COMMISSIONING OF THE LOW ENERGY BEAM TRANSPORT OF THE FRONT END TEST STAND*

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Abstract

The Front End Test Stand (FETS) at the Rutherford Appleton Laboratory is intended to demonstrate the early stages of acceleration (0-3 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^- beam from the ion source to the FETS Radio Frequency Quadrupole. We present the status of the installation and commissioning of the LEBT, and compare particle dynamics simulations with preliminary measurements of the H^- beam transport through the LEBT.

INTRODUCTION

The FETS [1] is being constructed at the Rutherford Appleton Laboratory (RAL) in the UK to demonstrate the production and perfect chopping [2] of a high intensity H^- ion beam. The FETS requirements are to fully transport a 3 MeV H^- 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 0.3π mm mrad. This front end will be suitable as an injector for a range of high power (MW range) proton accelerators (HPPAs), such as spallation neutron sources, accelerator driven subcritial reactors (ADSRs) and a neutrino factory. In this paper we present the current status of the commissioning of the Low Energy Beam Transport (LEBT), and show comparisons between measured beam distributions and simulated results.

DESIGN OVERVIEW

The goal of the LEBT is to transport the H^- beam from the ion source [3] into the entrance of the Radio Frequency Quadrupole (RFQ) [4]. The converging beam needs to fit inside the acceptance of the RFQ, which is expected to be approximately $\epsilon = 0.3\pi$ mm mrad. The design is based on the LEBT being used at ISIS, RAL. Figure 1 shows the layout of the LEBT, consisting of three 29 cm-long solenoids separated by vacuum drift sections of various lengths ($d_1 = 25$ cm, $d_2 = 14$ cm, $d_3 = 35$ cm and $d_4 = 17$ cm), all of which are supported by a metal frame that is aligned along the beam axis. The H^- beam passes from left to right along a 5 cm radius beam pipe running along the centre of the LEBT. The main drift vacuum vessel is mechanically decoupled from the second and third solenoids, and provides a vacuum pressure of 10^{-5} Pa (for a pumping speed of $\sim$ 2000 l s^{-1}). The first and second solenoids are connected by a flexible bellows to enable small adjustments to their position. There are also connecting power cables and water cooling pipes needed to operate the solenoids (not shown in the picture). Toroids that measure the beam current are positioned in the first drift (laser diagnostic) vessel, inside the main drift vacuum vessel between the second and third solenoids, and just after the third solenoid. A Faraday cup (with a grounded front plate and secondary electron suppression ring) is positioned inside the vacuum vessel, which also acts as a beam stop during LEBT commissioning. A slit-slit transverse emittance scanner is positioned after the last solenoid.

General Particle Tracer (GPT) simulations have shown that the H^- beam can be focused into the expected aperture of the RFQ for a wide range of initial space-charge conditions by simply changing the magnetic fields of the solenoids. For a typical ion source beam with a kinetic energy of 65-70 keV, required values for the solenoid fields are expected to be B_1 = 0.19 T, B_2 = 0.17 T and B_3 = 0.30 T.

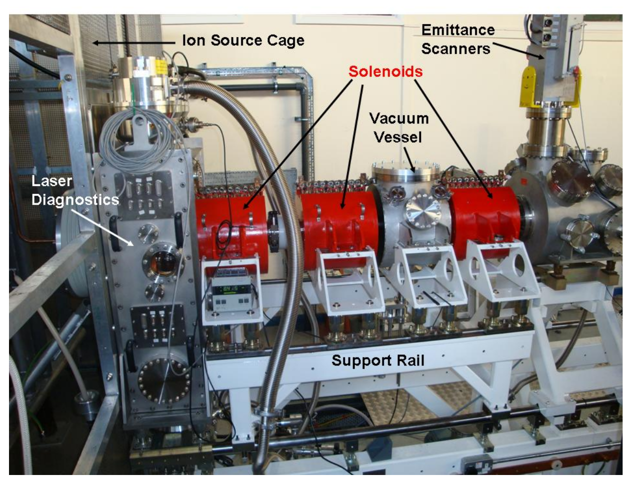

Figure 1: The LEBT installed at RAL. The H^- beam direction is left to right.

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SOLENOIDS

The LEBT has three solenoids that focus the beam from the ion source into the RFQ. Each solenoid has the same design, as shown in the schematic cylindrical geometry outlined in Fig. 2. The winding copper coils are grouped into a 2-5-2 arrangement, with the inner coil sections having smaller radii than the outer sections. This is to ensure that the axial (z) magnetic field distribution in the middle of each solenoid is reasonably flat. Each coil section is split into two smaller conductors to reduce the currents needed to produce the magnetic field (by a factor of four), simplifying the design of the power supplies and reducing the cooling requirements needed for stable operation. The number of wire turns for each coil conductor is approximately 11.1 cm^{-1}. Low levels of magnetic field saturation allow us to use standard low-carbon iron for the yoke surrounding the copper coils.

