ORBIT CORRECTION IN A NON-SCALING FFAG

D. J. Kelliher, S. Machida, ASTeC, STFC Rutherford Appleton Laboratory, UK
S. L Sheehy, John Adams Institute of Accelerator Science, Oxford University, UK

Abstract

EMMA - the Electron Model of Many Applications - is to be built at the STFC Daresbury Laboratory in the UK and will be the first non-scaling FFAG ever constructed. The purpose of EMMA is to study beam dynamics in such an accelerator. The EMMA orbit correction scheme must deal with two characteristics of a non-scaling FFAG: i.e. the lack of a well defined reference orbit and the variation with momentum of the phase advance. In this study we present a novel orbit correction scheme that avoids the former problem by instead aiming to maximise both the symmetry of the orbit and the physical aperture of the beam. The latter problem is dealt with by optimising the corrector strengths over the energy range.

INTRODUCTION

The EMMA non-scaling FFAG was originally devised as an electron model of a muon FFAG in a neutrino factory [1]. The fixed field allows rapid acceleration of muons and the lack of non-linear fields in the magnets lead to a large transverse acceptance. The small dispersion results in a small orbit shift with momentum, reducing the magnet aperture requirements. Bending and focusing in the EMMA FFAG is achieved using quadrupole doublets in which the beam pipe is offset from the magnet centres. There are 42 cells and in every second cell a 1.3 GHz rf cavity sits in the middle of the long drift (apart from at injection and extraction). A novel serpentine mode of acceleration is followed in which the rf frequency remains fixed. Details of the EMMA lattice are discussed in [2] and the main lattice parameters are listed in table 1

Table 1: EMMA Lattice Parameters

Energy Range	10 – 20 MeV
Cells	42
Norm. Trans. acceptance	3 mm-rad
rf cavities	19
rf frequency	1.3 GHz
Circumference	16.57 m
Magnet Length (F& D)	58.8, 75.7 mm
Magnet Shift (F& D)	34.0, 7.5 mm
Magnet Gradient (F&D)	-6.7, 4.7 T
Long drift	210 mm
Short drift	50 mm
Bunch Charge	16-32 pC

As an experimental machine, EMMA has a large number of beam position monitors (BPMs). There are two BPMs in every cell apart from in the injection and extraction areas. In fact, due to the presence of cavities in every other cell, the location of monitors in neighbouring cells differ, instead their locations repeat over pairs of cells. The 16 pC minimum bunch charge from the injector is at the limit at which the BPM can pick up a signal [3]. The quadrupoles are mounted on mechanical sliders whose primary function is to allow the machine to be set up in different configurations. These sliders also enable correction of misalignments in the horizontal direction. There are also 16 vertical corrector magnets in the lattice.

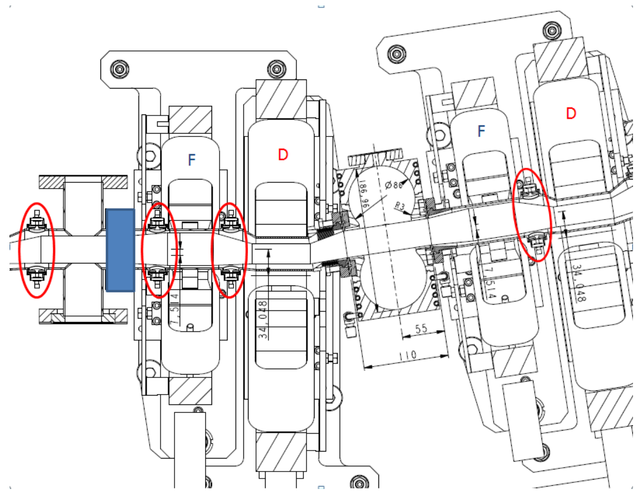

Figure 1: Two EMMA cells highlighting the location of the BPMs (circled in red) and the vertical corrector magnet (blue square). The two leftmost BPMs are at either end of a long drift.

In a linear non-scaling FFAG the tune varies with momentum such that many integer tune resonances are crossed. The closed orbit distortion due to magnet misalignments show peaks associated with these integer tunes. However when the beam is accelerated rapidly, in about 10 turns, these resonances are not seen. Instead the orbit distortion is excited by random dipole kicks due to the magnet misalignments [4]. Correction of the orbit with acceleration is discussed in ref. [5]. This paper deals the correction of closed orbit at fixed momentum.

