THE CONCEPTUAL DESIGN OF PXIE VACUUM SYSTEM

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Abstract

The Project X Injector Experiment (PXIE) [1] will be a prototype of the Project X front end to validate the design concept and decrease technical risks. It consists of a 30 kV, 5mA DC H^- ion source (IS); Low Energy Beam Transport (LEBT); 2.1 MeV CW RFQ; Medium Energy Beam Transport (MEBT) that forms a desired bunch structure by removing ~80% of bunches; two SC cryomodules (CMs) accelerating the 1 mA beam to ~25 MeV; and High Energy Beam Transport with a dump (HEBT). Its vacuum system design will also establish the design guidance for the entire vacuum system of Project X, especially the requirement of low particulate vacuum that is sufficient in practise and at the same time is cost efficient to ensure the performance of CMs.

GAS LOADS AND LIMITATIONS

The PXIE vacuum system consists of four regions that can be separated by vacuum gate valves for commissioning or repairs: IS-LEBT-RFQ, MEBT, Cryomodules, and HEBT-DUMP. Different regions have different gas load sources and different limitations.

The main gas load in IS-LEBT-RFQ region is the gas flow from the IS, ~500 mTorr·l/s. Also, commissioning and machine tuning will be done in a pulse mode, when a chopper in the LEBT produces pulses of variable duration from 1 μs to 16 ms at 60 Hz repetition frequency. In this mode, almost all beam generated by the IS is absorbed in the chopper, and protons recombining inside the chopper's absorber into hydrogen, create an additional load ~1 mTorr·l/s. Vacuum limitations in this region are two-fold. First, the beam loss resulting from H^- stripping should be small, <5%. Second, the pressure in the RFQ and, consequently, gas flow from LEBT should be low to avoid discharges. From practical experience of other labs, pressure < 10^{-6} Torr should suffice.

The gas load in the MEBT region is a combination of outgassing of vacuum surfaces and gaskets; a hydrogen flux from the MEBT absorber irradiated by ~4 mA of the chopped-out beam; and a load from the MEBT scraping system. In the MEBT, vacuum restrictions are related to proximity to SRF. In addition to a gas and microparticles incoming to CMs, which is discussed in the next section, a flow of neutral hydrogen atoms created by stripping of H^- ions should be limited. Such atoms fly along the direction of the parent ions and can reach 2K surfaces of the cryomodules. To make irradiation of CMs by these atoms negligible (≤0.1 W of additional heat load), the vacuum integral over the MEBT length is limited to1×10^{-6} Torr·m. Also, an aperture restriction after the MEBT absorber introduces differential pumping that dramatically improves pressure near the CM. Finally, scarpers installed at the end of MEBT additionally restrict the solid angle of penetration into the CMs.

Operating vacuum in the CMs is determined by the cryo-pumping and doesn't affect the beam directly. Vacuum limitations in the HEBT are determined mainly by the gas flow into SRF, and the main source of the gas is the beam dump.

Note that one of the vacuum-related effects considered in the course of PXIE design is a possibility of blistering. If hydrogen diffusion in a surface exposed to bombardment by the main beam or its tails is low, protons, implanted by an H^- ion impact, recombine in the bulk into hydrogen which is accumulated in dislocations until the built-up pressure breaks the overlaying material. Corresponding jump of local pressure can result in a beam loss. The issue is expected to be addressed by a system of collimation in LEBT and MEBT and preferential use of molybdenum for surfaces that are likely to be exposed to the beam irradiation.

THE SYSTEM DESIGN

A concept of beam line vacuum system derived from the limitations described above can be divided into three levels of vacuum environment (Figure 1):

1. Ultra High Vacuum and Low Particulate
2. High Vacuum areas (HV)
3. Transition areas

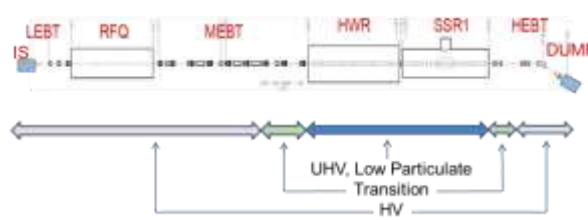

Figure 1: PXIE System Layout with classification of vacuum levels. HWR and SSR1 indicate location of two cryomodules.

UHV and Low Particulate Areas

These areas include two cryomodules, HWR and SSR1. With the cryomodules operating at 2K, cryo-pumping decreases the residual gas pressure below 10^{-10} Torr, mainly driven by the operation temperature. The challenge for this region is to achieve low enough pressure (10^{-7} Torr) at the room temperature before cooling down. Bypass vacuum pipe is designed to alleviate the conductance restriction due to the small aperture and large length of the cavity strings. To guarantee a low particulate environment for SRF operation, all necessary measures as proper handling,

Operated by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the United States Department of Energy
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clean rooms, gas flow control during pumping and venting etc. are applied. Cold cathode (CC) gauges are used to minimize the heat load from gauging.

