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STATUS OF THE PXIE LOW ENERGY BEAM TRANSPORT LINE*

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Abstract

A CW-compatible, pulsed H^- superconducting RF linac (a.k.a. PIP-II) is envisaged as a possible path for upgrading Fermilab's injection complex [1]. To validate the concept of the front-end of such machine, a test accelerator (a.k.a. PXIE) [2] is under construction. The warm part of this accelerator comprises a 10 mA DC, 30 keV H^- ion source, a 2m-long LEBT, a 2.1 MeV CW RFQ, and a MEBT that feeds the first cryomodule. In addition to operating in the nominal CW mode, the LEBT should be able to produce a pulsed beam for both PXIE commissioning and modelling of the front-end nominal operation in the pulsed mode. Concurrently, it needs to provide effective means of inhibiting beam as part of the overall machine protection system. A peculiar feature of the present LEBT design is the capability of using the ~1m-long section immediately preceding the RFQ in two regimes of beam transport dynamics: neutralized and space charge dominated. This paper introduces the PXIE LEBT, reports on the status of the ion source and LEBT installation, and presents the first beam measurements.

DESIGN CONSIDERATIONS

The design layout of the PXIE Low Energy Beam Transport (LEBT) is shown on Figure 1, and the list of LEBT requirements can be found in Ref [3]. The Ion Source/LEBT assembly consists of an H^- Volume-Cusp Ion Source (IS) [4], capable of delivering up to 15 mA DC at 30 keV, 3 solenoids, a slow switching dipole magnet, a chopper assembly and diagnostics to characterize and tune the beam.

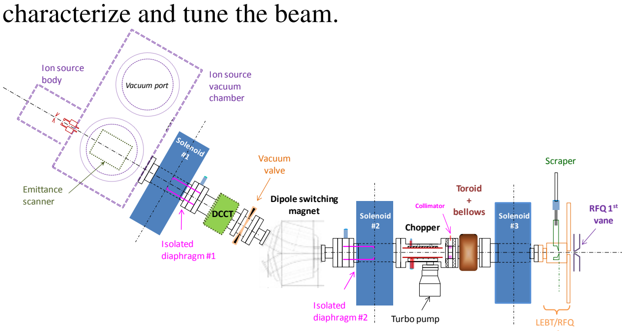

Figure 1:Schematic of the PXIE beam line.

Besides matching the beam to the RFQ, several other considerations influenced the LEBT design.

First, because of the relatively short life time of the ion source (~300 hours), the front end of PIP-II is expected to have two identical ion sources with a dipole magnet downstream of the first solenoid to quickly switch to a 'hot spare' when needed (e.g.: IS filament replacement). While at PXIE only one ion source will be used, we still plan to install the dipole magnet at a later stage of development. In addition, this bend filters out energetic neutrals and protons created by H^- stripping downstream of the ion source and is expected to be one of the personnel protection system elements.

Second, the RFQ reliability improves when decreasing the vacuum pressure and minimizing the irradiation of the RFQ vanes by the beam. The former is accomplished by the mere length of the LEBT (2.2 m) with extensive pumping, Vacuum calculations show that the gas flux into the RFQ can be maintained to $< 10^{-4}$ Torr·l·s^{-1}. The RFQ irradiation is addressed with the design of the transport scheme and by a system of scrapers.

Third, for PXIE commissioning as well as for demonstrating operation in the pulsed mode required for PIP-II, the LEBT design incorporates a chopper. The chopper will also be part of the machine protection system, turning the beam off after receiving an abort command.

One of the known aspects of pulsed operation is the transition during the pulse from a full space charge regime to transport with nearly full neutralization due to the background ions. This transition results in beam parameters at the beginning of the pulse being dramatically different from the steady state condition, which in turn can cause large beam losses. A typical solution is to degrade the vacuum to shorten the time it takes to reach neutralization. With the intention to keep good vacuum near the RFQ entrance ($< 5\cdot10^{-7}$ Torr), this time can reach hundreds of microseconds. On the other hand, the relatively low beam current at PXIE ($\leq$10 mA) allows considering an alternative scheme, where the major portion of the LEBT is kept neutralized while ions are cleared in the last ~1 m of the beam line before the RFQ by applying a small DC voltage to the kicker plates. In this scheme, changes of the optical functions during a pulse should be minimal. For PXIE, nominally operating CW, this scheme will help maintain the same optical functions for tuning in the short-pulse mode and true CW operation.

BEAM LINE MAIN COMPONENTS

Figure 2 shows a 3D model of the IS/LEBT assembly in the configuration expected at the end of 2014 (without the dipole magnet). The IS vacuum chamber includes ports for an Allison-type emittance scanner, which can be mounted either horizontally or vertically. A DCCT is placed just downstream of the first solenoid to measure the ion source beam current.

