

# PERFORMANCE OF THE LOW ENERGY BEAM TRANSPORT AT THE RAL FRONT END TEST STAND\*

J. Back<sup>†</sup>, University of Warwick, Coventry, UK

D. Faircloth, C. Gabor, S. Lawrie, A. Letchford, Rutherford Appleton Laboratory, Didcot, UK

J. Pozimski, Imperial College of Science and Technology, London, UK

## Abstract

The Front End Test Stand (FETS) at the Rutherford Appleton Laboratory (RAL) is intended to demonstrate the early stages of acceleration (up to 3 MeV) and beam chopping required for high power proton accelerators, including proton drivers for pulsed neutron spallation sources and neutrino factories. A Low Energy Beam Transport (LEBT), consisting of three solenoids and four drift sections, is used to transport the H<sup>-</sup> beam from the ion source to the Radio Frequency Quadrupole (RFQ). We present the current performance of the LEBT with regards to beam alignment, transmission and focusing into the acceptance of the RFQ.

## INTRODUCTION

The FETS [1] is being constructed at RAL in the UK to demonstrate the production and perfect chopping [2] of a high intensity H<sup>-</sup> ion beam. The FETS requirements are to fully transport a 3 MeV H<sup>-</sup> beam, with a pre-chopped current of 60 mA, in pulses up to 2 ms long at a frequency of 50 Hz, whilst maintaining the high quality of the beam. The design normalised transverse RMS emittance of the beam is 0.3 $\pi$  mm mrad. This front end will be suitable as an injector for a range of high power (MW range) proton accelerators, such as spallation neutron sources, accelerator driven sub-critical reactors and a neutrino factory. In this paper, we present the current status of the LEBT with regards to the transmission and alignment of the beam, as well as focusing for injection into the RFQ, which is in the final stages of manufacture [3].

## LEBT LAYOUT

The purpose of the LEBT is to focus the 65 kV, 70 mA H<sup>-</sup> beam from the ion source into the RFQ. Figure 1 shows a schematic of the LEBT beamline, which contains three identical 310 mm-long solenoids, that are used to focus the beam, separated by four vacuum drift sections of various lengths. The first drift section (245 mm) is immediately after the ion source and contains four 800 Ls<sup>-1</sup> and one 400 Ls<sup>-1</sup> turbo vacuum pumps, as well as the post-acceleration (PA) electrodes which accelerate the extracted ion beam to the 65 keV RFQ input energy [4]. Note that the inner radius of the protruding 28 mm-long PA section is only 12.5 mm, which is much smaller compared to the nominal beam pipe (i.e. solenoid) inner radius of 44.5 mm; this collimates the H<sup>-</sup> beam, reducing the typical ion source

current of 70 mA down to 55 mA. The second and third drift sections (150 and 350 mm) separate the solenoids; the latter contains a 2000 Ls<sup>-1</sup> vacuum pump. The start of the entrance flange for the radial matching section of the RFQ is located at  $z = 1655$  mm, equal to 20 mm inside the physical end of the third solenoid. This decreases the beam pipe radius from 19.5 mm eventually down to 12.5 mm. The H<sup>-</sup> beam must be focused within this radial envelope, converging at the RFQ entrance that, thanks to a flexible piping extension joint (bellows), can vary between  $z = 1812.8$  mm (fully inserted) and 1863.8 mm (fully retracted). Emittance scanners are placed at the end of the last drift section at  $z = 1886$  mm to measure the phase space of the beam; ideally we need to see a strongly diverging beam here to show that the beam has been focused at the upstream RFQ entrance.

