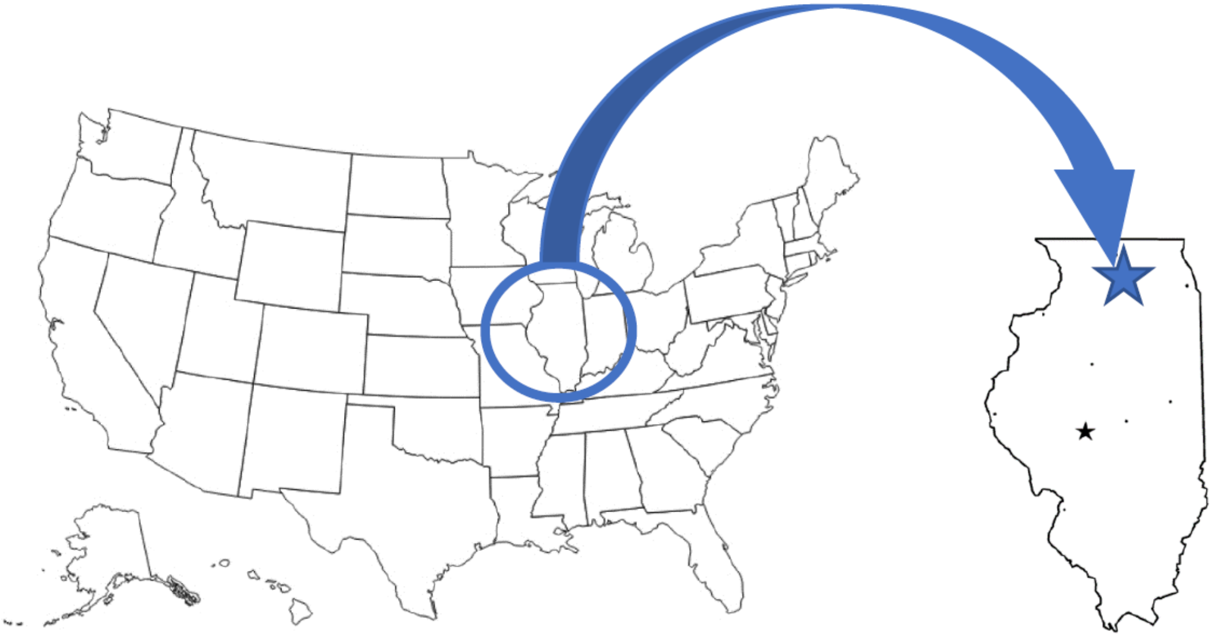


Figure 3. Regional view showing the location of the Fermilab site in Batavia, IL.

The Booster is located in the central campus on the Fermilab site. See Figure 4.

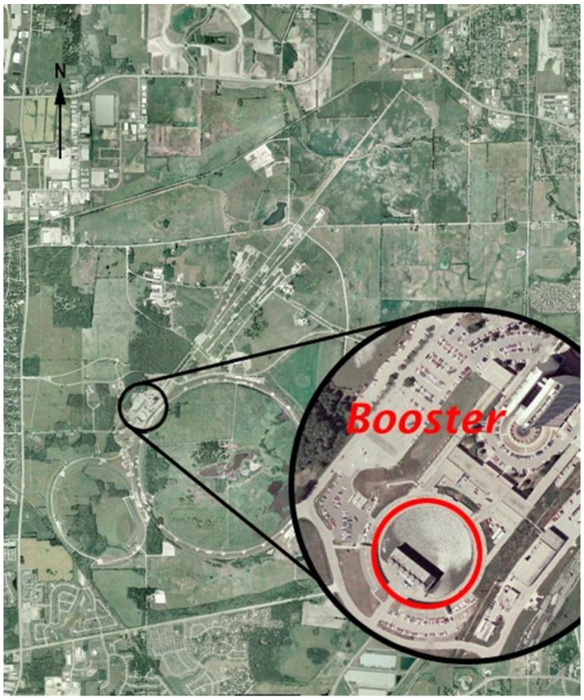


Figure 4. Aerial view of the Fermilab site, indicating the location of the Booster.

III-4.1.5 Management Organization

Managed by Accelerator Directorate, Beams Division, Proton Source department.

III-4.1.6 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 5E12 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/RR for the 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 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 septum. The septum, 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 septum, 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 [3]. The maximum yearly beam intensity transmitted to the Booster MI-8 absorber is 6.8E18 protons per year.

III-4.1.7 Inventory of Hazards

The following table lists all of the identified hazards found in the Booster enclosure and support buildings. Section III-4.9 *Appendix – Risk Tables* describes the baseline risk (i.e., unmitigated risk), any preventative controls and/or mitigative controls in place to reduce the risk, and residual risk (i.e., mitigated risk) for facility worker, co-located worker and Maximally Exposed Offsite Individual (MOI) (i.e., members of the public). A summary of these controls is described within Section III-4.2 *Safety Assessment.*

Prompt ionizing and Oxygen Deficiency Hazards due to cryogenic systems within accelerator enclosures have been identified as accelerator specific hazards, and as such their controls are identified as Credited Controls. The analysis of these hazards and their Credited Controls will be discussed within this SAD Chapter, and their Credited Controls summarized in the Accelerator Safety Envelope for the Fermilab Main Accelerator. Accelerator specific controls are identified as **purple/bold** throughout this Chapter.

