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INVESTIGATION OF THE BEAM PROPAGATION THROUGH THE FNAL LEBT*

Daniel C. Jones†, Daniel Bollinger, Valery Kapin, Kiyomi Seiya
Fermi National Accelerator Laboratory, 60510 Batavia, USA

Abstract

The Fermi National Accelerator Laboratory (FNAL) Pre-accelerator send 25 mA H^- beam with a 30 μs pulse length at 15Hz. The machine's uptime was increased in 2012 by the replacement of the Cockcroft Walton Accelerator with a Radio Frequency Quadruple (RFQ) system to take the 35 keV beam from the ion source to 750 keV. The initial beam transmission efficiency from the ion source to the entrance of the Drift Tube LINAC (DTL) was 47%; however, the transmission efficiency has decreased over the last 10 years to 40% with no clear explanation. To better understand the cause of this reduction in transmission efficiency a vertically movable beam scraper was installed between the first two solenoids allowing the beam size to be investigated in the middle of the Low Energy Beam Line (LEBT). Utilizing this new diagnostic system in addition to the Ion Source R&D Laboratory's emittance probes the approximate emittance and beam size were able to be inferred. This experimental data was able to further inform our simulations and a more complete picture of the beams propagation through the LEBT has come into focus. The new simulations show the beam's spot size and emittance is to large for the RFQ's acceptance.

INTRODUCTION

The H^- injector for the FNAL LINAC was upgraded and has been in operation since 2012 as part of the Proton Improvement Plan that aimed to increase the proton flux in booster to 2.3 x 10^{17} protons per hour. The new design consisted of an ion source, a Low Energy Beam Transport (LEBT) that matches the beam to a 4-rod Radio Frequency Quadrupole (RFQ), and a Medium Energy Beam Transport (MEBT) that injects into the drift tube LINAC [1]. The transmission efficiency from the ion source to the start of the LINAC is approximately 40% which is significantly lower than expected. Previous studies looking at the transmission efficiency focused on the MEBT and other beam line qualities [2]. Recent data exploring the possibilities that the LEBT is the main cause of the inefficiency are presented in this paper.

EXPERIMENTAL SETUPS

FNAL LINAC Injector

Figure 1 displays the FNAL 750 keV injector line. Prior to the 2021 shutdown the only beam diagnostic elements

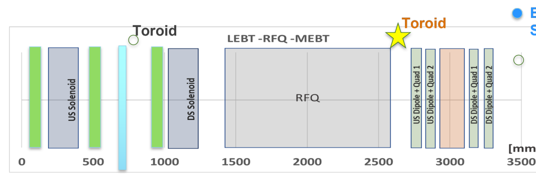

Figure 1: FNAL 750 keV injector line. The light blue line between the solenoids is the vertical beam scraper. The yellow star is where the MEBT toroid was placed during the 2021 shutdown period.

within the injector were a toroid in the LEBT and the toroid and emittance probes at injection into Tank 1 of the LINAC. In order to obtain more information about the beam two more diagnostic elements were used for this research. The MEBT toroid, the yellow star, was installed during the 2021 shutdown for a brief study period but had to be removed for the 2021-2022 run for the laser notcher re-installation. The vertical beam scraper, light blue line, was installed for the 2021-2022 run for continued diagnostics throughout the entire run.

Ion Source R&D Laboratory

The Ion Source R&*D* Laboratory houses a test bench which is identical to the operational LEBT through the first solenoid. After the first solenoid a set of emittance probes, located analogous to the beam scraper, were used to measure the beams transverse emittance in the middle of the LEBT.

FNAL LINAC INJECTION BEAM PROFILES

Utilizing the beam scraper in the LEBT and the emittance probes at Tank 1 beam profiles were obtained for both operational ion sources during the 2021-2022 run. Figure 2 displays several days of beam profiles within the 2021-2022 run period. The red dashed line corresponds to ion source A and the solid black line corresponds to ion source B. Ion source A displays a clear peak intensity approximately 1.5 cm above the center of the pipe. This is in stark contrast to the beam profiles of ion source B which display a much more uniform beam around the center of the pipe. This difference in beam profile was unexpected and is not easily explained.

