LINAC

SECTION III CHAPTER 01 OF THE FERMILAB SAD

Revision 3 March 1, 2024

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

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SAD Chapter Review

This Section III, Chapter 01 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD), *Linac*, 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.

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Accelerator Safety Department Head

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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
Maddie Schoell Jessica Malo	3	March 1, 2024	• Updated Section III-1.2.8.1, Fringe Fields • Included Risk level summary statement
John Stanton C.Y. Tan Lionel Prost	2	December 21, 2023	• Incorporation of maximum credible incident for a radiological hazard and a description of the credited/defense-in-depth controls that mitigate it. • Updated Section III-1.1.3, Description of the Linac
CY. Tan Salah Chaurize Mike Wesley	1	August 7, 2023	• Updated to incorporate updated SAD Layout • Incorporation of Risk Matrix tables and hazard discussion
William Pellico Fernanda G. Garcia	0	March 18, 2013	Initial Release of the Linac Accelerator Chapter for the Fermi National Accelerator Safety Assessment Document (SAD)

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Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ACNET	Accelerator Control Network System
AC	Alternating Current
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
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
E.F.D.	Equivalent Feet of Dirt
EMS	Environmental Management System
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
ESH	Environment, Safety & Health Division
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
^{3}H	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
ITA	Irradiation Test Area
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	Harge Hadron Collider
LLCF	Low Level Calibration Facility
LLN	Linac Laser Notcher
LLWCP	Low Level Waste Certification Program
LLWHF	Low Level Waste Handling Facility
LN2	Liquid Nitrogen
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
MeV	Mega-electron volt
MHz	Megahertz
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
NTF	Neutron Therapy 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 Injection Line
RMA	Radioactive Material Area
RMS	Root Mean Square
RPCF	Radiation Physics Calibration Facility

RPE	Radiation Physics Engineering Department
RPO	Radiation Physics Operations Department
RPP	Radiological Protection Program
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
SCL	Side Coupled Linac
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

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III-1. Linac

III-1.1. Introduction

This Section III, Chapter 01 of the Fermi National Accelerator Laboratory (Fermilab) Safety Assessment Document (SAD) covers the Linac segment of the Fermilab Main Accelerator.

III-1.1.1 Purpose/Function

The purpose of the Linac accelerator is to accelerate H^- ion beam from rest energy to 400 MeV. There are two possible beam energies and five possible extraction areas that Linac beam can be extracted to. Beam can be extracted at 66 MeV towards the Neutron Therapy Facility (NTF) and the remaining four areas are at 400 MeV. These areas are Booster synchrotron accelerator, the 400 MeV Test Area (MTA) and two Linac beam absorbers. The MTA beamline, including the portion of the Linac enclosure within which it is housed, is covered in Section III Chapter 2 of the Fermilab SAD.

III-1.1.2 Current Status

The Linac segment of the Fermilab Main Accelerator is currently: **Operational**.

The extraction area known as NTF is currently: **Non-Operational**.

III-1.1.3 Description

The Linac Facility at Fermi National Accelerator Laboratory overview map is shown in Figure 1.

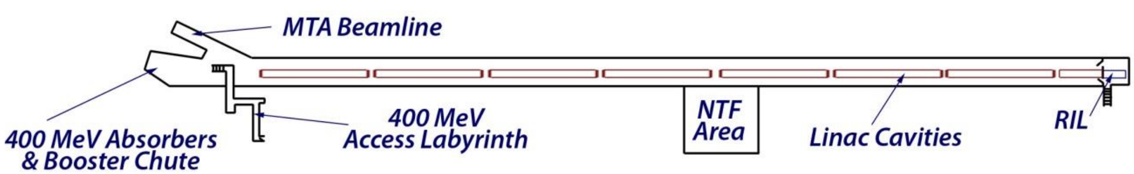

Figure 1: Linac overview.

The Radio Frequency Quadrupole Injection Line (RIL) is at the north end (See Figure 2) of the enclosure. The RIL is composed of two 35 keV magnetron sources followed by a 750 keV Radio-Frequency Quadrupole (RFQ). The line uses conventional technology such as solenoids, a buncher cavity, quadrupoles, and steering magnets to match into the Linac.

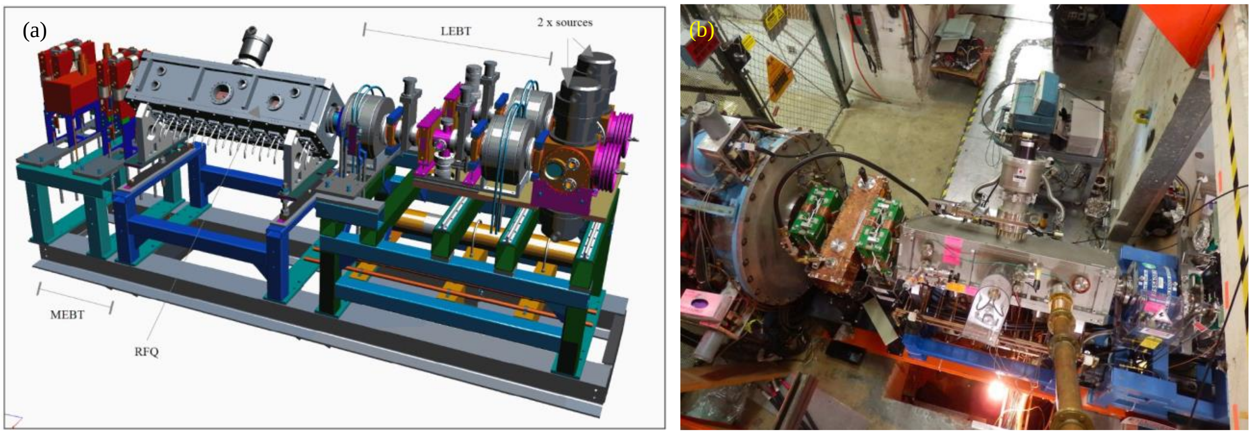

Figure 2: (a) A 3D drawing of the RIL. Shown here are the 2 H- sources (one active, and the other a hot spare), a short LEBT (low energy beam transport), RFQ and a very short medium energy beam transport (MEBT). (b) is the top view of the RIL connected to Tank 1.

The Linac is approximately 200 m long. It is made up of five 201.25 MHz drift tube linac (DTL) tanks that accelerate the beam from 750 keV to 116 MeV and seven 805 MHz side coupled linac (SCL) sections that accelerate the beam to its final energy of 400 MeV (See Figure 3). At the end of the Linac, there are transfer line components that transport beam to four different areas (See section III-1.1.6).

