THE EMMA ACCELERATOR AND IMPLICATIONS FOR HADRON NON-SCALING FFAGS

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Abstract

EMMA (Electron Model for Many Applications) is the worlds first non-scaling FFAG constructed at the Daresbury Laboratory, UK. Commissioning activities have recently been undertaken and beam dynamics results relevant to hadron non-scaling FFAGs are presented. The impact of these results on the future design of non-scaling FFAGs for high intensity hadron beam applications is discussed.

THE EMMA NS-FFAG

The EMMA accelerator has been built as a proof-of-principle demonstrator for ns-FFAG technology [1, 2, 3, 4]. The project aims to demonstrate feasibility of ns-FFAGs and to study the novel beam dynamics of these machines in detail. The availability of the partial EMMA ring in the initial stages of commissioning in August 2010 allowed a few basic measurements to be made including the betatron tune and dispersion. These measurements are relevant to the design of proton ns-FFAGs as they are a crucial test of the ZGOUBI simulation code, used both for the EMMA design and in existing work towards proton ns-FFAGs for low intensity [5] and high intensity [6] beams.

The ALICE 35 MeV electron energy recovery linac prototype [7] is used to inject appropriate beams into EMMA. During EMMA operation the two linac sections of ALICE (the booster linac and main linac) are used to provide beams in the 10 to 20 MeV energy range of EMMA. The electron beam is diverted out of ALICE to the EMMA injection line and so ALICE does not run in energy recovery mode during EMMA operation. Details of ALICE and its setup for EMMA can be found in Ref. [8].

The main parameters of EMMA are given in Table 1. EMMA consists of 42 cells which are physically organised into seven sectors, with six cells in each sector. For some of the experimental work outlined here, only four of the seven sectors of EMMA were used.

Table 1: Lattice Parameters of the EMMA Accelerator

Parameter	Value
Radius	2.637 m
Circumference	16.57 m
No. of cells	42
Cell type	DF doublet
Cell length	394.481 mm
RF	19 cavities; 1.3 GHz
Energy range	10 to 20 MeV

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EXPERIMENTAL METHOD

In planning the experimental commissioning work the decision was made to keep the beam energy of the ALICE injector constant and to represent different relative momenta by changing the EMMA quadrupole strengths while maintaining the ratio between the D and F quadrupoles (the D/F ratio). This means that to reproduce the dynamics of a relative momentum of $+5\%$ the main quadrupole magnet strengths have to be changed by -5%[1].

The EMMA ring is heavily instrumented with diagnostic devices as it is an experimental machine with novel beam dynamics that need to be studied in detail. The full EMMA Beam Position Monitor (BPM) system consists of 81 button BPMs. Each BPM includes a button electrode pickup and a pair of front-end modules connected via a single low loss cable 40 m in length to a VME module[2], where the pickup signals are measured using analog to digital converters (ADCs) [9].

During the initial commissioning process the electronic BPM readout system was not yet available. To read positions from the installed BPMs, seven coaxial cables were available which were connected directly from the BPMs to the control room where the analog signals were monitored using a Tektronix TDS6124C oscilloscope. For each BPM, the left-right signals are multiplexed onto the same cable with a set time delay, which is one of the main functions of the front-end module. This means that the horizontal position can be read from a single cable, and similarly for the top-bottom signals for the vertical position. The oscilloscope was used to read out the raw voltage signals from the BPMs and beam positions were calculated from these raw values using a pre-measured calibration algorithm [10].

With a total of just seven coaxial cables the amount of data taken was limited during this period, as each cable can only supply either a horizontal or vertical position. A machine shut down is required in order to change which BPMs are connected, so this is minimised during the commissioning shifts.

During the measurements only horizontal BPMs were connected to give the maximum of 7 horizontal positions simultaneously. The vertical offset prior to the injection septum was minimised using the vertical correctors in the injection line, though only to within a few mm.

[1]This change is not immediately obvious. As $B\rho \propto pc$, usually for constant B (in a fixed field accelerator) pc is increased and the bending radius ρ increases proprtionally. In this case we keep pc constant but want to mimic the increase in ρ, hence B is reduced.

[2]Versa Module Europa (VME)

Dispersion Measurement

To measure the dispersion, repeated measurements of the beam orbit are taken while varying the relative momentum of the beam. The dispersion is then calculated as:

$$D(p,s) = x(s)\left[\frac{\delta p}{p_0}\right]^{-1}. \tag{1}$$

For this measurement the horizontal readout of the BPMs situated between the D and F magnets in cells E12 to E18 are connected. The measurement is made well after the septum and kickers to allow the betatron oscillations to become roughly constant in amplitude.