## SIMULATED PERFORMANCE

The presence of the three solenoids in the LEBT provides a lot of flexibility with regards to focusing the beam. Ideally, we need to set the solenoid fields such that the beam is strongly focused at the RFQ entrance, avoiding situations where the beam is refocused midway inside the LEBT, which will lead to unwanted emittance growth. General Particle Tracer (GPT) [5] simulations were used to find the allowed solenoid current ranges to provide optimal focusing into the matched RFQ acceptance, which is defined by the Twiss parameters  $\alpha_x = 3.83$ ,  $\beta_x = 0.16$ ,  $\alpha_y = 3.41$ ,  $\beta_y = 0.14$  for a normalised RMS emittance of 0.25 $\pi$  mm mrad. A 4D waterbag distribution was assumed for the 65 keV initial beam from the ion source, with Twiss parameters  $\alpha = -0.95$  and  $\beta = 0.58$ , in both  $x$  and  $y$ , for a normalised RMS emittance of 0.32 $\pi$  mm mrad, together with a space charge of 5 mA. The  $r$ - $z$  magnetic fields of the solenoids were modelled using COMSOL [6]; the axial components closely match the measured fields obtained during the initial commissioning of the LEBT [7]. Table 1 shows the optimised solenoid current values. The results highlight the importance of having a high enough current ( $\geq 190$  A) in the last solenoid in order to adequately focus the beam. The current values for the first two solenoids are almost interchangeable; a high current in the first solenoid requires a lower current in the second, and vice versa. The beam becomes focused midway inside the LEBT if the first solenoid current is above 175 A, meaning that high currents are also required in the other two solenoids in order to refocus the beam at the RFQ entrance.

\* Work supported by the Science and Technology Facilities Council, UK

<sup>†</sup> J.J.Back@warwick.ac.uk

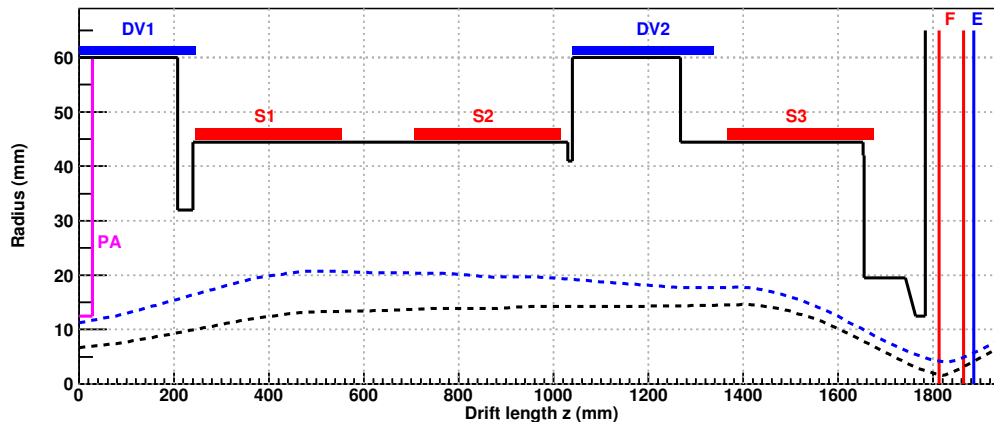


Figure 1: Schematic of the aperture radius (solid black line) along the LEBT beamline. The post acceleration region (PA) is shown in magenta, while the longitudinal extent of the drift vacuum pumping vessels (DV1, DV2) and solenoids (S1, S2, S3) are represented by the blue and red boxes, respectively. The range of allowed focusing positions into the RFQ are bounded by the red vertical lines (F), while the location of the emittance scanners is shown by the blue vertical line (E). The dashed lines show examples of simulated beam envelopes for normalised RMS emittances of  $0.3 \pi \text{ mm mrad}$  (black) and  $1.0 \pi \text{ mm mrad}$  (blue).

Owing to the geometrical constraints shown in Fig. 1, the required focal length  $f$ , corresponding to the distance between the physical end of the third solenoid and the entrance to the RFQ, must be between 138 mm and 189 mm. This means that the best solenoid currents  $I_1$ ,  $I_2$  and  $I_3$  are approximately  $125 \pm 10$ , 0–100 and 210–250 A, respectively. Maximal acceptance into the RFQ ( $\approx 88\%$ ) is achieved for the solenoid current settings 125, 80 and 240 A. Figure 2 shows the phase space distributions of this simulated beam at the RFQ entrance; the beam envelope is illustrated in Fig. 1.

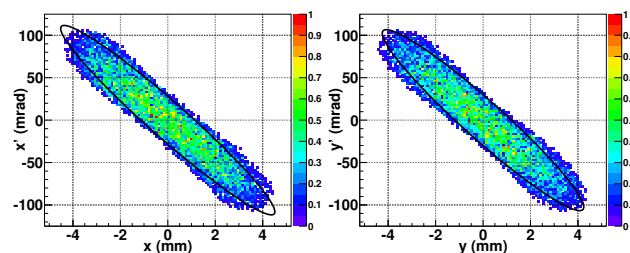


Figure 2: GPT simulation of the phase space distributions of an optimally transported  $\text{H}^-$  beam at the end of the LEBT overlaid with the matched RFQ acceptance ellipses.

