Linac Accelerator

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II - 2.1 Linac Accelerator Area Location on Fermilab Site

The following aerial photograph shows the location of the Linac area in relationship to the Fermilab site.

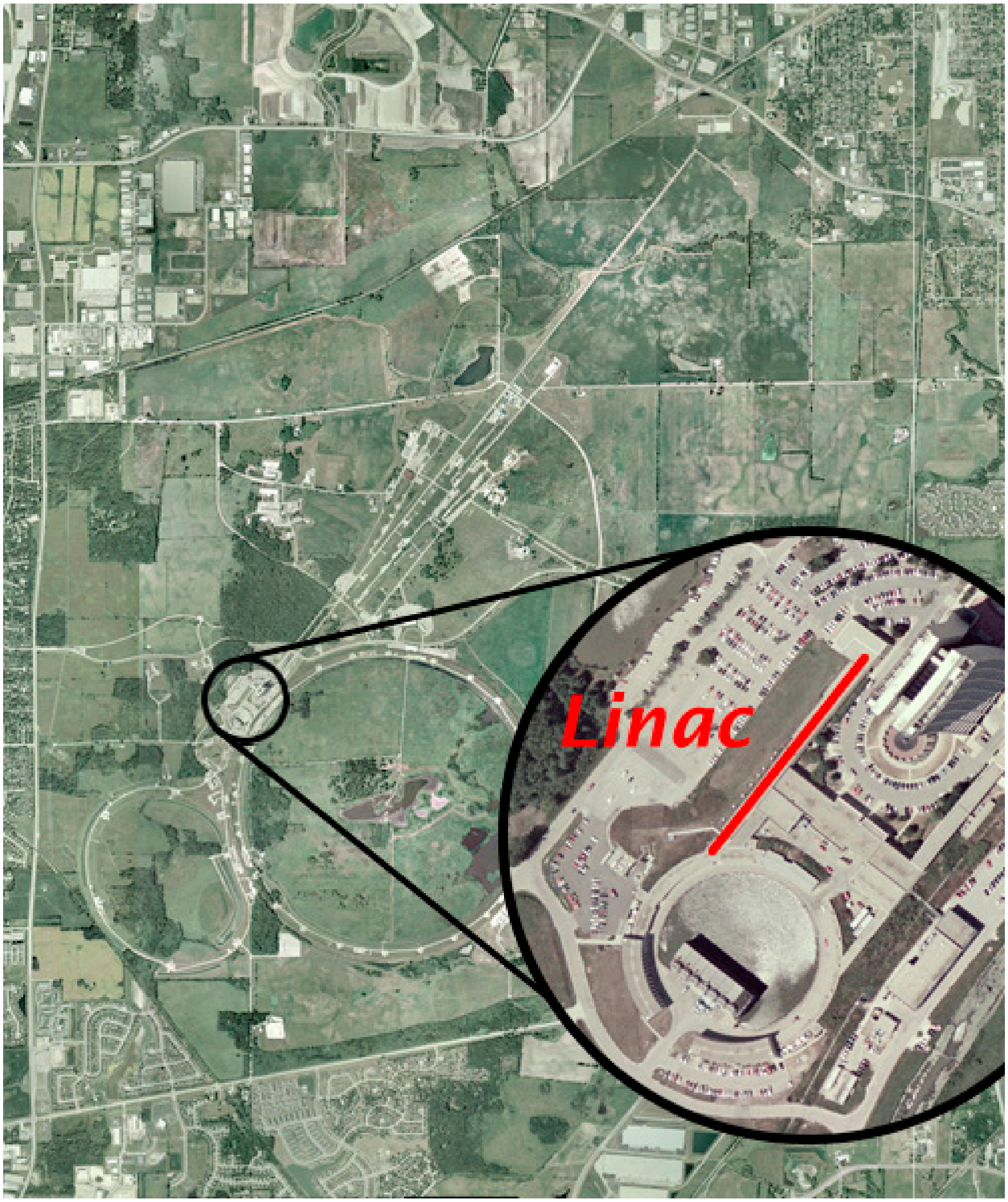

Figure 1 Bird's eye view of the Fermilab site showing the Linac location.