Tune Measurement

The measurement of the betatron tune in a ns-FFAG is a challenge, particularly with an incomplete ring. The lack of a reference 'closed orbit' to compare particle positions against means that an assumption has to be made about where the centre of the betatron oscillations ought to lie. In most cases, the mean of the measured particle positions is sufficient. In practice this may introduce problems if the beam has large oscillations or is clipped due to beam loss which could skew the position measurements. This is a problem specific to this type of machine as the beam is designed to be off-centre in the beam pipe and this off-centre position changes with energy. Measurements may be improved by minimising betatron oscillations to avoid beam loss.

An additional challenge in measuring the tune with only four sectors of EMMA is the small number of BPM readings available. Fourier analysis relies on a large number of BPM readings so is not reliable in this instance. The method adopted is a least squares fit to a sine wave.

In this method, it is assumed that the data points follow a curve of the form:

$$f(s) = A.\sin\left(\frac{2\pi\nu_x s}{l_{cell}} + \phi\right) + \Delta x \tag{2}$$

where l_{cell} is the design cell length[3] (0.394481 m). The remaining four variables, A, the amplitude of the oscillations, ν_x the horizontal cell tune, ϕ the phase and the horizontal offset of the 'orbit' from the centre of the BPMs, Δx, are all used as free parameters to make the least squares fit.

Simulating the EMMA Experiments

EMMA has been simulated using ZGOUBI [11] with a hard-edge magnet model. The geometry considered is the baseline lattice, which corresponds to one of eight different lattice configurations proposed as part of the EMMA experiment [12]. The lattice parameters used in this instance (additional to those in Table 1) are given in Table 2.

To ascertain the tunes and dispersion which ought to be observed during the EMMA four sector commissioning, closed orbits were found by locating the centre of the minimised phase space ellipse with multi-turn single particle tracking. These closed orbit positions are plotted relative to a small change in momentum in Fig. 1. In the small momentum range being considered, the dispersion can be approximated as linear in order to make a comparison with the experimental data. The dispersion is estimated by the gradient of a least-squares linear fit, the result of which is $D(s) = 53.9 \pm 0.52$ mm. The betatron tunes were also calculated at each momentum step, shown in Fig. 2. These results provide a point of comparison with the experimental data obtained in the next section.

[3]It is assumed in the tune measurements that the real distance between the BPMs is the same as the design cell length.

Table 2: Parameters Used to Describe the EMMA Accelerator in ZGOUBI

Parameter	Value
D offset	34.048 mm
F offset	7.514 mm
Long drift	210 mm
Short drift	50 mm
Quad length F	58.782 mm
Quad length D	75.699 mm
Quad radius (inscribed) F	37 mm
Quad radius (inscribed) D	53 mm
Quad gradient F	6.695 T/m
Quad gradient D	4.704 T/m

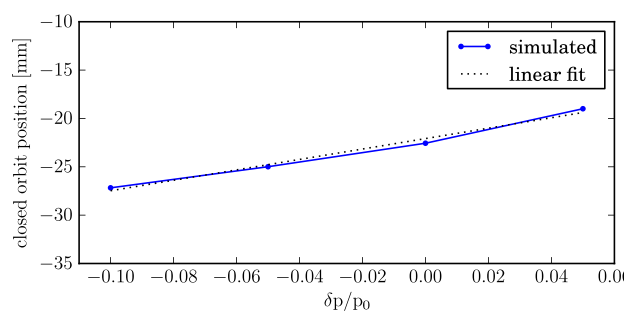

Figure 1: Simulated change of closed orbit position with momentum using ZGOUBI.

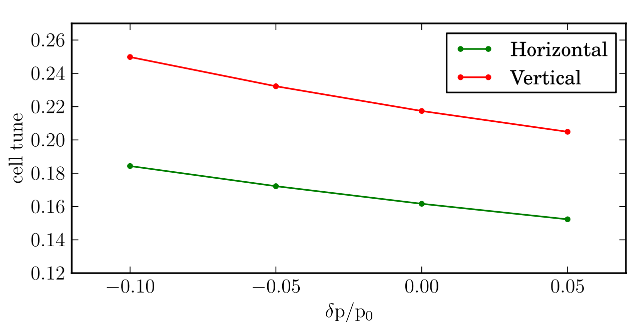

Figure 2: Simulated tunes for the baseline EMMA lattice using a hard-edge model in ZGOUBI.

RESULTS

Dispersion Measurement

Using the position data obtained, the centre of the orbit is approximated by taking the mean of the 7 horizontal beam position readings. The dispersion is then found by making a linear fit to the mean positions with relative momentum, as shown in Fig. 3. The measured mean dispersion in this momentum range is $D(p) = 42.01 \pm 12.1$ mm, compared to $D(p) = 53.9 \pm 0.52$ mm obtained from the earlier simulation. The error on this measurement is calculated as the difference between the best fit and the maximum/minimum linear fits which remain within the error bars of the data points.

