Fermi National Accelerator Laboratory

PIP2IT Hazard Analysis

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Document Approval

Signatures Required	Date Approved
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Revision History

Revision	Date Release	Description of Change
-	11/25/2019	Initial Release of PIP2IT Hazard Assessment

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1 Abstract

This document defines the commissioning plan for PIP2IT 25 MeV beam in the Cryomodule Test Facility (CMTF) as part of the Fermilab Proton Improvement Plan-II (PIP-II). It addresses hazards and their mitigations for activities associated with the commissioning and operations of the test beam line. It covers the provision of new components and modifications to existing systems necessary to demonstrate the capabilities of this room-size accelerator as the front-end of the PIP-II linac.

The objective of PIP2IT 25 MeV beam commissioning is to verify the functionality of the PIP-II warm front end and characterize the beam properties after being accelerated by the first two cryomodule types, to make initial measurements of its output beam parameters and to establish procedures and conditions for subsequent PIP2IT 25 MeV beam operations.

2 Introduction

A proposal to upgrade Fermilab's 400 MeV normal-conducting (NC) linac with a continuous wave (CW)-compatible, pulsed 800 MeV super-conducting (SRF) linac is being pursued as part of the Proton Improvement Plan-II (PIP-II). The H- beam accelerated by a 250-meter long superconducting linac to an energy of 800 MeV will be injected into the existing 8 GeV Booster synchrotron accelerator. An aerial view of what the current layout of the new accelerator is shown in Figure 1.

Figure 1: PIP-II Linac situated at the east side of the Fermilab site.

In order to validate the front-end of such machine, a test accelerator (a.k.a. PIP2IT) is under construction at Cryomodule Test Facility complex. Once complete, PIP2IT layout will consist of

- 30 keV H- ion source (IS);
- Low Energy Beam Transport (LEBT);

- 2.1 MeV Radio Frequency Quadrupole (RFQ); a Medium Energy Beam Transport (MEBT);
- Two Superconducting RF cryomodules: Half Wave Resonator (HWR) and prototype Single-Spoke Resonator (pSSR1);
- High Energy Beam Transport (HEBT) where at the end a 20 kW beam dump is located.

The current version of PIP2IT layout is shown in Figure 2.

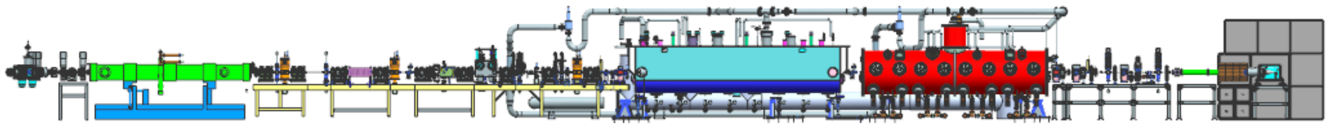

Figure 2*:* Complete PIP2IT layout.

The PIP2IT has been built in stages with the energy and intensity increasing as outlined in Table 2.1 below.

Table.2.1 PIP2IT stage, energy and intensity.

Stage	Energy	Macropulse Duration	Beam Repetition Rate	Intensity per bunch	Timeline
Ion source and LEBT	30 keV	10-16.6 ms	15 Hz-CW	30-60 pC	2014
162.5 MHz RFQ and MEBT	2.1 MeV	0.55-10 ms	20 Hz-CW	30-60 pC	2018
HWR and pSSR1 Cryomodules and HEBT	22 MeV	0.55 ms	20 Hz	30 pC	2020

3 Acronyms

AD	Accelerator Division
AHJ	Authority Having Jurisdiction
Chipmunks	Radiation monitor
CMTF	Cryomodule Test Facility
CTL	Cryogenic Transfer Line
CW	Continuous Wave
FNAL	Fermi National Accelerator Laboratory
FESHM	Fermilab Environment, Safety and Health Manual

