Functional Requirements Specification
PXIE
(PIP-II Injector Experiment)
PIP-II front-end integrated systems test

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Revision History

Revision	Date	Section No.	Revision Description
0	11/18/11	All	Initial Draft Release.
1	02/03/12	All	Initial Release
ED0001223 Rev -	02/11/13	All	Draft Update
ED0001223 Rev A	12/10/15	All	Realignment to PIP-II goals

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1. Introduction:

PIP-II is a high intensity proton linac conceived to support a world-leading physics program at Fermilab [1]. Initially PIP-II will provide high intensity beams for Fermilab neutrino program with future extension to other applications requiring CW linac operation (e.g. muon experiments). PIP-II is considered to be a 2 mA CW, 800 MeV H^- linac that should be capable of working initially in a pulse (0.55 ms, 20 Hz) mode for injection into the Booster.

The PIP-II Injector Experiment (PXIE) will be an integrated systems test for the PIP-II front end [2]. It is part of the broader program of research and development aimed at key components of the PIP-II. The successful completion of this test will validate the concept for the PIP-II front end, thereby minimizing the primary technical risk element within PIP-II. Successful systems testing will also demonstrate the viability of novel front end technologies that will find applications beyond PIP-II in the longer term.

2. Scope:

PXIE will be located in the existing Cryomodule Test Facility (CMTF) and will utilize available existing infrastructure. The PXIE accelerator will include the following seven subsystems shown in Figure 1:

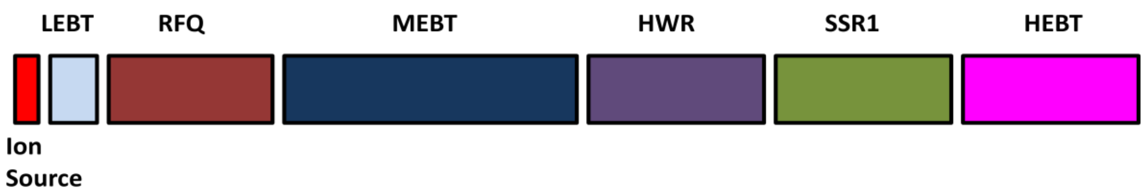

Figure 1: Major Subsystem in the PXIE Linac

- A DC H^- ion source capable of delivering up to 10 mA (5 mA nominal) at 30 keV [3].
- A Low Energy Beam Transport (LEBT) section with beam pre-chopping [4].
- A CW Radio Frequency Quadrupole (RFQ) operating at 162.5 MHz and delivering up to 10 mA at 2.1 MeV [5].
- A Medium Energy Beam Transport (MEBT) section with integrated fast programmable wideband beam chopper and 21 kW beam absorber capable of generating arbitrary bunch patterns at 162.5 MHz from the RFQ beam [6].
- Two low-beta superconducting cryomodules (HWR and SSR1) capable of accelerating up to 2 mA of beam to greater than 27 MeV [7, 8].
- A High Energy Beam Transport (HEBT) section [9], which consists of (1) a beam diagnostic section, capable of measuring particle distribution including tail distributions and the extinction ratio of removed bunches, and (2) a beam dump, capable of accommodating maximum beam power of 50 kW with energies of up to 30 MeV for extended periods.

Major PXIE Goals

Validate critical technologies required to support the PIP-II Reference Design concept.

- Provide a platform for demonstrating operations of PIP-II front end components at full design parameters
- Integrated systems test goals:
  - 2 mA average current with 80% bunch-by-bunch chopping of the beam delivered from the RFQ
  - Efficient acceleration with minimal emittance dilution through at least 27 MeV in both CW and pulse modes
  - Demonstration of stable beam acceleration in SSR1 cryomodule with pulsed RF
- Measurement and characterization of beam extinction for the removed bunches

3. Key Assumptions, Interfaces & Constraints:

- The PXIE Linac will be in the existing CMTF building. The building infrastructure will be shared between PXIE and Cryomodule Test Stand (CMTS-1), including floor space, cryogenics, wall power, water, and HVAC.
- A labyrinth for personnel access shall be located at the upstream end of PXIE. An emergency exit labyrinth, shared with the Cryomodule Test Stand (CMTS) will be located at the downstream end of PXIE.
- The cave shall be sized to accommodate beamline elements and a personnel access aisle. The cave roof shall be removable for installation, removal, and servicing of components.