All other hazards present in the Booster are safely managed by other DOE approved applicable safety and health programs and/or processes, and their analyses have been performed according to applicable DOE requirements as flowed down through the Fermilab Environment, Safety and Health Manual (FESHM). These hazards are considered to be Non-Accelerator-Specific Hazards (NASH), and their analysis will be summarized in this SAD Chapter.

Table 1. Hazard Inventory for Booster.

	Radiological		**Toxic Materials**
☒	**Prompt Ionizing Radiation**	☒	Lead Shielding
☒	Residual Activation	☒	Beryllium
☒	Groundwater Activation	☐	Fluorinert & Its Byproducts
☒	Surface Water Activation	☐	Liquid Scintillator Oil
☐	Radioactive Water (RAW) Systems	☐	Ammonia
☐	Air Activation	☐	Nanoparticle Exposures
☐	Closed Loop Air Cooling		**Flammables and Combustibles**
☐	Soil Interactions	☒	Combustible Materials (e.g., cables, wood cribbing, etc.)
☒	Radioactive Waste	☒	Flammable Materials (e.g., flammable gas, cleaning materials, etc.)
☒	Contamination		**Electrical Energy**
☒	Beryllium-7	☒	Stored Energy Exposure
☐	Radioactive Sources	☒	High Voltage Exposure
☐	Nuclear Material	☒	Low Voltage, High Current Exposure
☐	Radiation Generating Devices (RGDs)		**Kinetic Energy**
☒	Non-Ionizing Radiation Hazards	☒	Power Tools
	Thermal Energy	☒	Pumps and Motors
☒	Magnet Bakeouts	☒	Motion Tables
☒	Hot Work	☐	Mobile Shielding
☐	**Cryogenics**		**Magnetic Fields**
	Potential Energy	☒	Fringe Fields
☒	Crane Operations		**Other Hazards**
☒	Compressed Gasses	☒	Confined Spaces
☒	Vacuum/Pressure Vessels	☒	Noise
☒	Vacuum Pumps	☒	Silica
☒	Material Handling	☒	Ergonomics
	Access & Egress	☒	Asbestos
☒	Life Safety Egress	☒	Working at Heights

III-4.2. Safety Assessment

All hazards for the Booster segment of the Fermilab Main Accelerator are summarized in this section, with additional details of the analyses for accelerator specific hazards.

III-4.2.1 Radiological Hazards

The Booster presents radiological hazards in the form of a list of checked off radiological hazards shown in Table 1. A detailed shielding assessment[2] addresses these hazards and provide a detailed analysis of the facility demonstrating the required shielding, controls and interlocks to comply with the Fermilab Radiological Control Manual (FRCM)[1]. The hazards have been evaluated and are discussed further below and elsewhere in the Fermilab SAD. After completion of risk analysis shown in Section III-4.9 Appendix – Risk Tables, Tables 8.1-8.3, the Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken.

III-4.2.1.1 Prompt Ionizing Radiation

Prompt ionizing radiation is the principal 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. Operation of the area conforms to the FRCM to maintain exposures for operating personnel as low as reasonably achievable (ALARA).

This hazard has been evaluated via a Maximum Credible Incident (MCI) analysis that is described in Section III-4.3.1.1. This analysis specifies that Fermilab uses Credited Controls that flow down to the Accelerator Safety Envelope (ASE) to mitigate the consequences of the MCI to at or below the acceptable dose levels described in SAD Section I Chapter 4. A detailed description of each of the Credited Controls and their function is provided in Section III-4.4. The conclusion of these analyses is that the mitigated dose level associated with prompt ionizing radiation due to beam loss is acceptable.

The Booster Debuncher RF cavity in the 400 MeV line Booster enclosure contains electromagnetic fields of sufficient magnitude to accelerate ‘dark-current’ electrons to energies capable of producing X-ray radiation. The radiation safety interlock system for the Booster disables RF power to the cavity and thereby eliminates the x-ray hazard whenever personnel access the enclosure.

The 805 MHz RF power source for the accelerating cavity is also an X-ray producing source. X-ray shielding for the RF amplifier tubes was developed as part of the Linac/Booster 400 MeV upgrade project in the 1990’s. Fermilab Radiological Control Technicians (RCT), under the direction of the Accelerator Directorate (AD) Radiation Safety Officer (RSO), have documented that the X-ray level outside the shielding is well below the 0.25 mrem/hr threshold specified in the FRCM for the unlimited occupancy area in which the RF amplifier tubes operate. Without shielding, the levels are below 100 mrem/hr, thus credited controls are not required for the klystrons.

III-4.2.1.2 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 5. 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. The hazards have been evaluated and are discussed further below and elsewhere in the Fermilab SAD. RWPs and ALARA plans must be written and followed in accordance with the FRCM requirements.

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.