The effect of this difference in beam profiles, between the two ion sources, appears to be minimized by the RFQ when observing the beam at the entrance to the FNAL LINAC in Fig. 3. The horizontal beam profiles delivered by ion source A, the solid black lines, tend to have a peak position closer to the center of the pipe than the beam profiles delivered by ion source B, the dashed red lines though the delivered

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† dcjones@fnal.gov

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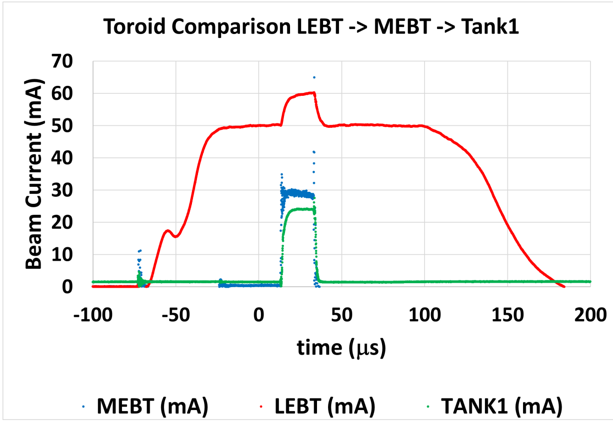

Figure 2: Comparing the beam intensity in the LEBT, in the MEBT, and at the entrance to the LINAC.

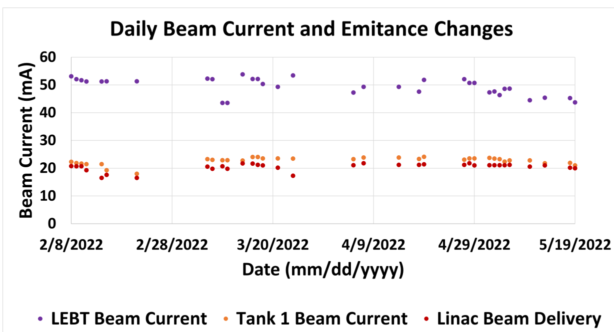

Figure 3: Daily beam current changes for the 2021-2022 run period of the FNAL accelerator. The purple points are the beam current within the FNAL LEBT. The orange points are the beam current injected into the FNAL LINAC. The red points are the output beam current of LINAC.

beam size is the same for both ion sources. The vertical beam profiles at the entrance to tank 1 are almost identical day to day and the beam size is identical between the two ion sources. The average horizontal rms beam size is 2.4 mm, and the average vertical rms beam size is 3.6 mm, for the injected beam. The fact that the beam entering the LINAC is relatively uniform in shape both day to day and ion source to ion source indicates that the RFQ is only accepting part of the beam seen in the LEBT.

The beam current was observed in the LEBT, at the entrance to tank 1 of the LINAC, and at the output of the LINAC is shown in Fig. 4. The FNAL LINAC has a transmission efficiency of approximately 92% and is very clearly displayed in Fig. 4 with how closely the output beam current, the red trace, corresponds with the LINAC input beam current, the orange trace. When comparing the LEBT beam current, the purple trace, to the LINAC input current there is absolutely no correspondence between the beam current at these two locations indicating that a large majority of the beam in the LEBT is being lost and that the RFQ is only delivering a small portion of the beam that is extracted from the ion source.

