THE EFFECT OF SPACE-CHARGE ON THE TOMOGRAPHIC MEASUREMENT OF TRANSVERSE PHASE SPACE IN THE EMMA INJECTION LINE*

M.G. Ibison[#1, 2], K.M. Hock[1, 2], D.J. Holder[1, 2], M. Korostelev[1, 2], B.D. Muratori[3, 2], and A. Wolski[1, 2]

[1]Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom
[2]Cockcroft Institute, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom
[3]ASTeC, STFC, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom

Abstract

Phase-space tomography for particle beams depends upon detailed knowledge of the particle transport through specified sections of a beam-line. In the simplest case, only the effects of magnets (such as quadrupoles) and drift spaces need to be taken into account; however, in certain parameter regimes (high charge density and low energy) space-charge forces may play a significant role.

The ALICE accelerator provides the electron beam for EMMA, a prototype non-scaling FFAG machine. Results are presented of investigations into space-charge effects on phase-space tomography in the transfer line between ALICE and EMMA.

The application of suitable correction techniques to the EMMA injection line tomography measurements in the presence of space-charge is also briefly discussed.

INTRODUCTION

ALICE is a 10-35 MeV electron accelerator, located at STFC Daresbury Laboratory, UK. One of its functions is to provide a beam for injection into the EMMA non-scaling Fixed-Field Alternating-Gradient (ns-FFAG) prototype accelerator, the first of its type in the world and currently in commissioning [1]. The ALICE beam is extracted by a dipole magnet into the EMMA Injection (EMI) line, where it is transported and matched for EMMA.

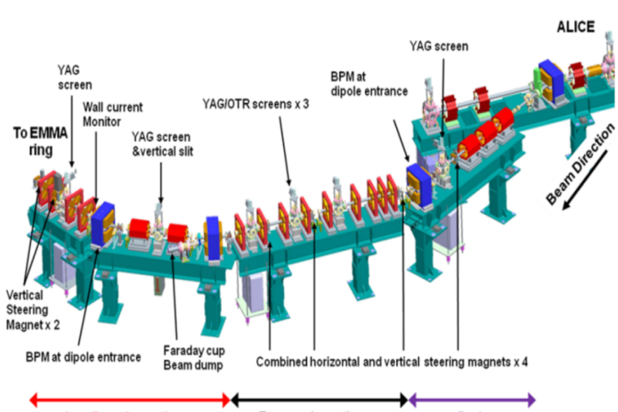

Figure 1: ALICE to EMMA injection line

*Work supported by the Science & Technology Facilities Council, UK.
#mark.ibison@stfc.ac.uk

The line also has a phase-space tomography section, shown in Fig. 1, which provides both diagnostics for ALICE and beam characterisation for EMMA injection. The tomography section consists of two FODO cells, having an Yttrium Aluminium Garnet (YAG) screen in between the cells as well as at both ends, giving three screens in all. Preceding the tomography section is a matching section of four quadrupole magnets.

TOMOGRAPHY METHOD

The use of tomography to reconstruct the phase-space distribution of a particle beam is based on concepts similar to X-ray CT imaging in medicine [2]. A series of views of phase-space is generated by x (or y) projection from screen images each taken at a different projection angle θ, given by the transfer matrix between the position of interest and the screen. In the quad scan method, a range of quadrupole current settings are used to give matrices M with the desired angles θ in the range (0° - 180°) at regular intervals, where

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad \text{and} \quad \tan\theta = \frac{M_{12}}{M_{11}}$$

Data is acquired as a set of images from a YAG screen moved into the beam path and viewed by a simple CCD camera [3]. Post-processing then follows a number of steps: (i) selection of windows around the beam image itself; (ii) correction for background; (iii) projection and scaling; (iv) calculation of centroids; (v) reconstruction using the standard Filtered Back-Projection (FBP) algorithm [4].

Finally, analysis software is applied to extract values of interest, principally the transverse emittance ε_x (or ε_y) and the Twiss parameters β and α, from the reconstructed distribution.

EFFECTS OF SPACE CHARGE

The effect of space-charge, which is used to denote the inter-particle electrostatic repulsive forces, is to produce defocussing of the beam, and thus a deviation from the behaviour predicted by simple linear transport theory. This has been studied in the EMI line during the design stage, by modelling with the General Particle Tracer (GPT) code. Early work predicted some emittance growth under certain conditions and modified quadrupole settings were calculated to restore the desired Twiss parameters in the tomography section [5]. Another study compared the predicted beam sizes at low energy (10MeV) for charges up to 30 pC, shown in Fig. 2 [6].

From the models, it was expected that space-charge would have a detectable effect on phase-space and the derived parameters, as measured by the tomography method. An experiment was therefore devised to test this prediction.

