ORBIT CORRECTION IN THE EMMA NON-SCALING FFAG SIMULATION AND EXPERIMENTAL RESULTS

D. J. Kelliher*, S. Machida, S. L. Sheehy, STFC Rutherford Appleton Laboratory, ASTeC, UK
J. S. Berg, BNL, Upton, Long Island, New York, USA; E. Keil, CERN, Geneva, Switzerland
J. K. Jones, B. D. Muratori, STFC Daresbury Laboratory, ASTeC and Cockcroft Institute, UK
I. W. Kirkman, The University of Liverpool, Liverpool and Cockcroft Institute, UK

Abstract

The non-scaling FFAG EMMA (Electron Model for Many Applications) is currently in operation at Daresbury Laboratory, UK. Since the lattice is made up solely of linear elements, the betatron tune varies strongly over the momentum range according to the natural chromaticity. Orbit correction is complicated by the resulting variation in response to corrector magnet settings. We consider a method to optimise correction over a range of fixed momenta and discuss experimental results. Measurements of the closed orbit and response matrix are included.

CLOSED ORBIT MEASUREMENTS

The measurement of closed orbit in EMMA is complicated by the effects of decoherence driven by the finite momentum spread of the beam and the chromaticity inherent in the ring. This effect leads to a smearing in transverse phase space which grows turn-by-turn until eventually the beam spreads around the entire phase space ellipse. The beam position monitors (BPM), which measure the beam centroid position, record an apparently damped betatron oscillation which disappears once the beam has fully decohered. Besides noise, the signal that remains records the average transverse coordinate, which approximates the closed orbit. Some factors, amongst others, that may affect the accuracy of this measurement include the BPM model [1] that maps pickup voltages to coordinates, non-linear effects due to the amplitude of the circulating bunch and any variation in the momentum of the beam for example due to beam loading.

An example of a closed orbit calculation using BPM data obtained via the control software EPICS is shown in Fig. 1. The mean coordinate out of many samples of data is shown in order to minimise shot-by-shot variations. The damped betatron oscillations can be seen for about the first 40 turns. In this example, the betatron oscillation before damping is large. This can be reduced by further optimisation of injection. A linear fit to the turn-by-turn coordinates subsequent to decoherence is made with a lower weight applied to turns with lower bunch charge and fewer samples. This has the effect of reducing the influence of later turns as both these quantities tend to progressively decline (some fraction of the measured bunch charge reduction may be due to debunching rather than beam loss). The closed orbit is assumed to be the value of the fit at the first turn.

* David.Kelliher@stfc.ac.uk

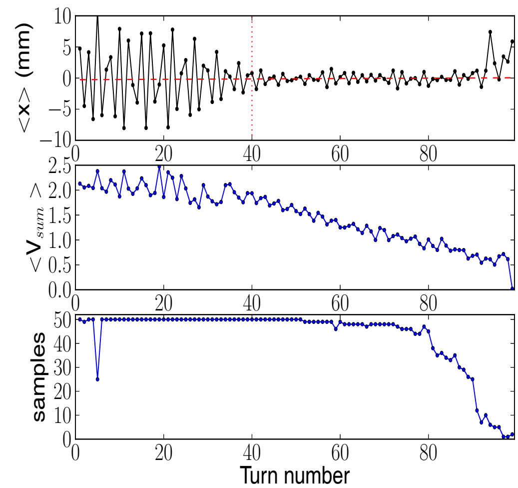

Figure 1: Turn-by-turn horizontal coordinate, measured at a particular BPM, averaged over a number of samples (top panel). The closed orbit is given by the red dashed line obtained by fitting to the data from turn 40 onwards (dotted line). The middle and bottom panels show the sum of the pickup voltages (proportional to bunch charge) and the number of samples, respectively.

COD CORRECTION AT MULTIPLE MOMENTA

COD correction using least squares is a standard technique used in many cyclic machines such as synchrotrons. In a linear non-scaling FFAG such as EMMA, where the tune and hence the phase advance between lattice elements changes with momentum, a correction setting that works at one momentum may not be effective at another. An alternative approach is to the adapt the least squares COD correction method to be effective for a range of momenta.

In the standard single momentum case, one corrects m closed orbit measurements $\mathbf{b}$ with n correctors by building a $m \times n$ response matrix A. Here we extend the correction to cover np momenta to create a $np * m \times n$ response matrix. The least squares algorithm then seeks to minimize the function

$$S = ||\mathbf{b} - \mathbf{b_t} - \mathbf{A} \cdot \mathbf{x}|| \quad (1)$$

where b_t is the target orbit at the measurement locations and x is the vector containing the n corrector strengths. The target orbit is calculated simply by taking the average

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of the closed orbit measurements around the ring at each momentum in an approach described in reference [2].

