# NEW RESULTS FROM THE EMMA EXPERIMENT

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*Abstract*

EMMA (Electron Model for Many Applications) is a prototype non-scaling electron FFAG operating at Daresbury Laboratory. After demonstrating serpentine channel acceleration and fast resonance crossing in 2011, studies continue of the beam dynamics to explore the large transverse and longitudinal acceptance, the detailed effects of integer tune crossing at slow acceleration rates, comparison of measurements to detailed field measurements, and the experimental mapping of the machine by relating the initial and final phase space coordinates. These recent results are reported in this paper, together with more practical improvements such as injection orbit matching with real-time monitoring of the bunch coordinates in transverse phase space.

## INTRODUCTION

The fixed-field alternating-gradient (FFAG) accelerator has enjoyed recent renewed interest [1, 2, 3] due to the possibility of rapidly accelerating high current proton beams for use in applications such as cancer therapy and accelerator driven reactor systems (ADS). Several examples of scaling proton FFAGs have been built [4, 5] 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.

In a scaling FFAG the radial dependence of magnetic field $B$ is chosen to scale with particle momentum $p$ such that its average value varies non-linearly with radius as

$$< B >\sim r^k. \quad (1)$$

The magnetic gradient $k$, defined as

$$k = \frac{r}{B}(\frac{dB}{dr}) \quad (2)$$

(where $r$ is the orbit radius) is chosen to be constant and its derivative with respect to particle momentum is zero in a scaling FFAG. As the azimuthal field profile is the same at all radii, the betatron tunes therefore remain constant during acceleration and are chosen to have values away from disruptive resonances. Although the FFAG has strong focusing that is advantageous compared to a cyclotron, it shares the latter's problem that a large acceleration range results in a large required magnet aperture.

A linear non-scaling FFAG (nsFFAG) has an average magnetic field chosen to vary linearly with radius, $< B >\sim kr$. If the lattice is designed to give a small and parabolic variation of path length with momentum, the momentum range can be made much larger for a given aperture than in a scaling FFAG - or equivalently allows smaller magnets for a desired momentum range - the price paid being that resonances must now typically be crossed during acceleration. Resonance crossing may be tolerated if rapid enough, and the Electron Machine for Many Applications (EMMA) was designed [6] and implemented [7] (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 [8].

## MEASUREMENT PROGRAMME

Work remains to be done to investigate the properties of EMMA, using as many diagnostic methods as possible. Bunch length and energy spread may be both measured and minimised prior to injection into EMMA [9], and a tomography section has been used to determine the injected emittance (see below) [11]. A wall current monitor determines bunch charge to give a complete six-dimensional characterisation of the bunches entering EMMA. 82 BPMs in EMMA monitor bunch position after injection, and careful attention has been paid to obtaining good accuracy from them (see below); in addition, a wall current monitor allows charge loss to be measured. Closed-orbit errors affect other measurements, and so considerable effort has been spent in trying to correct them [12]; the injection septum stray field has been determined to be the primary source of distortion in the horizontal plane.

Whilst acceleration has been successfully demonstrated over approximately ten turns [8] it remains an open question how slow the rate of acceleration can be whilst maintaining good beam quality. It would be expected that slower acceleration should result in greater beam disruption, but measurements to date do not support this conclusion [17].

Because one of the main applications of nsFFAGs is in future muon accelerators where a very large transverse acceptance is required, it is important to determine the acceptance of EMMA, estimated to be around 3000 mm-mrad.

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This is done by transverse phase space mapping and variation of time of flight (ToF) and tune with amplitude. The longitudinal acceptance is determined as well as the transverse: this is done by measuring the extracted bunch energy and hence mapping out the serpentine channel.

Through repeated extraction after successive turns whilst accelerating inside the RF bucket, it is also possible to determine both the longitudinal acceptance of EMMA and to look at phase rotation of the bunch over tens of turns, as proposed for the PRISM project [16]. Phase rotation in PRISM will take an initial short bunch with large energy spread, and rotates it to be elongated by with much smaller energy spread.

### *Tomography in ALICE to EMMA Transfer Line*

To better understand the role of space charge in the results of tomography studies [1], the tracking code GPT has been used to simulate the ALICE-to-EMMA injection line. This has been benchmarked against uniform and Gaussian beams in a drift space, for which analytical results are available, and with measured phase-space distributions at the beginning of the tomography section [10, 11]. Filtered back-projection reconstructions from quadrupole scan data indicate that space charge effects are significant for the larger injected bunch charges above approximately 80pC, and they must be taken into account in modelling acceleration in EMMA.