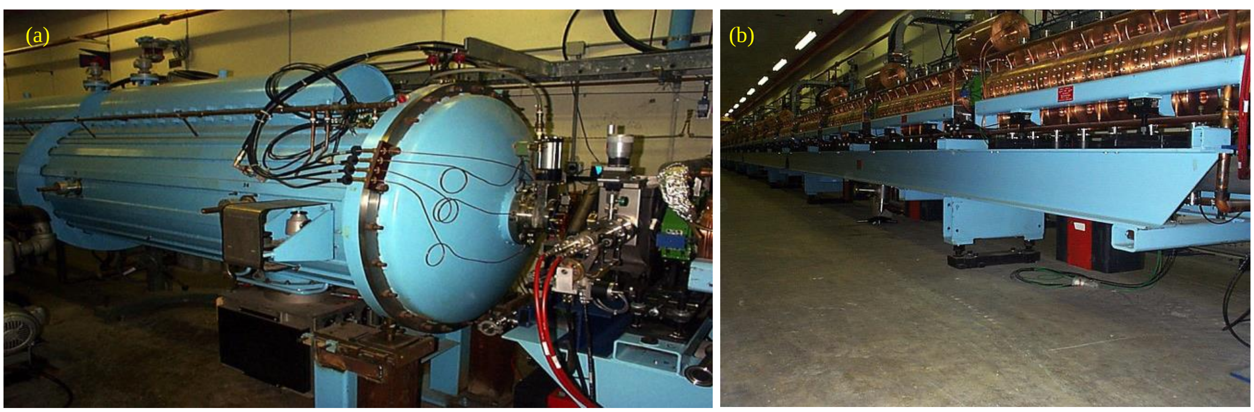

Figure 3: (a) One of the DTL tanks (blue cylinder). (b) The SCL sections sitting on a blue girder.

The Linac equipment gallery is located above and to the east of the enclosure floor level. The Linac radio-frequency (RF) and control equipment operate at 15 Hz repetition rate, but the actual beam cycle rate is dependent upon the users. The average beam current in the Linac is less than 30 mA.

For beam monitoring and diagnostics, Linac utilizes approximately 30 beam position monitors (BPMs), 30 beam loss monitors (BLMs), and 20 beam toroids that measure the beam current. The Linac also utilizes one emittance probe at the 10 MeV region and approximately a dozen single-wire scanners located along the high energy Linac for beam control. Linac diagnostics are typically located between the DTL tanks and SCL sections.

III-1.1.4 Location

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

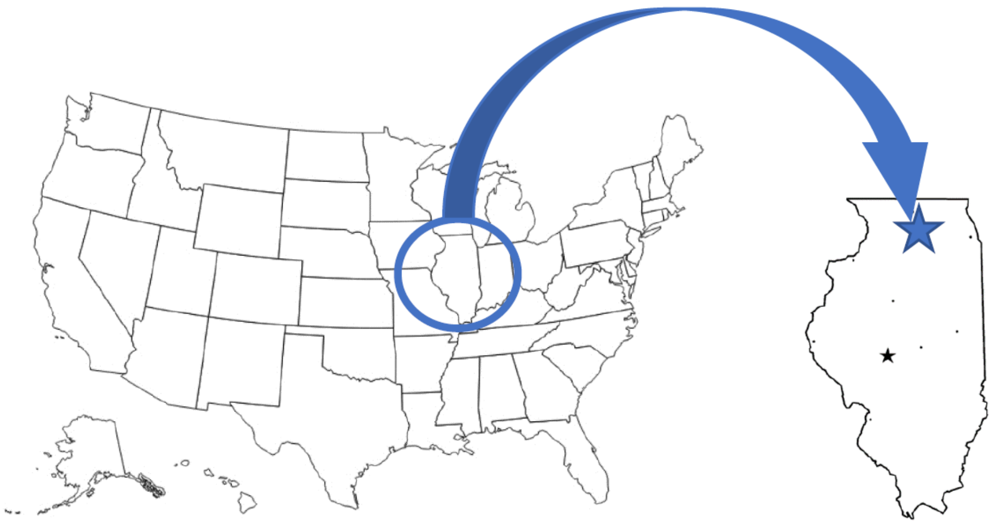

Figure 4. Regional view showing the location of the Fermilab site in Batavia, IL.

The Linac is located in the central campus on the Fermilab site. See Figure 5.

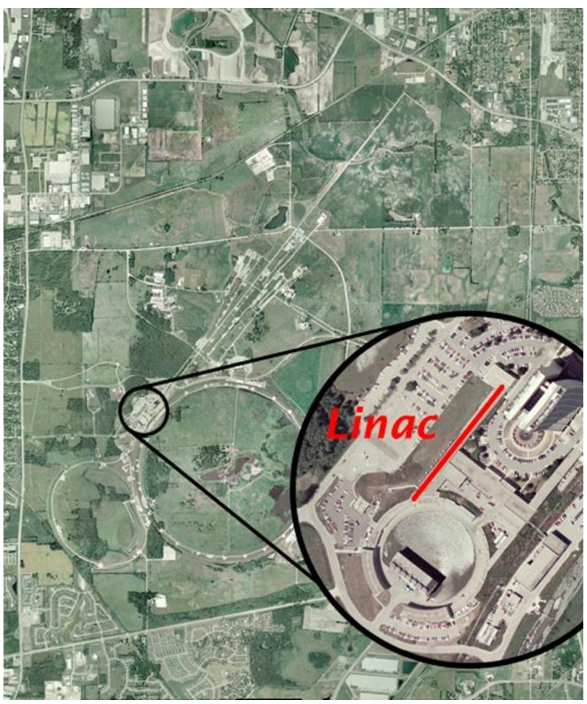

Figure 5. Aerial view of the Fermilab site, indicating the location of the Linac.

III-1.1.5 Management Organization

The Beams Division/Proton Source Department is responsible for the operation and maintenance of all Linac RF cavities, RF generators, power supplies, and instrumentation with support from the Accelerator Complex Technology Division. The Beams Division Operations Department monitors the state of the Linac from the Main Control Room (MCR) at all times and requests assistance from the Linac Group when there are deviations from normal operating conditions. Building infrastructure is maintained by the Infrastructure Services Directorate.

III-1.1.6 Operating Modes

The RIL extracts H^- beam and accelerates to 750 keV from the source on a 15 Hz duty cycle. When the beam permit system allows, the Pre-accelerator (Preacc) Pulse Shifter module synchronizes the timing of the RIL to match the 1st Linac RF cavity and beam is accelerated in the Linac. If there is no permit, beam arrives at the Linac when there is no RF present in the cavities and dissipates. This is known as a Standby Pulse. There are three accelerating modes of Linac operation:

- High Energy Physics (HEP) beam (Figure 6): This is the primary mode of operation where beam is accelerated to 400 MeV and extracted to the Booster synchrotron via an electrostatic chopper to the field region of the Booster Lambertson. For every 2.2 μs of H^- beam a laser is fired to neutralize a small portion of beam. The neutral beam is not accelerated and provides space for Booster beam manipulations. The repetition rate and pulse length are configurable up to 15 Hz and 44 μs, respectively. Beam current is dependent on conditions in the source but is typically from 20 to 25 mA at 400 MeV.
- MTA beam (Figure 6): The MTA beamline provides beam to the Irradiation Test Area (ITA) which is a 400 MeV fixed-target experimental enclosure. Additionally, the MTA beamline can be used to evaluate Linac emittance at 400 MeV. Beam is directed to the MTA beamline by two pulsed C-magnets before and after the electrostatic chopper. Operationally, MTA can extract up to eight 15 Hz Linac pulses once a minute. The MTA beamline, including the portion of the Linac enclosure within which it is housed, is covered in Section III Chapter 2 of the Fermilab SAD.
- Linac Studies (Figure 6): To evaluate 400 MeV beam or check proper functioning of equipment, Linac output can be directed to one of two beam dumps. The most common mode of operation utilizes a dipole magnet to direct beam to the momentum dump which can dissipate 10 kW of beam power; the maximum output of the Linac under normal running conditions. Linac Studies pulses can be requested at 15 Hz up to 60 μs width.

