

BEAM INSTRUMENTATION OF THE PXIE LEBT BEAM LINE *

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Abstract

The PXIE accelerator [1] is the front-end test stand of the proposed Proton Improvement Plan (PIP-II) [2] initiative: a CW-compatible pulsed H⁻ superconducting RF linac upgrade to Fermilab’s injection system. The PXIE Ion Source and Low-Energy Beam Transport (LEBT) section are designed to create and transfer a 1-10 mA H⁻ beam, in either pulsed (0.001–16 ms) or DC mode, from the ion source through to the injection point of the RFQ. This paper discusses the range of diagnostic tools – Allison-type Emittance Scanner, Faraday Cup, Toroid, DCCT, electrically isolated diaphragms – involved in the commissioning of the beam line and preparation of the beam for injection into the RFQ.

PXIE LEBT DIAGNOSTICS REQUIREMENTS

The PXIE LEBT beam line, described in [3] and shown in Fig. 1, consists of a 30 keV H⁻ ion source, three solenoids with a pair of dipole correctors in each, a chopping system inserted between the last two solenoids, and a set of diagnostics combined with collimation systems.

Some of the peculiarities of the PXIE LEBT are related to the plan to commission PXIE first in a short-pulse mode and then to increase the pulse length, eventually operating in true DC mode. This will ultimately be accomplished with the LEBT chopper, capable of forming 0.001-16.6 ms pulses with a rise time of ~100 ns at a frequency of up to 60 Hz. For the tuning of the LEBT itself, and to decrease the load to the LEBT chopper absorber, the ion source has been equipped with a modulator that can pulse the extraction electrode, also at 60 Hz but with a rise time of ~1 μs. The chopper starts forming the final pulse length after the first ~ 1 ms of the modulator pulse, allowing the neutralisation near the ion source to reach a steady-state.

Correspondingly, diagnostics are required to provide information about the beam in two modes: DC and pulsed. In the latter, the control system provides separate time triggers for the diagnostics channels upstream of the chopper and remaining part of the LEBT. The initial nominal pulse length for PXIE commissioning is 5 μs, chosen as a compromise between the chances of damaging the SRF section and the need for reasonable measurement accuracy of downstream beam instrumentation.

The LEBT diagnostics can be divided into three groups: current monitors, apertures and scrapers, and the emittance scanner.

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DIAGNOSTIC TOOLS

Current Monitors

The beam current can be measured by a DC Current Transformer (DCCT), an AC transformer (a.k.a. a toroid), and, at the commissioning stage, by the Faraday Cup (FC) at the end of the LEBT. Some indication of the beam current is also given by the ion source bias supply current but, because of a significant electron component at the ion source output, the latter may be up to 2 times higher.

The DCCT is installed downstream of the first solenoid and measures the beam current in DC or long-pulse ($\geq 500 \mu s$) modes. Its sensitivity to external magnetic fields requires a significant longitudinal space to ensure enough separation from both the first solenoid and a future bending magnet to be installed just downstream. Whilst the DCCT is currently the main tool used to measure the beam current the possibility of replacing it with a toroid during transition to the configuration with the bend is being discussed.

The LEBT toroid is installed downstream of the chopper. To measure the beam loss in the RFQ down to 1%, an identical toroid will be placed at the RFQ exit. A procedure to cross-calibrate both toroids with a relative accuracy at the 1% level is in development.

The Faraday Cup (FC) is a copper cylinder with an aperture radius, R, of 49.4 mm and a length, L, of 144.5 mm. By using the electrode in front of the FC (EID5) as a suppressor of secondary electrons it is shown that the capturing inefficiency is < 1%, in agreement with a simple estimation of $\sim 0.1 \times (L/R)^2$.

The resolution and bandwidth of the current monitors are shown in Tab. 1.

Isolated Electrodes and Scrapers

The PXIE LEBT beam line includes several Electrically Isolated Diaphragms (EIDs) (see Fig. 1), each biased with an individual +50 V floating power supply. The EIDs are copper, water-cooled tori with varying opening diameters depending on location (see Fig. 1 for sizes). Special circuitry allows measurement of the beam loss to an EID in DC and pulsed ($> 1 \mu s$) modes. In addition to beam control (physically scraping beam tails and altering neutralisation

Table 1: Parameters of the PXIE LEBT Current Monitors

| | Resolution | Bandwidth |
|-------------------------------------|------------|----------------|
| DCCT | < 10 μA | DC to 4 kHz |
| Toroid | < 10 μA | 10 Hz to 4 MHz |
| Faraday Cup, Isolated Electrodes | < 5 μA | DC to 20 MHz |