II - 2.2 Inventory of Hazards

The following table lists the identified hazards found in the Linac accelerator enclosure and support buildings. All hazards with an * have been discussed in Chapters 1-10 of the Fermilab Safety Assessment Document (SAD) and are not covered further in this section.

Radiation Ionizing radiation Residual activation x-ray producing devices Non-ionizing radiation Ground water activation Radioactive Waste	**Kinetic Energy** Power tools * Pumps and motors *
Toxic Materials Lead shielding * Beryllium components *	**Potential Energy** Crane operations * Compressed gases * Vacuum / pressure vessels * Vacuum pumps *
Flammable & Combustible Materials Cables * Flammable gasses	**Magnetic Fields** Fringe fields *
Electrical Energy Stored energy exposure High voltage exposure Low voltage, high current exposure *	**Gaseous Hazards** Confined spaces *
Thermal Energy	**Access / Egress** Life safety egress *

II - 2.3 Introduction

This section II, Chapter 2 of the Fermi National Accelerator Laboratory (Fermilab) SAD covers the pre-accelerator hereafter referred as RIL (Radio Frequency Quadrupole Injector Line), Linac accelerator area and Linac beam absorbers area. The 400 MeV transfer line, commonly called the Booster Chute, that transports the beam from Linac to Booster is covered in the Booster Safety Assessment Chapter[1].

II - 2.3.1 Purpose of the Linac Accelerator

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. 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 MuCool Test Area (MTA) and two Linac beam absorbers.

II - 2.3.2 Description of the Linac Accelerator

The Linac accelerator includes the injector area at the north end of the enclosure followed by approximately 200 meters of accelerating cavities and transfer line components to transport beam to four different areas (Figure 2). An associated equipment gallery is located above and to the east of the enclosure floor level.

The present injector, installed in 2012, replaced the 40 year old Cockcroft-Walton. It 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. The H^- ion beam is then accelerated to 116 MeV by five 201.25- MHz Drift Tube Linac (DTL) tanks and to 400 MeV by seven 805-MHz Coupled Cavity Linac (CCL) cavities. The Linac pulses at a 15 Hz repetition rate but the actual beam cycle rate is dependent upon the users. The average beam current in the Linac is 34.5 mA.

The 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. The aforementioned Linac diagnostics are typically located between the DTL and CCL accelerator cavities.

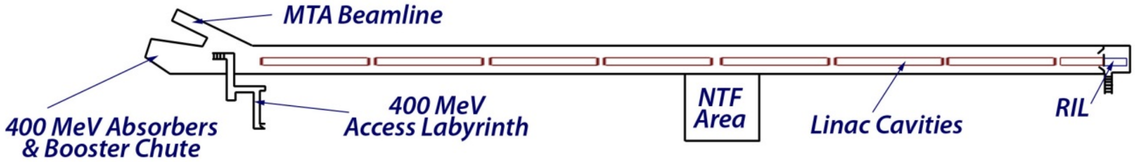

Figure 2 Linac Overview

II - 2.3.3 *Operating Modes*

The Linac has four modes of operations.

- **High Energy Physics (HEP) beam** (Figure 3): This mode corresponds to the primary 400 MeV operational mode which delivers H^- beam to the Booster accelerator. Up to 2012, the maximum delivery cycle rate for this mode was about 6.5 Hz. With the current upgrades to the Booster synchrotron, 15 Hz beam cycle rate will be achievable which matches the full Linac cycle rate. The Linac beam intensity for the Booster can vary depending upon user needs. The Linac pulse length can vary from approximately 2.2 to 44 μs with a typical current of 33 to 36 mA. For every HEP pulse, an additional 2 μs of beam is accelerated in the Linac and sent to the momentum absorber. This extra beam is due to amplitude and phase excursions in the 200 MHz RF system. The excursions occur at the beginning of the beam pulse and cause momentum drift and poor matching to Booster injection.
- **NTF beam**: The second Linac operational mode is for delivery of 66 MeV beam to the NTF. This one–of-a kind cancer treatment facility has been in use since the 1970's. The facility is currently used three days a week. The typical treatment mode for NTF is 15 Hz of 64 μs beam for durations of several minutes. The amount of beam or dose is part of a treatment plan set by the facility medical staff. This is the only mode in which beam does not use the entire Linac for acceleration and the 400 MeV beam absorber. The NTF beam line has also served industrial research uses.
- **MTA beam** (Figure 3)**:** The third operational mode is 400 MeV H^- beam delivery to the MTA. The MTA supports two modes of operation: beam emittance mode and MuCool experimental mode. In the emittance mode, the MuCool Shielding Assessment[2] demonstrates that the facility can operate up to 9.6×10^{15} protons/hour. The shielding assessment has determined that in the experimental mode the facility can be safely operated up to 9.6×10^{14} protons/hour, one order of magnitude lower than the emittance mode.
- **Tune-up mode** (Figure 3): The fourth and final operational mode is 400 MeV H^- beam for Linac studies. In this mode, the beam is transported directly to one of the two beam absorbers located at the end of the Linac. The common operational

