PROGRESS OF THE FRONT-END SYSTEM DEVELOPMENT FOR PROJECT X AT LBNL*

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Abstract

A multi-MW proton facility, Project X has been proposed and is currently under development at Fermilab. Project X is a key ingredient of an accelerator complex for intensity frontier of future high energy physics programs in the US. In collaboration with Fermilab, LBNL takes the responsibility in the development and design studies of the front-end system for Project X. The front-end system would consist of H^- ion source(s), low-energy beam transport (LEBT), 162.5 MHz normal conducting CW Radio-Frequency-Quadrupole (RFQ) accelerator, medium-energy beam transport (MEBT), and beam chopper(s). In this paper, we will review and present recent progress of the front-end system studies, which will include the RFQ beam dynamics design, RF structure design, thermal and mechanical analyses and fabrication plan, LEBT simulation studies and concept for LEBT chopper.

INTRODUCTION

Project X is proposed as a multi-functional proton accelerator complex at Fermilab to support high energy physics programs that could put the US on the leading role in the intensity and energy frontier research over next several decades [1]. The proposed accelerator complex consists of a front-end system, 3-GeV (with 1-mA average current) CW superconducting (SC) RF linac and a pulsed SC linac to accelerate protons to 8-GeV for injection to the existing Main Injector (MI) synchrotron, and various high-power beam targets as well. Project X is currently not an officially approved DOE project. As a critical technology development R&D program toward the success of Project X, Project X Injector Experiment (PXIE) has been proposed at Fermilab, aimed at studying, building and testing of the physics and engineering issues associated with the front-end system of Project X. The PXIE system will have a DC H^- ion source, LEBT, a 162.5-MHz 2.1-MeV CW RFQ, MEBT with wideband choppers and two SC cryomodules to accelerate beam to 30-MeV. The design parameters of PXIE are kept as close as possible to what have been proposed for the final front-end system of Project X [2].

In collaboration with Fermilab, LBNL takes the responsibility in the development of the ion source, LEBT, LEBT chopper and 162.5-MHz CW RFQ for PXIE.

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ION SOURCE AND LEBT

H^- Ion Source

A commercial available DC H^- D-Pace ion source was identified and purchased in 2011, as shown in Figure 1. The ion source meets the requirements of Project X, and also allows us for a quick start of experimental study programs of the ion source and LEBT. Acceptance test of the ion source was conducted at the vendor, and confirmed with the beam emittance and stability measurement at LBNL. The measurements meet the specifications. Table 1 lists the main parameters of the ion source.

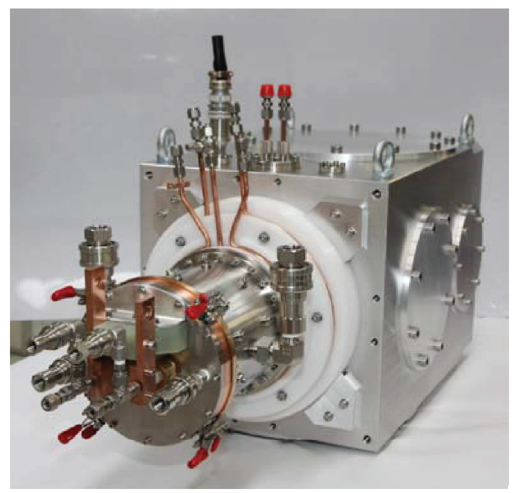

Figure 1: D-Pace H- Ion Source.

Table 1: Main Measured Parameters of the Ion Source

Extract energy	30	keV
Current	5	mA
Emittance (Norm. rms)	0.102	π-mm-mrad

LEBT

A magnetic LEBT is proposed for Project X. There are currently two LEBT optics designs are being under study: (1) two-solenoid design with a redundancy ion source (mainly due to limited ~ 350 hours (at 10-mA) of filament lifetime) and slow switching magnet, one arm of the ion source and LEBT layout is shown in Figure 2; (2) three-solenoids design with more space for diagnostics between the last solenoid and the RFQ, and improved/increased pumping speed at the absorber after the LEBT chopper. Both designs have an un-neutralized beam transport

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section. A number of simulation codes have been used to study the LEBT beam dynamics. Simulation results agree well for neutralized beam.

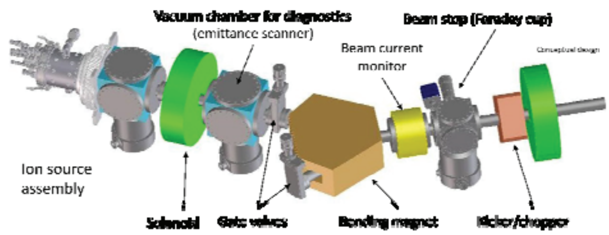

Figure 2: LEBT layout of one arm of 2-solenoid design.