Table 1: The optimal ranges of the currents in solenoids 2 and 3 ( $I_2$ ,  $I_3$ ), for the given current  $I_1$  in solenoid 1, based on GPT simulations of the  $\text{H}^-$  beam transported through the LEBT. The fractional number of particles within the matched RFQ acceptance is given by the range  $e_{\text{RFQ}}$  for the corresponding focal length  $f$ , which is measured from the physical end of the third solenoid ( $z = 1675 \text{ mm}$ ).

$I_1$ (A)	$I_2$ (A)	$I_3$ (A)	$e_{\text{RFQ}}$ (%)	$f$ (mm)
0	50–140	190–240	75–85	40–260
25	50–140	190–240	75–85	40–250
50	40–140	190–240	75–85	40–240
75	0–120	200–250	75–86	40–220
100	0–120	200–250	75–87	40–200
125	0–100	210–250	76–88	40–160
137	0–80	220–250	77–86	40–120
150	0–50	240–250	77–78	40–80
175	0–70	230–250	50–60	80–120
200	200–250	250	53–65	200–250

## EMITTANCE MEASUREMENTS

Using the solenoid current ranges suggested by the previous GPT simulation results, measurements of the  $x - x'$  and  $y - y'$  phase space distributions of the beam at the end of the LEBT were taken with emittance scanners. The emittance is plotted and calculated during the flat top of the  $300 \mu\text{s}$ -long beam pulse, with a minimum threshold of 5% of the maximum intensity applied to the data in order to reduce background noise. Figure 3 shows the results for the solenoid current settings 130, 80 and 220 A (for an ion source sector magnet current  $I_{\text{sm}}$  of 11.5 A, extraction voltage  $V_E$  of 21 kV and post-extraction acceleration voltage  $V_P$  of 44 kV). We can see that the beam is converging in both  $x$  and  $y$ , which implies that we have not yet focused the beam at the range of nominal RFQ entrance points. Slightly increasing the currents of the second and third solenoids up to 100 and 245 A, respectively, give the results shown in Fig. 4 (for  $I_{\text{sm}} = 12.5 \text{ A}$ ,  $V_E = 21 \text{ kV}$  and  $V_P = 44 \text{ kV}$ ). Here, we can see that the beam is now diverging in both  $x$  and  $y$ , which means that it has been focused close to the

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

nominal RFQ entrance point. Therefore, the predicted optimal ranges for the solenoid currents correspond to a focusing solution for the real beam. Despite this, further work is needed to see if refinements to the solenoid currents can show a beam that is enclosed within the matched RFQ acceptance ellipse that has been evolved to the location of the emittance scanner, which is at a distance between 138 and 189 mm from the RFQ entrance.

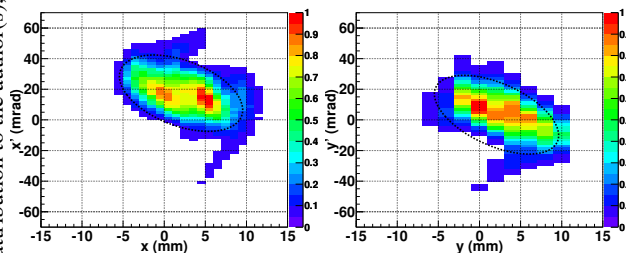


Figure 3: Measured horizontal (left) and vertical (right) emittance distributions at the end of the LEBT for the 65 keV  $H^-$  beam when the solenoid currents are set to 130, 80 and 220 A. The normalised RMS emittances are both equal to  $0.49\pi$  mm mrad. The centroid of the beam is (2.04 mm, 17.44 mrad) horizontally and (2.08 mm, 3.39 mrad) vertically. The dotted ellipses show the phase space area that is equal to four times the RMS emittance.