FRCM	Fermilab Radiological Control Manual
HA	Hazard Assessment
HEBT	High Energy Beam Transport
HWR	Half Wave Resonator
IS	Ion Source
LEBT	Low Energy Beam Transport
LOTO	Lock-out/Tag-out
MEBT	Medium Energy Beam Transport
MPS	Machine Protection System
NC	Normal Conducting
NML	New Muon Lab
ODH	Oxygen Deficiency Hazard
PIP2IT	PIP-II Injector Test Area
PIP-II	Proton Improvement Plan-II
RF	Radio Frequency
RFQ	Radio Frequency Quadrupole
RSIS	Radiation Safety Interlock System
RSO	Radiation Safety Officer
SA	Shielding Assessment
SSA	Solid-State Amplifier
SRF	Superconducting Radio Frequency
SSR	Single Spoke Resonator
WFE	Warm Front End

4 References

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[3] J. Carneiro, "PIP2IT Shielding Assessment -- Fermilab Shielding Assessments SharePoint Site," 2019. [Online]. Available: https://fermipoint.fnal.gov/org/eshq/sa/sitepages/home.aspx.

[4] "FESHM 5032 - Cryogenic System Review," [Online]. Available: http://esh-docdb.fnal.gov/cgi-bin/ShowDocument?docid=528.

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[6] R. Wang, "EN - PIP2IT Cryogenic Transfer Line Documentation (EN02881/EN02882/EN02884/EN02885)," Document location: TeamCenter, 2019.

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[8] "Fermilab Radiological Control Manual," [Online]. Available: http://esh.fnal.gov/xms/FRCM.

[9] "Fermilb Environment Safety & Health Manual," [Online]. Available: http://esh.fnal.ogv/xms/FESHM.

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5 Description of CMTF Building

PIP2IT is located at the CMTF facility that consists of two separated buildings located north of the New Muon Lab (NML).

The CMTF is a research and development facility used for accelerator science and technology, specifically for testing and validating SRF components. CMTF provides the capability to measure and characterize the performance of SRF cavities in a cryomodule. CMTF was designed to be a flexible test facility, configurable in different ways to meet the needs of current as well as future projects at Fermilab and abroad. Table 5.1 summarizes the main features of the building.

Table 5.1: CMTF building requirements

Parameter	Value	Comments
Building size	4,000 sqft 15,000 sqft 1,100 sqft	Compressor Building High Bay area Below-grade pit
Electrical Power	(4) 1,800 KVA transformers	Services and Electronics
Fire suppression	Sprinkler system	Code
Crane	20 ton	
HVAC	2,700 scfm	
LCW	315-ton chiller	cooling
Clean room areas	Class 10,100,10000	External preparation area
Compressed air	95 cfm	
Cryoplant	500 W cooling at 2K, 4K, 50K	Superfluid refrigerator
Occupancy	5-10 10-15	Permanent residents' users/visitors

The PIP2IT enclosure, constructed of concrete shield blocks, occupies near 2,400 sqft of the High Bay floor space area. An aerial view of the CMTF complex and the PIP2IT enclosure are shown in Figure 3.

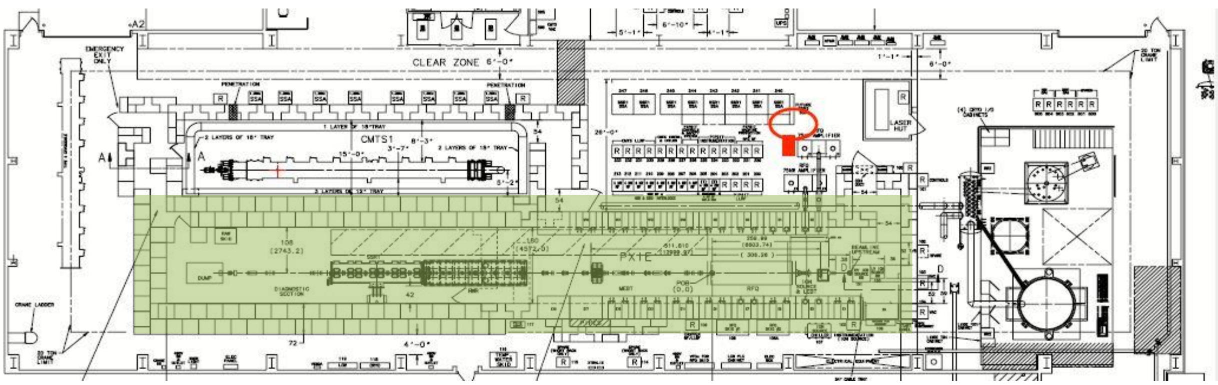

Figure 3. Aerial view of CMTF complex (a) PIP2IT enclosure (b)

There are two gated entrances to the enclosure. The primary entrance is at the northwest side of the building and an emergency exits from the enclosure at the south end. The gates form the radiation safety exclusion boundary for the enclosure.

