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BEAM DYNAMICS OBSERVATIONS OF SLOW INTEGER TUNE CROSSING IN EMMA*

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Abstract

In the nominal EMMA design, particles are accelerated rapidly in the serpentine channel between RF buckets. Many integer tunes are crossed in less than a turn in this regime without significant amplitude growth. Slower acceleration inside an RF bucket in EMMA allowed the exploration of slower integer tune crossing speeds. The effect on the coherent oscillation amplitude was observed and the charge loss at integer tune crossings indicated betatron amplitude growth to particles in the bunch. Aided by simulations in Zgoubi, it is observed that tune spread and natural chromaticity in EMMA drove transverse decoherence which is sped up by longitudinal decoherence from synchrotron motion. Amplitude growth from integer tune crossing can be observed, but detailed multi-particle simulations are needed to correctly interpret the observed behaviour.

INTRODUCTION

EMMA (Electron Machine with Many Applications) is a proof-of-principle, linear non-scaling FFAG (Fixed-Field Alternating-Gradient) accelerator based at Daresbury laboratory, UK. EMMA has 42 optically-identical cells constituting a circular ring, each containing an F-D doublet where each magnet is horizontally offset from the reference axis in order to provide an average dipole bending field [1]; Table 1 shows the main EMMA parameters. In its nominal configuration EMMA accelerates over its design acceleration range from 10 to 20 MeV by using a region of longitudinal phase space outside the RF bucket known as the serpentine channel [2]; the serpentine channel only appears between buckets at sufficient accelerating voltage per turn, and allows a very rapid acceleration in 5 - 10 turns with no significant accompanying betatron amplitude growth [3]. However, non-scaling proton FFAGs such as PAMELA (Proton Accelerator for MEdicaL Applications) [4] have been proposed to accelerate protons in a much greater number of turns (perhaps a few thousand), so that the integer tunes are crossed much more slowly. The emittance growth and beam loss from such slow crossing - which is expected to be dependent on lattice alignment errors - could result in unacceptable beam loss, and so is important to characterise. In this paper we present results of studies of this effect.

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Table 1: Main EMMA parameters for the nominal lattice configuration.

Parameter	Value
Momentum range	10.5 to 20.5 MeV/c
Circumference	16.57 m
Integrated quad. gradient (F/D)	0.402/-0.367 T
Radial shift (out) from ref. (F/D)	7.51/34.05 mm
Number of RF cavities	19
RF cavity frequency (fixed)	1.301 GHz
Integrated RF voltage per turn	0.2 - 2.0 MV
Tune shift over mom. range	0.3 to 0.1 per cell
Repetition rate	1 to 5 Hz

EXPERIMENTAL MEASUREMENTS

The primary lattice error in EMMA is the stray field from the injection septum, whose magnitude is estimated to be ~0.5 mTm [5]; this is expected to be large enough to cause net amplitude growth for slow enough integer tune crossing speeds.To measure this, we injected bunches at different phases within an RF bucket (thereby giving zero average acceleration over many turns); the energy change from the synchrotron oscillation causes a horizontal orbit shift and an accompanying crossing of integer betatron resonances, which resonance crossings can be selected by changing the lattice configuration. The rate of change of transverse tune per turn (Q') can be varied by adjusting the rate of change of energy, either via the initial phase of the injected bunch with respect to the bucket centre, or by changing the total cavity voltage. For small changes we have $\delta\nu_x = \xi_x \delta p$ where ξ_x is the linear chromaticity (around -7 at the chosen injection momentum of 17.5 MeV/c) and δp is the momentum spread of the injected bunch. Typical δp values from ±0.5% to ±1% [3] lead to estimated tune spread $\delta\nu$ from about 0.05 to 0.1.

The induced coherent oscillations of the bunch were recorded using BPMs in each EMMA cell, averaged over a sliding 21-cell window. The coherent amplitude in a given transverse plane $\mathcal{A}_{x,y}$, was calculated for the horizontal (x) and vertical (y) planes by taking the standard deviation of the BPM measurement (i.e. with respect to the average orbit at a particular energy). Figure 1 shows an example of the longitudinal orbit reconstruction where $Q'\approx 0.05$ turn^{-1}, and Fig. 2 shows the variation of $\mathcal{A}_{x,y}$ as integer tunes are crossed or approached. It can be seen in Fig. 2 that the initial coherent oscillation at injection quickly decoheres, and that thereafter there is apparent amplitude growth with the same

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period as the synchrotron period; we estimate simply the decoherence time as $\tau_t = 1/2\delta\nu_x$, which at 10 - 15 turns is consistent with the decoherence seen after injection.

Figure 3 shows the agreement between $\mathcal{A}_{x,y}$ (after initial decoherence) and the prediction/measurement of how the COD ($\sigma_{COD(x,y)}$) varies as a function of momentum [6, 7] given the assumed injection stray field. Agreement is good between the two in the situation where the synchrotron oscillation amplitude δp is small and the bunch centroid remains from integer tunes. However, the two measurements differ when δp is large enough to bring the centroid of the bunch close to an integer tune, indicated by the red points in Fig. 3.