configuration transports the beam to the momentum absorber area which is capable of dissipating 10 kW of beam power. 10 kW is the entire Linac beam power capability. During the tune-up mode, the beam cycle rate may be set to 15 Hz and the beam pulse width set to 80 μs. Typically the pulse width is set to 20 μs at 3 Hz.

Figure 3 shows the end of 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.

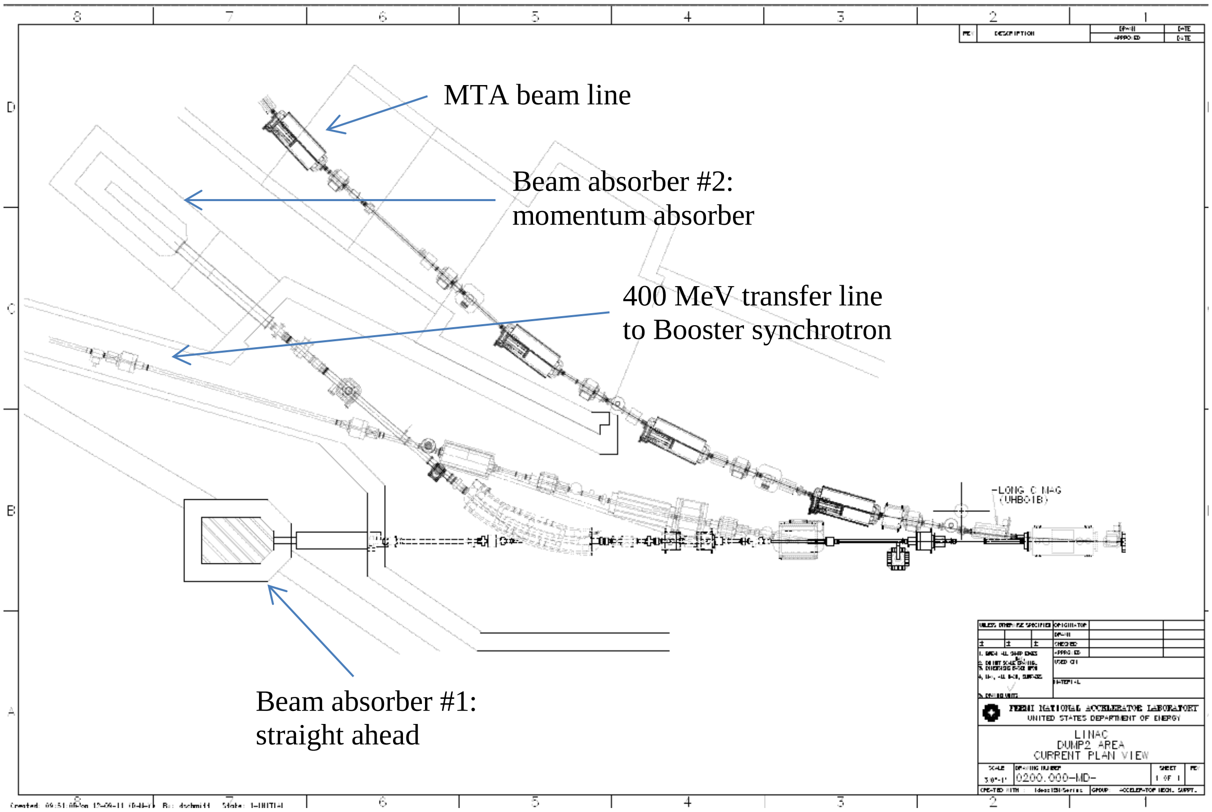

Figure 3 Linac 400 MeV extraction areas, two beam absorbers, 400 MeV transfer line to Booster and MTA extraction line. Each of these areas is indicated on the Figure.

