# RECENT RESULTS FROM THE EMMA EXPERIMENT

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*Abstract*

EMMA (Electron Model for Many Applications) is the only non-scaling electron FFAG, located at Daresbury Laboratory. Since the recent demonstration of acceleration in the so-called serpentine channel, the EMMA beam dynamics have been further studied. This entails the exploration of the large transverse and longitudinal acceptance and the effects of slower integer tune crossing on the betatron amplitude. A static closed-orbit correction has been implemented that is effective at multiple momenta, and hence over a significant range in tune space A comparison has been performed comparing a detailed model based on measured field maps with the experimental mapping of the machine by relating the initial and final phase space coordinates. These recent results are reported, together with more practical improvements such as injection orbit matching using real-time monitoring of the transverse phase space.

## INTRODUCTION

The fixed-field alternating-gradient (FFAG) accelerator has enjoyed recent renewed interest [1, 2] due to the possibility of rapidly accelerating high-current proton beams for use in applications such as cancer therapy and also allowing to achieve high averaged beam current for applications such as accelerator driven reactor systems (ADS). Several examples of scaling proton FFAGs have been built [3, 4] which demonstrate that a high repetition rate can in principle be achieved using a rapidly-sweeping radiofrequency (RF) acceleration system; the magnet fields do not need to be ramped during acceleration as they do in a synchrotron, allowing in principle for a very high repetition rate for the extracted bunches.

A linear non-scaling FFAG (nsFFAG), such as EMMA, has an average magnetic field chosen to vary linearly with orbit radius, $< B >\sim r$, unlike that in a scaling FFAG where the field varies as $< B >\sim r^k$, where $k = \frac{r}{B}(\frac{dB}{dr})$ is a constant. A linear nsFFAG lattice may be designed to have a small and parabolic variation of path length with momentum, so that the momentum range may be made much larger for a given aperture than in an equivalent scaling FFAG (or equivalently that allows smaller magnets for a desired momentum range). The price paid is that that resonances must now typically be crossed during the acceleration: resonance crossing may be tolerated if it is rapid enough, and EMMA was designed [5] and implemented [6] (at Daresbury Laboratory in the UK) to demonstrate such rapid resonance crossing. EMMA has recently demonstrated successful acceleration without undue beam degradation, using a serpentine channel outside of the traditional RF buckets to widen the available momentum acceptance [7].

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## RECENT DEVELOPMENTS IN CLOSED ORBIT CORRECTION

A substantial ($\sim$ 10 mm) closed-orbit distortion (COD) exists in EMMA in both the horizontal and vertical planes [8]. The response matrix has been measured at various momenta to reduce the COD. In the horizontal plane the closed orbit was measured while each of the 84 F- and D-quadrupoles were moved in turn either inwards or outwards by some fixed amount, typically a few millimeters; note that EMMA does not incorporate dipole magnets, and utilises offsets of the quadrupoles to accomplish bending whilst allowing flexible optics. Similarly, in the vertical plane a negative and positive current of equal magnitude was applied to each of the 16 vertical correctors located in some of the 42 EMMA cells. Fitting the response matrix with the function

$$R_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi Q} \cos(\Psi_i - \Psi_j \pm \pi Q)$$

allows the tune $Q$, the product $\beta_i \beta_j$ and the phase advance $\Psi_i - \Psi_j$ between corrector $i$ and BPM $j$ to be found. For simplicity it was assumed that the optics do not vary between cells.

A least-squares correction that minimises the COD at a single momentum may not be effective at other momenta where the tune and therefore phase advance between elements differ substantially. By optimising the least-squares correction over multiple momenta, where the tunes lie between different integer stopbands, a single static global correction may be obtained. Corrector (vertical) and quadrupole position (horizontal) settings were calculated using COD profiles measured at 14.3 MeV/c, 16.1 MeV/c and 18.0 MeV/c and using the measured response matrix as described above. In Fig. 1 it can be seen that these momenta lie between different integer tunes in both transverse planes, and that the correction is effective over a large momentum range. Furthermore, it can be seen that after correction COD measurements could be made at momenta close to some integer tunes, e.g. integer 7 in the horizontal plane at around 17.0 MeV/c. Without correction, measurements were not possible there due to the large amplitude of the COD.

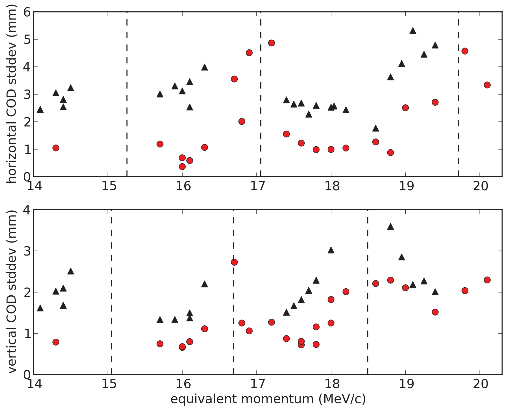


Figure 1: COD before (black triangles) and after (red circles) correction in the horizontal (top panel) and vertical (bottom panel) planes over the momentum range. The vertical dashed lines indicate the approximate location of integer tunes.

## INTEGER TUNE CROSSING

Experimental studies indicate that emittance growth in EMMA is small if resonances are crossed rapidly enough [7]. Fig. 2 (a) shows the experimental results for a bunch in a synchrotron bucket in EMMA with moderate (not fast or slow) acceleration rate of 0.5 MV/turn. Fig. 2 (b) shows results for a hard edge magnet model simulation performed in pyZgoubi with a horizontal dipole field error of 0.5 mTm and a realistic bunch distribution with 1000 particles. In figures 2 (a) and (b), there is some reduction in the standard deviation of the horizontal coordinate in the first 10 or so turns. After this in the experimental and simulation results there is an increase and decrease in the standard deviation of the horizontal coordinate correlated with particle loss occurring with the synchrotron period which is about 20 turns. It is believed that there is amplitude/emittance increases near/on crossing an integer tune and some particles are lost, increasing the standard deviation of the coordinate. Following the increase in amplitude of the particles there is decoherence and the standard deviation of the coordinate reduces. The decoherence of the transverse phase space in simulation can be seen in Figs. 3 and 4.