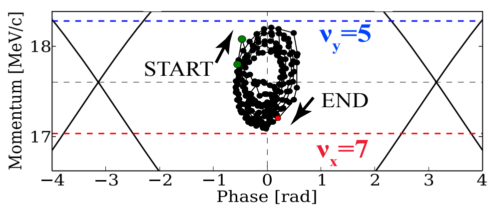

Figure 1: An example of longitudinal phase space reconstruction for a small amplitude synchrotron oscillation. The separatrix is shown in black, and horizontal and vertical integer tune locations are shown as red and blue dashed lines respectively. Each black point represents the reconstructed longitudinal phase space location after each turn.

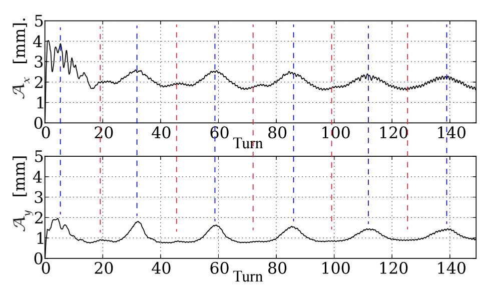

Figure 2: Example behaviour of $\mathcal{A}_x$ and $\mathcal{A}_y$ derived from BPM data. Red and blue dashed lines represent estimates either of integer tune crossings or times when they are approached most closely, for the integers $\nu_x = 7$ and $\nu_y = 5$ which are important in this particular lattice configuration.

It is typically observed in EMMA that slow crossing of integer tunes causes beam loss, an example of which is shown in Fig.4 for a particularly slow crossing speed. Whilst it would be expected that amplitude and emittance growth would both occur during resonance crossing, it appears that rapid decoherence makes it difficult to observe via BPM measurements of $\mathcal{A}_{x,y}$. To confirm this we carried out Zgoubi simulations of the crossing.

SIMULATIONS IN ZGOUBI

Zgoubi [8] was used to simulate EMMA in the experimental configuration [1], using a hard-edged approximation for the magnetic fields. A horizontal dipole field error of

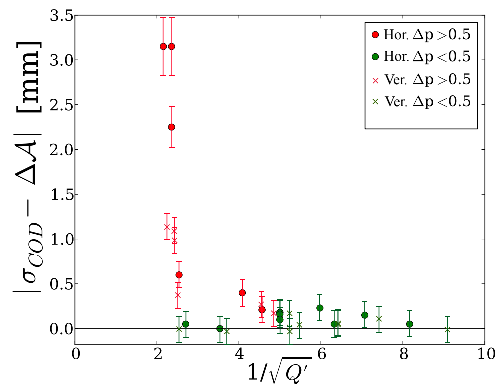

Figure 3: Variation of the difference between the COD measurements/predictions σ_{COD}) and the change in coherent amplitude $\Delta\mathcal{A}$ for both transverse planes as tune crossing speed varies. Red points indicate larger amplitude Δp cases where integer tunes are either crossed or closely approached. Green points indicate where Δp was small and where oscillations remained from from integer tunes.

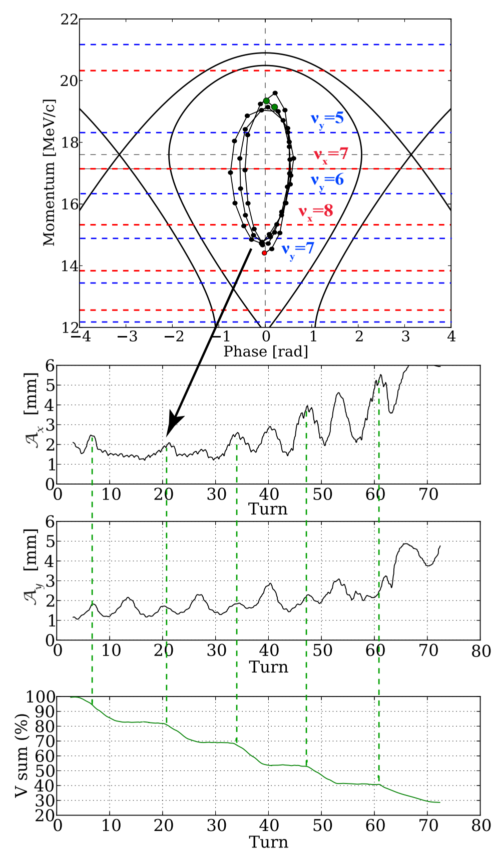

Figure 4: An example of longitudinal phase space is shown where many integers are crossed; ν_x=8 and ν_y=7 are crossed slowest (Q'≈ 0.1 and 0.25 turn^{-1} respectively) and are indicated by vertical dashed green lines. The amplitudes $\mathcal{A}_x$ and $\mathcal{A}_y$ are shown in the middle plots whilst thecharge loss is shown at the bottom.