When operating EMMA it was decided that rather than vary the momentum of the injected beam, which would require a substantial setup time for the ALICE injector and transfer line, instead the quadrupole currents in the ring would be scaled to set an equivalent momentum. A set of closed orbit measurements taken at a range of equivalent momenta is summarised in Table 1. It is clear that, as expected, the mean horizontal closed orbit moves outward and the betatron tunes decrease with momentum. It is also apparent both from the table and Fig. 2 that a substantial closed orbit distortion, of the order of several millimeters, exists in the ring.

Table 1: Mean and standard deviation of closed orbit data calculated from ring BPM measurements at a range of equivalent momenta p_{equiv}. The calculated betatron tunes are also shown.

p_{equiv} MeV/c	$\langle b_x \rangle$ mm	$\sigma(b_x)$ mm	$\sigma(b_y)$ mm	ν_x	ν_y
12.7	-6.4	1.85	1.16	9.88	8.62
14.6	-4.17	2.33	1.85	8.5	7.68
16.4	0.91	2.63	1.32	7.5	6.18
18.0	1.98	3.16	1.79	6.77	5.38
19.7	7.98	5.07	1.84	5.88	4.62

In the study reported here, the Zgoubi tracking code [3] is used to generate the response matrix. At each momentum the quadrupole gradients in the code are adjusted so that the simulated tune matches the measurements. In the code, a kick is then applied to F and D quadrupoles, and to the vertical correctors, and the response at the BPMs calculated. It is planned in the future to measure the response matrix directly (see subsequent section).

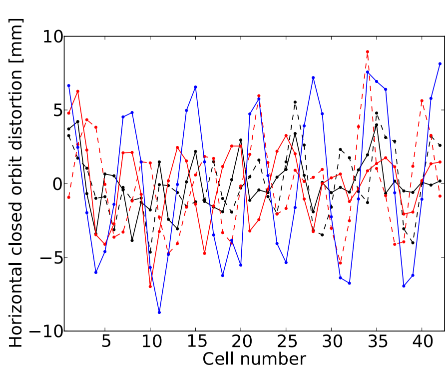

Figure 2: Horizontal closed orbit measurements at momenta listed in Table 1. For ease of comparison the mean closed orbit is subtracted from each measurement. Measurements are made in each cell at BPMs in between quadrupole doublets. In order of increasing momenta, the colours and line styles are black solid, black dash, red solid, red dash, blue solid.

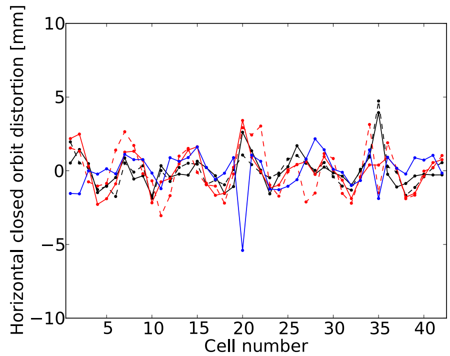

Figure 3: Residual closed orbit distortion that the algorithm predicts after correcting closed orbits shown in Fig. 2 with a single set of corrections.

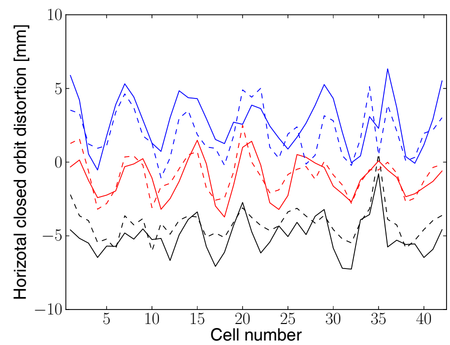

Figure 4: Compare measured residual horizontal closed orbit (solid) after correction with predictions (dash) at 14.3 MeV/c (black), 16.4 MeV/c (red) and 18.0 MeV/c (blue). For clarity the mean closed orbit is not subtracted in this case.

A least squares correction in the horizontal plane is carried out, including five closed orbits at the momenta listed in Table 1 and using all 42 D quadrupoles as correctors. Correcting with F and D quadrupoles that make up a doublet results in a singularity that causes the solution vector to be come unacceptably large. This can be avoided by correcting with F and D quadrupoles in alternate cells. However, since the F magnets are close to the outward limit of their movement it was decided to exclude them from the correction. The solution was further constrained in order to avoid large D magnet movements by including a weighting in the correction algorithm. This is achieved by extending the rows in response matrix A in Eqn. 1 with a $n \times n$ diagonal matrix and adding n zeroes to the measurement vector $\mathbf{b}$. The weighting factors on each corrector comprise the terms in the diagonal matrix.