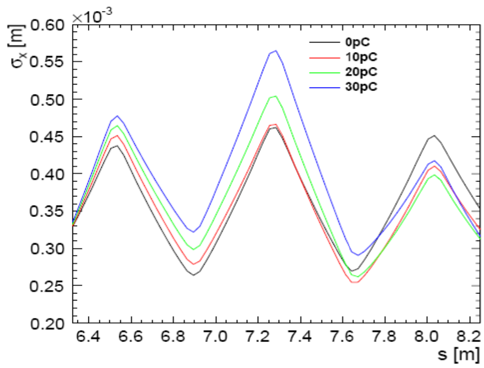

Figure 2: GPT simulations of the effect of bunch-charge on beam size in the EMI line tomography section.

EXPERIMENTS TO DETECT SPACE CHARGE EFFECTS

Two quadrupole-screen pairs within the EMI line were selected, based on the required range of projection angles and separated by a region of sufficient length that space-charge effects should have a measureable influence on beam properties between the two screens. A common reconstruction location was chosen for the quad-screen combinations, so that a direct comparison of results could be made as bunch charge was increased; in the absence of any space-charge effect, identical phase-space distributions would be expected from each dataset, at this location.

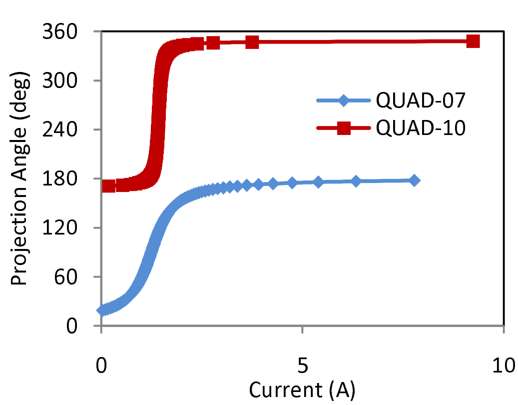

Figure 3: Projection angles versus quadrupole currents for 12MeV beam energy.

The range of projection angles available within the 10A current limits of the quadrupoles was found to be suitable for QUAD-07 and QUAD-10, with images being recorded on the first and third screens within the EMI line respectively (Fig. 3). It was also confirmed that for these quadrupoles, the angle ranges did not vary significantly over the whole extent of possible beam energies which might be used in the EMI line.

The beam-line configurations for each combination of quadrupole and screen are shown in Fig. 4 below. The first screen is identified as 'YAG-02', while the third is 'YAG-04'. It should be noted that in the second case, the effect of all preceding quadrupoles from QUAD-07 to 09, and the succeeding QUAD-11, is taken into account, both in the calculation of projection angles and in the processing of tomography data.

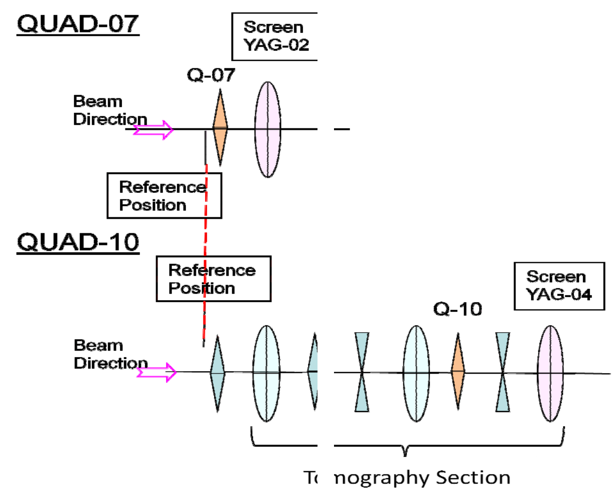

Figure 4: Tomography section elements used for space-charge studies, with the scanned quadrupole and screen indicated for each case.

RESULTS AND DISCUSSION

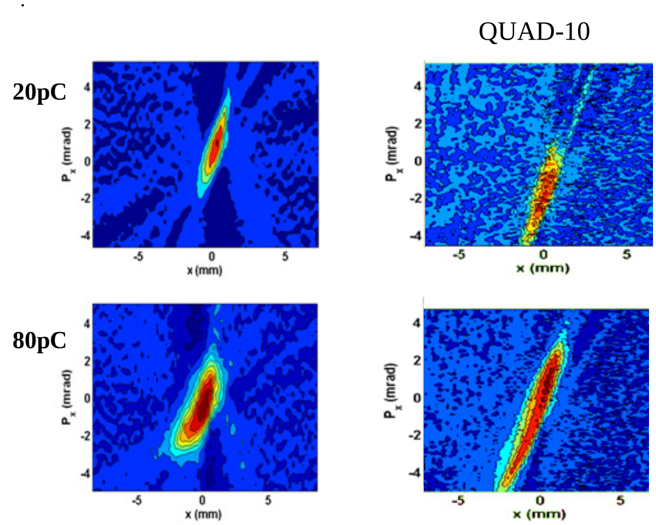

Figure 5: Reconstructed phase-space at the entrance to QUAD-07, from QUAD-07 & QUAD-10 scans.

Reconstructed phase-space distributions for the QUAD-07 and QUAD-10 scans, at low (20pC) and high (80pC) bunch charges are shown in Figure 5.