6 PIP2IT 25 MeV Beam Commissioning

The injector operates at a beam average intensity of 2 mA, with a repetition rate of 20 Hz and pulse length of 0.55 msec.

The ion source operates at typical beam current of 5 mA, either DC or long pulse mode at a high repetition rate, usually 20 Hz. The LEBT is equipped with a beam chopper which defines the macropulse beam pulse length at 20 Hz. Beam is then bunched and accelerated to 2.1 MeV by the RFQ cavity. At the MEBT region, the micropulse structure is defined by the chopping system that consists of two electrostatic kickers and an absorber. The chopping system provides a bunch-by-bunch selection which decreases the beam current from 5 mA down to 2 mA. The chopped-out beam is deposited at the absorber located downstream of the second kicker. The final pulse structure (0.55 msec, 2 mA, 20 Hz) is further accelerated by the two downstream cryomodules bringing the beam energy up to 25 MeV. The warm front end (WFE) (ion source, LEBT, RFQ, and MEBT) has been successfully commissioned in 2014-2018.

During the 25 MeV beam commissioning phase the mode will be pulsed beam with CW RF. The goal for this beam commissioning is to measure the beam parameters (e.g. energy, transmission, beam transverse size, and bunch length) as well as testing the performance of the SRF resonators. For more details on the beam commissioning plan, see Reference [1].

All beam commissioning activities will proceed within limits approved by the Radiation Physics Operations/Radiation Safety Officer (RPO/RSO) for the area or his/her designee. The PIP2IT 25 MeV beam commissioning activities will meet all applicable Fermilab Environment, Safety and Health Manual (FESHM) and Fermilab Radiological Control Manual (FRCM) requirements under provision title 10, Code of Federal Regulations (CFR), part 835 (10 CRF Part 835 -- Occupational Radiation Protection) and will abide by Accelerator Division beam operation practices.

7 Cryogenic Transfer Line (CTL)

The HWR and SSR1 cryomodules require a continuous supply of liquid helium. Cryogenic Helium is piped from the CMTF cryoplant, which is located on the north side of the facility footprint area. Once in the enclosure, thermal siphon "feedboxes" will distribute helium to the superconducting cryomodules. The feedboxes will also require liquid nitrogen. All the Cryogenic systems were designed in conformance with applicable American Society of Mechanical Engineers (ASME) standards and the Fermilab ESH manual. The potential Oxygen Deficiency Hazard (ODH) is addressed by the deployment of dedicated ventilation fans and the extension of the building HVAC system to the enclosure. Oxygen monitors are installed in the enclosure entrance. In an event of low level of oxygen is detected, the building HVAC system will bring in fresh air and alarms will be triggered.

The rest of this document addresses hazard analysis associated with the operation of the PIP2IT test line up to 25 MeV beam energy.

8 Hazard Analysis

The following is a synopsis of potential hazards that can be associated with operation of PIP2IT. The hazards associated with the 25 MeV beam operations include non-beam as well as beam-related hazards.

8.1 Description of the non-beam related hazards

Among the hazards present at PIP2IT are flammable gas area, lasers, high-power RF, high voltage electrical equipment, x-ray producing devices, oxygen deficiency hazard.

8.1.1 Flammable Gas Area

The PIP2IT ion source is a commercial style from D-Pace. A typical hydrogen bottle contains 31 scf of gas and 10-15 sccm for the flow is required to extract the maximum beam current provided by this ion source (15 mA).