ORBIT CORRECTION METHODOLOGY

The concept of a reference orbit defined at the outset by the geometry of the accelerator, while is useful in a synchrotron may not be applicable in the case of a FFAG. The orbit shifts in the horizontal direction with momentum and there is no reason to choose one momentum over another as the reference momentum. The closed orbit, even in the case of an ideal machine, is found iteratively by guessing an initial point in phase space and minimising the turn-by-turn variation (x,x'). While one may obtain closed orbits in this way from tracking codes, it is not clear that the results will be in agreement with the real machine since we do not know the field in the magnets precisely. For this reason, attempting to correct the machine to match the simulated ideal orbit may the wrong approach.

It is useful to consider the primary aims of orbit correction in a synchrotron and then see how they might be realised in a FFAG. Those aims are to

- Maximize physical aperture: If the orbit is shifted from the centre of the vacuum chamber the allowed range of betatron oscillations will be reduced. This is one of the main aims of orbit correction in a proton machine.
- Eliminate unwanted resonance driving terms: If the orbit is shifted vertically from the centre of sextupole for example, it excites a linear coupling resonance, i.e. horizontal and vertical motions will be coupled. This is one of the main goals of orbit correction in a synchrotron radiation ring and in an electron rings in general.
- Eliminate unwanted harmonic components of resonance: As long as the orbit keeps the ideal lattice symmetry (42 in EMMA), harmonic components of the resonance driving term except n*42, where n is an integer, can be ignored. Once the symmetry is broken due to different entrance angle to the magnets for example, harmonic component other than n*42 can be excited. This is important both in proton and electron rings.

All three aims listed above should be considered in FFAG orbit correction. Although EMMA does not have nonlinear magnets explicitly, the off-axis orbit in the region of fringe fields will excite unwanted resonance driving terms and introduce unwanted harmonic components. We propose that in an FFAG the correction scheme be guided by the following goals

- Maximize the physical aperture: The orbit at the injection and extraction momenta should be well within the aperture of the vacuum chamber. A method to measure the aperture of the machine with the beam is under development.
- Restore orbit symmetry in order to minimise unwanted harmonic components: In practice this means minimising the deviation in the horizontal coordinate read by BPMs from cell to cell. In EMMA one must ensure that BPMs located in the same position in a cell are compared.
- Ensure all vertical BPM signals are zero

TARGET ORBIT

Following the criteria of maximising orbit symmetry described above, we introduce the idea of a target orbit to take the place of a "reference orbit". This found by averaging the BPM readings over the ring for multiple turns, always ensuring that one averages BPMs located in the same place in a cell. The effect of betatron oscillations can be mitigated in EMMA due to the decoherence of the beam. Since there is uncorrected chromaticity in the lattice, the energy spread in the beam, will result in the loss in the betatron signal, leaving just the closed orbit signal. While this hampers the calculation of the tune, it is beneficial in this context. An example of target orbit is shown in Fig. 2.

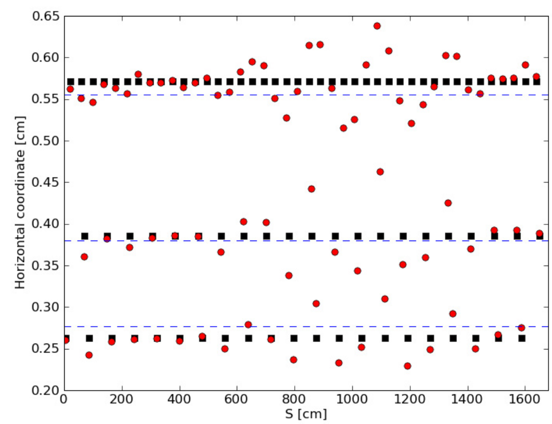

Figure 2: Horizontal coordinates (red squares) read by 84 BPMs in EMMA. The distortion in the signal is due to horizontal magnet misalignments with 50 microns sigma. The three groups represent the three locations of BPMs in the EMMA cell (see Fig. 1). The black squares represent the ideal closed orbit. The dashed blue line is the target orbit found by averaging the BPM signals.