0.5 mTm was used - equivalent to the expected septum stray field error - and for simplicity only initial horizontal trans-

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verse motion was considered. Simulated single-particle betatron amplitude growth has previously been shown to be consistent with simple estimates by R. Baartman and others in [9]. Figure 5 shows the difference in simulated orbit amplitude after an integer tune crossing, both for a single particle and for a bunch of 1000 particles with finite emittance and momentum spread that match the experimental conditions; the decoherence effect is clear.

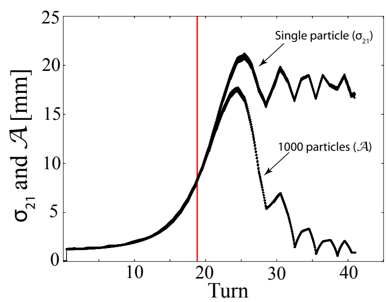

Figure 5: The standard deviation of the horizontal coordinate averaged over 21 cells σ_{21} and $\mathcal{A}_x$ for one particle, and for a bunch of 1000 particles with emittance and energy spread matching the EMMA experimental conditions. The red line indicates estimated point of integer tune crossing.

Figures 6 and 7 show an example of the simulated decoherence in both longitudinal and transverse phase space after ~9 turns and ~20 turns. The momentum spread increase is significant, being already ~ ±0.5 MeV at 9 turns. Due to EMMA's natural chromaticity, this drives tune spread which quickens the transverse decoherence after the initial betatron amplitude growth from an integer tune crossing. A value of $\delta p = \pm 0.5$ gives $\tau_t \approx 2.5$ turns. Figures 7 and 8 show that when an integer tune is crossed at turns ~10 and ~20, charge is also lost, indicated by red loss-points in Fig. 7. The small decoherence time due to integer tune crossing is consistent with experimental observations.

DISCUSSION

The rapid increase in tune spread from increasing momentum spread can significantly reduce the decoherence time for bunches that cross integer resonances, and this can occur on timescales similar to how fast such integer tunes are crossed. It is therefore important to compare experimental measurements with detailed multi-particle simulations when interpreting. In certain circumstances such as EMMA, the decoherence time is short enough that it can mask amplitude growth, and it remains difficult to obtain an indirect measurement of true emittance growth, although the pattern of beam losses and BPM signals seen are consistent with multi-particle simulations.

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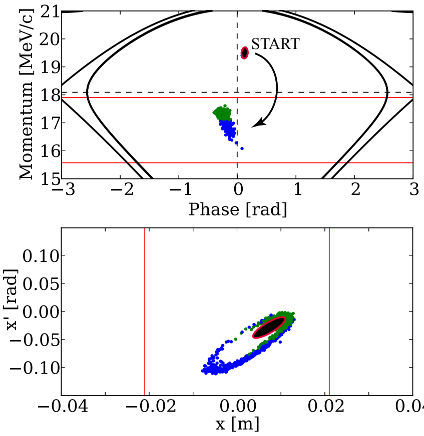

Figure 6: The longitudinal (top) and transverse (bottom) phase space are shown after 9 turns of a simulated synchrotron oscillation matching experimental measurements. The starting distribution is shown in black highlighted with a red boundary. Integer tune locations are shown in red in the longitudinal phase space and the physical aperture boundary is shown in red in the transverse phase space. Green and blue points indicate particles either above or below the mean momentum, respectively.

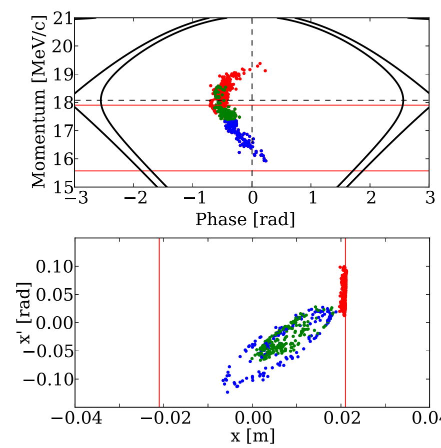

Figure 7: Shows the same case as in Fig. 6 but at turn 20 in the simulation. Red points indicate the location of lost particles.

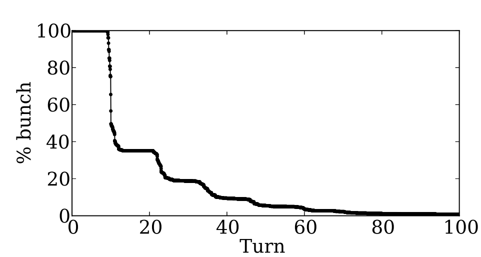

Figure 8: The charge loss due to integer tune crossings for the simulation case shown in Figs. 6 and 7.

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