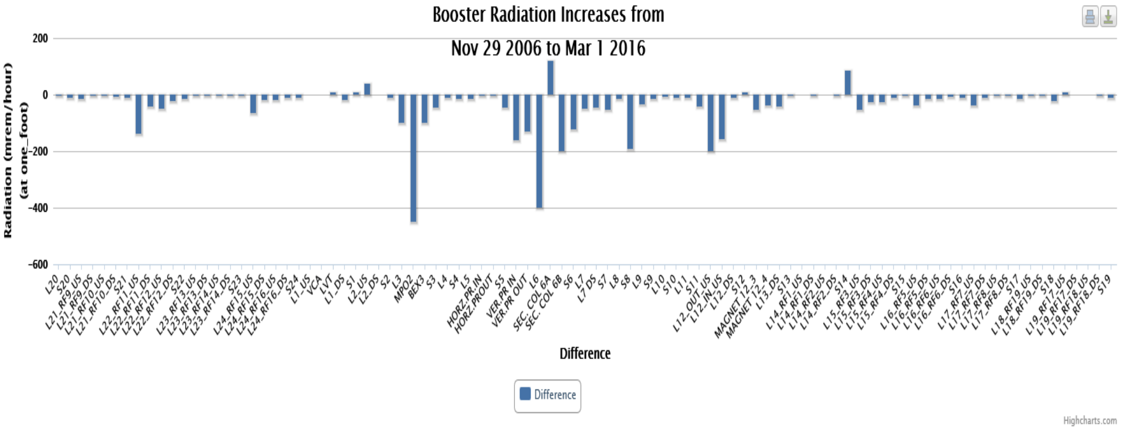


Figure 5: Booster radiation Increases from Nov 2006 to March 2016.

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 6). High initial rates, due to short lived activation, requires a cool down of up to 1 hour for most Booster access maintenance.

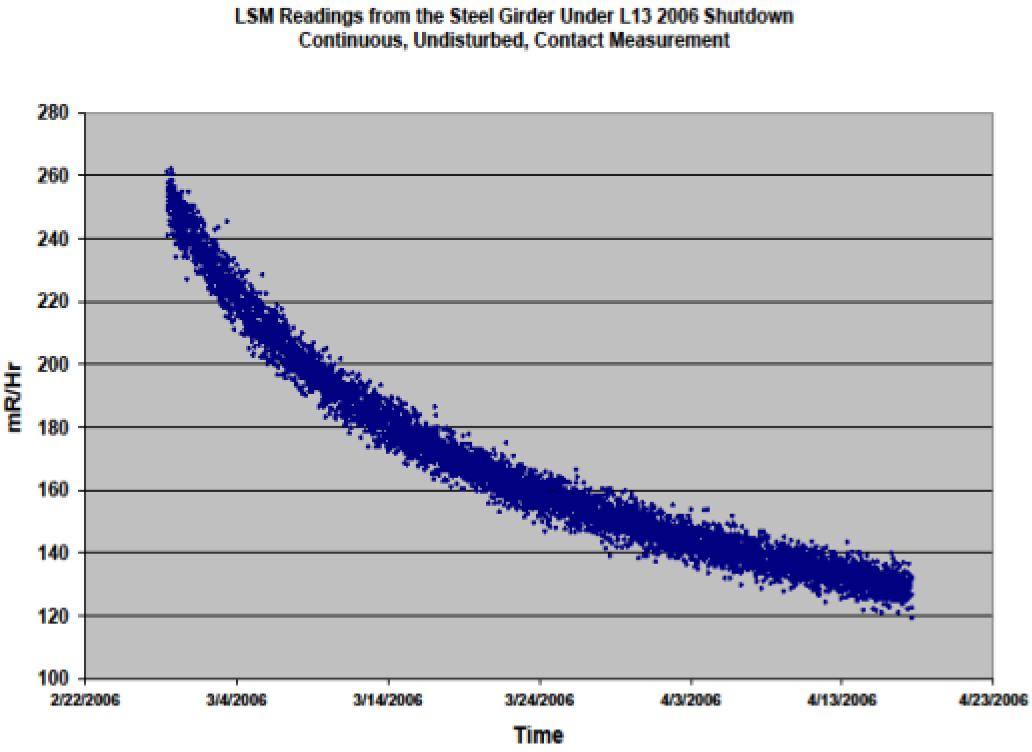


Figure 6: Measured decay rate at L13 over a 1-month period.

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, and Health (ES&H) Division Radiation Physics Operations (RP0) Department under the direction of the assigned Radiation Safety Officer (RSO).

III-4.2.1.3 Groundwater 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][6], 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 DOE Derived Concentration Standard of 2600 picocurie (pCi)/milliliter (ml) ^{3}H and 16 pCi/ml ^{22}Na. Ground water activation was found to be negligible.

The measured beam loss on the collimators [7] has been used to scale previous simulations of star density production rate [8]. The scaled star density production rate has been used for calculation of water activation [9]. 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 [10] used to calculate a surface water of 9.2% of the total limit and negligible ground water activation [11]. The ES&H Division RPO Group periodically samples the water at designated areas and Booster sumps to confirm safe operation.

This hazard has also been evaluated within the common Risk Matrix Tables included in SAD Section I Chapter 04 Safety Analysis. Work in the Booster area involving this hazard implements the controls specified in the common Risk Matrix Tables, Table C.11. The Baseline risk of R IV remains a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.1.4 Surface Water Activation

See section III-4.2.1.3.

III-4.2.1.5 Radioactive Water (RAW) Systems

N/A.

III-4.2.1.6 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 an offsite member of the public to 10 mrem/year [12], [13]. 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. Continuous monitoring is required for emission points when the effective dose equivalent from air emissions to an offsite member of the public exceeds 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 109 minute 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, Booster Absorber Air Activation, April 4, 2016, AD Beams-doc-5133-v1 [14].

After completion of the risk analyses shown in Section III-4.9 Appendix – Risk Tables, Tables 8.1-8.3, the baseline risk level I has been reduced to a residual risk level of IV.

This hazard is not applicable to this area with the above calculations.

III-4.2.1.7 Closed Loop Air Cooling

N/A.

III-4.2.1.8 Soil Interactions

N/A.

III-4.2.1.9 Radioactive Waste

Radioactive waste produced in the course of Booster operations is managed within the established Radiological Protection Program (RPP) and as prescribed in the Fermilab Radiological Control Manual (FRCM).