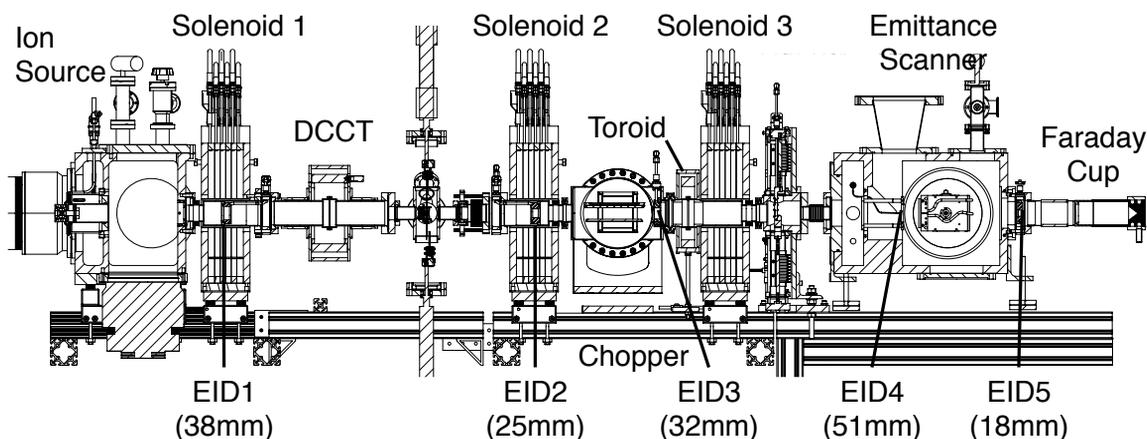


Figure 1: A schematic of the PXIE LEBT beam line, highlighting the beam diagnostic devices.

through biasing [3]), EIDs are used as a diagnostics tool in combination with the solenoid dipole correctors upstream. By changing the correctors' currents, using a dedicated Java program, the beam is moved across the aperture of an EID, recording the current to the EID itself and/or another current monitor downstream. The program may then calculate the beam size and position of the beam centroid with respect to the EID center (Fig. 2), by fitting the data to an analytical formulation of a beam being moved across a round aperture assuming the current density distribution to be either Gaussian or uniform.

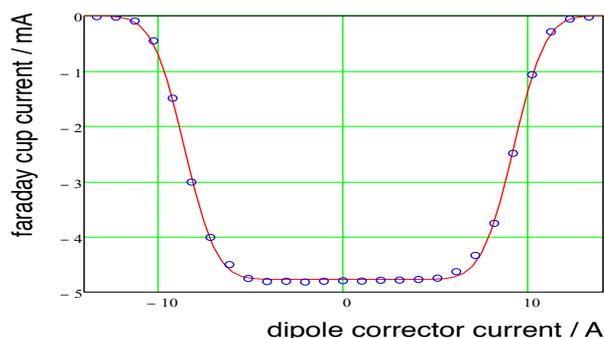


Figure 2: Beam current reaching the FC versus the dipole corrector current. Blue circles are measurements, and the solid red curve is the fit which produces a value for beam size and beam centre.

At the LEBT exit a so-called 'LEBT scraper' is installed. It is an electrically isolated, water-cooled, vertically movable copper plate with three openings: two apertures of 5 mm and 14 mm diameter, and a larger opening with a straight horizontal edge. The operational position is expected to be with the 14 mm hole centered with respect to the RFQ vanes, such that the diaphragm intercepts $\sim 1\%$ of the beam. Variations of the beam loss will then provide an indication of beam size and position stability, which may be incorporated in a feedback loop that would keep the beam parameters constant. The 5 mm hole will be used to produce a 'pencil' beam for commissioning, while the straight edge is used for

measurement of the vertical beam profiles. An example of a LEBT scraper scan can be seen in Fig. 3.

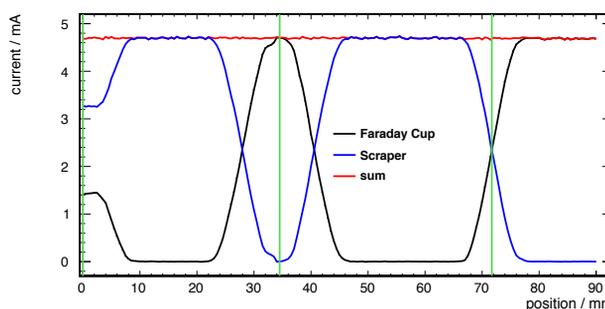


Figure 3: Currents (inverted) of the LEBT scraper and Faraday Cup as functions of the LEBT scraper position. The vertical green lines represent the positions of the 5 mm, 14 mm, and straight edge openings respectively.

Also shown in Fig. 1 is a set of four temporary scrapers, which are prototypes for future use in the MEBT. They are radiation-cooled, independently movable molybdenum plates, typically biased to +50 V in order to record beam profiles (see example in [3]). Reading of all EIDs and scrapers were calibrated with a standard current source. Then, with biasing to suppress secondary electrons, the balance of currents, defined as the difference between the current measured by the DCCT and the sum of all other current readouts, can be kept to within 2%.