HV Areas

The areas from the H- ion source up to the beam absorber at MEBT and downstream of the transition area in HEBT, where the residual gas pressure is 10^{-7} Torr or above, are classified as HV. Turbo pumps are chosen for locations with the highest gas load: the ion source, LEBT chopper, RFQ, MEBT absorber, and the beam dump. Otherwise, pumping is provided by ion pumps.

The DC ion source is continuously supplied with hydrogen gas. Inside the plasma chamber, the hydrogen pressure of $3\cdot10^{-2}$ Torr is to be maintained while the pressure downstream is 10^{-6} Torr in order to avoid large beam loss due to H^- stripping. The pressure gradient is achieved by a differential pumping scheme with two 1000 l/s turbo pumps.

Pressure ~10^{-6} Torr in LEBT is achieved by installing a 300 l/s turbo pump at the chopper, where the large gas load is expected when the chopper intercepts major fraction of the beam, and by a 100 l/s ion pump in the middle of the beam line.

In the RFQ, ~10^{-7} Torr vacuum required for reliable operation is provided by two 1000 l/s turbo pumps. Additional two vacuum ports can be used to increase the total pumping capacity if found necessary.

The HV portion of the MEBT is from the RFQ to downstream of the absorber. The absorber, the largest source of the gas load in the MEBT, is pumped by two 1000 l/s turbo pumps, while two upstream ion pumps compensate outgassing of vacuum surfaces. The beam optics downstream of the absorber is adjusted to decrease the beam size and allow placing a 10 mm ID, 200 mm length tube for differential pumping.

The HEBT line consists of magnets and beam instrumentations at room temperature. Its portion starting ~2m downstream of the SSR1 cryomodule is designated as HV. Pumping here is done with several ion pumps. Because a large amount of hydrogen is produced in the beam dump, 2000 l/s turbo pumping is applied. A differential pumping scheme is applied in the first 2m region in order to achieve UHV in the vicinity of SSR1.

Transition Areas

The optimum design of areas providing transitions between UHV and HV will be one of the study goals for the PXIE experiments. These areas, the downstream portion of MEBT and upstream portion of HEBT, are used to minimize the risk of degrading SRF cryomodules due to migration of gas and microparticles from HV components. The gas flow to the cryomodules causes a gas deposition on cryogenic surfaces. While there are no exhaustive experiments or a cohesive theory on the subject, there are indications in the literature that such accumulation at the surface of cryogenic cavities degrades their performance. On the other hand, the closest analogue, a HWR in the Argonne National lab, successfully operates at the pressure of 5×10^{-8} Torr immediately upstream of the cryomodule, though with the residual gas composed primarily by water [2]. To be on a safe side, the pressure in the transition areas is specified to be $\leq1\times10^{-9}$ Torr (H_2). In addition, the optics was designed so that the CM element closest to the room-temperature elements is a solenoid, so that the cryo surfaces inside it could effectively shield the SRF cavities.

A low particulate vacuum practices are applied to ~2m of immediate vicinity of the cryomodules. The roughing/venting ports are arranged in the way minimizing the particle migration towards CM, and the flow rate of roughing/venting is regulated to reduce the risk of particle migration. Note that specific of the PXIE

Table 1: Summary of System Parameters [3][4][5]

Pressure (torr)	10^{-2} - 10^{-6}	10^{-7}	10^{-7}	10^{-7}	10^{-7} - 10^{-10}	10^{-10}	10^{-10}	10^{-10} - 10^{-7}	10^{-6}
Leak Check Sensitivity (mbar.l/s)	$2x10^{-9}$	$2x10^{-9}$	$2x10^{-10}$	$2x10^{-9}$	$2x10^{-10}$	$2x10^{-10}$	$2x10^{-10}$	$2x10^{-10}$	$2x10^{-9}$
Pumping	Turbo, Ion Pump				Ion Pump	Cryo Pumping		Ion Pump	Turbo, Ion Pump
Vacuum Seals of Joints	metal gaskets or elastomers; CF or KF				CF only; metal gasket only				
Part Cleaning	UHV procedures								
Gauging	Ion gauge					cc gauge		Ion Gauge	
Low Particulate practice	no	no	no	no	Yes	Yes	Yes	Yes	no
controllers	equipped with RS485 to communicate with control system ACNET via PLC								

ISBN 978-3-95450-138-0

is a CW beam, which space charge may assist in transport of microparticles between different location during operation. We believe that such effect would manifest itself as degradation of properties of SRF cavities closest to the warm elements, and, if found, may require lengthening of the transition areas in the design of the Project X.