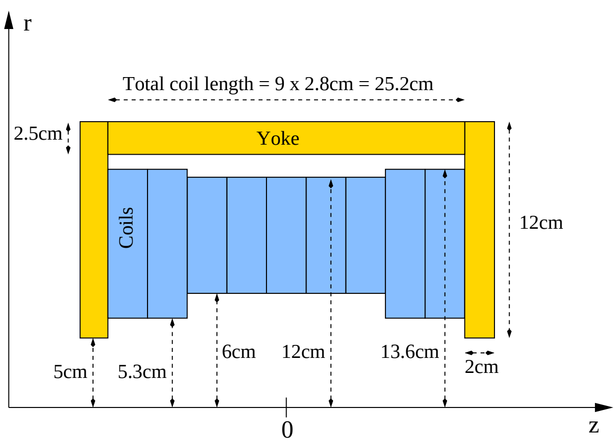

Figure 2: Schematic of the solenoid design.

The solenoids incorporate built-in Lambertson correction dipoles for beam steering (up to a maximum deflection of 4°). These copper dipoles are wrapped around an alignment tube running along the inner radius of each solenoid bore, subtending a polar angle of $\pm 45^\circ$ from the $x-y$ axis. Cooling is achieved by a series of pipes connected along the length of the solenoid. The water supply manifolds are carefully integrated into the yoke body and the end plates of each solenoid. The power supply for each solenoid has a maximum voltage of 25 V, corresponding to a maximum magnetic field value of 0.35 T.

The magnetic field of one of the solenoids has been measured with a standard Hall probe [5], and compared to finite element (CST) calculations, in order to check that the solenoids were made to the required specifications. Figure 3 shows a comparison of the axial magnetic field profile (B_z) along the z axis between the field map data and CST calculations for one half of the solenoid, for different radial positions r. The simulations use the same geometry as shown in Fig. 2, with the current in each coil approximated by three current elements at the inner, outer and mid-radius positions. It is clear that there is excellent agreement between both sets of results, showing that the solenoids have been constructed to the correct specifications. Slight discrepancies are only apparent as we go further away from the z axis (increasing r), which can be explained by the finite element approximation that is used to represent the currents in each of the coils. These differences have a negligible effect on beam dynamics calculations.

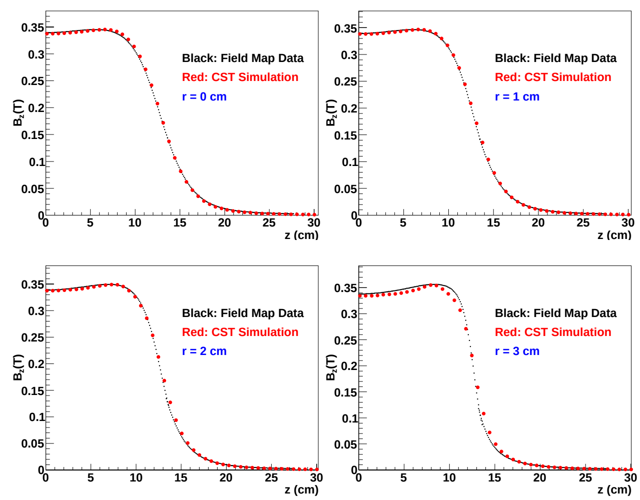

Figure 3: $B_z(z)$ measured and simulated field map distributions for one of the solenoids at different radii.

The calibration of the coil currents I producing the (peak) magnetic field B follows the solenoid field equation $B = \mu n I$, where n is the effective number of coil turns ($11.1\,\text{cm}^{-1}$) and μ is the permeability of vacuum. The design magnetic fields 0.19 T, 0.17 T and 0.30 T are achieved by the coil currents 137 A, 123 A and 216 A, respectively. The only remaining issue for the solenoid commissioning is the need to reduce the high frequency noise of 25 kHz from the solenoid power supplies. Figure 4 shows the effect this has on the toroid current measurements. A solution is being formulated to fix this problem.

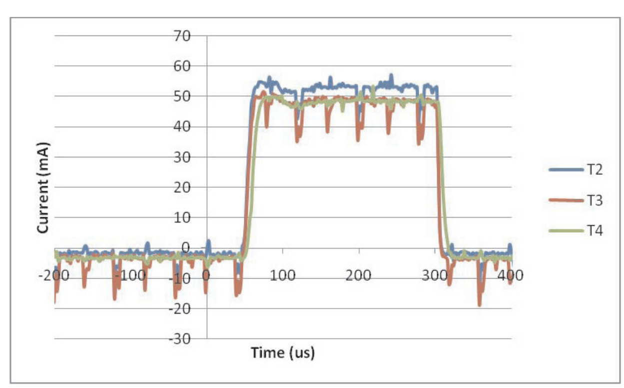

Figure 4: Beam currents in the toroids (T2 is at the end of the second solenoid, while T3 and T4 are at either end of the last solenoid).