Radioactive waste is a standard radiological hazard that is managed within the established RPP 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, beam loss and, in the case of some beam diagnostics devices, intentional interception of the beam will result in activation of beam line elements. Reuse of activated items will be carried out when feasible. Activated items that cannot be reused will be disposed of as radioactive waste in accordance with the FRCM requirements.

III-4.2.1.10 Contamination

Contamination resulting from beam operations in the vicinity of accelerator components is a hazard that is mitigated with periodic measurements and decontaminations. Signage is added when required and contaminated regions are isolated by stanchion barriers. RWPs are in place to describe the requirements for work in these regions under approval of the assigned RSO. After completion of risk analysis shown in Tables 8.1-8.3, the Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. RWPs and ALARA plans must be written and followed in accordance with the FRCM requirements.

III-4.2.1.11 Beryllium-7

Be-7 has been detected in periods 1, 2, 3, 6, 7 and the Beam Absorber. These areas of contamination have been found along the beamline components and not the aisle way. These areas have been roped off and signage has been posted. After completion of risk analysis shown in Tables 8.1-8.3, the Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken.

III-4.2.1.12 Radioactive Sources

N/A.

III-4.2.1.13 Nuclear Material

N/A.

III-4.2.1.14 Radiation Generating Devices (RGDs)

N/A.

III-4.2.1.15 Non-Ionizing Radiation Hazards

The Booster RF 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 ES&H Division Industrial Hygiene Group periodically monitors for stray RF fields in the work areas.

III-4.2.1.15.1 Lasers

There is a Class IV Nd:YAG (neodymium-doped yttrium aluminum garnet) laser 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. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.1. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken.

III-4.2.2 Toxic Materials

The Booster Facility contains lead and beryllium. The hazards have been evaluated and are discussed further below and elsewhere in the Fermilab SAD.

There are legacy lead shielding bricks at L13 Notch Absorber. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.2. The Baseline risk of R II has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.2.1 Beryllium

There is a beryllium window in the Booster dump. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.2. The Baseline risk of R II has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.2.2 Fluorinert & Its Byproducts

N/A.

III-4.2.2.3 Liquid Scintillator Oil

N/A.

III-4.2.2.4 Pseudocumene

N/A.

III-4.2.2.5 Ammonia

N/A.

III-4.2.2.6 Nanoparticle Exposures

N/A.

III-4.2.3 Flammables and Combustibles

The Booster presents flammable and combustible hazards identified in Table 1. Unusual hazards are present in the form of flammable hydrogen gas used in the source.

III-4.2.3.1 Combustible Materials

The source of combustible materials in Booster come mainly from current carrying cables. These cable outer insulation jackets have been specified to be fire retardant. After completion of risk analysis shown in Tables 8.7-8.9, the Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken.

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table in Appendix C of this document. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.3.2 Flammable Materials

The risk of flammable materials catching fire in the Booster tunnel is reduced by good housekeeping. In addition to normal work in Booster which includes good housekeeping, there are tunnel cleanups during annual shutdowns. Therefore, this hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.3. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.4 Electrical Energy

The Booster electrical hazards fall within the scope described in Section I, Chapter 04 of the Fermilab SAD. The notable accelerator-specific electrical hazards are the power supplies for the beamline magnetic components and the modulators/Bias supplies 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. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.4. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.4.1 Stored Energy Exposure

The Booster electrical hazards from the alternating current (AC) power distribution systems and the power supplies for the beam line magnetic components have been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix table. The notable accelerator-specific electrical hazard is the modulators and Bias supplies for the high-power RF sources, e.g. RF systems. The RF modulators represent sources of high voltage and high stored electrical energy. These hazards are mitigated by containing this equipment in interlocked cabinets and by following RF Department written Lock Out / Tag Out procedures for access to the RF system enclosures for maintenance of the equipment.

The Booster Gradient Magnet Power Supply system utilizes capacitor banks to create a resonant circuit for generating the AC current to power the main combined function magnet system. These capacitors normally discharge when the system is turned off. Their Standard Operating procedures to mitigate this hazard. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table 8, 8.10-8.12. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.4.2 High Voltage Exposure

The Booster RF systems magnet and power supply systems as well as instrumentation and vacuum systems with high voltage hazards are addressed in the standard operating procedure.

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common

Risk Matrix Table 2, 2.10-2.12. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.4.3 Low Voltage, High Current Exposure

The Booster RF Cavity system and pulsed Magnets utilizes high current hazards that are addressed in the standard operating procedure which address this hazard.
This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table 2, 2.10-2.12. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.5 Thermal Energy

The hazards associated with thermal energy are covered below.

III-4.2.5.1 Magnet Bakeouts

Historically, Booster does not perform magnet or beam pipe bakeouts. However, if there is a need for bakeouts, this hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C5. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.5.2 Hot Work

Welding, brazing and cutting may need to be done during Booster maintenance periods. If there is a need for this type of work to be done, this hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C5. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.5.3 Cryogenics

N/A.

III-4.2.6 Kinetic Energy

The Booster presents kinetic energy hazards identified in Table 1. All kinetic energy hazards present in Booster areas are in the form of Non-Accelerator-Specific Hazards (NASH), and their analysis will be summarized in this SAD Chapter.

III-4.2.6.1 Power Tools

Powered hand tools are used as needed. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.6. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.6.2 Pumps and Motors

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.6. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.6.3 Motion Tables

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.6. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.6.4 Mobile Shielding

N/A.

