PXIE AT FNAL

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Abstract

The Project X Injector Experiment (PXIE) [1,2], a test bed for the Project X front end, will be completed at Fermilab at the end of 2016. The goal of this facility is to demonstrate the most challenging technologies proposed for Project X. PXIE will operate at full specified parameters for Project X and should demonstrate upgradability of the front-end for 2 mA operation.

In MEBT section a dedicated chopper will form a 1 mA H- beam with an arbitrary selected bunch pattern from the initially 5 mA 162.5 MHz CW train provided by RFQ. MEBT section will transport and match beam from RFQ to superconducting accelerator, provide enough diagnostics to measure all beam parameters after RFQ and before SRF cryomodules, dump ~80% of the beam after chopping and collimate the beam to minimize beam losses in upstream SRF. This paper presents the PXIE scheme and status of development of its elements, including ion source, LEBT, RFQ, the kickers and absorber, SC cavities and cryomodules, beam extinction experiment and 50 kW beam dump at the end of facility.

INTRODUCTION

PXIE is a front-end of the Project X. It includes: ions source, Low Energy Beam Transport (LEBT) section with diagnostics and pre-chopper, RFQ, Middle Energy Beam Transport (MEBT) section with bunch-to-bunch chopper, two superconducting cryompodules (HWR and SSR1), beam diagnostics and 50 kW beam dump. The general layout of the PXIE facility is shown in Figure 1. The total length of facility is ~40 m.

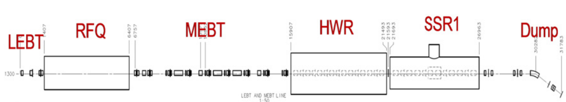

Figure 1: PXIE layout.

These goals of PXIE are:

- reliable operation of 2.1 MeV RFQ in CW regime
- a bunch-by-bunch chopper,
- low-β acceleration in SRF cryomodules.
- small emittance growth during initial acceleration
- good particle extinction for the removed bunches

Bunch by bunch chopper in MEBT section will be able to form arbitrary pattern of the beam structure for multi-user experimental program, by removing up to 80% bunches from 5 mA beam accelerated in RFQ. Layout of PXIE beam optics and transverse and longitudinal 3-sigma envelopes for passing trough beam are shown in Fig. 2 (LEBT and RFQ are not included). In the vertical plane yhe passing trough beam is deflected by two kickers and then returned back to the axis by DC corrector in MEBT section [3].

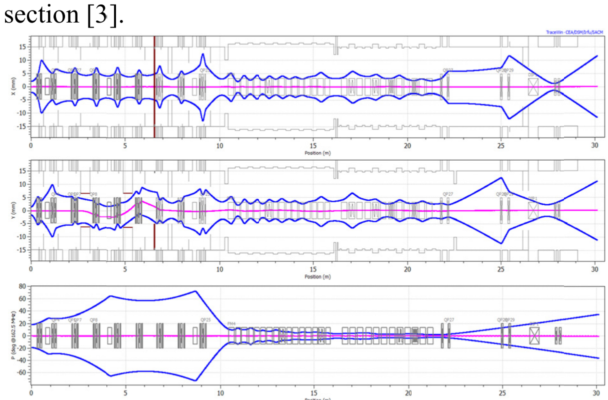

Figure 2: 3-sigma beam envelopes (X, Y and Z-longitudinal bunch phase) in PXIE (after RFQ) for 5 mA.

ION SOURCE AND LEBT

PXIE ion source should provide H^- source working in DC regime with 5 mA nominal current and possibility to regulate output current in the range of 1-10 mA. PXIE specify voltage 30 kV and lifetime 350 hrs or better. TRIUMF type H^- volume-cusp source produced from D-Pace was purchased and commissioned at TRIUMF and LBNL [4]. The general view of the source and result of emittance measurements in the range of 1-10mA beam current are shown in Figure 3. Measured normalized emittance at the exit of source is current is below 0.12 π·mm·mrad and not sensitive to the output beam current.