The transition areas also include fast acting valves on both ends of the cryomodules to prevent catastrophic failures in a case of vacuum accidents in the room temperature parts.

Vacuum requirements for various locations of the PXIE vacuum chamber are summarized in Table 1, and calculated pressure profiles are shown in Figures 2-4.

Other Vacuum Systems

Besides the beam vacuum, there are two other vacuum systems in cryomodules.

The RF couplers in the HWR cryomodule have two ceramic windows which separate coupler vacuum from the beam vacuum and atmosphere. The power coupler vacuum systems are at $\leq 10^{-6}$ Torr. These small volumes of vacuum are maintained by ion pumps (one per coupler). This vacuum system has to be monitored in real time because the ceramic window isolate it from cryomodule beam vacuum is under high RF power and is very delicate. Classified as HV region.

Insulating Vacuum in HWR and SSR1 is required for cryo-isolation. The pressure shall be 10^{-5} Torr prior to cooldown. These systems will be pumped with turbo and roughing pumps. Pressure shall be maintained 10^{-6} Torr or better at cold. CC gauges shall be used. The pumps once used in this system shall not be used for UHV system because of contamination.

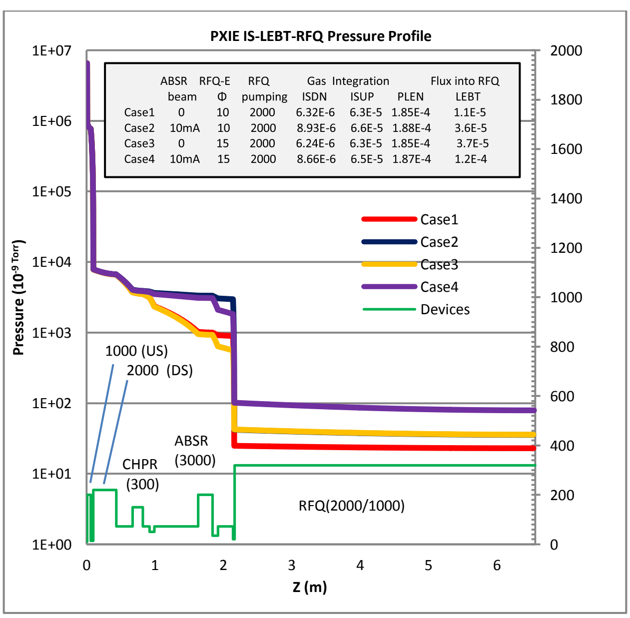

Figure 2: The pressure profile in IS-LEBT-RFQ. The number in parentheses is pumping speed in l/s. The IS has 1000 l/s turbo in its upstream chamber and 2000 l/s in down stream chamber. The flow rate of hydrogen is 0.5 torr·l/s. the gas integration is in Torr·m. the equivalent aperture of devices is in mm. there is no gas flow at the downstream end of RFQ.

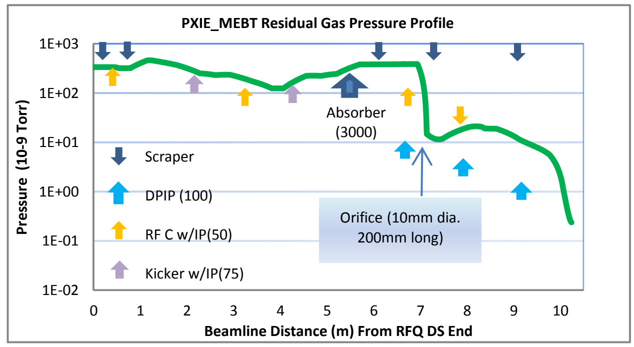

Figure 3: The pressure profile in MEBT. There is no gas flow at the both ends. The number in parentheses is pumping speed in l/s.

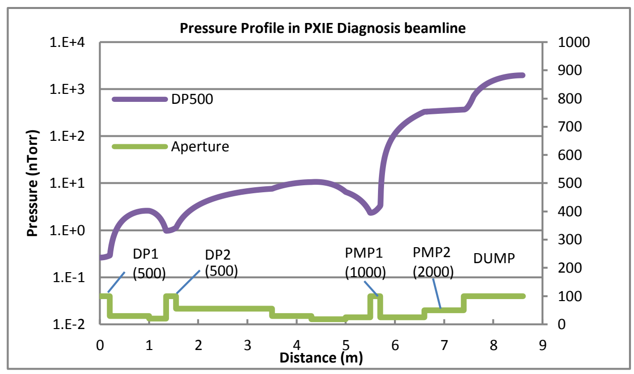

Figure 4: The pressure profile in HEBT-DUMP. The number in parentheses is pumping speed in l/s. there is no gas flow at the ends.

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