Orbit distortion can be defined as the deviation of the BPM readings from the target orbit. In order to correct the orbit, a response matrix must be calculated that relates the corrector settings to the closed orbit determined at the BPMs. Just as the ideal orbit is not well known in a FFAG, so to the phase advance must be determined experimentally. In the case of horizontal correction in EMMA, the sliders on the quadrupoles are used. By shifting each of these quadrupoles by a small known amount (the minimum shift 3 microns) and calculating the resulting change in the closed orbit, the response can be calculated. In the case of vertical correction, a kick should be applied at the vertical corrector magnets and the response measured.

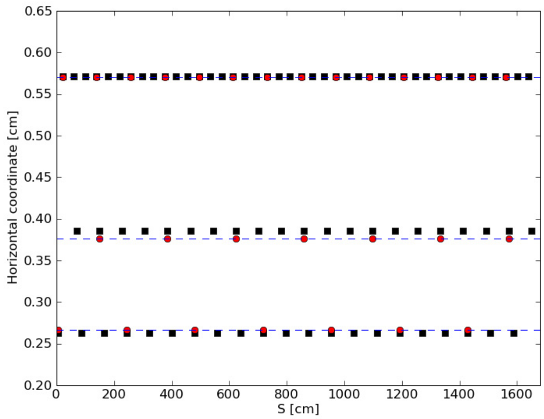

Figure 3: Horizontal coordinates (red squares) read by 84 BPMs in EMMA after correction. The original distorted measurements are shown in Fig. 2.

Once the response matrix has been obtained the orbit can be corrected using established techniques such as least square minimisation. The aim is to minimise the quantity |A.x – b| where A is the response matrix, x the corrector magnet setting or quadrupole shift and b is the distortion at the BPM. In Fig. 3 all 84 quadrupoles are shifted in order to correct the distortion measured in Fig.2 using the measured response matrix.

APERTURE

Another aim of orbit correction in a FFAG, as described above, is to maximise the physical aperture of the beam. The emittance of the EMMA bunch is much smaller than the aperture. It is desirable to scan the aperture by steering the injected bunch. In EMMA this scanning can be achieved in the vertical plane using a vertical steering magnet in the injection line and in the horizontal plane by using a dipole in the injection line or by using the septum or kickers used for injection.

In order to calculate the aperture the phase space must first be measured. In EMMA there two BPMs in a long drift in every other cell (Fig. 1). The change in coordinate between these BPMs gives a measure of the horizontal and vertical angle. High level software is currently in development to help analyze and control the EMMA machine once it is commissioned [6]. A virtual accelerator has been created that interacts with the high level software via EPICS just as in the real machine. This will facilitate the development of software for orbit correction in EMMA.

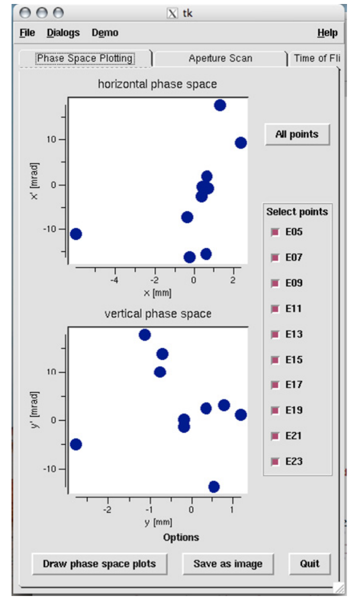

Figure 4: High level software for EMMA showing phase space measurement in a selection of BPMs.

DISCUSSION

A new approach to correct the orbit in a FFAG has been proposed. The concept of a reference orbit in a synchrotron is not applicable. Instead the correction algorithm aims to maximise the symmetry of the orbit and the physical aperture over the momentum range. This orbit correction method is currently being implemented in high level software that will be available for commissioning of the real machine.

REFERENCES

[1] C. Johnstone et. al. Fixed Field Circular Accelerator Designs, PAC99, New York, March 1999, p3068
[2] T.R. Edgecock et. al., THPEC090, Proc. of IPAC10
[3] A.Kalinin et. al. "Diagnostic System Commissioning of the EMMA NS-FFAG Facility at Daresbury Laboratory", these proceedings (MOPE068)
[4] S Machida and D. J. Kelliher, Phys. Rev. ST Accel. Beams 10 (2007) 114001
[5] D. J. Kelliher, "EMMA – Orbit Correction", FFAG08, Manchester, UK (2008); http://www.cockcroft.ac.uk/events/FFAG08
[6] Y. Giboudet et. al., "Recent developments on the EMMA On-line Commissioning Software", these proceedings (THPD024)