Emittance Devices

To measure the phase space at the end of the beam line (and, when the RFQ is installed, at the ion source exit), the PXIE LEBT employs a water-cooled Allison-type emittance scanner [4]. This device is based on an SNS design [5] and was constructed in close co-operation with the SNS team. This type of scanner was chosen over others due to its relatively fast scan time and low signal-to-noise ratio.

Once the emittance scanner box is placed in the beamline, the beam impinges upon the front slit of the scanner box with

the emerging beamlet passing between a pair of electrically charged deflection plates, driven by two ± 1000 V power supplies. At specific plate voltages the beam is deflected such that only its portion with a given angle is transmitted through the rear slit and onto a collector, where the current of the transmitted particles is recorded. Hence, to obtain a full two-dimensional map of the beam in $x - x'$ phase space, the scanner box is stepped through the entire beam, each step corresponding to a position coordinate. An example of the measured phase space distribution can be seen in Fig. 4 as a 2D contour plot, where the colour scheme indicates the signal amplitude.

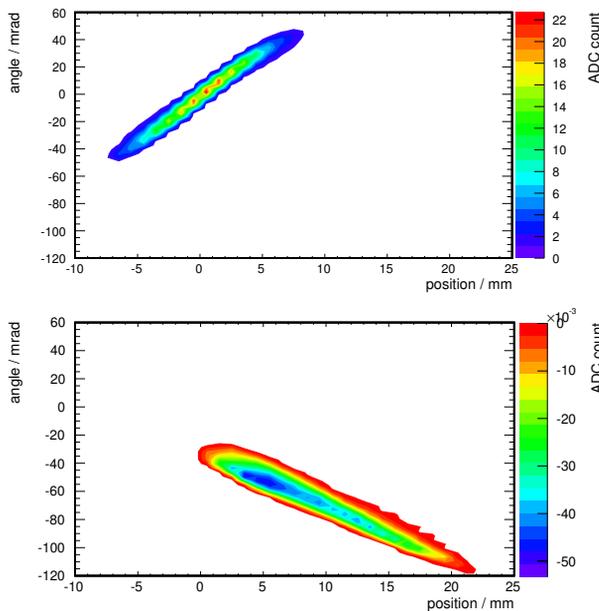


Figure 4: The phase space as recorded by the Allison scanner, for a 5 mA H^- beam (top), and the associated positive signal (bottom). Note the change in intensity scale for each plot.

The emittance scanner electronics use a ± 10 V, 16-bit ADC. As an illustration of the dynamic range, Fig. 4 also includes the Allison scanner collector signals with opposite polarity, which correspond to protons created immediately downstream of the ion source through charge-exchange of the primary H^- ions with the residual gas. Note that the scale of the proton signal is ~ 400 times smaller than for the H^- image.

A more detailed description of the Allison scanner – schematics, resolution, electronics, calibration etc. – can be found in [6].

The Allison scanner software calculates the position of the beam centroid in x and x' , the Twiss parameters, and the RMS emittance, typically after applying a 1% threshold cut to eliminate the background. For the distribution in Fig. 4 the RMS normalised emittance is calculated to be 0.119 ± 0.011 mm mrad. The reported uncertainty includes statistical noise as well as known systematic errors. As described in [6], the emittance measured with the Allison scanner agrees (within errors) with the value reconstructed

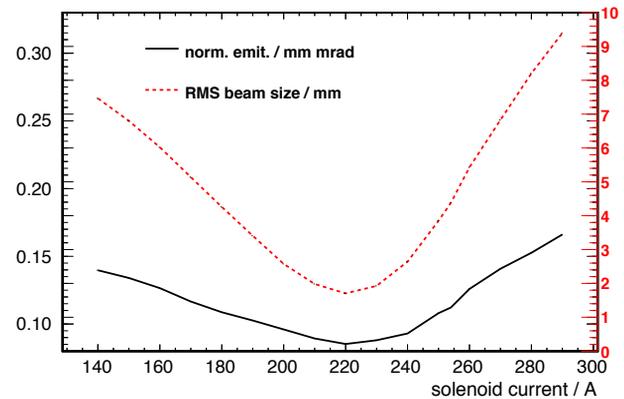


Figure 5: The RMS beam size and normalised emittance as seen at the Allison scanner as a function of solenoid three current.

from solenoid scans using the beam size measurement technique presented in Fig. 2.

However, we observed that when the ion source is tuned to produce the minimum emittance at the end of the LEBT, the dependence of the emittance measured with the Allison scanner as a function of the Solenoid 3 current has a characteristic ‘V-shape’ (see Fig. 5), not yet reproduced in simulations. Large reported emittances seem to coincide with large beam sizes (see Fig. 5).

Part of this correlation can be attributed to the finite size of the scanner slits: at large beam sizes, the angular spread of the beamlet coming out of the first slit, and, correspondingly, the beamlet width at the second slit, are low, and the relative contribution of the slit sizes on the reported emittance increases. This effect can be estimated according to formulae derived in [7] but still cannot account for the majority of the apparent growth.

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