III-4.2.7 Potential Energy

The Booster presents potential energy hazards identified in Table 1. All potential energy hazards present in Booster areas are in the form of Non-Accelerator-Specific Hazards (NASH), and their analysis will be summarized in this SAD Chapter.

III-4.2.7.1 Crane Operations

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.7. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.7.2 Compressed Gasses

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.7. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.7.3 Vacuum/Pressure Vessels/Piping

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.7. The Baseline risk of R I has been reduced to a residual risk level of R III after control measure were taken. No unique controls are in use.

III-4.2.7.4 Vacuum Pumps

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.7. The Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken. No unique controls are in use.

III-4.2.7.5 Material Handling

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.7. The Baseline risk of R I has been reduced to a residual risk level of R III after control measure were taken. No unique controls are in use.

III-4.2.8 Magnetic Fields

The Booster presents magnetic field hazards identified in Table 1. Unusual hazards are present in the form of fringe fields which may interfere with implanted medical devices.

III-4.2.8.1 Fringe Fields

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. After completion of risk analysis shown in Tables 8.22-8.23, the Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken.

Inside the tunnel, the fringe field hazard mainly comes from powered corrector magnets and permanent magnets that are in ion pumps. Fields are nominally only hazardous to people who have heart pacemakers. The likelihood of the fringe field causing a malfunction to the pacemaker is reduced by work planning, warnings in the hazard specification sheet and warnings at all Booster entry points about this hazard. After completion of risk analysis shown in Tables 8.22-8.23, the Baseline risk of R I has been reduced to a residual risk level of R III after control measures were taken.

III-4.2.9 Other Hazards

The Booster presents other hazards identified in Table 1. All other hazards present in Booster areas are in the form of Non-Accelerator-Specific Hazards (NASH), and their analysis will be summarized in this SAD Chapter.

III-4.2.9.1 Confined Spaces

The confined space is at L1/L24 400 MeV injection chute. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.9. The Baseline risk of R

I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.9.2 Noise

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.9. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.9.3 Silica

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.9. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measure were taken. No unique controls are in use.

III-4.2.9.4 Ergonomics

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.9. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.9.5 Asbestos

Potential for Asbestos in Booster could be found on legacy infrastructure. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.9. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.9.6 Working at Heights

Tall ladders are needed to perform occasional task for repair or maintenance. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.9. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.10 Access & Egress

III-4.2.10.1 Life Safety Egress

There are 7 egress points in Booster: 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. These egress points are spaced so that this hazard has been evaluated to be within the common

Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.10. No unique controls are in use.

III-4.2.11 Environmental

III-4.2.11.1 Hazard to Air

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.11. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.2.11.2 Hazard to Water

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.11. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measure were taken. No unique controls are in use.

III-4.2.11.3 Hazard to Soil

This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Booster involving this hazard implements the controls specified in the common Risk Matrix Table C.11. The Baseline risk of R I has been reduced to a residual risk level of R IV after control measures were taken. No unique controls are in use.

III-4.3. Maximum Credible Incident Scenario(s) for the Accelerator Specific Hazard(s)

III-4.3.1 Definition of a Maximum Credible Incident

This section of the Booster SAD evaluates the maximum credible incident (MCI) scenario that could happen in the Booster segment. Consideration and analysis of this MCI is focused on an onsite facility worker, onsite co-located worker, and a maximally exposed off-site individual (MOI).

III-4.3.1.1 Radiological Hazard

The Booster accepts H- ion beam from the Linac which it then converts to protons during the injection process. The proton beam is then accelerated from 400 MeV to 8 GeV with various components bending and focusing the beam while the RF system accelerates the particles until they are extracted. The beam is sent to downstream users or a beam absorber. During this process beam could be lost due to various reasons. Most if not all cases of beam loss are typically detected and controlled via normal monitoring and loss detection systems.

The beam loss magnitude can vary from a small percentage to complete extinction of the beam. Beam loss in the Booster Accelerator system can occur due to beam scraping carrier beam pipe and magnet assemblies as beam undergoes its 33ms trip from injection to extraction. A series of failures taking place in such a way that beam could be lost at the highest intensity and for a duration of time sufficient to cause the greatest radiological hazard at locations requiring more rigorous protection, will be considered for our maximum credible incident (MCI) scenario.

Based on Booster Synchrotron Accelerator system design and historical performance data of actual beam operations, the following MCI scenario is presented for the current Booster configuration and capabilities.

Booster Design Parameters relevant to MCI Scenario:

1. Booster Beam was initially designed for 4E12 protons per cycle. TM-405 0300[15]
    a. With accelerator improvements Booster can now deliver between 4.5-5E12 protons per pulse or 15-Hz cycle at about 93% efficiency for normal operation.
    b. Based on simulations, Booster could accept up to 1E13 protons at injection based on simulations noted in "Booster Beam Injection Simulations with SC using ESME for Current Operation for SAD" [16] but lacks the RF beam loading compensation to accelerate beam from 2 GeV onwards due to Robinson instability, as noted in "The required number of wide bore cavities for PIPII"[17]
    c. The maximum intensity seen extracted historically on studies pulses at 8Gev to the downstream machine is 6E12 to 6.5E12 with 80-85% efficiency for studies purposes.
2. Machine cycle time is 15Hz which is defined by resonant circuit design of the GMPS Magnet System.
3. Multi-turn injection is limited to 60us due to physical flattop current of Injection device ORBUMP.