The predicted correction is shown in Fig. 3. The absolute maximum and mean D movement required for the correction is 2.0mm and 0.6 mm, respectively. The maximum and standard deviation of the closed orbit, averaged over all momenta, is reduced from 6.9 mm and 3.0 mm before correction to 4.1 mm and 1.3 mm after, respectively. The applied weighting, which in this case reduced the maximum required D movement from 2.9 mm to 2 mm, has only a marginal effect on the correction (< 0.1 mm).

The correction was applied in EMMA and closed orbit measurements were made at a number of momenta. The measured and predicted residual COD is compared in Fig. 4. While it proved not possible to reestablish injection at the lowest momentum, measurements of closed orbit were made at or close to the other momenta listed in Table 1. The comparison at the highest momentum is not shown, since an error in the tune calculation meant the correction there resulted an increase in COD. At the three intermediate momenta, while the details of the closed orbit pattern differ, the magnitude of the residual distortion is similar. Indeed the difference between the maximum and standard deviation of the COD is at most 0.8 mm and 0.1 mm, respectively.

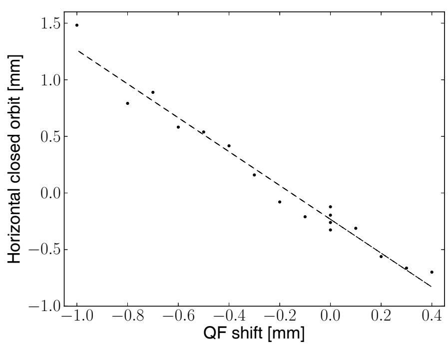

Figure 5: Variation of measured closed orbit at a single BPM (in cell 19) with F quadrupole horizontal shift (in cell 14). The dashed line is a linear fit to the data. Zero shift represents the nominal position.

MEASURED RESPONSE MATRIX

Measuring the response matrix directly should help with correcting the orbit distortion. In addition, it may be compared with a model response matrix and so provide additional information about the machine. Establishing an experimental algorithm is still in its early stages; some initial results are given here. The response to moving a single F quadrupole at 18 MeV/c was measured at all BPMs in between quadrupole doublets. 50 samples of orbit measurements were taken using EPICS. At each BPM the turn-by-turn mean orbit was calculated and the closed orbit calculated as described above. The measurement was made with the F quadrupole in the nominal position and then at each stage after shifting the magnet outward and then inward in increments of 0.1 mm. In order to monitor the stability of the injected beam momentum, measurements of the beam position at the first YAG screen in the injection line and of TOF in the ring were made at each stage.

The variation of the closed orbit at a single BPM with quadrupole shift is shown in Fig. 5. Despite some scatter

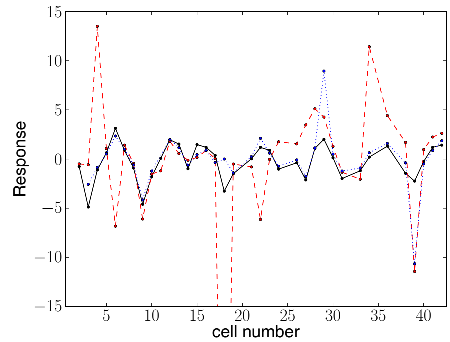

Figure 6: Measured response to F quadrupole shift in cell 14 at 42 BPMs in between quadrupole doublets. The response calculated by a linear fit to the closed orbit measured at all quadrupole shifts (black solid) and using data with the quadrupoles shifted by ± 0.1 mm (red dash) and ± 0.4 mm (blue dot) is shown.

in the data, the dependence of closed orbit on shift is evident. The number of outward shifts was restricted since the F magnet is close to its limit in that direction. One measure of the response is given by the slope of a linear fit to the data found by least squares. Another method is simply to take the difference in closed orbit with the magnet shifted inwards and outwards by identical shifts. The results at ± 0.1 mm and ± 0.4 mm are compared in Fig. 6 to the linear fit method. It is reasonable to expect that the error in the closed orbit calculation dominates the response measurement for small shifts, as is apparent at ± 0.1 mm, whereas at ± 0.4 mm the result begins to approach the linear calculation.

FUTURE WORK

The principle of COD correction at multiple momenta has been demonstrated in EMMA for a range of fixed momenta. The effectiveness of this method in correcting the accelerated orbit distortion remains to be demonstrated.

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REFERENCES

[1] I. Kirkman et al.,"Calibration of the EMMA Beam Position Monitors: Position, Charge and Accuracy", MOPPR060, these proceedings.

[2] D. J. Kelliher, S. Machida and S. L. Sheehy, "Orbit Correction in a non-scaling FFAG" IPAC'10, Kyoto, Japan, July 2010, THPD027, p. 4337, http://www.JACoW.org

[3] F. Méot, Nucl. Instr. Meth. Phys. Res. **A313** (1992) 429.