The CMTF Facility imposes the following constraints on the PXIE:

- The available cryogenic supply from the Superfluid Cryogenic Plant (SCP) has a maximum capacity as listed in Table 1:

TABLE 1: CMTF SCP Cryogenic Capacity

Temperature Level	Capacity
2 K	500 W
5 to 8 K	600 W
40 to 80 K	4,100 W

- Electric power is provided by 480V, 3 phase switchboards capable of delivering at least 900 kW to PXIE equipment (RF, magnet power supplies, vacuum, diagnostics, and controls).
- The current building HVAC has enough capacity to provide heating and cooling of empty building throughout the year. On top of that, the AC system is capable of removing heat from CMTS1 equipment and, in addition, at least 70 kW of heat from CMTF equipment.

- The PXIE requires Low Conductivity Water (LCW) provided by the CMTF LCW system. The capacity of this system available for PXIE is at least 900 kW. minimum.
- The PXIE Linac will require compressed air, provided by the CMTS air system. The capacity of this system available for PXIE is 150 ft^3/min at 90-120 psig.
- The CMTF building has a 20-ton overhead crane with a maximum hook to floor clearance of 24 feet.

4. Requirements

Technical Requirements:

PIP-II is based on a 800 MeV superconducting H^- linac, with beamline elements designed for continuous-wave operation. PXIE represents the PIP-II frontend and is therefore required to generate and deliver the same quality beam as PIP-II but at a reduced energy. The PXIE functional requirements are listed in Table 2.

TABLE 2: PXIE FRS

Functional Requirements Specification - PXIE		
L1	Delivered beam energy, minimum/maximum	15/30 MeV
L2	Average beam power	≤ 50 kW
L3	Nominal/maximum Ion Source and RFQ current	5/10 mA
L4	Average beam current (averaged over >1 μsec)	2 mA (at MEBT end)
L5	Beam normalized transverse RMS emittance*	< 0.25 mm-mrad
L6	Beam normalized longitudinal RMS emittance**	< 1 eV-μs
L7	Maximum bunch intensity (ppb)	3.8×10^8
L8	Minimum bunch spacing	6.2 nsec (1/162.5 MHz)
L9	The MEBT shall include a Wideband Chopper capable of removing bunches in arbitrary patterns at 162.5 MHz	<5% beam loss in unremoved bunches; <0.01% residual beam in removed bunches at MEBT end
L10	Individual components should meet PIP-II requirements - Ion Source, LEBT, RFQ, MEBT, HWR & SSR1. Exceptions to this requirement shall be documented.	
L11	The MEBT shall be capable of disposing of 100% of the beam coming from the RFQ	
L12	The beamline shall be 1.3 m above floor elevation	
L13	Radiation shielding shall be sufficient for an unlimited occupancy designation, as defined by FESHM, outside the PXIE enclosure	
L14	Accuracy of measuring the beam extinction for removed bunches***	$<10^{-6}$ of nominal bunch intensity
L15	PXIE should be capable of reproducing PIP-II pulsed mode of operation for the Booster injection	0.55 ms beam pulses at 20 Hz
L16	Appropriate diagnostic systems shall be developed, installed and commissioned to verify and quantify all of PXIE requirements in this document	

* The normalized rms emittance is defined using the moments of the particle distribution in phase space (e.g. $x - x'$) as follows: $\varepsilon_x = \beta\gamma\left(\overline{x^2}\,\overline{x'^2} - \overline{xx'}^2\right)^{1/2}$. For Gaussian beams, it is based on 100% of particles; both in modeling and in experiments, it may be based on a

truncated number of particles (95-100%) to reduce the effect of far tails on the calculated emittance value.

** To express the longitudinal rms emittance in mm-mrad, multiply it by $(M_p c)^{-1}$, 0.32 mm-mrad/(μs-eV) for protons and H^- ions.

*** As measured at HEBT. If the beam extinction is measured to be lower than the specified accuracy, the measuring apparatus shall be modified to improve accuracy to the level that is the largest of either measurable population of the removed bunches or of the interest for a perspective user (presently 10^{-10}).

Fermilab engineering and ES&H policy also imposes the following requirements for the PXIE Linac:

- The engineering design of all aspects of the PXIE Linac is subject to the process detailed in the Fermilab Engineering Manual [10].
- All sections of the Fermilab ES&H manual shall be adhered to at all times [11].

Safety Requirements:

The design of the PXIE Linac enclosure should have special attention given to the safety requirements in the following area:

- Radiation safety – the proper design of cave shielding and entrance/exit labyrinths to maintain unlimited occupancy outside the PXIE cave and the cave roof area.
- Fire Safety – the proper design of fire detection & suppression systems and proper egress pathways around beamline components
- Oxygen Deficiency Hazard (ODH) Safety – the proper design of all pressure vessel and cryogenic systems as to maintain the ODH classification of the test cave as ODH0 or ODH1, and the CMTF (outside the PXIE cave) at ODH0.
- Personnel Protection System – have in place a design that allows for a controlled and supervised access into the test cave.
- Machine protection – a proper monitoring and interlock design to prevent damage to PXIE components.