Upstream machine MCI condition parameters if applied in addition to MCI events in Booster would not be credible as it would be an unreasonable scenario with too many failures in series leading to the Booster MCI. The Booster MCI will be defined in a manner that is consistent with the intent and purpose of this section. The MCI reflects theoretical accident scenarios for the Fermilab Booster requiring many unlikely conditions to be met to establish a higher than normal beam intensity and subsequent beam loss.

The following parameters contribute to the following analysis and calculation of the maximum credible beam intensity in Booster:

The maximum injected beam scenario is characterized by the following values:

35mA (Linac) * 60us (Booster Orbump Limit) * 6.25E9 = 1.3E13 injected protons per 15Hz pulse at 400 MeV for an hourly rate will be 7E17 protons per hour.

Due to the Booster RF bucket size, capture capability is limited to 1E13 protons based on simulations at 400MeV. It follows that the hourly rate of 1E13 protons * 54000 pulses/hr * 0.7(cycle eff due to RF Robinson instability, beam loading) = 3.8E17 protons/hour at 8 GeV.

This analysis shows that the maximum credible incident intensity for the Fermilab Booster is:

- 7E17 protons/hour at an energy of 400 MeV persistently lost on a beamline component at the injection region with non-circulating beam.
- 5.4E17 protons/hour being captured, circulating. The reduction in beam intensity is due to the Booster RF bucket limit.

- The beam intensity will be 3.8E17 protons per hour for 8 GeV, which is less than the 400 MeV value, due to inherent efficiency losses in capture and acceleration. The Booster could yield up to 7E12 protons per 15Hz cycles potentially to downstream machines under the most favorable and unlikely scenarios.

This accident condition describes, as currently understood, scenarios for the Fermilab Booster. The maximum intensity/loss is a result of the following conditions:

1. Booster Injecting 240% of the normal beam intensity at 400 MeV and extracting 140% of normal 8GeV beam intensity per 15-Hz pulse for an hour and losing all the beam in a single turn at random times in the cycle.
2. Beam requested at 15 Hz rep rate for one hour.
3. Beam is mis-steered at any point in the acceleration cycle and lost completely for the following possible reasons:
    a. Failed or improperly set magnets/kickers or other accelerator devices.
    b. Operator errors in selecting operational parameters.
    c. Accelerator system timing errors.
    d. Solid beam obstruction in beam path.

The Booster has a series of credited active controls that are set to inhibit beam once exposure levels reach a preset level. These consist of Total Loss Monitors (TLMs) and Chipmunks described later in Section III-4.4.2 Active Engineered Credited Controls. This would make the scenario of losing high intensity beam for an hour unlikely.

Assuming no shielding is present, this incident would result in a dose to the MOI exposure could be as high as 8e6 rem. The result is that the uncontrolled baseline qualitative risk level associated with this accident is not acceptable.

Fermilab uses Credited Controls that flow down to the Accelerator Safety Envelope (ASE) to mitigate the consequences of the MCI to the following conditions:

- 5 rem in one hour in any area accessible by facility workers or co-located workers
- 500 mrem in one hour in all Laboratory areas to which the public is assumed to be excluded
- 100 mrem in one hour at Fermilab's site boundary and/or in any areas onsite in which the public is authorized (which includes Batavia Road, Prairie Path, parking lots open to the public, and general access areas including Wilson Hall, Ramsey Auditorium.

These credited controls are discussed in Section III-4.4.

The accumulated dose outside of the berm is mitigated, by use of Credited Controls, to less than 500 mrem in an MCI. The closest possible location of a member of the public to the Booster enclosure is the Wilson Hall parking lot. This location is more than five feet away from the berm, which would result in a dose of less than 100 mrem applying a conservative dose reduction of 1/r. Other locations where the public is authorized near Booster, including public parking lots, roads, Wilson Hall, and Ramsey Auditorium, are further away and therefore would result in dose of much less than 100 mrem applying the same conservative dose reduction of 1/r.

III-4.4. Summary of Credited Controls

This section describes the credited controls that are required to reduce the risk associated with the maximum credible incident to the conditions outlined in Section III-4.3.1.1.

III-4.4.1 Credited Engineering Controls

The purpose of this section is to provide the information necessary to understand the engineering controls that are used to prevent or mitigate the consequences of the maximum credible incident. Engineering controls can be classified as passive or active. This section presents a separate discussion of the engineering controls that fall under each classification.

III-4.4.1.1 Passive Credited Engineering Controls

Passive controls are elements of facility design that require no action to function properly. These are fixed elements of the beam line that take direct human intervention to remove. The Booster enclosure is designed and constructed as a permanent concrete and earth-covered radiation shield that uses a combination of permanent shielding, movable shielding, and penetration shielding to protect personnel from radiological exposure due to the MCI.

III-4.4.2 Shielding

III-4.4.2.1.1 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. 12.5 efd shielding minimum for the Booster enclosure.
2. Injection Beam Line downstream of the 400 MeV chute;
3. Booster Ring (twenty-four periods);
4. Extraction Beam Line up to the MI-8 803/804 location;
5. Transfer Beam Line to, and including, the Booster 8 GeV Beam Absorber; and
6. 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. There is a minimum of 12.5 e.f.d. of shielding in Booster comprised of concrete, dirt and steel around the enclosure.

All existing shielding is a credited.

III-4.4.2.1.2 Movable Shielding

The Booster has no outside areas with movable shielding. However, there are three regions internal to Booster with removable 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.

III-4.4.2.1.3 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 2 gives the location and number of penetrations around the Booster enclosure.

Table 2: 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.

