PROGRESS OF THE RFQ ACCELERATOR FOR PXIE*

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Abstract

The proposed Project X Injector Experiment (PXIE) is currently under development at Fermilab. PXIE is an R&D test accelerator that will replicate the front-end portion of Project X. The PXIE accelerator complex consists of a H^- ion source(s), low-energy beam transport (LEBT), a 162.5 MHz normal conducting CW Radio-Frequency-Quadrupole (RFQ) accelerator, medium-energy beam transport (MEBT), broad-band beam chopper(s) and two superconducting cryomodules. In this paper, we will review and present recent progress of the PXIE RFQ, which will include an overview of the RFQ beam dynamics design, RF structure design, detailed thermal and mechanical analyses, fabrication test results and fabrication plan and schedule.

INTRODUCTION

Project X is a proposed multi-MWs proton accelerator complex currently under development at Fermi National Accelerator Laboratory (FNAL), its ultimate goal is to construct and operate the foremost intensity frontier high energy physics (HEP) facility in the world. With Project X, the high energy frontier can be achieved through a path toward a muon source for possible neutrino factory and a muon collider. A complete concept design of Project X has been developed [1]. It consists of a warm section of front-end system, 3 GeV CW superconducting linac with 1-mA average beam current and 3-8 GeV pulsed SC linac (1.3 GHz ILC design) capable of delivering 340 kW beam power at 8 GeV and an upgrade to the Recycler and Main Injector to provide ≥ 2 MW to a neutrino target at 60-120 GeV. To mitigate technical risks, a number of Project X R&D programs have been launched at FNAL. One of them is the PXIE (Project X Injector Experiment) and being considered as the centrepiece of the R&D program [2]. The goal of PXIE is to design, build, integrate, commission and operate an identical front-end system with the performance and beam parameters needed for Project X. PXIE is a multi-lab collaboration project, and will be completed by the end of 2018 with 1-mA average H- beam at 25 MeV.

The accelerator complex for PXIE consists of a 5-mA H^- ion source, a Low Energy Beam Transport (LEBT), a 2.1 MeV normal conducting CW RFQ accelerator, a Medium Energy Beam Transport (MEBT) with re-bunchers and broad-band choppers, two SCRF cryomodules at 2K - one Half Wave Resonator (HWR) and one Single Spoke Resonator (SSR1), a High Energy Beam Transport (HEBT) and a beam absorber.

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As one of the collaboration institutes in PXIE, LBNL is responsible for the design and construction of the 2.1 MeV normal conducting CW RFQ accelerator, and assists with the ion source and LEBT design studies. We will support and participate with RFQ beam commissioning at PXIE experimental hall. This paper gives an overview of the PXIE RFQ design, status and plan.

PXIE rfq accelerator

LBNL has a long and successful history of the design and construction of normal conducting RFQ accelerators. The SNS RFQ, currently under routine operation is the latest RFQ designed and built by LBNL, in collaboration with the SNS at Oakridge National Laboratory. PXIE RFQ will be the first CW normal conducting RFQ that LBNL designs and builds. PXIE RFQ design is complete; a few key fabrication tests are either complete or will be finished soon. Fabrication of the production RFQ will start soon at LBNL. The PXIE RFQ design is optimized based on our previous successful RFQ design experience, and recent advance in RFQ design and construction elsewhere.

Beam Dynamics Design

PXIE RFQ beam dynamics design is complete. The design was conducted using PARMTEQ code and has been frozen since early 2012 [3]. The design either meets or exceeds the Project X requirements in terms of capture and transmission efficiency and emittance growth. Table 1 lists the major requirements for the PXIE RFQ.

Table 1: PXIE RFQ Design Requirements

Parameters	PXIE	Unit
Ion Type	H minus	
Output Energy	2.1	MeV
Duty factor	100	%
Frequency	162.5	MHz
Beam current	5 (nominal); 1-10	mA
Transverse Emittance	< 0.25 (norm. rms)	πmm-mrad
Longitudinal Emittance	0.8-1.0	keV-nsec
Input energy	30	kV
Emittance Growth	10	%
Transmission	95	%
TWISS Parameter αs	Less than 1.5	

We adopted a low input energy of 30 keV and vane to vane tip voltage of 60 kV (lower vane to vane voltage results in less required RF power, and therefore easier for thermal management of the RFQ structure), a very good beam dynamics design is achieved with longitudinal emittance (0.7 keV-nsec) optimized at 5-mA nominal current, and over 98% of transmission for beam current from 1 to 15 mA, as shown in Figure 1 and 2. A summary of the PXIE RFQ beam dynamics design with main parameters is listed in Table 2. Error analyses have been conducted after the beam dynamics design. A number of error types have been considered and studies, these errors include TWISS parameters matching conditions, input beam current, flat gradient errors, gradient tilts, and 20 sections with random errors and etc. The error studies show that PXIE RFQ beam dynamics design is very robust, large field errors result in small emittance growth.