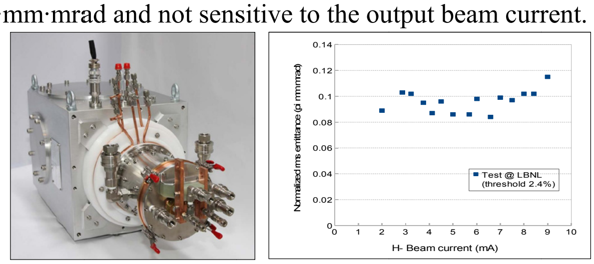

Figure 3: Ion source and emittance vs. beam current.

LEBT original design, proposed by LBNL includes beam emittance diagnostics, pumping, electrostatic chopper and two solenoids to match beam from IS to the RFQ [5]. Switchable bending magnet in this design will bend beam from one of the two ion sources to the RFQ. In current configuration the replacement of the ion source will not disturb operation of the Project X complex. In PXIE we are not planning to use second leg of LEBT with spare source. Beam space charge in LEBT transport line is compensated by neutralized ions. Recently it was proposed to modify this design by adding ion cleaning electrode after bending magnet and extra solenoid as shown in Fig. 4 [6]. The goal of this modification is to

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have un-neutralized beam at the vicinity of chopper and RFQ, which allows eliminate transition time after chopping cycle, required for re-ionization of gas in case of neutralized beam. LEBT layout and beam optics are shown in Figure 4.The total length is about 2m.

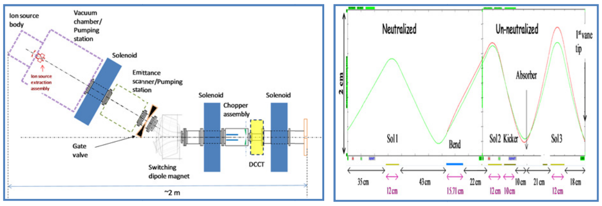

Figure 4. Layout and optics of the PXIE LEBT.

RFQ

The PXIE RFQ design proposed by LBNL is a 162.5 MHz, 4.45 m long, four-vane CW structure of four longitudinal modules that will accelerate a 5 mA H- beam from 30 keV to 2.1 MeV using a 60 kV vane-to-vane voltage [7]. Most of the RF input power (~100 kW) is dissipated on the cavity walls to establish the needed RF field with only about 12% beam loading. Each of the approximately 1.1 m long RFQ modules will consist of four solid OFHC copper vanes that are modulated prior to being brazed together. A brazed copper structure has been chosen due to the high power CW operation. A series of 32 water-cooled pi-mode rods provides quadrupole mode stabilization, and a set of 80 evenly spaced fixed slug tuners is used for final frequency adjustment and local field perturbation correction. The RF design studies have been conducted through a close collaboration with Fermilab, detailed EM simulation studies can be found in [8]. Mechanical design and thermal simulations are mostly completed. An overall view of the full four-module RFQ is shown in Figure 5.

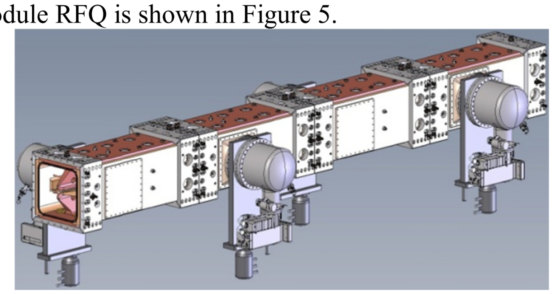

Figure 5: CAD model of the full four-module RFQ.

The beam dynamics design of PXIE RFQ is optimized using the measured beam distribution from the H- ion source. The design has over 96% transmission for beam current from 1 to 15-mA. At 5-mA nominal current, 99.8% beam capture is achieved with transverse and longitudinal emittance of 0.15-π-mm-mrad and 0.64-keV-nsec (or 0.22 -π-mm-mrad), respectively. The beam dynamics design was conducted using PARMTEQM, and cross-checked with TOUTATIS and TRACK codes. TRACK simulation was done with using 3D filed map generated by MWS based on realistic model of the RFQ.
Various errors studies (field, alignment, mismatch, etc.) were performed in PRAMTEQM and TOUTATIS. Figure 6 shows transverse and longitudinal sizes of the beam and emittance growth in RFQ in presence of 50% mismatch in twiss parameters. After a series of key fabrication tests are completed, construction of the actual RFQ modules will begin later this year.