Operational mode	Approximate intensity	Extraction line
HEP mode (beam to Booster synchrotron)	2.2 - 44.4 μs of 35 mA. Rate depends upon HEP program (Up to 2012 typical rate was up to 6.5 Hz. Post 2012 15 Hz is expected)	400 MeV transfer line (The first 2 μs of each HEP beam pulse goes to the 400 MeV beam absorber)
NTF mode	Linac beam pulse width 64 μs Rate depends upon HEP program – up to 15 Hz	NTF extraction – after DTL tank 4
MTA mode	Capable of full pulse width of ~80 μs	Extraction after Klystron cavity 7
Linac tune-up	Depends upon HEP program but up to 15Hz at full pulse width of ~80 μs	400 MeV beam absorber

Table 1 Linac Operational modes

II - 2.4 Safety Assessment

This section contains an analysis of the unique accelerator-specific hazards of the Linac accelerator. The radiological hazards include ionizing radiation, residual activation, x-Ray producing devices, non-ionizing radiation, groundwater activation, and radioactive waste. Flammable gas from hydrogen hazards and electrical from the high power Radio Frequency (RF) sources are also present.

II - 2.4.1 Radiological Hazards

Radiation safety is considered in all aspects of Linac operations. In the Linac there are two predominant radiation hazards. The first hazard is ionizing radiation due to the interaction of primary beam particles that produce secondary particle showers in the materials surrounding the beam pipes, beam line elements, and diagnostic equipment. Other hazards include hazards due to x-ray emission from the high gradient Radio Frequency (RF) cavities and non-ionizing radiation.

There are 3 categories of beam-induced radiation hazards:

1. Prompt ionizing radiation levels inside and surrounding the enclosures that are present during beam transport. These include protons, neutrons, muons, and other energetic particles;
2. Residual ionizing radiation due to activation of beam line components, which can give rise to radiation exposure to personnel during accesses to the beam enclosures for repair, maintenance, inspection, and operation activities; and

3. Environmental activation of groundwater, due to the operation of the beam transport system.

A detailed shielding assessment for the Linac[3] has been compiled, reviewed, and updated to address these radiological concerns. The assessment provides a detailed analysis that documents the required shielding overburden, and the use of signs, fences, and active interlocks to comply with the Fermilab Radiological Control Manual[4] (FRCM). The shielding assessment also analyzes the beam line areas with respect to residual activation of beam line components. Residual activation of components substantially impacts access to the enclosure when access is required for equipment changes or repair. The shielding assessment for the Linac accelerator has analyzed the beam line areas from the injector through the Linac enclosure. The results of the assessment are summarized in Sections 2.4.1.1 through 2.4.1.5 below.

II - 2.4.1.1 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 detectors to keep any prompt radiation within acceptable levels. Operation of the area conforms to the FRCM to maintain exposures for operating personnel ALARA.

The assessment requires that:

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

The Linac Shielding Assessment concludes

- *The facility is in conformance with all FRCM requirements and can be operated safely with the following beam parameters:*
    - *Maximum intensity is 3.54 x* 10^{18} *protons per hour;*
    - *Maximum energy is 400 MeV;*
    - *Annual limit of 6.4 x* 10^{20} *protons to either the straight ahead or momentum absorbers.*

II - 2.4.1.2 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 CCL 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 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.

II - 2.4.1.3 X-Ray Producing Devices

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 Division (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.

II - 2.4.1.4 Non-Ionizing Radiation

Hazardous levels of RF electromagnetic energy are generated by the RF power sources in the Linac. This energy is not radiated where it would become a hazard to workers. The RF energy is contained within waveguides, coaxial transmission lines, or accelerating cavities. Specific

"Lock-out/Tag-out" procedures are in place to establish safe conditions for personnel working on these systems. Surveys are performed on an as-needed basis by the AD Environment, Safety and Health (ES&H) Department for stray RF fields. However, to eliminate the X-rays that are emitted, the gradients of all the RF sources are interlocked to the Linac Radiation Safety System and reduced below the generation threshold during an enclosure access.

II - 2.4.1.5 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[5] and 17[6]. 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 MARS[7] Monte Carlo 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[8]. 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 2, after 15 years of continuous operation of 6.4×10^{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) .