BEAM TRANSPORT

Preliminary measurements of the beam transmission through the LEBT have been made [6]. The ion source routinely produces a 65-70 mA H^- beam at the design RFQ injection energy of 65 keV. At present, collimation in the laser diagnostic vessel between the ion source and the first solenoid reduces the beam current by about 20%. Using the design magnetic field settings of the solenoids (0.19 T, 0.17 T and 0.30 T), the remaining 55 mA beam is almost completely transported through the LEBT. By comparing the beam currents at the toroids positioned at the start and end of the vacuum pumping vessel, we estimate that only 4% of the beam is lost as a result of residual gas pressure stripping of the H^- ions.

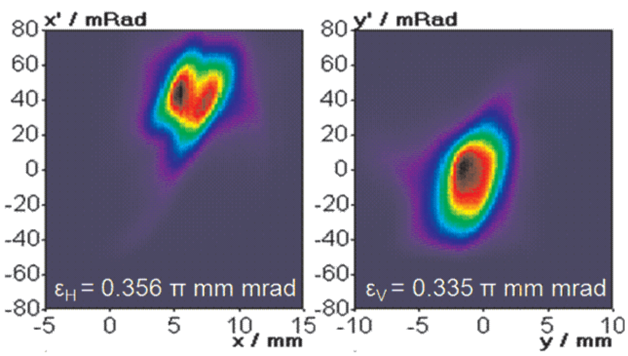

Figure 5: Measured phase space distributions of the beam at the end of the LEBT.

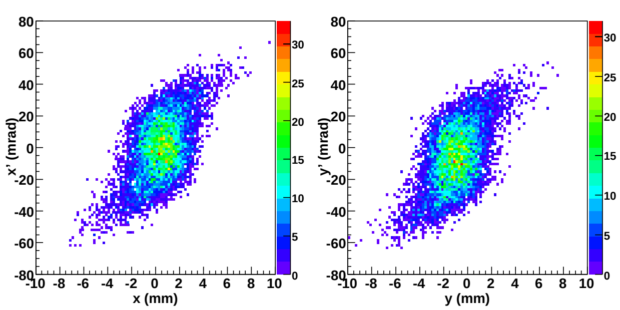

Figure 6: GPT simulation of the phase space distributions of the beam at the end of the LEBT.

Figure 5 shows the phase space distributions of the transported beam measured using the slit-slit transverse emittance scanners at the end of the LEBT. Because the ion source is not perfectly aligned with the LEBT support frame, the distributions are not centred on the origin, and we can also see some filamentation in the phase space plots. However, the beam is well focused after being transported through the LEBT. Figure 6 shows the results of a GPT simulation of the LEBT, assuming a space charge current of approximately 10% (5 mA). We see a reasonable agreement for the overall shapes of the distributions, with most of the beam concentrated in the centre. The non-zero space charge introduces slight aberrations to the phase space distributions, similar to features seen in the data. Figure 7 shows the simulated x and y beam envelopes, where the dotted vertical lines show the start and end positions of the solenoid and drift sections. We see a weak focusing effect, which is what is required to reduce emittance growth, and the beam converges at the nominal entrance point of the RFQ aperture. However, the emittance scanners are 5 cm further along the nominal focusing point, which leads to the beam becoming divergent again. We also see that the simulated beam envelope is well within the aperture of the solenoid, which is consistent with our observations that the losses in the LEBT are predominantly from residual gas stripping. The normalised transverse RMS emittance values for the simulated beam are $\epsilon_x = 0.33\pi$ mm mrad and $\epsilon_y = 0.34\pi$ mm mrad, which agree with the measured values of $\epsilon_x = 0.36\pi$ mm mrad and $\epsilon_y = 0.34\pi$ mm mrad.

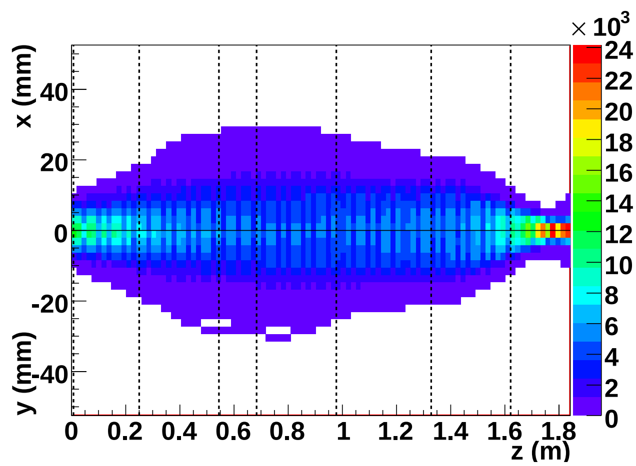

Figure 7: GPT simulation of the x and y beam envelopes along the length of the LEBT.

SUMMARY

We have shown several aspects of the commissioning of the LEBT, which is installed at RAL. The solenoids have been constructed to the required specifications, with the only remaining issue being the need to eliminate the electronic noise from the power supplies. The ion source beam is almost completely transported through the LEBT, and we have shown comparisons between measured and simulated beam distributions, which agree rather well. Further work will be done to improve the beam focusing and alignment.

REFERENCES

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