Figure 6 shows the end of the Linac enclosure area with the 400 MeV transfer line to Booster, the MTA extraction line, and the two possible beam absorbers for Linac beam. Table 1 presents a summary of all available Linac beam operational modes.

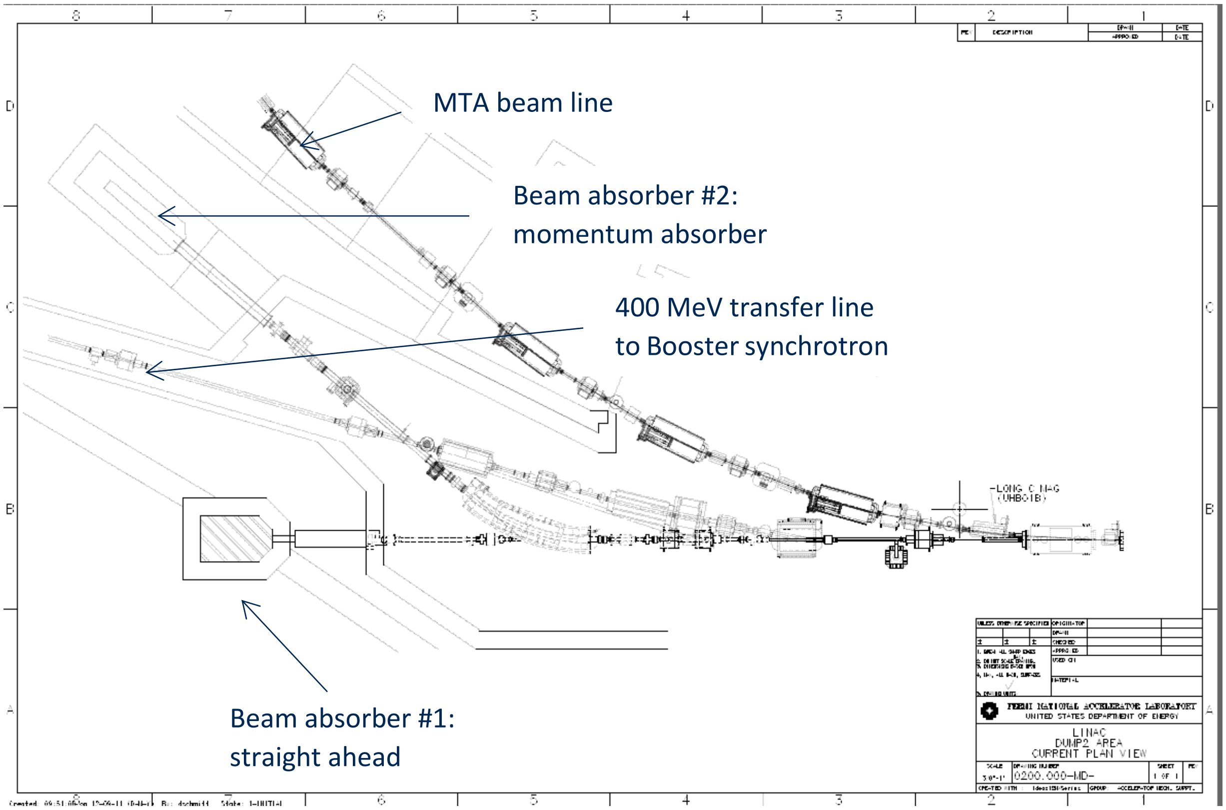

Figure 6: Linac 400 MeV extraction areas, two beam absorbers, 400 MeV transfer line to Booster and MTA extraction line are indicated here.

Table 1: Linac operational modes.

Operational mode	Approximate intensity	Extraction line
HEP mode (beam to Booster synchrotron)	2.2 - 44.4 μs of < 30 mA. Rate depends upon HEP program (Up to 15 Hz is expected)	400 MeV transfer line (The first 2 μs of each HEP beam pulse goes to the 400 MeV beam absorber #1)
MTA mode	Defined in Section III Chapter 2 of the Fermilab SAD.	MTA beamline
Linac tune-up	Depends upon HEP program but up to 15 Hz at full pulse width of 60 μs	400 MeV beam absorbers

III-1.1.7 Inventory of Hazards

The following table lists all of the identified hazards found in the Linac enclosure and support buildings. Section III-1.9 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-1.2 *Safety Assessment.*

Prompt ionizing radiation 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. Cryogens are not present in quantities sufficient to present an oxygen deficiency hazard (ODH) hazard for Linac areas.

All other hazards present in Linac areas 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 other hazards are considered to be Non-Accelerator-Specific Hazards (NASH), and their analysis will be summarized in this SAD Chapter.

Table 2. Hazard Inventory for Linac.

Radiological		Toxic Materials	
☒	Prompt Ionizing Radiation	☒	Lead
☒	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
☒	Bakeout	☒	Motion Tables
☒	Hot Work	☐	Mobile Shielding
☒	Cryogenics	**Magnetic Fields**	
Potential Energy		☒	Fringe Fields
☒	Crane Operations	**Other Hazards**	
☒	Compressed Gasses	☒	Confined Spaces
☒	Vacuum/Pressure Vessels/Piping	☒	Noise
☒	Vacuum Pumps	☒	Silica
☒	Material Handling	☒	Ergonomics
Access & Egress		☒	Asbestos
☒	Life Safety Egress	☒	Working at Heights

III-1.2. Safety Assessment

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

III-1.2.1 Radiological Hazards

The Linac presents radiological hazards identified in Table 2. Detailed shielding assessments in references [1],[2] address these hazards and provide a detailed analysis of the facility demonstrating the required shielding, controls and interlocks necessary to comply with the Fermilab Radiological Control Manual (FRCM)[1].

After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level I has been reduced to a residual risk level of III or lower.

III-1.2.1.1 Prompt Ionizing Radiation

Ionizing radiation due to beam loss is a primary concern for beam transported through the Linac enclosure. In order to protect workers and the general public, the enclosures and beam pipes are surrounded either by sufficient amounts of shielding (earth, concrete or iron), and/or networks of interlocked radiation detectors to keep any prompt radiation 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-1.3.1.1. 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-1.4. The conclusion of these analyses is that the mitigated dose level associated with prompt ionizing radiation due to beam loss is acceptable.