Protons Delivered to Target	Projected Concentrations pCi/ml-y	Regulatory Limit Groundwater* pCi/ml-y
6.4×10^{20}	0.12 ^{3}H	20 ^{3}H
	0.0034 ^{22}Na	0.4 ^{22}Na

Table 2 – Momentum Absorber Groundwater

*Source: 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.

II - 2.4.1.6 Radioactive Waste

Radioactive waste hazards and disposal will be managed within the program established throughout the Fermilab accelerator complex and as prescribed in the FRCM. Waste minimization is an objective of both the Linac accelerator area design and operational procedures. Although production of radioactive material is not an operational function of the Linac accelerator, accidental beam loss and, in the case of some beam diagnostics devices, intentional interception of the beam will result in activation of beam line elements. Activated items that cannot be reused will be disposed eventually as radioactive waste in accordance with the FRCM requirements.

II - 2.4.2 Flammable Gases

The injector source utilizes two 30 cubic ft 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 Fermilab Environment, Safety, and Health Manual (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” [9].

II - 2.4.3 Unique Electrical Hazards

The Linac electrical hazards from the AC power distribution systems and the power supplies for the beam line magnetic components fall within the scope described in the “Electrical Hazards” paragraph of Section 1, Chapter 4 of the Fermilab SAD. 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.

II - 2.5 Credited Controls

II - 2.5.1 Passive 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, penetration shielding, and Radiation Area fences to protect personnel from radiological exposure during beam operations.

II - 2.5.1.1 Permanent Shielding Including Labyrinths

The permanent shielding encompasses the structural elements surrounding the beam line components and extraction lines. The concrete structure is contiguous with the Linac and includes an upstream equipment access area, a personnel access labyrinth at the 400 MeV area with one exit, utility penetrations, and earthen berms and overburden.

The permanent shielding and shielding efficacy have been quantitatively analyzed for the enclosure and documented in the Linac Shielding Assessment. For normal operating conditions, the enclosure has sufficient earth overburden such that radiation levels on the top of the berm and in the lower level Linac equipment area are less than 5 mrem/hr and less than 0.25 mrem/hr at the ground floor level of the enclosure. Interlocked radiation detectors limit the duration of accident conditions to short periods of time and the accidental dose rates to less than 100 mrem/hr on top of the berm and in the lower level Linac gallery and less than 5 mrem/hr on the Linac ground floor level.

II - 2.5.1.2 Movable Shielding

The Linac has no areas with movable shielding to outside areas. An equipment access hatch, midway between the Linac and MTA 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 MTA experimental hall. The concrete block wall is considered permanent shielding.

II - 2.5.1.3 Penetration Shielding

The Linac enclosure has several utility and RF waveguide penetrations routing between the exclusion areas and occupied areas which were analyzed3 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. These penetrations have concrete shielding installed in front of, and in, the penetrations. An interlocked radiation detector has been placed just above the RF transmission line at the middle penetration which is the weakest link for shielding to insure accident condition beam losses result in an accidental dose rate of less than 100 mrem/hr in the Linac lower level.

The upper waveguide penetrations for the 400 MeV Linac upgrade waveguides 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 also protected by the interlocked radiation monitors in the Linac lower level above the RF transmission lines. The Linac lower level interlocked radiation monitors will limit beam losses in the Linac from 1% to 10%, therefore preventing the dose rates from the upgrade penetrations from exceeding 3 mrem/hr. In summary, the prompt dose rates at the exits of the penetrations are within the limits established in the FRCM.

II - 2.5.1.4 Radiation Fencing

Fences are used and posted to designate potential Radiation Areas during machine operations. The MuCool Facility Shielding Assessment2 concluded that the radiation levels along the MTA beamline require radiation fences. The entire Linac berm along with the MTA beamline was fenced and posted consistent with its identification as a Radiation Area in accordance with the FRCM. The Linac shielding assessment identified three small areas near the NTF in the Linac lower level that are also fenced and posted as Radiation Areas during NTF operations.

II - 2.5.2 Active Controls

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

II - 2.5.2.1 Radiation Safety Interlock System

The Linac enclosure employs a Radiation Safety Interlock System. 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 CCL cavities.