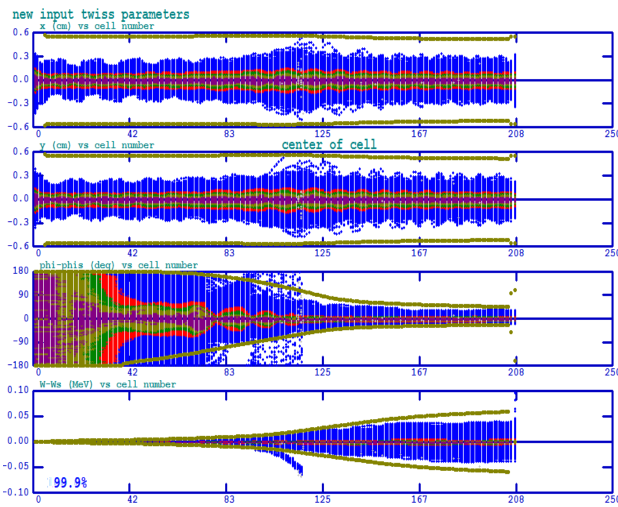

Figure 1: PARMTEQ simulation results shows 99.9% beam transmission of the PXIE RFQ: beam distribution derived from H- ion source emittance measurements was used for the simulations.

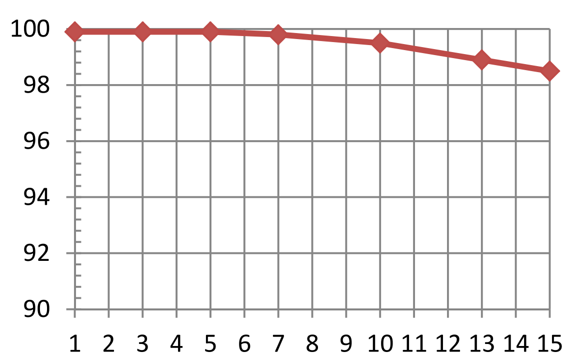

Figure 2: Beam transmission (%, vertical axis) versus beam current (mA, horizontal axis)

Table 2: Main parameters of PXIE RFQ Beam Dynamics

Parameters	Value	Unit
Vane Tip Voltage	60	kV
RFQ Length	4.45	m
Transmission	99.8	%
Transverse Emittance	0.15	πmm-mrad
Longitudinal Emittance	0.70	keV-nsec

TWISS Parameters α_x, α_y	0.187 -0.088	
Minimum longitudinal r	1.029	cm
Max. modulation index m	2.3	
Total number of cells	208	

RF Design

RF design of the PXIE RFQ is a result of close collaboration between LBNL and FNAL [4]. Many modern RF simulations codes are available and have been used. However, the RF design is mainly carried out using CST Microwave Studio (MWS), a CST MWS model of PXIE RFQ is shown in Figure 3. In addition, we also used ANSYS and SLAC ACE3P codes to verify the simulation results. The RF design and study have included mode stabilization with pi-mode rods, cut-back design, tuner sensitivity, tuning of the field flatness and etc. Power dissipation density is an important parameter for thermal management, very careful attention and efforts have been paid to simulate/study and deal with it correctly in the RFQ structure. Table 3 is a summary of the RF simulation results.

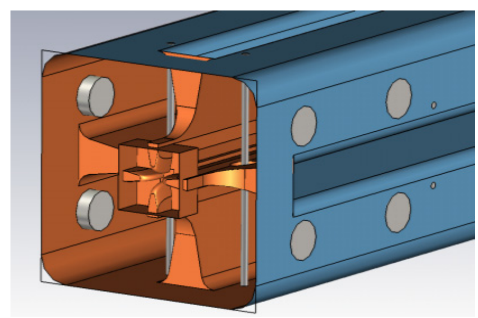

Figure 3: The CST MWS model of PXIE RFQ showing the tuners, pi-mode rods and cut-back are included.

Table 3: RF Simulation Results

Parameters	RFQ	Units
Frequency	162.493	MHz
Frequency of dipole mode	181.99	MHz
Q factor	14660	
Q factor drop due to everything	-14.7	%
Power loss per cut-back (In/Out)	336/392	Watts
Max power loss density at cut-back	7.9	W/cm^2
Total power loss	74.6	kW
H (1/2 of the inner width of RFQ)	172.73	Mm

Engineering and Mechanical Design

PXIE RFQ consists of four modules; each module is about 1.1 meters long. There are 32 pi-mode stabilization rods (8 per module), 80 slug-tuners (20 per module) and 48 RF sensing probes (12 per module), two RF power couplers at middle of the RFQ. A CAD module of PXIE RFQ is showed in Figure 4.