The current setup has the system located inside the CMTF building, adjacent to the northeast wall of the building. The hydrogen bottle is enclosed in a plexiglass cage and enough ventilation is achieved with a wire mesh located at the top of the cubic box. This system has been operational as early as 2013 and is fully compliant with the requirements in FESHM. In Reference [2] a detailed explanation of the hazard analysis performed, and mitigation plans can be found.

8.1.2 RF Radiation Hazards

Hazardous levels of radio frequency electromagnetic energy are generated by RF power sources (Solid-State Amplifiers – a.k.a. *SSA*) for the PIP2IT beamline. This energy is not normally radiated and is nominally confined within coaxial transmission lines and the accelerating structures. Specific “Lock-out/Tag-out” (LOTO) and configuration control procedures are in place to establish safe conditions for personnel working on or around these systems. Antennae have been installed in the control racks for each RF system to monitor leakage and automatically shut off the appropriate RF system. Periodic surveys for stray RF fields are also expected to be performed by Fermilab ESH Section.

At PIP2IT the RF cavities that can generate RF Radiation Hazards are:

1. One RFQ
2. Three Bunching Cavities
3. One HWR
4. One pSSR1

With RF components and transmission line when they are properly connected, there is no electrical hazard due to contact with the amplifier or associated components. In an event of maintenance or work on the RF amplifier system, each RF power source is powered by a dedicated breaker and can be disabled and LOTO'ed for safe access.

8.1.3 X-ray Producing Devices

The potential radiation source at PIP2IT will be x-rays generated within the RF accelerating structures even in the absence of ion beam. These x-rays are due to electrons from ionized background gas or surface emission that are accelerated in the electric field of the cavities.
During previous operation of the room-temperature part of the PIP2IT, no significant ionizing radiation was observed from the RFQ and bunching cavities, in agreement with estimations. They are not considered to be hazardous in this respect.

The PIP2IT shielding assessment [3] provides analysis of the field emissions for the superconducting RF cavities. The results of testing of individual cavities demonstrated that maximum possible level of radiation outside of the enclosure area without the concrete walls is below 0.25 mrem/hr. The enclosure walls were constructed to satisfy beam loss attenuation requirements and provide additional attenuation for x-rays. More detailed information about this analysis can be found in the current shielding assessment.

The safety interlock system for the PIP2IT enclosure disables RF power to the accelerating cavities thereby mitigating the x-ray hazard whenever personnel access the enclosure.

Shielding requirements for radiation due to 25 MeV beam operation will be described in section 8.1.8.

8.1.4 Cryogenic and Oxygen Deficiency Hazards

The oxygen deficiency hazards are related to the increase risk of fatality or injury caused by low concentration of oxygen in a case of a catastrophic failure of a cryogenic system or from small leaks in a cryogenic system coupled with a failure of ventilation and detection systems.

The PIP2IT enclosure requires cryogenic system to operate the superconducting cryomodules. Cryogenics are widely used at Fermilab and there are many locations that pose ODH. Personnel who work in these areas require special training.

The PIP2IT enclosure area is regulated in accordance with existing Fermilab policy and in compliance with FESHM Chapter 5032, "*Cryogenic System Review*" [4], and Chapter 4240, "*Oxygen Deficiency Hazards*" [5].

Cryogenics hazard at PIP2IT was subjected to an ODH review, which included the potential for oxygen deficient atmospheres due to catastrophic failure of the cryogenic systems, thermal (cold burn) hazards from cryogenic components, and pressure hazards. Initiators studied included the failure/rupture of cryogenic systems from overpressure, failure of insulating vacuum jackets, mechanical damage/failure, deficient maintenance or improper procedures. All piping system were designed and installed to comply with applicable ASME and ANSI standards. The Fermilab Cryogenic Safety Subcommittee is the Authority Having Jurisdiction (AHJ) for reviewing and approving of all cryogenic systems and operational procedures. The PIP2IT CTL system review documentation and report can be found in reference [6].

With any cryogenic system there is a potential for thermal burns. The PIP2IT CTL system is adequately marked and protected from inadvertent contact. All staff and visitors of the PIP2IT enclosure, as with all accelerator complexes, will undergo general hazard awareness training that will cover the potential hazards of cryogenic material and the necessary protective gear to be worn when working around cryogens.