The assessment requires that:

- All penetrations be filled with shielding as specified.
- All movable shielding blocks be installed as specified.
- All interlocked radiation detectors be installed as specified.
- The radiation safety interlock system be certified as working.
- The average beam intensity in the Linac be limited to 3.54 x 10^{17} protons per hour in the form of 35 mA pulses of 30 μs duration repeated at a frequency of 15 Hz.

This hazard analysis concludes:

- The facility is in conformance with all FRCM requirements and can be operated safely with the following beam parameters:
    - Maximum intensity:
        - Through the DTL Linac is 4.98 x 10^{18} protons per hour
        - Through the SCL Linac is 2.57 x 10^{18} protons per hour
    - Maximum energy:
        - 116 MeV at the end of the DTL Linac
        - 400 MeV at the end of the SCL Linac
    - -Annual limit of 6.4 x 10^{20} protons to either the straight ahead or momentum absorbers.

The RF cavities in the Linac enclosure contain 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 Linac disables RF power to the cavities and thereby eliminates the x-ray hazard whenever personnel access the enclosure.

The 201 and 805 MHz RF power sources for the accelerating cavities are also X-ray producing sources. X-ray shielding for the RF amplifier tubes was developed as part of the Linac 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-1.2.1.2 Residual Activation

High intensity beam delivery of ionizing radiation in the Linac will produce activated materials inside the enclosure which can pose a residual radiation hazard to personnel entering the enclosure. The residual dose rate found in the Linac from initial entry surveys is historically less than 5 mrem/hr. Exceptions include some localized losses found at the transition between the DTL and SCL of less than 20 mrem/hr, and at the 400 MeV area at the Linac-extraction Lambertson, which sets the start of the 400 MeV transfer line to the Booster enclosure, of less than 200 mrem/hr.

Access to activated components in the Linac enclosure is tightly controlled. All potential residual activation hazards are handled operationally as in all other primary beam enclosures. These controls include verification of training, centralized authorization, and key entry. The level of control depends on the level of residual radiation. The controls will follow the administrative controls and safety guidelines found in the Radiological Work Permit (RWP). In most cases, the general RWP for accesses will suffice. A job-specific RWP and an 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. RWPs and ALARA plans must be written and followed in accordance with the FRCM requirements. After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.1.3 Groundwater Activation

Radioactivity induced by the interaction of high-energy ionizing radiation with the soil that surrounds the beam absorbers is addressed in this section. The production of ^{3}H and ^{22}Na is the greatest concern due to production rate and leachability into the groundwater as well as the long half-lives of the radionuclides. Fermilab standards pertaining to groundwater activation are provided in the FRCM, and the methodologies used for making groundwater activation estimates, are given in Environmental Protection Notes No. 8 [4] and 17 [5]. The methodology is designed to achieve a conservative estimate of groundwater activation. Additionally, the annual integrated intensity used in the calculations is estimated well above the practical beam delivery limits.

Calculations estimating groundwater activation were performed using the Monte Carlo Shielding Computer Code (MARS) simulation programs for the momentum absorber when the absorber developed an internal vacuum leak. Instead of replacing the absorber, an insert with a titanium window was installed 3 ft. inside the soil shielding. The results indicate a less than 5% effect due to adding the titanium window [6]. The momentum and straight-ahead absorbers are geometrically similar. The calculations show that both absorbers can safely operate at up to 6.4×10^{20} protons per year. As shown in Table 3, after 15 years of continuous operation of 6.4 x 10^{20} protons delivered per year to the momentum absorber, an accumulation of ^{3}H and ^{22}Na in the groundwater is significantly less than the regulatory limits defined in the Derived Concentration Standard set forth in Department of Energy (DOE) Order 458.1 (DOE O 458.1).

Ground water activation is not applicable to this area.

Table 3: Momentum absorber groundwater.

Protons Delivered to Target	**Projected Concentrations pCi/ml-y**	**Regulatory Limit Groundwater*[1] pCi/ml-y**
6.4x10^{20}	0.12 ^{3}H	20 ^{3}H
	0.0034 ^{22}Na	0.4 ^{22}Na

III-1.2.1.4 Surface Water Activation

N/A.

III-1.2.1.5 Radioactive Water (RAW) Systems

N/A.

III-1.2.1.6 Air Activation

Illinois state regulations and the Fermilab registration in Registration of Smaller Sources (ROSS) program, administered by the Illinois Environmental Protection Agency (IEPA), govern releases of airborne radionuclides. The regulations limit the effective dose equivalent delivered to a member of the public to 10 mrem/year [1]. Fermilab has established a secondary goal of keeping the maximum effective dose equivalent at the site boundary due to air emissions under 0.1 mrem/yr.

The principal radionuclides of concern to 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 110 minute half-life, which is produced by thermal neutron capture on argon-40). Normally the ventilation systems in the enclosure would have a slow air transit time in minutes through protected areas before air is released to an outdoor area, which helps eliminate the short-lived particle emitters through decay during the transit time.

Based on releases expected from the existing accelerators and the current and near future experiments, Fermilab will remain in compliance with EPA requirements [7]. After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level I has been reduced to a residual risk level of IV.

[1] The value for ^{3}H in groundwater is taken from the Federal drinking water standards set forth in 40 CFR 141. The value for ^{22}Na is 4% of the DCS of DOE Standard-1196-2011 as set forth by DOE O 458.1.

III-1.2.1.7 Closed Loop Air Cooling

N/A.

III-1.2.1.8 Soil Interactions

N/A.

III-1.2.1.9 Radioactive Waste

Radioactive waste produced during Linac operations will be managed within the established Radiological Protection Program (RPP) and as prescribed in the 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 Linac, 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. After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.1.10 Contamination

Although not typically encountered, contamination has been noted occasionally at the 400 MeV extraction region. Personnel are required by the RWP to wear gloves and shoe covers when accessing the SCL and 400 MeV areas of the Linac enclosure. RWPs must be written and followed in accordance with the FRCM requirements. After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.1.11 Beryllium-7

N/A.

III-1.2.1.12 Radioactive Sources

N/A.

III-1.2.1.13 Nuclear Material

N/A.

III-1.2.1.14 Radiation Generating Devices (RGDs)

N/A.

III-1.2.1.15 Non-Ionizing Radiation Hazards

Hazardous levels of RF electromagnetic energy are generated by the RF power sources in the Linac. During normal operations, RF energy is contained within waveguides, coaxial transmission lines, or accelerating cavities. The engineering of the RF power sources is sufficient to shield personnel from hazardous levels of non-ionizing radiation. A survey conducted by the ESH Industrial Hygiene group in January of 2023 showed no hazardous fields present in the Linac gallery. Specific “Lock-out/Tag-out” procedures are in place to establish safe conditions for personnel working on these systems. RF field surveys are performed on an as-needed basis by the Industrial Hygiene Group. After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level II has been reduced to a residual risk level of IV.