It is crucial to understand the time dependent beam dynamics, in particular beam matching (beam stability and emittance growth) into RFQ after LEBT chopper where beam transition from nearly neutralized to un-neutralized. The three-dimensional PIC code, WARP-3D at LBNL, a widely used code in fusion research, has most of the built-in physics models and features needed for simulating the time-dependent LEBT beam dynamics correctly. Further code development has been carried out to include multiple interactions with the background gases in the LEBT, such as charge exchange, ionization and detachment. Preliminary simulation studies show very promising results, an example is shown in Figure 3. A bench-mark experiment has also been proposed.

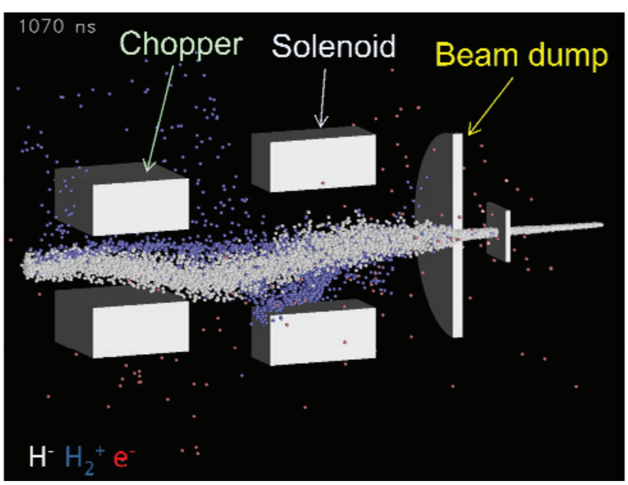

Figure 3: WARP-3D time-dependent simulations of chopper beam dynamics in the LEBT.

LEBT Chopper

The LEBT chopper will provide up to 1-MHz chopping capability with rise/full time less than 100-nsec. A conceptual design is developed to use ~ 10-cm long four quadrant electrodes. Pre-programmed/designed pulse structures are applied to appropriate electrodes so that the beam can be deflected in either horizontal or vertical directions. A simple two-parallel-plates chopper will be used for the bench-mark experiment at LBNL or/and Fermilab. Preliminary engineering design has just begun.

RFQ

A 162.5-MHz CW normal conducting RFQ accelerator is proposed for Project X. The RFQ design is optimized to capture 30-keV and 5-mA H^- beam from the ion source and LEBT, bunch and accelerate the beam to 2.1-MeV. Beam dynamics and RF structure designs are complete, engineering design, thermal and structure analyses are nearly complete. Fabrication of the RFQ expects to start in November 2012.

Beam Dynamics Design

The beam dynamics design of PXIE RFQ is optimized using the measured beam distribution. 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, respectively. The beam dynamics design was conducted using PARMTEQ; Figure 4 shows the simulation results at 5-mA. Error analyses have been completed recently; it indicates the RFQ design tolerates very well with mechanical and TWISS parameter errors.

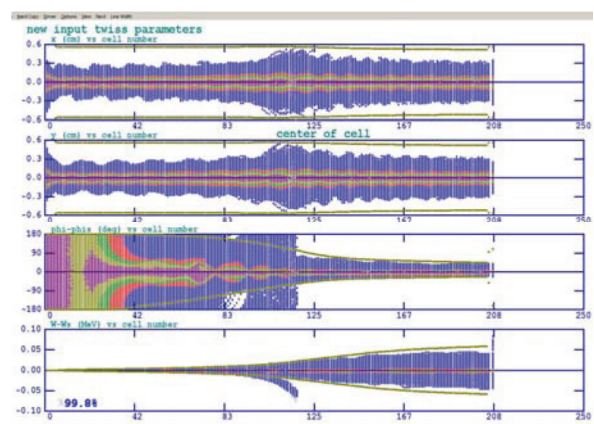

Figure 4: PARMTEQ simulations of the RFQ at 5-mA.

RF Design Studies

The RF design studies have been conducted through a close collaboration with Fermilab, detailed EM simulation studies can be found in [3]. These studies include mode stabilization (schemes), field flatness due to π-mode stabilization rods, radial matcher, entrance and exit terminations (cut-backs). Table 2 summarizes the RF design results.

Table 2: Main parameters of the PXIE RFQ EM design

Parameters	RFQ
Frequency, MHz	162.493
Frequency of dipole mode, MHz	181.99
Q factor	14660
Q factor drop due to everything, %	-14.7
Power loss per cut-back, W (In/Out)	336/389
Max power density at cut-back, W/cm^2	~ 7.9
Total power loss, kW	73.8

Engineering Design

Engineering design of the RFQ is nearly complete [4]. The design utilizes the proven techniques and low risk techniques developed in the previous RFQs at LBNL. The design features include:

- Four vane copper-to-copper braze with gun-drilled water cooling channels;
- Fly (formed cutter) cut modulated vane tips;
- Brazed, water cooled π-mode stabilization rods;
- Low profile, bolted module joints;
- Removable fixed slug tuners.