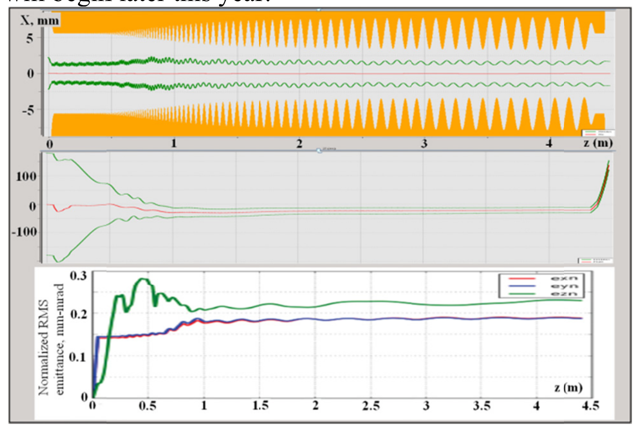

Figure 6: Transverse (up), longitudinal (middle) beam profile and beam emittance growth (below) for 50% mismatch of initial Twiss parameters (TOUTATIS).

MEBT

The PXIE MEBT will be a ~10 m beam line between RFQ and the first Half-Wave Resonator cryomodule (HWR) [6]. It should form the required bunch pattern, match the optical functions between RFQ and SRF, include tools to measure properties of the beam coming out of RFQ and coming to SRF, and clean transverse halo particles while transporting the bunches selected for the following acceleration with a low emittance dilution and a low beam loss. The main MEBT requirements are listed in Table 1.

Table 1: The Main MEBT Functional Requirements

Parameter	Value	Unit
Beam kinetic energy	2.1 +/-1%	MeV
Input frequency of bunches	162.5	MHz
Nominal input beam current	5	mA
Beam current operating range	1-10	mA
Nominal output beam current	1	mA
Relative residual charge of removed bunches	< 10-4	
Beam loss of pass through bunches	< 5%	
Nominal transverse emittance	< 0.27	µm
Nominal longitudinal emittance	0.8	eV-µs
Relative emittances increase	<10%	

General Design and Functions

Transverse focusing in the MEBT is provided mainly by equidistantly placed quadrupole triplets (Fig. 7) except two doublets at the MEBT upstream end. Sections between neighbouring triplets or doublets are represented by rectangles colour-coded according to their main function. The regular period is 1140 mm, which leaves

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650 mm (flange-to-flange) space for equipment (350 mm in the section #0). Longitudinally the beam is focused by three bunching cavities made of copper.

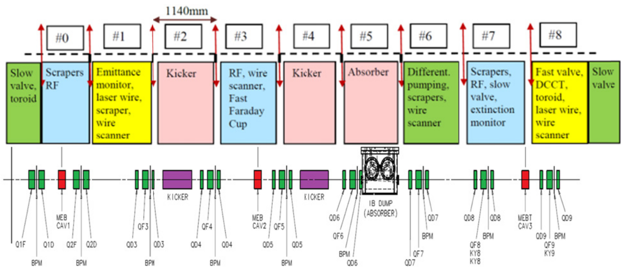

Figure 7: MEBT functional schematic (top) and layout (below). Red - chopping system, blue- RF, yellow – diagnostics, green – vacuum.

The undesired beam bunches will be removed in the MEBT by a chopping system consisting of two identical kickers separated by 180º transverse phase advance and an absorber at 90º from the last kicker. The schematic of MEBT optics and beam envelopes for chopped out and passing beam are shown in Figure 8.

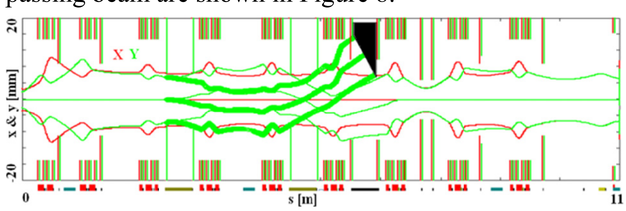

Figure 8: Scheme of MEBT optics and the beam envelopes. The thin lines show the central trajectory and 3σ envelope of the passing beam; thick lines show the Y envelope of the chopped-out beam. Below beamline components: red colour- quadrupoles, blue- bunching cavities, brown- kickers.