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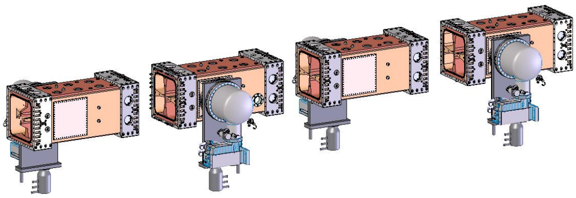

Figure 4: CAD Model of the PXIE RFQ.

Engineering and mechanical design and as well as the fabrication have been based on LBNL's experience and techniques developed and used successfully for the SNS RFQ [5]. These include four vane copper-to-copper braze; profile cutter to machine vane modulations; brazed water cooled pi-mode rods; low profile and bolted module joints and removable fixed slug tuners. Each module consists of four separately machined vanes with precision ground mating surfaces, highly reliability copper-to-copper braze to form each cavity module, as shown in Figure 5.

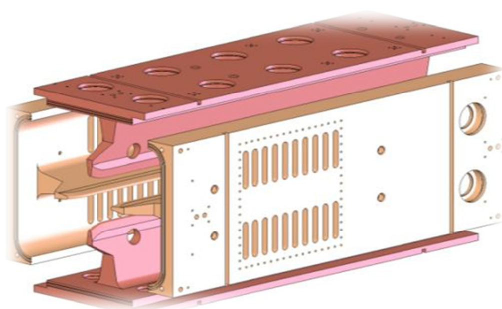

Figure 5: One module with four vanes to form a cavity through a highly reliable copper-to-copper braze.

Thermal Management

Water cooling channels are embedded in each vane by gun-drill. Dynamic RF frequency tuning can be realized by combination of adjusting water cooling temperatures between vanes and walls (similar to the SNS RFQ design). Numerous engineering and thermal analyses have been carried out to validate the design. Simulation techniques have been developed at LBNL to calculate RF field, power dissipation density (compared well with SUPERFISH, CST MWS and ACE3p) using ANSYS multi-physics module. The model is readily for stress and thermal analyses in ANSYS. Figure 6 shows an ANSYS model of PXIE RFQ.

Fabrication Tests and Plan

Three key fabrication tests have been designed and will be conducted to validate the engineering design and fabrication techniques before production RFQ starts. These tests are (1) profile cutter; (2) braze-clamp and braze test and (3) a full length vane machining. Test (1) is complete; test (2) is nearly ready and test (3) will be completed in mid-June 2013. Fabrication of the production RFQ will start in July 2013 and should finish by mid-2015. Most of the fabrication materials already arrived at LBNL.

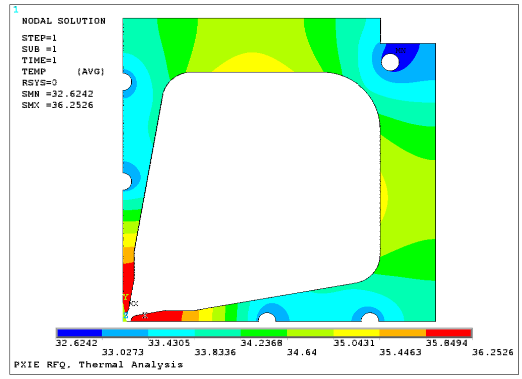

Figure 6: 2D ANSYS model of PXIE RFQ showing temperature distribution and water cooling channels at vane and walls.

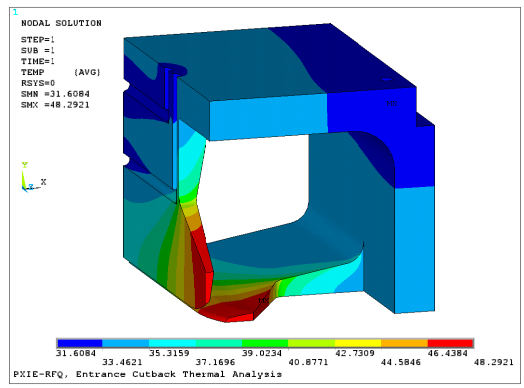

Figure 7: 3D ANSYS model with radial matcher and cut-back showing temperature distribution at steady state.

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We would like to thank Dr. Chuan Zhang from University of Frankfurt for valuable discussions on RFQ beam dynamics design, many colleagues at FNAL for productive collaboration. LBNL is also responsible for another CW RFQ design for Institute of Modern Physics (IMP), Lanzhou, China. IMP RFQ is very similar to the PXIE RFQ, fabrication tests conducted and experience learned at IMP have benefited greatly to both the IMP and PXIE RFQ design and fabrication. We thank IMP colleagues for friendly and productive collaboration.

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