ACCEPTANCE AND TRANSMISSION SIMULATIONS OF THE FETS RFQ

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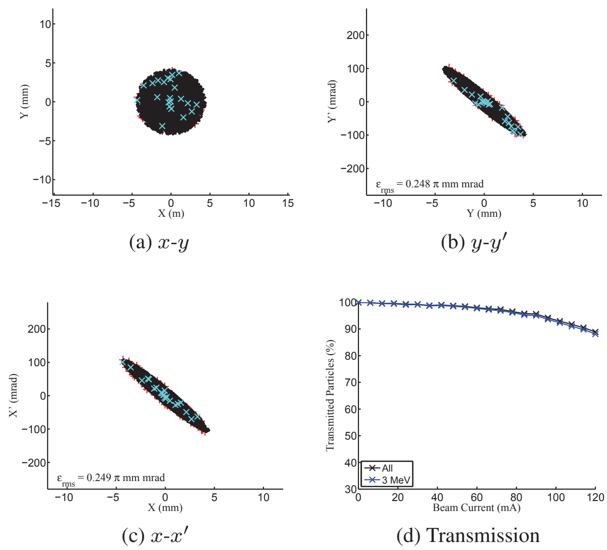
Abstract

A 4 m-long, 324 MHz four-vane RFQ, consisting of four coupled sections, has been designed for the Front End Test Stand (FETS) at RAL in the UK. A novel design method, integrating the CAD and electromagnetic design of the RFQ with beam dynamics simulations, was used to optimise the design of the RFQ. With the design of the RFQ fixed, the focus has been on optimising the transmission of the RFQ at 3 MeV and matching the output of the FETS Low Energy Beam Transport (LEBT) to the RFQ acceptance. Extensive simulations have been carried out using General Particle Tracer (GPT) to map out the acceptance of the FETS RFQ for a 65 keV H^- input beam. Particular attention has focussed on optimising the simulations to match the optimised output of the FETS Penning-type H^- ion source. Results are presented of the transverse phase space limits on the RFQ input acceptance in both the zero current and full space charge regimes.

INTRODUCTION

As part of the ongoing development of future high power proton accelerators (HPPA's) and to contribute to the UK design effort on the Neutrino Factory, the Front End Test Stand (FETS) is being constructed at the Rutherford Appleton Laboratory (RAL) in the UK. The aim of FETS is to demonstrate the production of a 60 mA, 2 ms, 50 pps chopped beam: a detailed description of the project and the current status is given in [1]. To accelerate the beam to 3 MeV, a 4-vane RadioFrequency Quadrupole (RFQ) channel, consisting of 4 1 m sections operating at 324 MHz, has been selected for FETS. In order to fully optimise the design of the FETS RFQ, an integrated design method was developed [2]. This design process has resulted in an RFQ that is currently in the late stages of manufacture [3]. With the design stages complete, focus has shifted to maximising the transmission of the RFQ.

Based on the method outlined in [2], simulations have been carried out using the General Particle Tracer simulation code (GPT). A field map of the final RFQ geometry is imported using the GPT `map3D_EB` function: an input beam distribution is then created using a custom GPT function, `setWBemittance`, that creates a 4-D Waterbag distribution according to the desired *rms* emittances and Twiss parameters. The FETS RFQ is designed to transmit a 60 mA H^- beam to 3 MeV with an input emittance of $\epsilon_{x,\mathrm{rms}} = \epsilon_{y,\mathrm{rms}} = 0.25\,\pi$ mm mrad. The matched Twiss parameters at the RFQ entrance, some 21 mm upstream of the start of the radial input matcher, are $\alpha_x = 3.8263$; $\beta_x = 0.15996$; $\alpha_y = 3.4091$; and $\beta_y = 0.14152$. For a 60 mA