III-4.4.2.2 Active Credited Engineering Controls

Active engineered controls are systems designed to reduce the risks from the MCI to an acceptable level. The active controls in place for Booster operations are discussed below.

III-4.4.2.2.1 Radiation Safety Interlock System

The Booster enclosure employs a Radiation Safety Interlock System (RSIS).

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.

Prior to accelerator operations, a Search and Secure is performed to establish the interlock system for the Exclusion Area(s). This Search and Secure ensures no personnel are remaining within the Exclusion Area(s) during accelerator 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) and chipmunk radiation monitors both internal and external to the enclosure. The following figure shows the configuration of the TLMs and Chipmunks. The credited control trip limits for these interlocked radiation detectors are set to levels that prevent any individual from receiving a dose rate beyond what is defined in Section III-4.3.1.1. Operationally, the trip levels are set lower than this value to satisfy occupancy requirements per 10 CFR Part 835 through the direction of the Radiation Physics Operation Department (RPO).

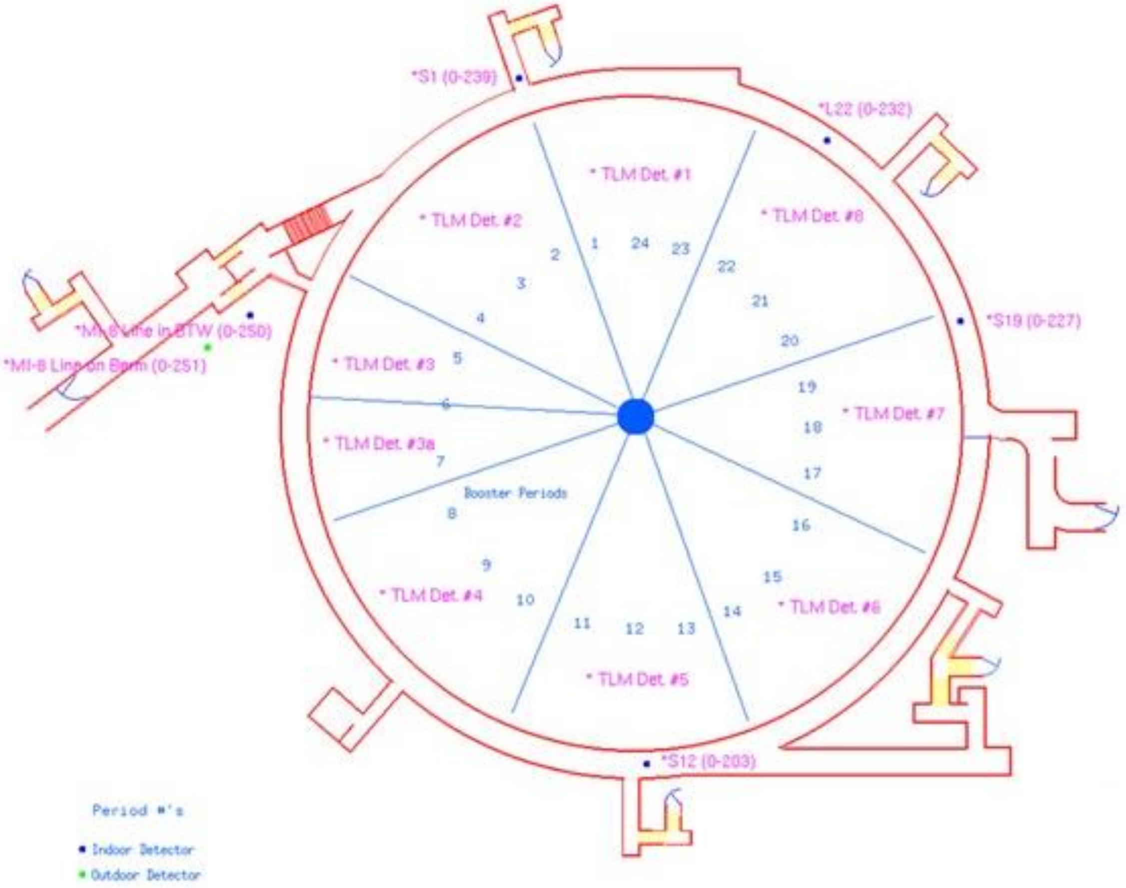


Table 3 Summary of the interlocked radiation detectors used by the Booster RSIS.

Type	Location	CC Limit
Chipmunk	Booster East Fan Room (Short 12)	490 mrem/hr
Chipmunk	Booster Crossover at CUB (Short 19)	490 mrem/hr
Chipmunk	Booster/Line W Gal Intersect (Long 22)	235 mrem/hr
Chipmunk	Booster Per 1 Exit Stairwell (Short 1)	490 mrem/hr
Chipmunk	MI-8 Line in WBT (12’ US of Buttress)	39 mrem/hr
Chipmunk	MI-8 Line on Berm (WBT)	490 mrem/hr
TLM	BSTR TLM1 Per 23, 24, 1	10000 nC/min
TLM	BSTR TLM2 Per 2, 3, 4	10000 nC/min
TLM	BSTR TLM3 Per 5, 6	10000 nC/min
TLM	BSTR TLM4 Per 8, 9, 10	10000 nC/min
TLM	BSTR TLM5 Per 11, 12, 13	10000 nC/min
TLM	BSTR TLM6 Per 14, 15, 16	10000 nC/min
TLM	BSTR TLM7 Per 17, 18, 19	10000 nC/min
TLM	BSTR TLM8 Per 20, 21, 22	10000 nC/min
TLM	BSTR TLM3a Per 6, 7	10000 nC/min

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.