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Each solenoid incorporates a pair of dipole correctors. In addition, within the bore of the first two solenoids, there are electrically isolated diaphragms (EIDs), which are water-cooled electrodes with a round aperture. EIDs are used for beam scraping, estimation of the beam halo, and, in combination with the dipole correctors, to measure the beam position. Positive biasing of an EID prevents background ions from moving from one section of the LEBT to another.

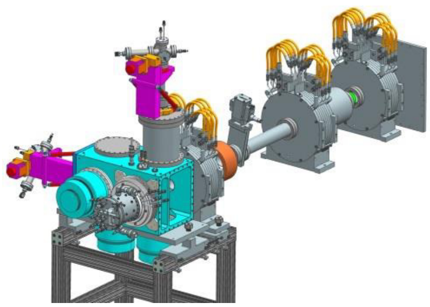

Figure 2: 3D model of the PXIE beam line (end of 2014).

The chopper is located between solenoids 2 and 3. One peculiarity of the chopping system is that it combines the kicker with the absorber, i.e. when deflected the beam impinges onto one of the kicker electrodes. This electrode is designed to sustain the full beam power, 300W DC.

The beam pulse exiting the chopper is measured with a current transformer (CT) just upstream of the last solenoid. There is another isolated diaphragm in between, which protects the CT ceramic break from irradiation from the primary and reflected beams. Finally, just in front of the RFQ, there is a movable electrically insulated ‘scraper’, which also incorporates a round opening. As for the EIDs, the scraper serves as a beam position monitor and beam size measuring device. In addition, the default configuration for the aperture is to remain in front of the RFQ during normal operation, acting as an additional protection device (collimator). In its completely inserted position, it may also serve as a beam dump.

OPTICS

The baseline optics design (blue trace in Figure 3) incorporates two regions: the beam is considered to be fully neutralized as it exits the ion source assembly and with full space charge downstream of solenoid #2.

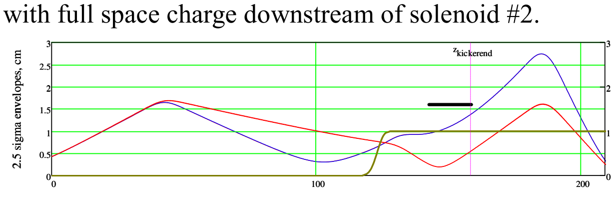

Figure 3: Beam radius (2.5σ) for a 30 keV, 10 mA beam with Gaussian distribution. The initial beam parameters are taken from the IS acceptance tests measurements (β = 21.5 cm, α = -1.39, $\varepsilon_{n,rms}$ = 0.11 µm). Red trace: zero current transport; Blue trace: space charge dominated transport over the last ~1 m of the LEBT. Beige trace: neutralization factor (0 ≡ fully neutralized). The black segment shows the chopper aperture and length.

The main drawback of transport with full space charge is that it results in some emittance growth. However, PIC-like simulations [5] showed that in the chosen scheme at the maximum beam current of 10 mA the emittance grows from 0.11 µm (rms, normalized) to 0.15 µm, well within the specifications (i.e. < 0.25 µm). Note that the same hardware allows transporting a fully neutralized beam to the RFQ entrance with the proper Twiss parameters (red trace in Figure 3) by adjusting the solenoids currents and the voltages on the EIDs and kicker plates. If the experimental data show that neutralized transport is overall preferential, the MEBT kicker will be used to clean the leading edge of the pulse generated by the LEBT chopper.

FIRST BEAM SIZE MEASUREMENTS

First beam measurements were performed in a short configuration consisting of the ion source, one solenoid, the DCCT, an additional electrically isolated diaphragm (a.k.a. ‘donut’) similar to EIDs but not water cooled, and a Faraday cup (FC). Pulsed operation was achieved by modulating the IS extraction electrode voltage from 0 to several kV depending on the beam current desired. The modulator provides a wide variety of duty factors, 1 µs to 16 ms pulse width at 0.2 – 60 Hz.

Routine operation both in DC and pulsed modes has been achieved. For the measurements presented, a 5mA, 30 keV beam was pulsed at 10 Hz and a pulse width of 200 µs. The choice of the pulse length is such that it is long enough to observe the neutralization processes while keeping a low duty factor to avoid accidental overheating of beam line components.

The measurement of the beam size consists in steering the beam over the ‘donut’ with the solenoid dipole correctors and recording the amount of beam that passes through. The result is a plot of the beam intensity in the FC versus the correctors’ currents (Figure 4, blue circles). Knowing the diaphragm opening diameter, a beam size can be inferred. Note that prior to the start of a series of such scans, the beam was centered within the hole, and the correctors calibration (in mm/A) was measured using similar scans at small beam size.

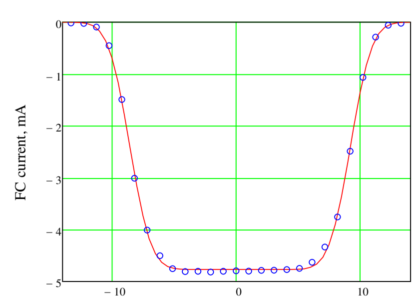

Figure 4: Illustration of the fitting of a corrector scan data for determining the beam size. ‘Donut’ diameter: 18mm.