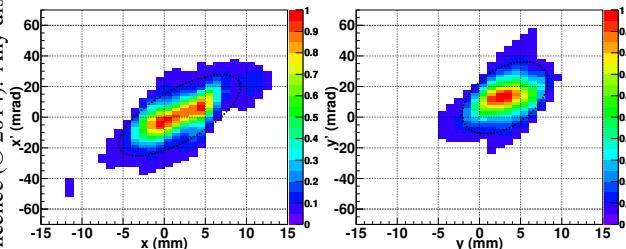


Figure 4: Measured horizontal (left) and vertical (right) emittance distributions at the end of the LEBT for the 65 keV  $H^-$  beam when the solenoid currents are set to 130, 100 and 245 A. The normalised RMS emittances are  $\epsilon_x = 0.41\pi$  mm mrad and  $\epsilon_y = 0.32\pi$  mm mrad. The centroid of the beam is (1.86 mm, 1.27 mrad) horizontally and (3.09 mm, 12.71 mrad) vertically. The dotted ellipses show the phase space area that is equal to four times the RMS emittance.

An important requirement for the beam is that it must be aligned along the  $z$  axis. This is necessary in order to avoid losing beam as it propagates along the LEBT and passes through the aperture of the RFQ entrance, which implies that we require  $(\langle x \rangle, \langle x' \rangle) = (\langle y \rangle, \langle y' \rangle) = (0, 0)$ . Previously, large misalignments in both position and angle, equivalent to  $\sim 1$  cm, were observed for the beam at the location of the emittance scanners. Improvements to the alignment of the ion source and post-acceleration region with

respect to the solenoid magnets along the FETS beamline have significantly reduced the offset of the beam. However, we can see from the results shown in Figs. 3 and 4 that the misalignment of the beam has not been completely solved. One reason for this is that the solenoids have central and fringe field imperfections at the level of a few milli-Tesla, which can missteer the beam [8]. To tackle this problem, each solenoid has horizontal and vertical steering dipoles that can be used to correct the trajectory of the beam. Previous measurements using a reduced 3 mm-sized pencil beam have shown that these steering magnets can be potentially used to correct such offsets [8]. However, the strong non-linear coupling of the dipole fields with the main solenoid fields makes it difficult in practice to predict what are the required dipole settings to recentre the beam at (0,0) for  $x$  and  $y$  *simultaneously*. A possible way forward is to apply systematic variations to the horizontal and vertical dipoles for the optimal main solenoid current settings mentioned earlier and measure the beam offsets within  $3 \times 3$  grids; this is still work in progress.

## CONCLUSION

We have presented the current performance of the LEBT for FETS at RAL, which is used to focus the  $H^-$  beam from the ion source into the entrance of the RFQ and consists of three identical solenoids separated by four vacuum drift sections. Simulation studies of the beam transport along the LEBT show that the best set of solenoid currents ranges are equal to  $125 \pm 10$ , 0–100 and 210–250 A. Using these current values as a guide, emittance scanner measurements show that the  $H^-$  beam can be fully transported to the end of the LEBT and focused at the location of the RFQ entrance. Further measurements with the steering dipoles are required in order to achieve a consistent positional and angular alignment of the beam along the  $z$  axis.

## REFERENCES

- [1] A. Letchford et al., “Status of the RAL Front End Test Stand”, IPAC’13, Shanghai, China, May 2013, THPWO086.
- [2] M. A. Clarke-Gayther, “A two stage fast beam chopper for next generation high power proton drivers”, IPAC’11, San Sebastián, Spain, September 2011, TUPS104.
- [3] P. Savage et al., “Production of the FETS RFQ”, IPAC’13, Shanghai, China, May 2013, THPWA043.
- [4] D. C. Faircloth et al., “Installation of the Front End Test Stand high performance  $H^-$  ion source at RAL”, EPAC’08, Genoa, Italy, June 2008, MOPC144.
- [5] GPT, Pulsar Physics, <http://www.pulsar.nl/gpt>
- [6] COMSOL software, <http://www.comsol.com>
- [7] J. Back et al., “Commissioning of the Low Energy Beam Transport of the Front End Test Stand”, IPAC’10, Kyoto, Japan, May 2010, MOPEC078.
- [8] C. Gabor et al., “Matching an  $H^-$  beam into the FETS RFQ at RAL”, Rev. Sci. Instrum. 85, 02A745 (2014).