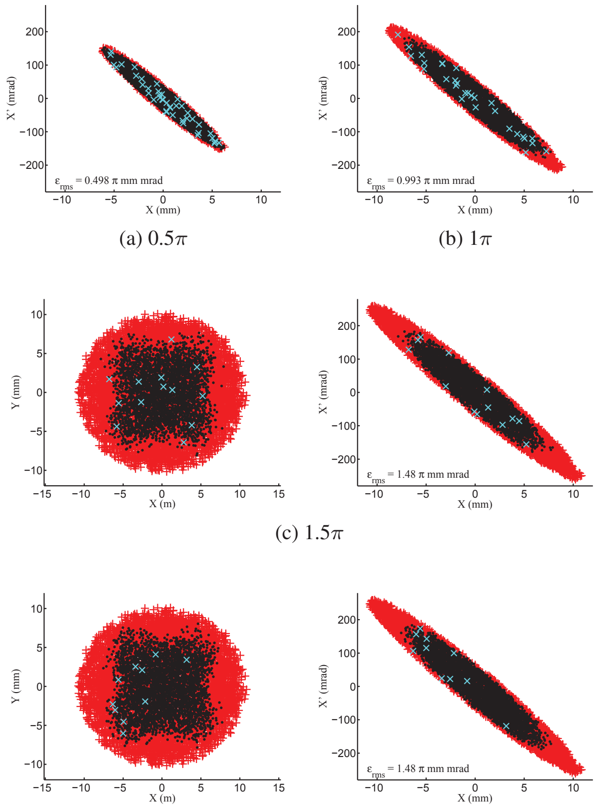
(a) x-y (b) y-y' (c) x-x' (d) Transmission

Figure 1: RFQ transmission and input beam distributions for design input parameters and emittances (see main text). Input distributions are coloured according to particle survival: black are transmitted to 3 MeV, red are lost and blue transmitted but not correctly accelerated.

input current, beam transmission in the region of 98% is observed for particles at 3 MeV: this is shown in Fig. 1. For the design parameters, significant losses only appear above currents of ∼90 mA: 3 MeV transmission only drops below 90% for currents above 120 mA, well above the design specifications of the RFQ and of the capabilities of the FETS Penning-type H^- ion source. However, it would be somewhat foolish to assume that the output beam of the FETS LEBT will match the design acceptance exactly! As such, simulations have been carried out to map the RFQ input acceptance and attempt to match the measured beam from the LEBT into the RFQ.

MAPPING THE RFQ INPUT ACCEPTANCE

Determining the input acceptance of the FETS RFQ is not a trivial process. For a low current RFQ, a zero current approximation could be used: simulations without space charge would be a reasonable approximation and the input acceptance could be mapped simply by introducing a beam with a very large emittance and recording the initial locations in phase space of the surviving particles. However, the FETS RFQ will operate with a large beam cur-



(a) 0.5π (b) 1π

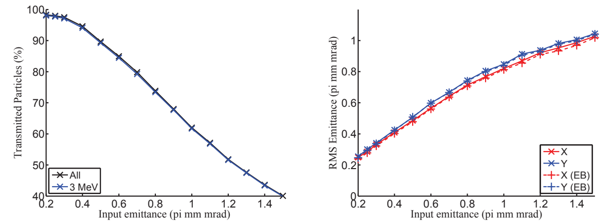
(c) 1.5π

(d) 1.5π (0 mA)

Figure 2: Beam profiles and horizontal emittance distributions for RFQ transmission simulations using the matched Twiss parameters. Captions indicate the normalised *rms* input emittance: see Fig. 1 for particle colouring.

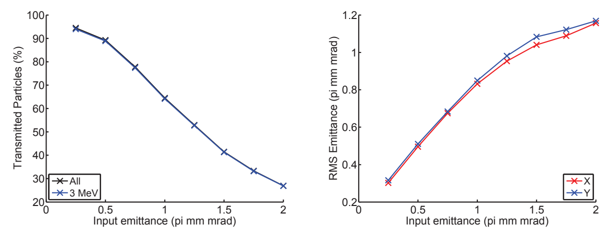
rent: such significant space charge effects not only cause the acceptance to shrink, but prevent such simple acceptance mapping. Following Maxwell's equations, adding a uniform cylinder of charge (*i.e.* a "halo" of extra particles) around a beam should not modify the space charge forces inside that cylinder: however, particles losses will cause nonuniformities in the particle distribution and lead to extra effects from this additional charge. As such, simulations must be carried out for a range of emittance distributions to properly map the acceptance.