III-1.2.1.15.1 Laser Notcher

The Booster synchrotron must contain an extraction gap in the Booster beam to provide a beam free region for the extraction kicker rise time to minimize losses at extraction. The Class IV Linac Laser Notcher (LLN) System, installed at the downstream end of the 750 keV RFQ, is utilized to create this extraction gap outside of the Booster tunnel. It accomplishes this goal by neutralizing multiple 80 ns portions of the 201.25 MHz Linac bunch train at the Booster revolution period for injection into Booster. The laser system is a Master Oscillator Power Amplifier laser system consisting of a low power continuous wave (CW) diode seed laser, an arbitrary waveform generator as input to an optical modulator creating the required laser pulse pattern. This laser pulse pattern is then amplified by four specially designed fiber lasers and two final high energy solid state free-space amplifiers and associated optics to deliver the laser into a neutralization interaction cavity to interact with the Linac bunches.

Because of the location of the Laser Notcher, it must be operated as a Class I system to prevent any unauthorized access to laser light or accidental exposure of personnel passing through the area. The free space amplifier system, a transport system and a laser dump system are all completely enclosed in light tight enclosures and are interlocked to prohibit accessing the enclosures when the laser is operating. The laser interaction cavity is installed in the accelerator MEBT vacuum system which is interlocked to prohibit any laser beam from being generated, if there is a potential for personnel working on the vacuum system. Local view ports on the upstream of tank 1 have a light tight blanking flange and CAUTION Do Not Remove signage. The Laser Notcher system is interfaced to the Accelerator Division Critical Device Control module which monitors the status of all interlocks and the status of the MEBT vacuum system and if and only if all inputs are made up a permit is issued to the various amplifiers. The interface module between the LLN and the critical device controller (CDC) is a local interface chassis which monitors all interlocks and provides the ability to locally enable the permits and allow operation. This module located in the electronics rack for the fiber lasers also contains a CRASH button for removal of the permits to the LLN. Prior to initial operation of the laser system, a full operational readiness clearance (ORC) was performed. The LLN Safety interlock system is regularly tested by the ESH AD Interlock group. After completion of the risk analyses shown in Section III-1.9 Appendix – Risk Tables, Tables 5.1-5.3, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.2 Toxic Materials

The Linac presents toxic material hazards identified in Table 2. Hazard Inventory for Linac. All toxic material hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I, Chapter 04.

III-1.2.2.1 Lead

The primary lead hazard is in the form of lead solder from older electronics still in use. Lead radiation shielding is used in several areas in the Linac, typically in the form of encased lead blankets. Lead exposure in Linac areas have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving lead implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level II has been reduced to a residual risk level of IV.

III-1.2.2.2 Beryllium

N/A.

III-1.2.2.3 Fluorinert & Its Byproducts

N/A.

III-1.2.2.4 Liquid Scintillator Oil

N/A.

III-1.2.2.5 Pseudocumene

N/A.

III-1.2.2.6 Ammonia

N/A.

III-1.2.2.7 Nanoparticle Exposures

N/A.

III-1.2.3 Flammables and Combustibles

The Linac presents flammable and combustible hazards identified in Table 2. Unusual hazards are present in the form of flammable hydrogen gas used in the source. Combustible Materials
Common combustible materials (paper, wood pallets, etc.) are typically found in the Linac gallery. Combustible materials in Linac areas have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use.

III-1.2.3.1 Flammable Materials

Common industrial lubricants, solvents, and paints are used by Linac technicians to maintain equipment and are stored in flammable materials lockers. Most flammable materials present in Linac areas have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table.

The injector source utilizes two 30 cubic feet cylinders containing a total of 0.15 kg of highly flammable hydrogen gas. One cylinder will be operational and the other used for the backup injector source. The injector source installation contains less than 0.6 kg or 250 standard cubic feet (SCF) of hydrogen which corresponds to a Flammable Gas Risk Class 0 area in accordance with the FESHM. The area is appropriately posted with signs "Danger-Flammable Gases, No Ignition Sources". A contact list of people responsible for the system is posted. All cylinders are appropriately secured, and the stored cylinders are kept capped.

Detailed analysis of the hydrogen safety issues, and identification of the hazard mitigations are found in "Flammable Gas Risk Calculation and Installation Requirements for Commissioning and Operation of the RFQ Ion Source in the I-Pit" [8]. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.4 Electrical Energy

The Linac presents electrical energy hazards identified in Table 2. Unusual hazards are present in the form of exposed low voltage, high current conductors used for DTL RF and replacement capacitors in storage.

III-1.2.4.1 Stored Energy Exposure

The Linac 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 Linac involving this hazard implements the controls specified in the common Risk Matrix table. The notable accelerator-specific electrical hazard is the modulators for the high-power RF sources, e.g. the 201 and 805 MHz 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 Proton Source Department Linac written Lock Out / Tag Out procedures for access to the cabinets and maintenance of the equipment. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.4.2 High Voltage Exposure

Linac RF systems rely on large capacitor banks to create high voltage pulses. Replacement capacitors are stored in the gallery in the event of equipment failures. These capacitors can passively store charge when unattended and present a shock hazard if not properly stored. All spare capacitors are stored with their terminals grounded and kept out of high traffic areas.

After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.4.3 Low Voltage, High Current Exposure

Both the 7835 & 4616 power tubes for DTL RF systems have high current filament power supplies with exposed conductors. To protect against incidental contact which may cause burns, insulating guards are in place and cabinet doors where conductors exist are closed. Trained electrical workers doing work near low voltage, high current conductors are to remove all metal jewelry and use nonconductive tools. In the event of a metal tool accidentally coming into contact with the conductors, overcurrent protection circuits exist to limit the incident energy of the arc flash After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.5 Thermal Energy

The Linac presents thermal energy hazards identified in Table 2. Hazard Inventory for Linac.. All thermal energy hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I, Chapter 04.

III-1.2.5.1 Bakeout

Historically, Linac does not do magnet or beam pipe bakeouts. However, if there is a need to do bakeouts, this hazard has been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving Bakeout implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.5.2 Hot Work

Qualified welders occasionally work in the Linac gallery and tunnel to repair waterlines and other metalwork. Hot work in Linac areas has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.5.3 Cryogenics

There are several Dewars in the Linac gallery which store liquid nitrogen (LN2) for vacuum traps in the Linac tunnel. The Dewars are not of sufficient volume to represent an ODH hazard. These Dewars and LN2 handling procedures have been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.6 Kinetic Energy

The Linac presents kinetic energy hazards identified in Table 2. All kinetic energy hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I Chapter 04.

III-1.2.6.1 Power Tools

Power tools are commonly used when working on Linac equipment in the gallery and tunnel. Power tool use has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.6.2 Pumps and Motors

Standard industrial pumps and motors are utilized throughout the Linac area for water cooling and vacuum systems. These have been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac areas involving pumps and motors implement the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of III.

III-1.2.6.3 Motion Tables

Linac technicians use mechanical motion tables to install equipment and improve ergonomics when conducting maintenance or repairs. Motion tables have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving motion tables implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of III.

III-1.2.6.4 Mobile Shielding

N/A.