To analyse the data, the beam is assumed to be axially symmetric and to have either a Gaussian or constant current density distribution. Then, the data for the portion

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of a beam passing through a hole at a given displacement were fitted to analytical formulae using the beam size as the only fitting parameter. An example of the result of such fit is shown on Figure 4 (red line).

An ensemble of beam size measurements have been carried out for several solenoid currents (a.k.a. solenoid scan). For each solenoid scan, the FC current was recorded after a given time delay with respect to the leading edge of the beam pulse, $\delta\tau$, namely, for the data presented on Figure 5, 0.01, 0.03, 0.05 and 0.1 ms.

The notable result from the solenoid scans is twofold. First the minimum beam size decreases along the beam pulse; the minimum beam size at $\delta\tau$ = 0.01 ms is ~1.5× larger than at $\delta\tau$ = 0.1 ms. Second, the solenoid current value at which the beam size is minimum decreases as $\delta\tau$ increases. These effects are consistent with an increase of the beam neutralization along the pulse but also likely indicate *some* emittance growth. Emittances derived from the curves in Figure 5a (not taking into account space charge) are shown on Figure 5b. At $\delta\tau$ = 0.1 ms, the emittance is 0.1 µm (rms, normalized).

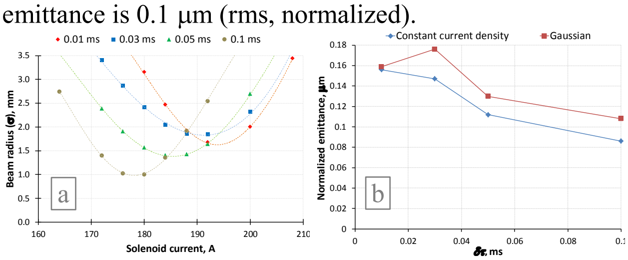

Figure 5: a- Results from fitting corrector scans data for several solenoid current settings at several delays with respect to the leading edge of the pulse. Dashed lines are arbitrary polynomials functions to guide the eye. Gaussian distribution is assumed for fitting. b- Corresponding emittances as a function of $\delta\tau$ using a constant current density distribution (blue) and a Gaussian distribution (red) for the corrector scans fits.

Note that while the statistical error from the fit itself is negligible, the choice of the model (e.g.: particle distribution) leads to variations on the beam size calculation of the order of 10%.

Simulations [5] reproduce reasonably well the beam size minimum and the value of the solenoid current at this minimum for $\delta\tau$ = 0.01 ms, where the neutralization is likely negligible. Simulations at lower beam currents but same initial conditions predict that the solenoid current where the beam size is minimal depends on the degree of neutralization (assuming a constant neutralization factor along the beam). Comparing these simulations with the data of Figure 5a gives an estimate of the neutralization factor at the end of the pulse ($\delta\tau$ = 0.1 ms) of ~70%.

In parallel to these measurements, it was noticed that the 'donut' temperature increases even with the beam propagating through it without measurable losses. This temperature rise can be attributed to energetic neutrals. With further measurements, we estimated that the total production of fast (30 keV) neutrals is ~7% of which ~10% reach the Faraday cup.

CONCLUSION AND PLANS

The beam size measurement method with limiting apertures has proven to be a useful tool to investigate the beam dynamics in the LEBT. From these measurements, the beam emittance in steady-state is found to be 0.1 µm (rms, normalized) in agreement with the IS acceptance tests.

The latest configuration of the LEBT shown on Figure 6 includes a diagnostics 'box' with an Allison emittance scanner located upstream of the 'donut'. The latter has been designed and constructed in collaboration with SNS's Ion Source group within the Research Accelerator Division. It will allow cross-checking our current beam size and emittance measurements, and provide a detailed description of the beam phase space that may help refine simulations.

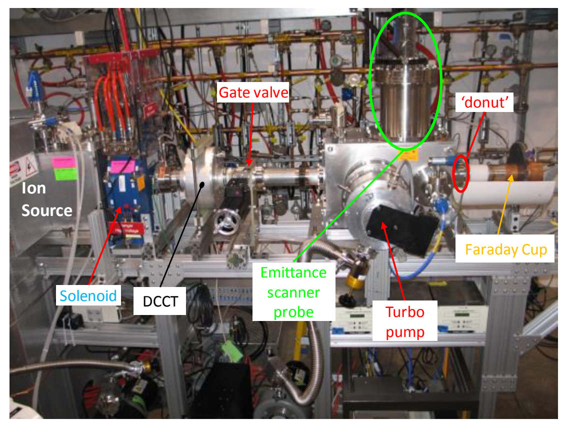

Figure 6: Beam line configuration with the newly installed Allison emittance scanner (vertical orientation).

We expect to complete the installation of the entire LEBT (without the bending magnet) this summer. RFQ commissioning is planned for the 3rd quarter of FY15.

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