Figure 2 shows the results of RFQ beam transmission simulations using the matched Twiss parameters for various transverse emittances. Some key observations can be made from the red halo of lost particles in each plot. Hard limits are apparent in both position and angle, with any particle more than ~7 mm off axis or with a convergence angle greater than ~180 mrad lost. The transmitted beam profile is not circular but actually has a slight four-leaf-clover shape, which is most apparent in the 1.5π 0 mA case: this is shape one may expect from the close approach of the four electrodes to the beam axis. Close comparison of Figs. 2c and 2d shows that the transmitted region of phase space is marginally larger for the zero current beam as expected.



(a) Transmission (b) Emittance

Figure 3: Transmitted current and emittance as a function of input emittance for the matched Twiss parameters. Exit emittance measured at a fixed point in time is marked "EB".

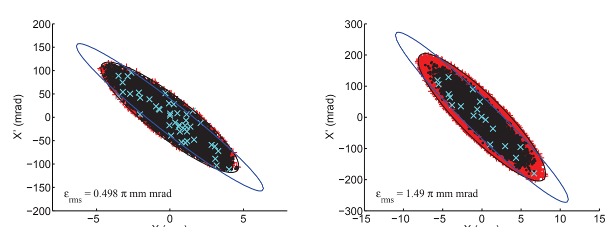


(a) Transmission (b) Emittance

Figure 4: Transmitted current and emittance as a function of input emittance for 60 mA beam using recalculated Twiss parameters (see main text).

The corresponding transmitted current and emittance are shown in Fig. 3. As expected, large fall-off in transmitted current is observed for larger emittances, with less than 90% transmission observed above 0.5π mm mrad. Slight emittance growth is seen at low input emittances before beam losses take over and the transmitted emittance falls below the input emittance.

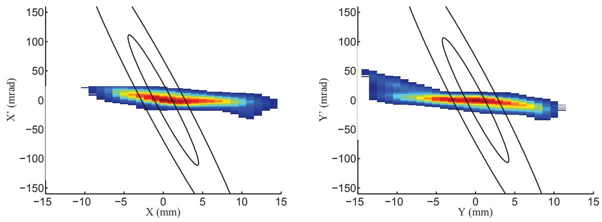
Also apparent from Fig. 2 is that the shape of the input emittance ellipse for the transmitted particles is slightly different from that obtained from the matched Twiss parameters. Recalculating the Twiss parameters based upon these transmitted particles gives $\alpha_x = 1.9435$; $\beta_x = 0.08712$; $\alpha_y = 1.912$; and $\beta_y = 0.08774$. Transmission



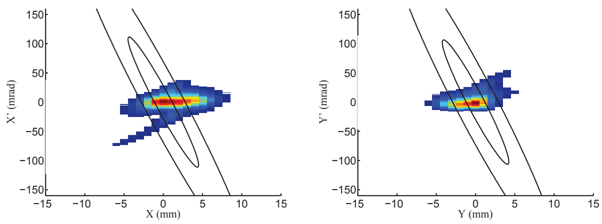
(a) 0.5π (b) 1.5π

Figure 5: Horizontal emittance distributions for recalculated Twiss parameters (see main text): the matched emittances ellipses are shown in blue.