III-1.2.7 Potential Energy

The Linac presents potential energy hazards identified in Table 2. All potential energy hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I, Chapter 04.

III-1.2.7.1 Crane Operations

Trained technicians utilize various hoists lifts, and bridge cranes to move, maintain, and install equipment in the Linac gallery and tunnel. Crane hazards have been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac involving cranes implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.7.2 Compressed Gasses

Compressed nitrogen, argon, and hydrogen are present in Linac areas to facilitate machine operations. Compressed gas cylinders are stored, used, and moved throughout the Linac gallery and tunnel. Compressed gas hazards have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving compressed gas implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.7.3 Vacuum/Pressure Vessels/Piping

Vacuum vessels are present in Linac in the form of beam pipes, RF cavities, and other beamline components. Pressure vessels are present in the form of cryogen storage Dewars, RF waveguides, and power amplifier tubes. Vacuum and pressure vessels have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of III/IV.

III-1.2.7.4 Vacuum Pumps

Vacuum pumps are used throughout the Linac to maintain vacuum on beamline and RF generating components. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of III.

III-1.2.7.5 Material Handling

Trained personnel operate forklifts, stackers, and hand carts to move materials throughout the Linac area. DTL power amplifiers can be moved using an air caster system. Additionally, heavy equipment may be moved short distances utilizing team lifts. Individual lifting is limited to items 50 pounds or less. These hazards have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04

Safety Analysis. Work in Linac involving this hazard implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.8 Magnetic Fields

The Linac presents magnetic field hazards identified in Table 2.

III-1.2.8.1 Fringe Fields

The fringe field hazard mainly comes from powered magnets and permanent magnets that are in ion pumps. Fields are nominally only hazardous to people who have medical implants. The likelihood of the fringe field causing a malfunction to individuals with medical implants is reduced by work planning, warnings in the hazard specification sheet, and warning signs at all Linac entry points about this hazard. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Baseline risk for this hazard was R I and, after control measures were evaluated, the residual risk level was R III.

III-1.2.9 Other Hazards

The Linac presents other hazards identified in Table 2. All other hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I, Chapter 04.

III-1.2.9.1 Confined Spaces

Confined spaces in the form of DTL RF cavities are present in the Linac tunnel. These are accessed for maintenance and inspection purposes by personnel trained in confined space entry. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving confined spaces implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level III has been reduced to a residual risk level of IV.

III-1.2.9.2 Noise

Operating cooling water systems creates a potential noise hazard in the lower Linac gallery. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving high levels of noise implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level III has been reduced to a residual risk level of IV.

III-1.2.9.3 Silica

Silica dust may be created when drilling into concrete floors or walls. Silica hazards have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving silica dust implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of III.

III-1.2.9.4 Ergonomics

Both office and technical work in Linac areas may involve sitting or standing for long periods of time, repetitive motion, cramped conditions, and other ergonomic concerns. Ergonomic hazards have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving ergonomic concerns implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.9.5 Asbestos

Access penetrations connecting the Linac gallery to the enclosure tunnel are asbestos lined due to common fire prevention practices during the period when the building was constructed. Due to the age of the building, asbestos may be present in other areas as well. The asbestos penetrations have been evaluated within the common Risk Matrix table included in SAD Section I, Chapter 04 Safety Analysis. Work in Linac involving asbestos implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.9.6 Working at Heights

Linac technicians utilize ladders, step stools, and mobile work platforms to conduct maintenance in Linac areas. Utilizing fall protection equipment, trained personnel may work on top of equipment where there is a chance of falling. Work at height has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Working at heights in Linac areas implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of III.

III-1.2.10 Access & Egress

The Linac presents access and egress hazards in the form of a list of checked off hazards shown in Table 2. All other hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I, Chapter 04.

III-1.2.10.1 Life Safety Egress

The Linac tunnel has access and egress points at both the north and south ends of the tunnel. Both the upper and lower Linac gallery have multiple points of entry. Life safety egress in Linac areas has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac involving egress hazards implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.11 Environmental

The Linac presents environmental hazards in the form of a list of checked off hazards shown in Table 2. All environmental hazards present in Linac areas are in the form of Standard Industrial Hazards discussed in SAD Section I, Chapter 04.

III-1.2.11.1 Hazard to Air

N/A.

III-1.2.11.2 Hazard to Water

Transformer oil found in Linac RF sources has the potential to leak or spill and spread contamination. This hazard has been evaluated within the common Risk Matrix table included in SAD Section I Chapter 04 Safety Analysis. Work in Linac involving transformer oil implements the controls specified in the common Risk Matrix table. No unique controls are in use. After completion of the risk analyses shown in SAD Section I Chapter 04, the baseline risk level I has been reduced to a residual risk level of IV.

III-1.2.11.3 Hazard to Soil

N/A.

III-1.3. Maximum Credible Incident Scenario(s) for the Accelerator Specific Hazard(s)

III-1.3.1 Definition of a Maximum Credible Incident

This section of the Linac SAD evaluates the maximum credible incident (MCI) scenario that could happen in the Linac. 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-1.3.1.1 Radiological Hazard

The Linac is designed to produce and transport a beam of H- ions to downstream machines. There are many devices in the Linac that are designed to accelerate, focus, and shape the beam pulses to ensure that a maximum number of ions reach the intended destination. Misdirection of the beam so that it impacts the beam tube and surrounding structures inside the accelerator enclosure can occur from a single failure of many of these devices or erroneous operation of them. A MCI would be one that produces the greatest beam loss for the longest period of time.

There are effectively an infinite number of individual beam loss events that can be postulated. As a result, this analysis selects the MCI to be defined by the maximum design parameters of several critical accelerator components including the ion source, the radio frequency quadrupole and the side coupled Linac cavities. The maximum design parameters of these components bound the credible intensities for the Linac beam through the DTL and SCL separately.

Maximum Design Parameters:

1. 130 mA of beam current from the ion source.
    a. Child Langmuir Limit (space charge limit) out of the Ion Source based on the extraction gap.
2. RFQ Transmission efficiency of 98%.
    a. Design and simulation efficiency from "The 750 keV RFQ Injector Upgrade" [9].
3. Linac Transmission efficiency of 100%.
    a. Defined as the ratio between the beam measured, via toroid, at the entry of the first accelerating cavity and the beam current measured, via toroid, at the exit of the last accelerating cavity.
4. Repetition Rate of 15 Hz.
    a. Arc modulator and gas valve pulser hardware limits rep rate to 15 Hz.
    b. Marx modulator and quadrupole power supplies have 15 Hz rate limiters in them that will trip them off.
5. Maximum beam pulse width through the DTL of 116 µs.
    a. Dictated by the maximum pulse width of the RFQ which is 116 µs.
6. Maximum beam pulse width through the SCL of 60 µs .
    a. Dictated by the design of the SCL coupling cavities. They physically cannot support a longer pulse width without overheating.