In the broadband, travelling-wave kickers [9], the transverse electric field propagates through their structures with the phase velocity equal to the speed of H- ions, 20 mm/ns. Depending on polarity, bunches are either kicked toward the absorber surface or on a pass through path. In either case, the voltage on opposite plates is +/-250V with respect to ground. The gap between the kicker plates is 16 mm. Protection electrodes with 13 mm gap are installed on both sides of each kicker and will be used for beam collimation and machine protection.

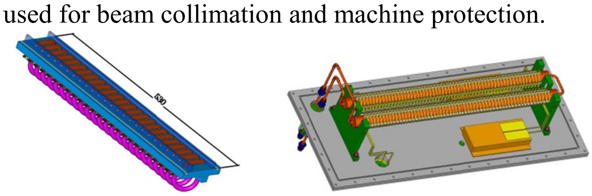

Figure 9: Mechanical schematic of the a) 50-Ohm kicker and b) 200-Ohm dual-helix kicker.

Because of critical importance of the kicker performance, presently two versions of the kicker are been developed: planar 50-Ohm design driven by a 1-kW linear amplifier and helical 200 Ohm kicker to be driven by broadband, DC coupled switches in the push-pull configuration, which are under development at FNAL. Mechanical models of both designs (shown in Fig. 9) were built and all RF properties were measured. Recent progress on kicker R&D program was presented in [6,9].

The MEBT absorber should withstand irradiation by a 21 kW H^- beam with the nominal rms beam radius of ~2mm. The design is shown in Fig. 10 addresses concerns about the heat load and resulting mechanical stresses as well as possible blistering issues [6].

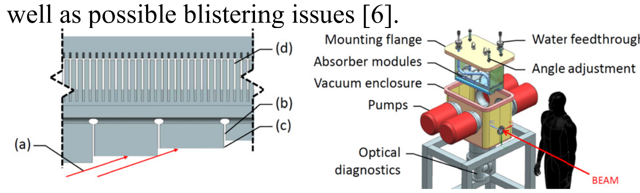

Figure 10: Conceptual design of the MEBT absorber. Left: side view of absorber showing (a) beam incident on surface, (b) axial stress relief slits, (c) shadowing step increment (magnitude exaggerated), (d) 300µm wide by 1mm pitch water cooling channels. Horizontal scale exaggerated. Right: exploded view.

To decrease the power density, the beam is directed to the 40-cm long absorber at a 29mrad grazing angle. The absorber is made of the molybdenum alloy TZM and is cooled by water flowing through transverse micro-channels. The axial stress is relieved by transverse slits. Thermal and stress analysis showed feasibility of the design[10]. A 10-cm long prototype is being manufactured, and its thermal properties will be tested with an electron beam.

The main purpose of two yellow-colored sections in Fig. 7, #1 and #8, is to house beam diagnostics. A fully equipped PXIE diagnostics should allow characterizing the beam coming in and out of MEBT and out of SSR1 as well as its optics. Detailed description can be found in Ref. [15].

SUPERCONDUCTING CRYOMODULES

After chopping in MEBT the 1 mA beam will be accelerated in two cryomodules: Half-wave resonator (HWR) and single-spoke resonator (SSR1) cryomodule (CM). The basic parameters of the cavities used in each CM are shown in Table 2.

Table.2: Parameters of the Cavities

cavity type	β_g	Freq, MHz	pipe ø mm	E_{acc} MV/m	E_{pk} MV/m	B_{pk} mT	R/Q Ω	G Ω
HWR	0.12	162.5	33	8.2	38	41	272	47.7
SSR1	0.22	325	30	12	46	70	242	84

Design of the HWR cavity and cryomodule is done in collaboration with ANL and Fermilab [11-13]. Each cryomodule contains 8 cavities and 8 SC solenoids (cavity and solenoid per period). Plan is to order cavity prototype in 2012 and test in 2013. ANL will deliver one CM for PXIE in 2016.

SSR1 cryomodule contains four periods with 2 cavities and one solenoid per period with structure: CSC, where C is cavity, S-solenoid. SSR1 cavity was designed and several prototypes were built and successfully tested at

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Fermilab. Batch of 10 cavities for PXIE (including spares) was ordered in Niowave; currently 6 cavities were delivered and 2 of them tested at vertical test stand. Both cavities demonstrated high accelerating gradient > 20 MV/m and Q0 well above specification. Design of the HWR and SSR1 cavitiy and CM is shown in Figure 11.