III-4.4.3 Credited 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 below.

III-4.4.3.1 Operation Authorization Document

Beam will not be transported through the Booster enclosure without an approved Beam Permit and Running Condition. The Beam Permit specifies beam power limits as determined and approved by the AD Associate Laboratory Director, in consultation with the ES&H RPO Head, assigned RSO, AD Operations Department Head, and AD Proton Source Department Head. The Running Condition for the Linac describes the operating configuration as reviewed by the assigned RSO, AD Operations Department Head, and AD Proton Source Department Head and as approved by the AD Associate Laboratory Director.

III-4.4.3.2 Staffing

Commissioning, normal operations, and emergency management of the Booster are all conducted under the auspices of the AD Headquarters, the AD ES&H Department, and the AD Operations Department in accordance with the Fermilab SAD.

The MCR must be appropriately staffed according to ensure operations within bounding conditions specified in Operation Authorization Document, and to disable beam operation to the Booster and initiate an immediate response in the event of a determined ASE violation.

The following staffing shall be in place during applicable beam operation:

- At least one member of the AD Operations Department who has achieved the rank of Operator II or higher shall be on duty and on site.
- At least one member of the AD Operations Department shall be present in the Main Control Room (MCR).
- A single person could satisfy both of these conditions.

III-4.4.3.3 Accelerator Operating Parameters

To ensure operations within bounding conditions used in the MCI analysis, the following intensity shall not be exceeded: 7E12 protons/hr at 8 GeV with a cycle rate of 15Hz. For an hour.

III-4.5. Summary of Defense-in-Depth Controls

The Fermilab Booster has additional controls in place that reduce the risk associated with the maximum credible incident, but that are not required to mitigate it. These controls are considered defense-in-depth, and they are defined in the following sections.

III-4.5.1 Defense-in-Depth Engineering Controls

Under normal operating conditions, the Booster is not hazardous to members of the public. Defense in depth exists in the form of active and passive controls sufficient to contain hazards even during unforeseen events. The Booster is not in a designated public area.

III-4.5.1.1 Active Defense-in-Depth Engineering Controls

III-4.5.1.1.1 Machine Protection Controls

The Booster also uses beam loss monitors and vacuum monitors will inhibit beam due to high beam loss. RF systems will inhibit due to excessive beam loading and beam loss events at cavities.

III-4.5.1.2 Defense-in-Depth Administrative Controls

III-4.5.1.2.1 Fencing and Posting

Select Booster berm areas are posted or fenced for ALARA purposes.

III-4.5.1.2.2 Training

All personnel engaged in the commissioning, operation, and emergency management of the Booster shall have at a minimum, Fermilab's Radiation Worker training current. Furthermore, personnel approved for access into the Booster's interlocked enclosure shall have Fermilab's Controlled Access training current as well.

III-4.5.1.2.3 Procedures

As applicable, either Fermilab's General Lock Out-Tag Out or Written Departmental Lock Out-Tag Out procedures shall be used. As per Fermilab's FESHM Chapter 2100, Written Departmental Safety procedures shall be reviewed and re-approved every twelve (12) months, at a minimum, or when the configuration of the equipment has been altered. Re-training for these procedures shall also be carried out every twelve (12) months to remain current.

III-4.6. Decommissioning

DOE Field Element Manager approval shall be obtained prior to the start of any decommissioning activities for Booster.

III-4.7. Summary and 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 this Fermilab Safety Assessment Document.

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.

III-4.8. References

[1] Fermilab Radiological Control Manual

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

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

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

[5] N.V. Mokhov, *The MARS Code System User's Guide*, Fermilab-FN-628 (1995).

[6] 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).

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

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

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

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

[11] W. Schmitt, *Booster Notcher Absorber Groundwater & Surface Water 10-20-2016*, October 2016.

[12] 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.

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

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

[15] TM-405 0300 Booster Synchrotron, E.L. Hubbard 1973

[16] Booster Beam Injection Simulations with SC using ESME for Current Operation for SAD, C. Bhat AD Beams-doc-10058-v1, November 10, 2023.

[17] The required number of wide bore cavities for PIPII. C.Y. Tan, C. Bhat, W. Pellico, February 4 2022

[18] Booster MCI Analysis justification

III-4.9. Appendix – Risk Tables

Risk Assessment methodology was developed based on the methodology described in DOE-HDBK-1163-2020. Hazards and their potential events are evaluated for likelihood and potential consequence assuming no controls in place, which results in a baseline risk. A baseline risk (i.e., an unmitigated risk) value of III and IV does not require further controls based on the Handbook. Events with a baseline risk value of I or II do require prevention and/or mitigation measures to be established in order to reduce the risk value to an acceptable level of III or IV. Generally, preventive controls are applied prior to a loss event, reflecting a likelihood reduction, and mitigative controls are applied after a loss event, reflecting a consequence reduction. For each control put in place, likelihood or consequence can have a single "bin drop", resulting in a new residual risk (i.e., a mitigated risk). This risk assessment process is repeated for each hazard for Facility Workers (FW), Co-Located Workers (CLW), and Maximally-Exposed Offsite Individual (MOI). At the conclusion of the risk assessments, controls that are in place for the identified accelerator specific hazards are identified as Credited Controls and further summarized in Section III-4.4 of this Chapter as well as SAD Chapter VII-A.1 *Accelerator Safety Envelope – Fermilab Main Accelerator*.