The Linac utilizes chipmunk and scarecrow radiation detectors located at the north end of the enclosure, at the 400 MeV labyrinth area, outside the enclosure at each of the RF transmission line penetrations, and on the berm above the two beam absorbers. When personnel access the Booster accelerator, two additional detectors are enabled in the Booster Chute area, the area where the Linac Beam is injected into the Booster accelerator. The detectors monitor radiation levels to protect personnel by disabling the beam should prompt radiation from operations exceed specific limits.

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

Trained and qualified personnel from the AD Operations Department are required to search and secure the enclosure before permits from the radiation safety interlock system may be reestablished following any personnel access to the enclosure, except under strictly specified controlled access conditions. The Radiation Safety Interlock Systems including requirements 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 requirements stated in the FRCM.

II - 2.5.3 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.

II - 2.5.3.1 Beam Permits and Run Conditions

Beam will not be transported to the Linac beam line without an approved Beam Permit and Run Condition. The Beam Permit specifies beam power limits as determined and approved by the AD Head in consultation with the AD ES&H Department Head, AD RSO, AD Operations Department Head, and AD Proton Source Department Head. The Run Conditions list the operating modes and safety envelope for the Linac. Run Conditions are issued by the AD ES&H department, and are signed by the AD Operations Department Head, AD RSO, and AD Head.

In order to run beam to the Linac, the radiation safety interlock system for the Linac enclosure must be searched and secured; the critical device Linac Vacuum Valve, accelerator control system name L:LVV, must be open and the Linac RFQ, accelerator control system name L:RFQ, must be energized.

II - 2.5.3.2 Summary of beam operating and safety envelope parameters

The Linac is assessed for a beam current of 35 mA for 30 μs at 15 Hz with a maximum kinetic energy of 400 MeV. This results in an operating envelope of 3.54×10^{17} protons/hour, at 400 MeV. The current operating envelope beam power limits exceed future laboratory programmatic goals. Therefore, no further action is required in Linac except continuing monitoring the area.

II - 2.5.3.3 Beam line Operations

Commissioning, normal operations, and emergency management of the Linac 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.

II - 2.6 Summary & 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 this Fermilab 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.

II - 2.7 Glossary, Acronyms

AD	Accelerator Division
ALARA	As Low As Reasonably Achievable
BPM	Beam Position Monitor
CCL	Coupled Cavity Linac
DCS	Derived Concentration Standard
DTL	Drift Tube Linac
ES&H	Environment, Safety and Health
Fermilab	Fermi National Accelerator Laboratory
FESHM	Fermilab Environment, Safety, and Health Manual
FRCM	Fermilab Radiological Control Manual
HEP	High Energy Physics
Hr	Hour
Hz	Hertz
KeV	kilo-electron volt
kg	kilo-grams
kW	kilo-Watt
mA	milli-amp
MeV	Mega-electron volt
mrem	milli-rem
MTA	MuCool Test Area
NTF	Neutron Treatment Facility
RCT	Radiological Control Technician
RF	Radio-Frequency
RFQ	Radio-Frequency Quadrupole
RIL	RFQ Injector Line
RSO	Radiation Safety Officer
RWP	Radiation Work Permit
SA	Shielding Assessment
SAD	Safety Assessment Document
SCF	Standard Cubic Feet
µs	micro-seconds

II - 2.8 References

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[1] William Pellico, *Booster Safety Assessment Document*, April 2011(currently in draft).

[2] MuCOOL Facility Shielding Assessment, November 1, 2010, C. Johnstone, I. Rakhno, N. Mokhov, W. Higgins.

[3] C. Schmidt, T. Kroc, L. Allen, E. McCrory, *Radiation Shielding Assessment of the Linac Enclosure*, April 26, 1991. C. Schmidt and T. Kroc, *Radiation Shielding Assessment of the Linac High Energy Enclosure Following the 1993 Upgrade Installation and Low Intensity Commissioning*, September 1993.

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

[5] Use of a Concentration-Based Model for Calculating the Radioactivation of Soil and Groundwater at Fermilab - J.D. Cossairt - December 1994

[6] The Concentration Model Revisited - J. Donald Cossairt, A. J. Elwyn, P. Kesich, A. Malensek, N. Mokhov, and A. Wehmann - June 24, 1999

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

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

[9] R. Lewis, 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.