ISBN 978-3-95450-122-9



(a) 150 A



(b) 216 A

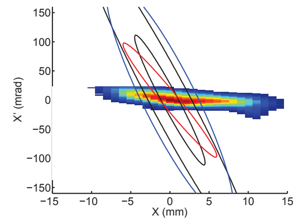
Figure 6: Horizontal and vertical emittance measurements at the LEBT exit for different currents in the final LEBT solenoid. Also shown are 100% emittance ellipses for 0.25 π and 1.5 π for the matched Twiss parameters.

and emittance evolution results using these modified parameters are shown in Fig. 4, with some sample input distributions shown in Fig. 5: note that a uniform halo of red lost particles is now present in Fig. 5b. While the 0.25 π transmission is slightly lower, at larger emittances there is actually a slight increase in transmission: 0.5 π transmission at 60 mA is now above 90%. This exercise may appear purely academic given that the design requirement for the FETS RFQ was to transmit a 0.25 π beam: however, a fatter, rounder ellipse shape and the possibility of transmitting larger emittances provides a better match to the measured data from the FETS LEBT.

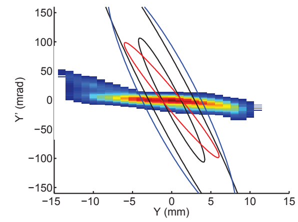
MATCHING THE LEBT BEAM

Emittance measurements at the exit of the FETS LEBT are shown in Fig. 6. Note that there is a significant difference between the measured beam and the design input acceptance for the RFQ (indicated on each plot in black). Such a disparity is a significant issue in optimising the transmission of the RFQ. While it may be possible in time to provide a closer match by optimising the LEBT solenoid settings, a maximum convergence angle above 100 mrad is highly undesirable because of the introduction of significant nonlinearities to the emittance through over focussing by the final LEBT solenoid: such an effect is clear in Fig. 6b. As such, simulations have been carried out to ascertain the transmission of the RFQ using emittances more closely resembling the measurements shown in Fig. 6.

Figure 7 shows a modified 0.25 π emittance ellipse, with $\alpha_x = 4.5281$, $\beta_x = 0.2838$, $\alpha_y = 4.6135$ and $\beta_y = 0.290$, overlaid on the measured emittance data from Fig. 6a in red: also shown in blue are the 1.5 π ellipses from Fig. 5b. Note that, although the shift from black to red is in the

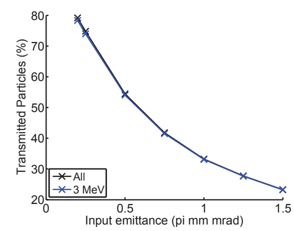


(a) Horizontal

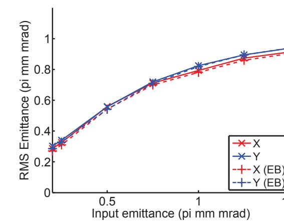


(b) Vertical

Figure 7: Modified plots from Fig. 6a with additional emittance ellipses (see main text).



(a) Transmission



(b) Emittance

Figure 8: Transmitted current and emittance as a function of input emittance for 60 mA beam using emittance ellipse shown in Fig. 7.

right direction, there is still a significant discrepancy with the measured data. The corresponding transmission and emittance evolution are shown in Fig. 8. There is clearly a significant degradation in transmission as a result of the modification to the Twiss parameters, with the 0.25 π transmission now below 75%. As such, further work is clearly required to better match the LEBT output beam to the RFQ input acceptance.

CONCLUSIONS

While it is useful to demonstrate the total acceptance of the RFQ, the disparity with the measured LEBT exit emittances is disappointing. However, knowing the absolute acceptance limits of the RFQ provides guidance in adjusting the LEBT solenoid focussing to optimise the RFQ transmission. Work must now focus on improving the LEBT beam in order to meet the design requirements of FETS.

REFERENCES

[1] A. Letchford *et al.*, "Status of the RAL Front End Test Stand", IPAC'13, THPWO086, these proceedings.

[2] S. Jolly *et al.*, "Integrated Design Method and Beam Dynamics Simulations for the FETS Radiofrequency Quadrupole", IPAC'10, MOPEC076, p. 645–647.

[3] J. Pozimski *et al.*, "Production of the FETS RFQ", IPAC'13, THPWA043, these proceedings.

[4] J. Back *et al.*, "Commissioning of the Low Energy Beam Transport of the Front End Test Stand, IPAC'10, MOPEC078, p. 648–650.