## AMPLITUDE-DEPENDENT ORBITAL PERIOD

The dependence of orbital period upon betatron oscillation amplitude has been measured and compared with theory. The experimental procedure involved varying the vertical betatron amplitude by changing the strength of a vertical corrector within the EMMA injection line; the orbital period was then measured for each setting of vertical amplitude by using the phase of the 1.3 GHz ALICE RF waveform as a reference. To measure the momentum distribution of the bunch, the betatron oscillation frequency

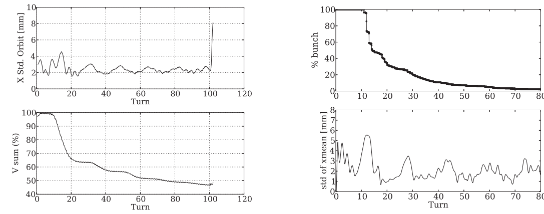


Figure 2: (a) shows the standard deviation of the horizontal BPM measurement and the charge reduction for an experiment in EMMA. (b) shows the same parameters for a bunch simulated in pyZgoubi with a magnetic model and bunch distribution approximately the same as the experiment. The beam is placed in a synchrotron bucket with 0.5 MV/turn acceleration.

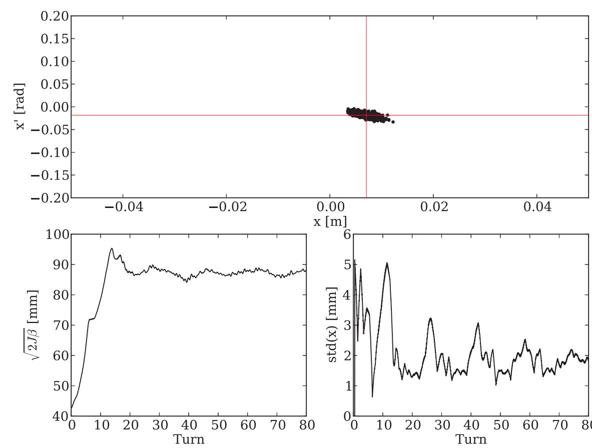


Figure 3: Initial transverse phase space evolution for the simulation in figure 2 (b). The red cross-hair represents the mean. The bottom left panel shows the mean betatron amplitude of the bunch. The bottom right panel shows the standard deviation of the horizontal coordinate.

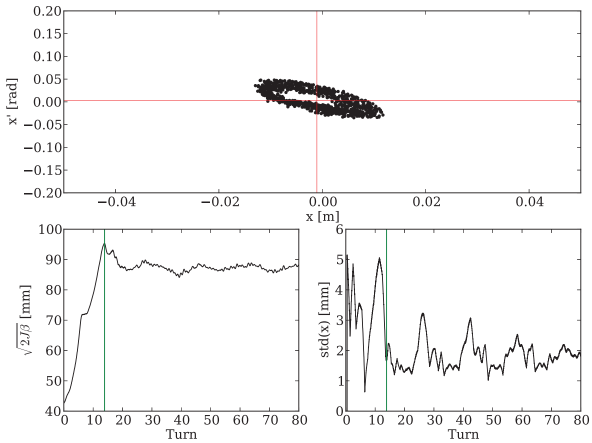


Figure 4: The same as for figure 3 but after 14 turns. The green line in the bottom panels indicates the turn.

spectrum of the bunch is first found by applying a discrete Fourier transform to the turn-by-turn BPM signal measured as the kicked bunch circulated in EMMA. As the source of the frequency spread in EMMA is predominantly the momentum spread of the bunch coupled with the chromaticity of the lattice, then the previously measured chromaticity of EMMA can be used to estimate the bunch momentum distribution [10, 11]; the orbital period is then fitted to a theoretical model [12]. The experimental values were found to be in good agreement with theory (see Fig. 5). We consider this a significant demonstration relevant to large emittance bunches in high-chromaticity accelerators, such as future muon collider rings.

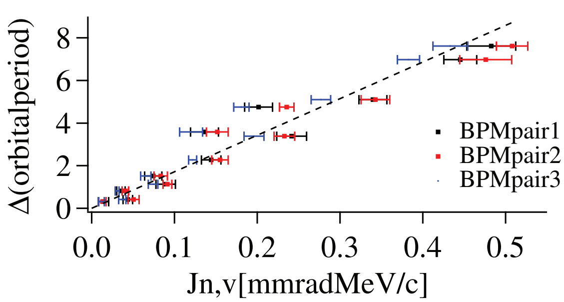


Figure 5: Change in orbital period vs. vertical transverse action. Dashed line is from theory.

## TRANSVERSE PHASE SPACE MAPPING AND PRISM

PRISM (Phase Rotated Intense Slow Muon source) is a next-generation muon-to-electron conversion experiment to obtain intense quasi-monochromatic muon beams by performing RF phase rotation in an FFAG ring [13, 14]. The baseline design for PRISM assumes a scaling FFAG, but an alternative could be an nsFFAG. As a transverse-to-longitudinal coupling is present in nsFFAGs due to their natural chromaticity, the effect of the coupling on the final energy spread and beam quality must be determined to know if they can be successfully used for phase rotation. This is currently being investigated.

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