### *Determining BPM Response*

A CST EM studio model using 4.5M mesh points was used to predict the expected response from each of the three types of BPM assemblies used in EMMA (in either a cylindrical or rectangular beam pipe), the results checked with simpler 2D electrostatic modelling, theory, and stretched-wire bench measurements [13]. The sensitivity response to beam offset was obtained across the whole physical aperture, and linearisation was characterised using, for example, a 7th-order 2D polynomial to predict the real position from the measured position to an accuracy of about 10$\mu$m over +/-8mm of beam offset. Sum (charge) measurement linearisation is predicted to be better than 5% over the whole aperture.

### *Closed-Orbit Correction*

The betatron oscillations in EMMA decohere after a few tens of turns. After that the BPMs – which measure the beam centroid – should in principle record the closed-orbit position: a significant closed-orbit distortion (COD) of the order of several mm is measured. In the horizontal plane the major source of this distortion is due to the injection septum stray field; the source of vertical distortion remains to be determined. Although a COD correction can be made at a single fixed momentum it will in general not be effective at other momenta due to the change of phase advance. Instead, a correction was carried out simultaneously for multiple momenta: experimental results are found to be consistent with predictions (Fig. 2). However, whether the accelerated orbit distortion is also reduced remains to be shown; more details are published elsewhere in these proceedings [12].

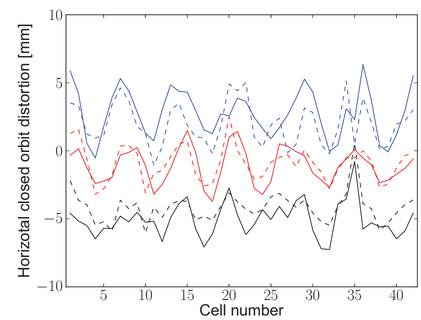


Figure 1: Comparison of measured residual horizontal COD (solid) after correction with predictions (dashed) at 14.3 MeV/c (black), 16.4 MeV/c (red) and 18 MeV/c (blue).

### *Slow Resonance Crossing*

Slow integer tune crossing was studied by tune variation during synchrotron oscillation within an RF bucket, at speeds $dQ/dT \sim 0.1$ that are up to a factor of 10 smaller than the nominal EMMA serpentine channel acceleration rate. The standard deviation of the beam orbit in a window sliding over 21 of the 42 ring BPMs was taken to be the size of the beam oscillations. For motion close to the separatrix where the rate of tune change is minimum, the beam experiences large oscillation amplitude growth and complete beam loss; nearer to the stable fixed point where the rate of tune change is higher, crossing an integer gives oscillation growth which is reverse. Simulations in Zgoubi are being performed to investigate the possible mechanisms that explain this [17].

### *Amplitude-Dependent Revolution Time*

A nsFFAG with only linear magnetic elements should have a very large dynamic aperture that can therefore accommodate a huge emittance beam, for example to allow acceleration of a muon beam from a target. However, path length difference depending transverse betatron oscillation amplitude emerges which is normally negligible with a moderate emittance bunch [14] and with chromaticity correction [15]. Although some nonlinearities arise in the lattice from fringe fields in the relatively thin quadrupoles and from fabrication errors of the magnets, the measured chromaticity is approximately the ideal value. An amplitude-dependent revolution time should therefore be measurable experimentally.

Conditions are set such that the injected bunch survives for many turns without much loss: we assume that the betatron oscillation amplitude is minimised by this adjustment. Using either a change in injector septum strength or kicker timing this optimised condition was changed to introduce


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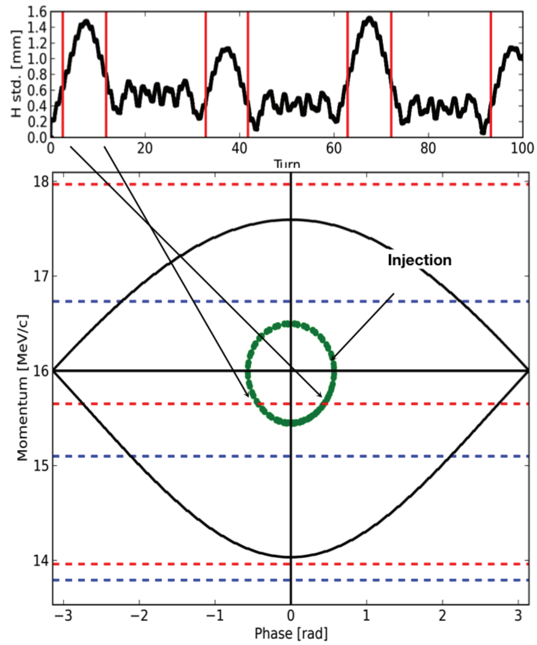