HW-to-SSR1 transition goes through short room temperature vacuum chamber with ~20 cm space available for beam diagnostics, scrapper and vacuum port.

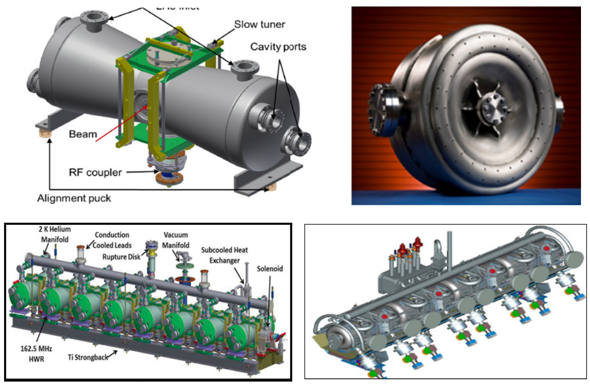

Figure 11: Design of the HWR (left) and SSR1 (right)

Each SC solenoid has built-in X/Y correctors, which allow relax alignment tolerances to 0.5 mm. Each solenoid (and each focusing lens in room temperature part of the PXIE) has attached button-type BPM able to measure bunch transverse position and arriving time. Nominal cryogenic losses not exceed 10 W per cavity. Status of R&D on superconducting section of PXIE is presented in [13] in more details.

DIAGNOSTICS AND BEAM DUMP

The parameters of the accelerated in SC section beam with energy ~25 MeV will be measured in ~3m long diagnostic line. One of the goal of beam diagnostic is to measure extinction in empty bunches (chopped out in MEBT) at the level 10^{-4} or better. For that a 243.75 MHz deflecting cavity will separate empty and full bunches by kicking them +/- 5mrad in opposite directions. Nearby DC corrector will cancel out deflection for pass through full bunches and double deflecting angle for empty bunches. In place when bunches have more than 10-sigma separation, extinction will be measured by detector (see Fig. 12).

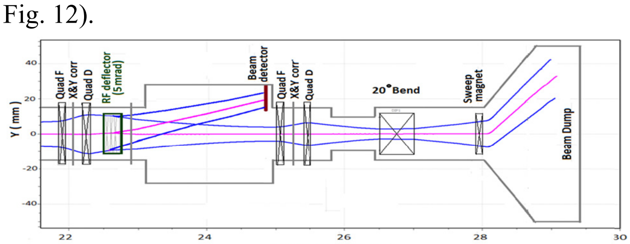

Figure 12: Schematic of the diagnostic line with 50 kW beam dump and extinction measurement experiment.

Beam diagnostics included current monitor, halo monitors, slits and laser profile monitors for emittance measurements. 20 degrees bending magnets will send beam down to beam dump and provide spectrometry for energy measurements.

PXIE beam dump (absorber) should accept 50 kW beam (2 mA x 25 MeV) current. To provide reasonably low power density in dump a special sweeping magnet will rotate beam in azimuthal direction with 60 Hz revolution frequency. Absorber will be made of copper with ~ 2mm thick nickel inside. Simulations of sputtering and blistering in nickel show that absorber will survive in these conditions. Local radiation shield made of 60 cm iron and 20 cm polyethylene will provide the required level of shielding [14]. Figure 13 demonstrates the conceptual design of the beam dump components.

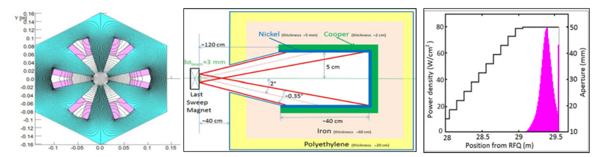

Figure 13: Design of the 6-pole sweeping magnet (left), 50 kW dump with local radiation shielding (middle) and power density distribution in dump surface (right).

OTHER SUBSYSTEMS

Several other subsystems are at different stages of development: quadrupoles, scrapers, vacuum system, and diagnostics.

The triplet assembly, which will consist of a central (larger) and two smaller quadrupoles, a pair of dipole correctors, and a button BPM mounted between the quadrupoles in MEBT and diagnostic section, is under technical design.