The PXIE RFQ is a 4.45-meter long OFHC copper structure consisting of four modules. There are 32 π-mode stabilization rods (8 per module), two RF power coupler ports, 80 slug-tuners (20 per module), 48 RF probes and 8 vacuum pumping ports. A 3-dimensional CAD model of the PXIE RFQ is shown in Figure 5. The RFQ engineering design is well advanced. Numerous engineering analyses have been carried out to validate the design. The 1st RFQ design review was held at LBNL in April 2012. The RFQ fabrication readiness review is scheduled to be held in October 2012.

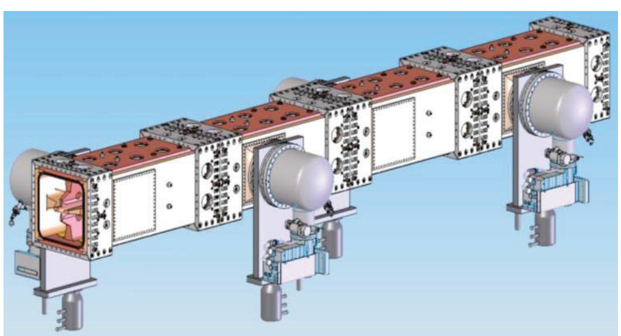

Figure 5: 3-D CAD model of PXIE RFQ.

Thermal and Structure Analyses

Thermal analyses of the RFQ have been carried out using ANSYS code (multi-physics). We have developed a methodology to conduct RF, thermal and structural analysis using ANSYS model. The RF simulation results from ANSYS agree well with CST MWS simulations. Figure 6 shows an example of 2-dimensional (a thin 3D slice) ANSYS simulation results.

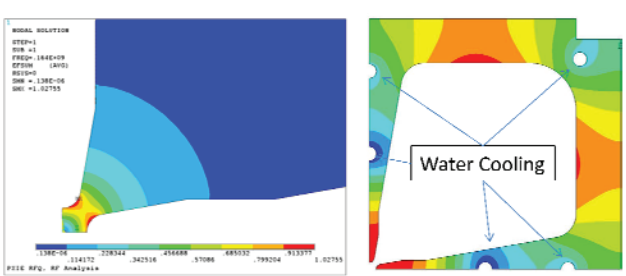

Figure 6: ANSYS simulation studies: RF simulation (left) and thermal simulation (right) with water cooling channel in the vanes.

Peak power dissipation density is located at the two ends of the RFQ termination/cut-backs; the cut-back geometry and appropriate water cooling channel designs are important to maintain the temperature rise and thermal stress at an acceptable level. Figure 7 shows the ANSYS structural analysis (deduced from thermal analysis) of the RFQ entrance. Thermal and structural analyses of π-mode stabilization rods and slug tuner are shown in Figure 8, more design and analysis details can be found in [4].

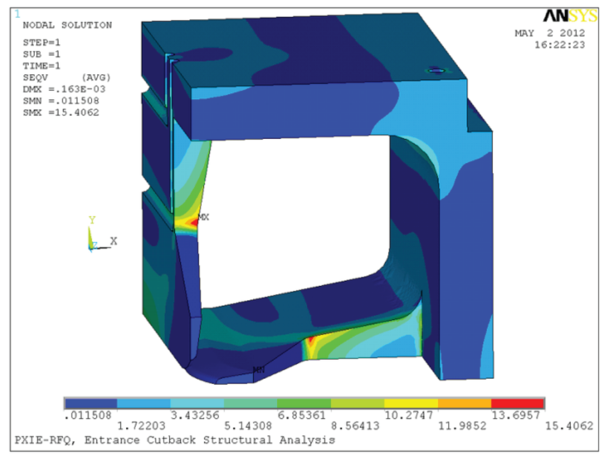

Figure 7: ANSYS Structural analysis of the PXIE RFQ entrance/cutback showing maximum stress of 15.4 MPa, well below the maximum yield stress.

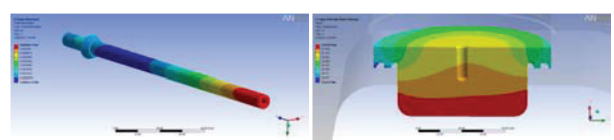

Figure 8: Thermal analysis of π-mode rods (left) indicating that the rod must be water cooled; and slug-tuner (right) does not need to be water cooled.

Fabrication Tests

In order to validate engineering design and fabrication techniques for PXIE RFQ, a number of fabrication tests have been proposed and are currently in progress at LBNL. These tests include fabrication of formed cutter for vane modulation, water cooling channel fabrication by gun drill, brazing test of four vanes with a proposed brazing clamping scheme, and etc. These tests are important and must be completed before we can finalize the design.

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