ODH mitigation includes employing oxygen deficiency sensors that alarm locally and read back into the Control Room at times when the oxygen levels fall below preset levels. Emergency response procedures are in place for responding to these alarm systems.

8.1.5 Mechanical Hazards

The potential consequences of mechanical hazards include serious injury or death to equipment operators and bystanders, damage to equipment, and interruption of the program. A dropped or shifted load, equipment failure, improper procedures or insufficient training/qualification of operators could initiate these hazards. These hazards are largely mitigated by design practices and work, following FESHM Chapter 2060, "*Work Planning and Hazard Analysis*" [7].

The PIP2IT beam line is composed of motorized equipment, such as

- Alison emittance scanner;
- Scrappers located at LEBT, MEBT and HEBT region;
- Beam absorber.

All of those slowly moving elements are shielded to eliminate possibility of pinching a body part.

Another moving part in the CMTF building is an overhead crane. It is operated by the qualified personnel only. During the beam commissioning, the roof of PIP2IT enclosure is enclosed by shielding blocks, eliminating the hazard.

8.1.6 Electrical Hazards

Electrical hazards include the potential for serious injury, death, and equipment damage caused by electrical shock or arc flash due to exposed conductors, defective and substandard equipment, lack of adequate training, inadequate protective gear or improper procedures. Fire and smoke from defective equipment/components has been experienced at accelerator complexes in the past.

The high voltage hazard from the ion source high voltage (30 kV) is addressed by placing all HV equipment inside shielded cabinets, with interlock system preventing the dangerous contact. The PIP2IT magnets are low-voltage, and all magnet powered leads have electrical shielding addressing the arcing hazard.

8.1.7 Radiation Hazard

8.1.7.1 Laser Hazard

A laser will be used in the PIP2IT enclosure as the light source for the beam line instrumentation – called laser wire. The laser source is located at a dedicated hub outside the PIP2IT enclosure. The laser light will be transported to the PIP2IT enclosure via a dedicated pipe until reach the optical cavity which will be located at a permanent location within the MEBT region. Appropriate safety measures (e.g. control of exposed beams) will be in accordance with FESHM 5260 Lasers chapter. All users of lasers will be reviewed and controlled as required in national consensus standards and Fermilab regulations.

The laser to be used at PIP2IT is expected to be Class IV, low-peak power, high repetition rate fiber laser with optical fiber transport to the accelerator.

8.1.7.2 PIP2IT Shielding Assessment

A detailed PIP2IT Shielding Assessment (SA) [3] was developed and reviewed by the FESHCom Shielding Assessment Review Panel and approved by the Senior Radiation Safety Officer in accordance with FRCM requirements. Within this document, normal operations mode, which corresponds to beam transmitted to the absorber without losses along the beamline and accident scenario, which corresponds to beam been entirely lost anywhere along the beamline were studied. Beam operation mode is expected to be 2 mA, at 20 Hz and pulse length of 0.55 msec, corresponding to a beam power of 550 W. The PIP2IT enclosure is about 40 meters long and constructed with one entrance at the north side of the CMTF building and a south emergency exit.

The shielding assessment provides a detailed analysis of radiation shielding requirements, which includes labyrinth and penetrations, residual dose rates, air activation, muon production, skyshine and ground water activation.

8.2 Description of the beam-related ionizing radiation hazards

The PIP2IT enclosure has radiological hazards associated with beam-induced in the form of prompt radiation and residual ionizing radiation from activated components. The former may induce neutrons and other energetic particles and the later can give rise to radiation exposures to personnel during accesses to the beam enclosures for repair, maintenance and inspection activities.

Detailed shielding assessment address these concerns with analyses of the area, the utilization of signs and application of radiation safety interlocks to comply with the FRCM (Ref. [8]).

8.2.1 Permanent Shielding

The permanent shielding includes concrete blocks that are intended to protect personnel in the case of various accident condition as specified in the shielding assessment.