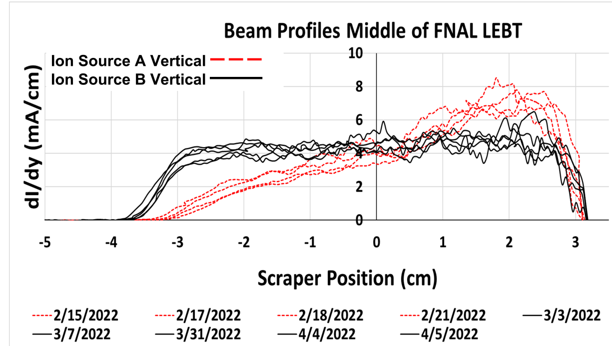

Figure 4: Vertical beam profiles obtained from the FNAL operational LEBT with the vertically actuating scraper. The current I is the current read back by the beam scraper. The red dashed lines are vertical beam profiles obtained from ion source A on a variety of days during the 2021-2022 run period. The black solid lines are the vertical beam profiles obtained from ion source B on a variety of days during the 2021-2022 run period.

BEAM TRANSMISSION

The MEBT toroid allowed the beam intensity loss to be quantified and verify that the beam was primarily being lost before exiting the RFQ. Figure 5 displays the beam current for the LEBT toroid (red trace), the MEBT toroid (blue trace), and the toroid at the entrance to tank 1 (green trace). Comparing these traces the transmission efficiency was determined to be 47% from the LEBT to the MEBT while the MEBT had a transmission efficiency of 83% leaving a transmission efficiency of 39% from the LEBT to the start of the LINAC.

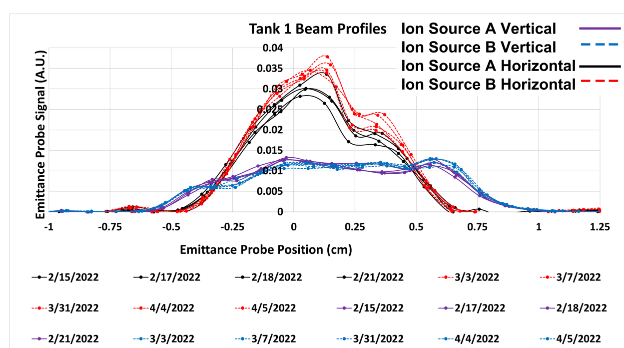

Figure 5: Vertical and horizontal beam profiles at the entrance to the FNAL LINAC. The red and black traces are the horizontal beam profiles where black indicates ion source A and red indicates ion source B. The blue and purple traces are the vertical beam profiles where purple indicates ion source A and blue indicates ion source B. Further ion source A is the solid traces and ion source B is the dashed traces.

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EMITTANCE MEASUREMENTS

Utilizing the emittance probes on the test bench in the Ion Source R&*D* Laboratory the beam emittance was able to investigated analogous to the point where the LEBT scraper system was located. Figure 6 displays the heat maps from the emittance probes, the direction of investigation is denoted in the upper right corner of each image, for a commonly used operational solenoid setting. The heat maps show that the beam is spiraling in phase space with large arms on either end. Unfortunately, the beam is too large to be fully captured by the emittance probes due to the probes limited stroke. Even though the emittance values were not able to be reliably obtained; the heat maps mixed with the beam profiles were able to provide useful information for a TraceWin simulation to be setup for the FNAL LINAC Injector Line.

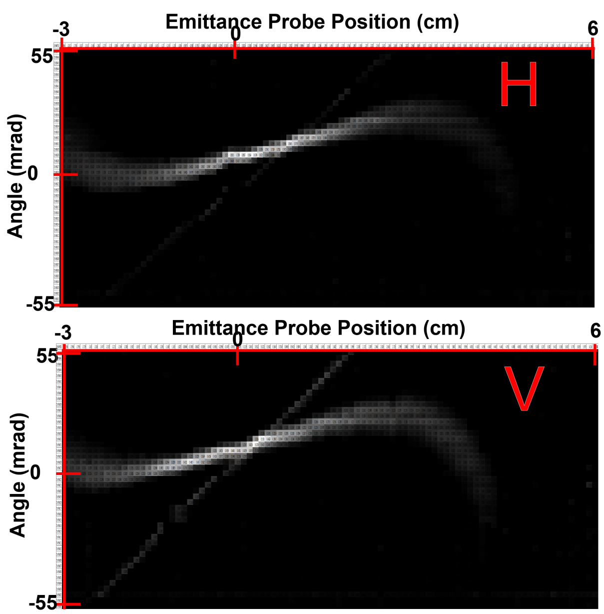

Figure 6: Heat maps from the test bench emittance probes for a commonly used solenoid setting of 430 A applied current. The top image is the horizontal heat map. The bottom image is the vertical heat map.