The scraping system concept assumes installation of 16 scrapers grouped in 4 sets in MEBT with two X and two Y scarpers per set. Each scraper is an electrically isolated, ~100W-rated plate precisely movable across half of the aperture. The scrapers will be used for several purposes:

- For beam halo measurements and removal
- To protect the downstream equipment from beam losses.
- Beam density distribution diagnostics (pulse mode)
- To form a pencil beam for measurements downstream (pulse mode)

One pair of scraper sets is to be installed at the beginning of the MEBT to protect the MEBT elements (first of all, kickers), and the second pair is located after the absorber as a protection for cryomodules. The sets in each pair are separated by ~90º of the phase advance.

The vacuum system design is at a conceptual stage. The vacuum requirements are determined by the electron detachment in the H- beam and by the necessity to have a low gas flow into the HWR cryomodule from MEBT side and into SSR1 cryomodule from diagnostic line side. Obviously, the electron detachment results in a loss of H- beam intensity; an additional restrictive effect is a flux of created neutral hydrogen atoms that may reach the SRF cavities. For the design of the vacuum system, we adopted the requirement of keeping the integral of the pressure over the length of the MEBT to be below $1\cdot10^{-6}$ Torr·m,

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which corresponds to loosing ~10^{-4} in the beam intensity and adding an additional ~0.1 W heat load to SRF by the neutrals.

The gas flow from the room-temperature MEBT to the 2K HWR cryomodule causes a gas deposition on the cryogenic surfaces. To be on a safe side, we aim to keep the pressure upstream of PXIE's HWR at or below of $1\cdot10^{-9}$ Torr (H_2). The main source of the vacuum load in the MEBT is expected to be a flow of hydrogen created from recombination of protons at the absorber. To maintain a high vacuum near the SRF, first, the absorber is placed into a large box with effective pumping speed of 2500 l/s by turbo pumps and, second, the absorber is followed by a differential pumping section (#6 in Fig. 5), where the vacuum chambers are separated by a 10mm ID, 200 mm long pipe. Similar approach will be applied for preventing flow of hydrogen from 50 kW dump to SSR1 cavities. We are planning to have large pumping capability close to dump and use a differential pumping section before bending magnet to provide vacuum below of $1\cdot10^{-9}$ Torr (H_2) in vicinity of SSR1 cryomedule.

PXIE require two types of room temperature cavities working in CW regime: 162.5 MHz bunching cavity and 243.75 MHz deflecting cavity. Beam loading in these cavities is negligible with compare to power dissipation in copper walls. The design of these cavities was optimized to keep power losses as small as possible. The EM designs of both cavities are shown in Figure 14. For the nominal parameters bunching cavity will require ~1kW, while deflecting power are ~3kW.

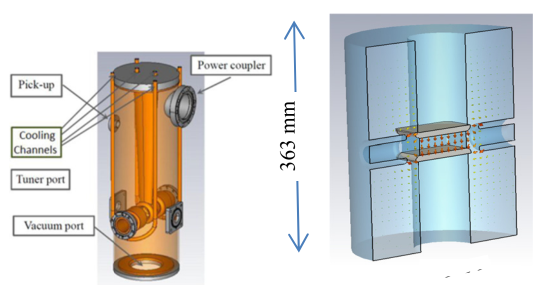

Figure 14: Preliminary design of the quarter-wave 162.5 MHz buncher cavity (left) for MEBT and 243.25 MHz deflecting cavity for extinction experiment.

The PXIE RF systems will include all CW amplifiers that are intended for reuse in the Project X front end. The complete PXIE RF system consists of three frequencies at power levels ranging from 4 to 150 kW with total of 21 RF systems. Each cavity will be powered by individual power source. At PXIE frequencies and power levels, solid-state amplifiers have been chosen for the RF power sources, which have high reliability, module structure and compact.

CONCLUSION AND PLANS

The proposed scheme of the PXIE contains all elements required for shaping and characterizing the beam coming to the Project X SRF linac. The extensive test of the front-end operation is planned to be carried out in PXIE. The FY2013 schedule includes manufacturing and testing components for LEBT and prototypes for the absorber, kicker, quadrupoles, and BPM. Plan is to start full parameters operation in PXIE at the end of 2016.

ACKNOWLEDGMENT

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