8.2.2 Access points, penetrations

The enclosure is constructed from movable concrete shielding blocks. Access are made from the CMTF high-bay floor at the northwest end through a labyrinth constructed of shielding blocks. An emergency exit labyrinth is at the southeast end of the enclosure. The access points have beam interlocked gates.

There is one penetration in the east shielding wall for cryogenics transfer line to enter the enclosure area, twenty-eight penetrations in the east-west shielding wall for signal cables, utilities and RF to enter the enclosure area. The current shielding assessment [3] details the mitigations necessary for the enclosure and each penetration to comply with the requirements of the FRCM from both normal operation and accident conditions.

8.2.3 Active Controls

Active engineered controls are systems designed to reduce the risks from accelerator operations to acceptable levels. These automatic systems limit operations, shut down operations, or provide warning alarms when operating parameters are exceeded. The active controls in place for the PIP2IT area include transmission loss system, such as comparing beam current monitors at specific locations along the beamline and radiation safety interlock system.

8.2.3.1 Monitors

As mentioned earlier in this document, the 25 MeV beam commissioning mode will be CW RF pulsed beam. The primary protection from a CW mode operating running will be done by the Machine Protection System (MPS).

The PIP2IT beamline is instrumented with AC Current Transformers (ACCTs), DC Current Transformers (DCCT), Scrapers, Kicker Protection electrodes and Ring Pickups (RPUs). These devices are used in various combinations to protect the LEBT, MEBT and the HEBT section of the machine. A calibrated DCCT located in the upstream of the HWR cryomodule monitors the average beam intensity and is used, in part, as the tool to control the administrative limit. The beamline transmission is controlled by a set of pulse current transformers (ACCT). These systems are monitored by the MPS that stops the beam within a single macropulse if parameters exceed the specified threshold. Invasive device such as scrapers directly monitor excessive current losses in location, while Protection Electrodes sacrificially measures beam current that could otherwise damage kickers. These signals are also integrated and monitored by the MPS.

Radiation monitors (a.k.a. *chipmunks*) will be interlocked to the Radiation Safety Interlock system to ensure radiological limits around the enclosure are not exceed. Placement of these integrating radiation detectors were determined as a part of the shielding assessment based on a series of potential accident conditions. The radiation detectors are interlocked to the PIP2IT Radiation Safety Interlock System (RSIS) to ensure compliance with FRCM requirements. The detectors are placed with appropriate trip levels so that beam loss producing radiation flux that exceeds the allowable dose limit to that area will trip critical devices that prevent further beam operations until condition is understood.

8.2.3.2 Radiation Safety Interlock System

The PIP2IT enclosure employs a RSIS. The characteristics of the system are described in FRCM Chapter 10 [8]. The PIP2IT RSIS prevents personnel access to the enclosure with beam enabled by inhibiting the beam when disabled.

The RSIS inhibits beam by two separate controlling critical devices: IS HV power supply and the LEBT dipole making it impossible for any beam to leave the LEBT.

Trained and qualified personnel from the AD Operations Department is required to search and secure the enclosure before permits from the RSIS can be reestablished following any personnel access to the area except under controlled access conditions. The RSIS including requirements for hardware and system testing, inventory of interlock keys, search and secure procedures, controlled access procedures, personal training requirements and procedures for maintenance of interlock systems is maintained in conformance with the requirements stated in the FRCM.

8.2.4 Administrative Controls

8.2.4.1 Beam Operations

The PIP2IT was assessed [3] for intensities not to exceed 5×10^{17} H^- per hour at energies up to 25 MeV to the beam dump. Accelerator operational requirements will be documented in the PIP2IT Radiological Work Permit for PIP2IT beam commissioning and approved by the assigned RSO.

During beam running, regular radiation survey will be conducted to verify that the operation of the 25 MeV does not produce radiological area concerns.

8.3 Conclusions

It is the intent of the PIP-II Project that the technical and scientific goal of the PIP2IT can be achieved in a safe and environmentally sound matter. This document has summarized a variety of potential ESH hazards that might be encountered in the operation of the PIP2IT enclosure at CMTF. The conclusion is that all major hazards have been identified and has been or soon will be addressed by the means discussed here. This Hazard Analysis will serve as the basis for the Operational Conditions and approvals.