Figure 2: Slow resonance crossing near a stable fixed point during a synchrotron oscillation. Orbit growth is reversed.

an additional injected orbit mismatch. With a large enough difference the resulting bunch oscillation becomes too large and it strikes the vacuum aperture within a few turns.

We measured the centroid of oscillations using a single turn-by-turn BPM position measurement. Because of the natural chromaticity, the signal from the initially coherent oscillation of the bunch centroid decoheres within a few tens of turns even though the single particle betatron amplitudes remain constant. This introduces a large errors in the estimate of betatron amplitude measurement. A preliminary result shown in Figure 1; we cannot yet conclude that the revolution time is quadratically dependent on the betatron oscillation amplitude as expected, and further measurement is planned.

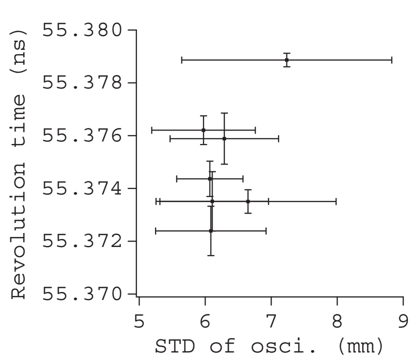


Figure 3: Dependence of bunch revolution time measured at a single BPM against the initial size of the coherent oscillation.

### *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 [16]. 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.

Preliminary experiments have been performed using EMMA in which a bunch is allowed to undergo 1/4 of a synchrotron oscillation (over 3 turns), as would be the case in PRISM (over 6 turns); this is accomplished by injecting a bunch of known energy into the centre of an RF bucket, and then extracting 3 turns later to measure the longitudinal phase space.

## REFERENCES

[1] S.Machida, Nucl. Instrum. Methods Phys. Res. **A503**, 4146 (2003)

[2] E. Keil and A. Sessler, Nucl. Instrum. Methods Phys. Res. **A538**, 159177 (2005)

[3] M. Apolliono et al., J. Instrum. 4, P07001 (2009)

[4] M. Tanigaki et al., Proc. EPAC2006, 23672369 (EPS-AG, 2006).

[5] M. Aiba et al., Proc. EPAC2000, 581583 (EPS-AG, 2000).

[6] J. S. Berg, Nucl. Instrum. Meth. Phys. Res. **A596**, 276284 (2008).

[7] R. Barlow et al.(2010). Nucl. Instrum. Meth. Phys. Res. **A624**, 1-19 (2010).

[8] S. Machida et al. (2012). *Nature Physics,* **N8**, *243247 (2012).*

[9] F. Jackson et al. (2011). “Beam dynamics at the ALICE Accelerator R&D Facility”, Proc. IPAC11.

[10] M. G. Ibison et al., J.Inst. 7, P04016 (2012)

[11] M.G. Ibison, K.M. Hock, B.D. Muratori, and A. Wolski, ’Modelling Space Charge and its Influence on the Measurement of Phase Space in ALICE by Tomographic Methods’, these proceedings

[12] D. J. Kelliher et al, ”Orbit Correction in the EMMA Non-scaling FFAG - Simulation and Experimental Results”, these proceedings

[13] I. W. Kirkman et al. ”Calibration of the EMMA Beam Position Monitors: Position, Charge and Accuracy”, these proceedings

[14] S. Machida, Phys. Rev. S.T. Accel. Beams **9**, 104002 (2006).

[15] J. S. Berg, Nucl. Instrum. Meth. Phys. Res. **A570**, 15-21 (2007).

[16] J. Pasternak et al. (2012). “Status of the PRISM FFAG Design for the Next Generation Muon-to-Electron Conversion Experiment”, these proceedings.

[17] J. Garland et al. (2012). “An Experimental Investigation of Slow Integer Tune Crossing in the EMMA Non-scaling FFAG” ,these proceedings.