These values contribute to the following calculations for the maximum credible beam intensities of the Linac:

1. Maximum credible beam intensity through the DTL:

$$130mA * 0.98 * 15Hz * 116\mu s * 2.25E13\ (conversion\ factor) = 4.98E18 protons/hour$$

2. Maximum credible beam intensity through the SCL:

$$130mA * 0.98 * 15Hz * 60\mu s * 2.25E13\ (conversion\ factor) = 2.58E18 protons/hour$$

This analysis defines the maximum credible incident for the Fermilab Linac as a beam with the maximum credible intensity, through the DTL or SCL, that is persistently lost on a beamline component. This accident bounds all known scenarios for the Fermilab Linac. The maximum credible intensity is a function of the following parameters:

Event Causes (all numerical steps must happen simultaneously for MCI to occur):

1. Source running at 130 mA (maximum design output).
2. Either:
    a. Einzel lens chop timers (HEP or studies) set to 60 µs or greater by one of two consoles in the MCR.
    b. Einzel lens complete failure, allowing full source pulse width to the RFQ, only limited to 60 µs by SCL cavities.
3. LEBT tuned perfectly to maximize RFQ transmission.

4. Linac tuned perfectly to maximize transmission efficiency.
5. Beam requested at 15 Hz rep rate continually (studies or HEP).
6. Beam mis-steered continually via any of the following events:
    a. Failed magnet.
    b. Operator error.
    c. Autotune error.

Assuming no shielding is present, this incident would result in a dose to any individual higher than 100 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:

- Less than 500 mrem in one hour in all Laboratory areas to which the public is assumed to be excluded
- Less than 100 mrem in one hour at Fermilab's site boundary and/or in any areas onsite in which the public is authorized
- Less than 5 rem in one hour in any area accessible by facility workers or co-located workers

These credited controls are discussed in Section III-1.4.

The accumulated dose outside of the shielding in the Linac Lower Gallery 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 Linac enclosure is the Linac Upper Gallery where public tours are conducted. This location is more than five feet away from the location of the Credited Control radiation monitors, which would result in dose of less than 100 mrem applying a conservative dose reduction of 1/r. Other locations where the public is authorized near Linac, including public parking lots, roads, Wilson Hall, and Ramsey Auditorium, is further away than the Linac Upper Gallery and therefore would result in dose of much less than 100 mrem applying the same conservative dose reduction of 1/r.

III-1.4. 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-1.3.1.1.

III-1.4.1 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-1.4.1.1 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 Linac 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-1.4.1.1.1 Permanent Shielding

Permanent shielding encompasses the structural elements surrounding the beam line components and extraction lines.

This includes the walls, ceilings, doors, berms, shielding labyrinths and shielding blocks. Topographical surveys of the Linac enclosure and berm, completed during October 2023, conclude that there is a minimum of 10.5 Equivalent Feet of Dirt (e.f.d.) shielding between the interior surface of the enclosure walls and the surface of the berm. The wall between the interior of the enclosure and the Linac galleries does not have a constant thickness and some of its sections are thinner than the 10.5 e.f.d. shielding that is present between the enclosure walls and the surface of the berm. The section of wall that spans the length of Tanks 1 through 3 of the DTL is 3 feet thick. The section of wall that spans the length of Tanks 4 through 5 of the DTL is 7 feet thick. The section of wall that spans the rest of the length of the Linac is 12 feet thick.

The efficacy of this permanent shielding has been quantitatively analyzed using a MARS model constructed to simulate the MCI as defined in Section III-1.3.1.1. This analysis finds that, under the conditions present in the MCI, a peak dose rate of 8995 mrem/hr would occur at the Lower Linac Gallery wall which is a non-public area of the campus. In this condition, a MOI would receive a dose of 500 mrem in 200 seconds. Thus, additional credited controls are required to mitigate the consequences of the MCI.

The credited control for the permanent shielding is defined as 9.6 e.f.d. shielding between the interior surface of the enclosure walls and the surface of the berm. As mentioned above, there are a number of areas along the Linac beamline with less than 9.6 e.f.d. shielding which will require active engineering controls as described below in addition to the existing shielding. The reduction in the credited permanent shielding from the minimum measured value is factored into the configuration of the interlocked radiation detectors. These interlocked radiation detectors are a part of the Radiation Safety Interlock System which is defined as a credited control in Section III-1.4.1.2.1. This reduction in credited shielding ensures that Credited Controls collectively can protect any individual from receiving an unacceptable dose even if unforeseen modifications to the permanent shielding were to occur. Such acts could include erosion of the berm or digging into the berm by a human or animal.

III-1.4.1.1.2 Movable Shielding

The Linac has no areas with movable shielding to outside areas. An equipment access hatch, midway between the Linac and ITA experimental hall, was previously used for lowering equipment into the 400 MeV end of the Linac enclosure. The equipment access hatch has been filled with concrete blocks. These blocks now separate the Linac enclosure and the ITA experimental hall. The concrete block wall is considered permanent shielding.

III-1.4.1.1.3 Penetration Shielding

The Linac enclosure has several utility and RF waveguide penetrations routing between the exclusion areas and occupied areas which were analyzed [1, 2] for required shielding. Each of the original nine Linac accelerating tanks has three 30-inch penetrations passing from the lower-level gallery into the Linac tunnel. The penetrations are filled with concrete shielding blocks, and additional concrete shielding blocks are installed in front of them in the enclosure. An interlocked radiation detector has been placed just above the RF transmission line at the middle penetration of each set (of 3) which is the weakest link for shielding to ensure accident condition beam losses result in an accidental dose of less than 500 mrem in the Linac lower level.

The upper waveguide penetrations for the 400 MeV Linac upgrade that are downstream of the NTF treatment room pass through the top of the Linac gallery and enter the Linac enclosure through vertical penetrations in the Linac berm. These vertical penetrations are filled with poly beads and are also protected by the same interlocked radiation monitors in the Linac lower level above the RF transmission lines. These interlocked radiation monitors are defined as a credited control in Section III-1.4.1.2.1.

III-1.4.1.2 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 Linac operations are discussed below.

III-1.4.1.2.1 Radiation Safety Interlock System

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

There are two entrances to the Linac enclosure: one interlocked gate on the north side of the enclosure and one interlocked door located at the south end of the enclosure. The interlock system inhibits transport of beam beyond the Linac 400 MeV extraction point to the Booster or MTA and inhibits RF power to the DTL and SCL cavities.

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 RSIS utilizes interlocked chipmunk and scarecrow radiation detectors. The general locations of these detectors are shown in Figure 7 below:

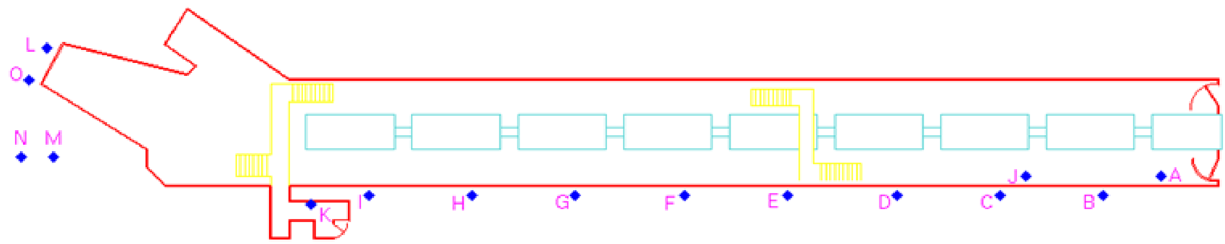

Figure 7: Simplified map of the Linac enclosure from a top down perspective (beam moves from right to left). Interlocked radiation detector locations are labeled A through O.