For all reconstructions, parameters were extracted from the distributions by the analysis methods described in [3], by fitting a 2-D Gaussian function to the data. For both of the quadrupole measurement datasets the horizontal emittance as determined by tomography shows a rising trend with increasing bunch charge (Fig. 6(c)). The difference between the two cases is not statistically significant, and in fact the plots appear to converge at charges of 70 pC and above. At lower charge, reduced image intensity contributes to greater measurement uncertainty due to noise. The observed emittance growth is a result of the ALICE injector settings, which would require a further detailed investigation to optimise them in compensation for changing bunch charge. Nevertheless, as both datasets show a similar trend in emittance, there is no clear evidence of space-charge effects in the EMI line.

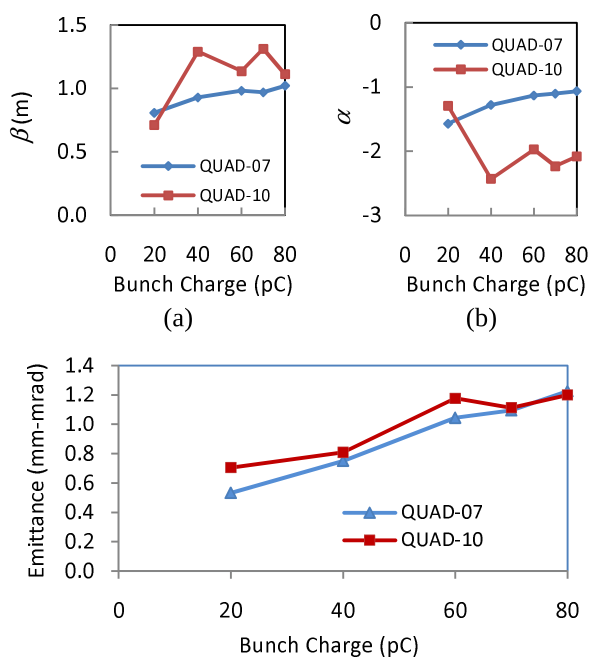

Figure 6: Comparison of tomography data, QUAD-07 vs. QUAD-10: (a) β function; (b) α function; (c) emittance.

While the QUAD-07 Twiss parameter data for both β and α show a slow and consistent trend with bunch charge, there is much more scatter in the QUAD-10 values. This would be expected, due to the accumulation (in the QUAD-10 case) of uncertainties in the multiple quadrupole current settings contributing to the calculation of the transfer matrix between the reconstruction point and measurement screen [8]. Although there does appear to be some systematic difference in the values for β and α determined (for the same point in the beam-line) from the two quadrupole scans, this result is far from conclusive. Although space-charge may be a possible explanation for the observations, more detailed studies are needed to allow a full understanding to be developed.

A correction scheme for tomography of space-charge dominated beams has been developed by Stratakis *et al.* [7], and the results of experimental studies compared with the results of a particle-in-cell tracking code. In the case of ALICE, however, the beam current is much lower and the beam energy much higher than the system studied in [7], and the space-charge corrections to the tomography algorithm itself are negligible.

CONCLUSION

We have investigated the effect of space-charge on phase-space tomographic measurements in the EMMA injection line. We have shown that in this experiment, tomographic results do not give clear evidence of detectable effects.

Further simulation work with input parameters refined by this experimental tomography data will help to build a more realistic model of the EMMA injection line for future studies. Simulation results will also be useful as an indirect means of validating the results of reconstructions from tomography data.

The authors would like thank Ben Shepherd for assistance with the image acquisition software.

REFERENCES

[1] R. Edgecock *et al.*, “EMMA: The World’s First Non-Scaling FFAG,” Proceedings of EPAC’08, Genoa, Italy.

[2] C.B. McKee, P.G. O’Shea, J.M.J. Madey, Nuclear Instruments and Methods in Physics Research A 358 (1995) 764.

[3] M.G. Ibison *et al.*, “Measurements at the ALICE Tomography Section”, in Proceedings of IPAC11, San Sebastian, Spain, 2011.

[4] A.C. Kak and M. Slaney, “Principles of Computerized Tomographic Imaging”, (SIAM, Philadelphia, USA, 2001), pp. 60-75.

[5] D.J. Holder and B.D. Muratori, “Modelling the ALICE electron beam properties through the EMMA Injection Line Tomography Section,” Proceedings of PAC09, Vancouver, Canada.

[6] R.T.P. D’Arcy, D.J. Holder, B.D. Muratori, J. Jones, “Modelling of the EMMA NS-FFAG injection line using GPT,” in: Proceedings of IPAC10, Kyoto, Japan, 2010.

[7] D. Stratakis *et al.*, “Phase space tomography of beams with extreme space charge”, in Proceedings of PAC07, Albuquerque, New Mexico, USA (2007).

[8] K.M. Hock *et al.*, “ALICE Tomography Section: Measurements and Analysis”, submitted to Phys. Rev. ST Accel. Beams, July 2011