SIMULATIONS

Utilizing the experimental results a beam simulation was setup using TraceWin software [3]. The input current was 60 mA with space charge and an assumed RMS emittance of 0.59 π*mm*mrad based on the RFQ acceptance. Figure 7 displays the TraceWin simulation results in the middle of the LEBT. Similar spiraling tails are found in the simulation as were seen on the test bench emittance profiles. The beam is shown to be large in physical space occupying almost the entire beam pipe as expected from the LEBT vertical beam profiles. Figure 8 displays this beam once it has propagated the length of the LEBT, encountered the second solenoid, and is entering the RFQ. A large amount of the beam is lost at this location, approximately 60% confirming for us that the beam is not being sufficiently focused into the RFQ and that most of the beam loss that is leading to the poor transmission efficiency is occurring within the LEBT.

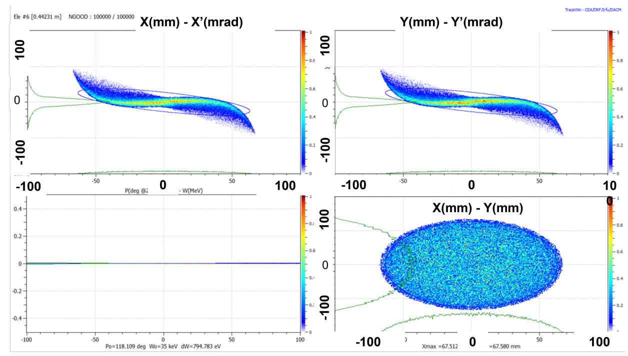

Figure 7: TraceWin simulation at the location of the LEBT scraper and the test bench emittance probes.

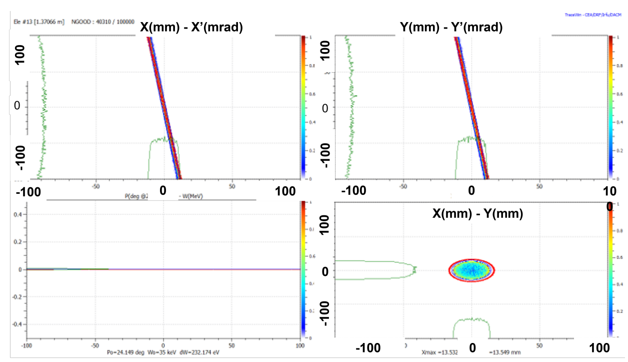

Figure 8: TraceWin simulation showing that 60% of the beam from the middle of the LEBT is lost at the RFQ entrance.

SUMMARY

Based on the data presented in this paper it appears that the primary contribution to the low beam transmission efficiency is the beam properties in the LEBT not matching the RFQ acceptance parameter. Data taken with the MEBT toroid shows that the LEBT efficiency is 47%. That coupled with the MEBT transmission efficiency of 83% gives the injector line an overall efficiency of 39%. Simulations that use data taken from the scrapper and test stand emittance probes, show that only 40% the beam seen by the LEBT toroid is entering the RFQ. In the short term there is a plan to turn the vertical beam scraper into a beam collimator to verify that the RFQ emittance is not being matched by the LEBT. A more long time solution is being investigated to insert an Einzel Lens right after the ion extraction to fully match the RFQ acceptance parameters.

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[3] TraceWin, `https://dacm-logiciels.fr/tracewin`.