Interlocked radiation detectors are located at the north end of the enclosure (A and J), at the 400 MeV labyrinth area (K), outside the enclosure at each of the RF transmission line penetrations (B through I), and on the berm above the two beam absorbers (M and N). When personnel access the Booster accelerator, two additional interlocked radiation detectors are enabled in the Booster enclosure, near the Booster Chute area and the area where the Linac Beam is injected into the Booster accelerator (L and O). The interlocked radiation detectors protect personnel by disabling the beam should prompt radiation from operations exceed specific dose rate limits. 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-1.3.1.1, even with an unforeseen reduction of the permanent shielding between the interior of the enclosure walls and the surface of the berm by 0.9 e.f.d. at the time of the maximum credible incident. The analysis to determine the credited control trip limits is provided as a reference in the “Linac MCI Justification” document [10]. This analysis evaluates the consequence of the maximum credible beam intensity being lost at multiple points throughout the DTL and SCL separately. The specific detector type, their locations and their credited control trip limit values are presented in Table 4 below. 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 4: Summary of the interlocked radiation detectors used by the Linac RSIS

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

The RSIS inhibits beam by controlling redundant critical devices. In the case of Linac, the primary critical device is the 120 V supply for the injector beam valve (L:LVV), the second is the power supply to the low-level amplifier used by the RFQ (L:RFQDS1). In the event of a critical device failure, the system has a failure mode function which disables the 480 V contactor for the ion source extractor power supply that will inhibit beam to the Linac.

The RSIS including requirements for hardware and system testing, inventory of interlock keys and procedures for maintenance of interlock systems. The RSIS hardware enforces the administrative Search and Secure and Controlled Access processes. The RSIS is designed, installed, and configuration managed in conformance with the requirements stated in the FRCM.

III-1.4.2 Credited Administrative Controls

All Linac accelerator operations with the potential to affect the safety of employees, researchers, or the public, or to adversely affect the environment, are performed using approved laboratory, division, or department procedures. These procedures are the administrative controls that encompass the human interactions that define safe accelerator operations. The administrative procedures and programs considered necessary to ensure safe accelerator operations are discussed below.

III-1.4.2.1 Operation Authorization Document

Beam will not be transported to the Linac 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-1.4.2.2 Staffing

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 Linac 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.
- 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-1.4.2.3 Accelerator Operating Parameters

To ensure operations within bounding conditions used in the MCI analysis, the following intensity shall not be exceeded:

- 2.58E18 protons/hr at 116 MeV
- 4.98E18 protons/hr at 750 keV

III-1.5. Summary of Defense-in-Depth Controls

The Fermilab Linac 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-1.5.1 Defense-in-Depth Engineering Controls

III-1.5.1.1 Passive Defense-in-Depth Engineering Controls

III-1.5.1.1.1 Permanent Shielding

The defense-in-depth control for the permanent shielding is defined as 0.9 e.f.d. excess shielding, present in the Linac berm. Credited controls collectively protect the MOI from receiving an unacceptable dose even if unforeseen modifications to the defense-in-depth permanent shielding were to occur. Such acts could include erosion of the berm or digging into the berm by a human or animal.

III-1.5.1.2 Active Defense-in-Depth Engineering Controls

III-1.5.1.2.1 Machine Protection Controls

The Linac is protected by beam loss monitors, vacuum monitors, and RF leak detectors.

III-1.5.1.3 Defense-in-Depth Administrative Controls

III-1.5.1.3.1 Fencing and Posting

Fences are used and posted to designate potential Radiation Areas during machine operations. The entire Linac berm was fenced and posted consistent with its identification as a Radiation Area in accordance with the FRCM.

III-1.5.1.3.2 Training

All personnel engaged in the commissioning, operation, and emergency management of the Linac shall have at a minimum, Fermilab's Radiation Worker training (FN000731: Rad worker just in time; FN000471: Rad worker practical factors; FN000470: Rad worker classroom (virtual)) current. Furthermore, personnel approved for access into the Linac's interlocked enclosure shall have Fermilab's Controlled Access (FN000311) training current as well.

Equipment specific to the operation of the Linac such as klystrons, RF power amplifiers shall be operated by or with the supervision of the corresponding expert, who ensures that the equipment is being used according to its specifications and unique safety measures.

Training in Fermilab's General or system specific Lock Out-Tag Out procedures shall be required to perform troubleshooting and maintenance as applicable.

III-1.5.1.3.3 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-1.6. Decommissioning

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

III-1.7. Summary and Conclusion

Specific hazards associated with commissioning and operation of the Linac accelerator are identified and assessed in this chapter of the Fermilab SAD. The designs, controls, and procedures to mitigate Linac-specific hazards are identified and described. In addition to these specific safety considerations, the Linac accelerator is subject to the global and more generic safety requirements, controls and procedures outlined in Section 1 of the Fermilab Main Accelerator Complex SAD.

The preceding discussion of the hazards presented with Linac accelerator operations, and the credited controls established to mitigate those hazards demonstrate that the Linac can be operated in a manner that will produce minimal risk to the health and safety of Fermilab workers, visiting scientists, the public, as well as to the environment.

III-1.8. References

[1] C. Schmidt, T. Kroc, L. Allen and E. McCrory, *Radiation Shielding Assessment of the Linac Enclosure, 26 April* 1991.

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[3] Fermilab Radiological Control Manual

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[5] J. Cossairt, A. Elwin, P. Kesich, A. Malensek, N. Mokhov and A. Wehmann, *The Concentration Model Revisited, 24 June* 1999.

[6] L. Allen, F. J., F. Garcia, M. Gerardi, B. Higgins, K. Vaziri, G. Lauten, A. Lee, D. Newhart, B. Ogert, I. Rakhno, R. Reilly and D. Reitzner, *Linac Momentum Beam Dump Vacuum, November* 2011.

[7] 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

[8] R. Lewis and D. Bollinger, *Flammable Gas Risk Calculation and Installation Requirements For Commissioning and Operation of the RFQ Ion Source in the I- Pit (October 2012 Configuration), October* 2012.

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[10] L. Prost, *Linac MCI Justification*, December 2023

III-1.9. Appendix – Risk Tables

Risk Assessment methodology was developed based on the methodology described in DOE-HDBK-1163-2020 and is presented in Tables 5.1-5.31. 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 onsite facility workers, onsite co-located workers, and a maximally exposed off-site 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-1.44 of this Chapter as well as SAD Chapter VII-A.1 *Accelerator Safety Envelope – Fermilab Main Accelerator*.