Cryogenic Operation Requirements:

Specifications for PXIE cryogenic distribution system (CDS) should be described in a separate document taking into account the following requirements.

The CDS has to allow for the ability to operate both the CMTS1 and the PXIE Linac simultaneously or separately. Warm-up/cooldown of the PXIE shall be with minimal interruption to CMTS1 operation.

The design of the PXIE CDS shall support the following operations modes to allow for independent operation of each cryomodule (HWR and SSR1):

TABLE 3: Cryogenic Operations Modes

Mode	HWR	SSR1
Non-operation	Warm	Warm
Simultaneous operation	Cold	Cold
HWR operation	Cold	Warm
SSR1 operation	Warm	Cold

It is permissible to accomplish "HWR Operation" or "SSR1 Operation" modes by removing the connecting U-tubes of the cryomodule that is to stay warm.

The design of the cryogenic system shall permit transitions between modes as depicted in Fig.2.

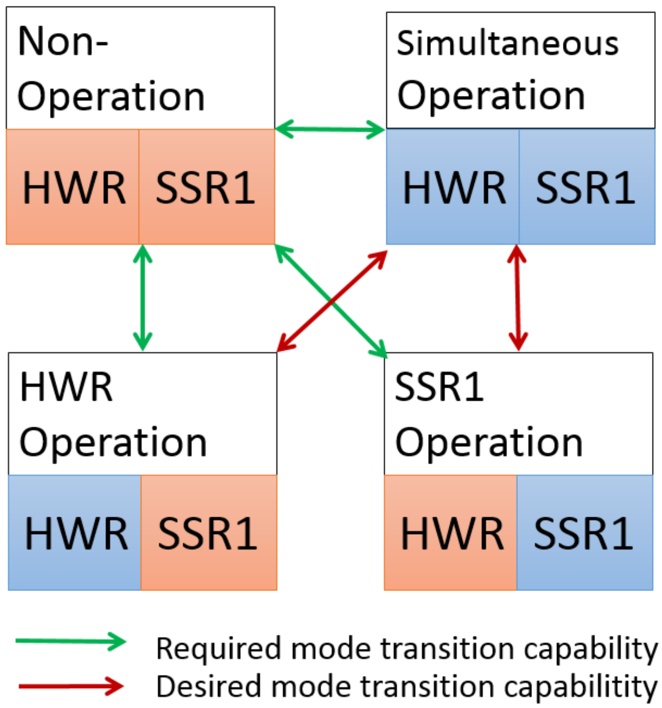

Figure 2: Required mode transitions for PXIE cryogenics

In transitions between Simultaneous Operation and HWR Operation or SSR1 Operation, transient temperature excursions of the non-transitioning cryomodule (i.e. the cryomodule that is staying cold) shall be < 50K (TBR) at the cavities to limit thermal cycling magnitude and avoid the Q-disease regime.

Commissioning Requirements:

The project requires flexibility to handle a phased commissioning of the accelerator components.

Operational Requirements:

The facility needs to have the capability of continuous and remotely controlled operations. This operation can utilize the Accelerator Division Operations Department (AD/OPS) through the training of Main Control Room (MCR) personnel.

Procedures for cleaning, certification, assembly, and servicing of beamline vacuum shall be established and followed to ensure that particulate migration to the cold SCRF cavities does not degrade long term performance.

5. References:

PIP-II documents are referred by their numbers in TeamCenter. In some cases, links to uncontrolled (i.e. not necessarily up-to-date) copies of the documents are included for convenience as well.

[1] PIP-II Functional Requirements Specification, ED0001222, http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1

[2] PXIE White Paper, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=966

[3] PXIE Ion Source Functional Requirements Specifications, ED0001288, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=968

[4] PXIE LEBT Functional Requirements Specification, ED0001289, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=912

[5] PXIE RFQ Functional Requirements Specification, ED0001300, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=894

[6] PXIE MEBT Functional Requirements Specification, ED0001303, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=938

[7] PXIE HWR Cryomodule Functional Requirements Specification, ED0001313 http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=967

[8] PXIE SSR1 Cryomodule Functional Requirements Specification, ED0001316 http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=931

[9] PXIE HEBT Functional Requirements Specification, to be written

[10] Fermilab Engineering Manual http://www.fnal.gov/directorate/documents/FNAL_Engineering_Manual_REVISED_070810.pdf

[11] Fermilab ES&H Manual http://www-esh.fnal.gov/pls/default/esh_home_page.page?this_page=15053