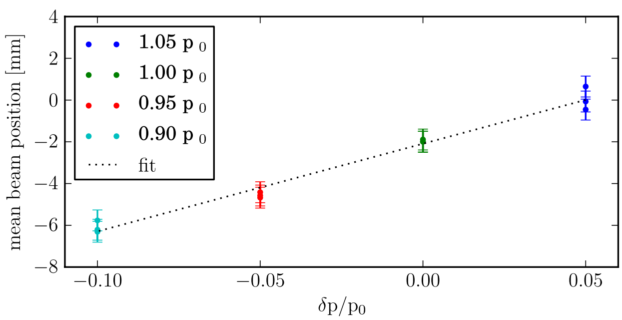

Figure 3: Measured dispersion in EMMA four sector setup.

Horizontal Tune Measurement

The measured horizontal cell tunes taken on 5th August 2010 are shown with the simulated tune values in Fig. 4. Given the difficulty of measuring the tune in this scenario, the agreement with simulation for the two higher momenta is remarkable. However, the two lower momentum values differ significantly from the expected tunes.

During the measurements at lower momenta there appears to have been significant beam loss occurring upstream of the BPMs. Although there is no beam loss monitor to verify this hypothesis, there was a reduction in the amplitude of the raw BPM signals observed. Further information can be gained by looking at the sinusoidal fit to the BPM data points. It is clear that the sinusoidal fit to the data points in Fig. 6 is far superior to that in Fig. 5. Beam loss upstream of the BPMs or in the 7 cells in which these measurements were taken would result in a non-uniform and mis-shapen bunch which could give false or misleading position measurements. As the tune measurement relies on the frequency component of these position measurements, the tune measurements at lower momenta cannot be considered to be reliable.

On August 30th, further measurements were made of the beam position with varying momenta. The same central momentum of 18.5 MeV/c was used and the BPMs in cells E12 to E18 were measured, this time for two turns in the EMMA accelerator with the RF system off. The same

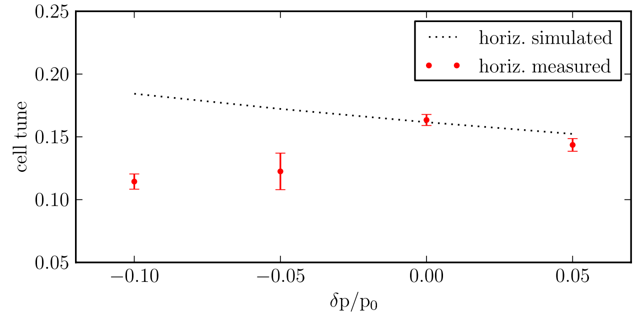

Figure 4: Measured horizontal cell tunes in the EMMA four sector setup.

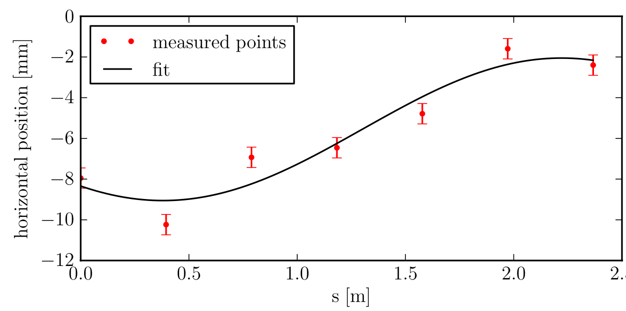

Figure 5: Sinusoidal fits to measured data points for the lower momentum $p/p_0 = 0.9$.

method as before was used both for taking the measurements and to find the horizontal betatron tunes.

Full Ring Experimental Results

The measured horizontal cell tunes using the full EMMA ring over two turns are shown in Fig. 7. The tunes measured in this case agree with the ZGOUBI simulation presented earlier and seem to resolve the ambiguity of the low momentum tunes in Fig. 4. A detailed comparison of codes for EMMA has been undertaken previously [13]. The predicted tunes using a second simulation code called the Polymorphic Tracking Code (PTC) [14] from the code comparison are included for reference.

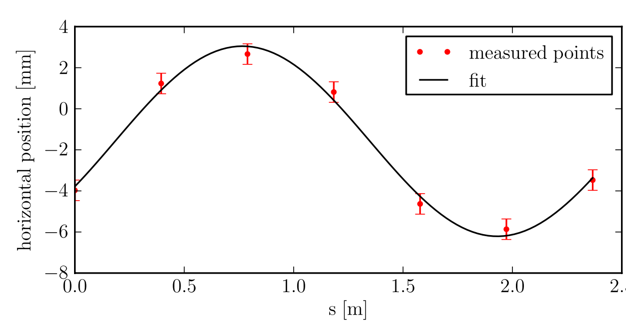

Figure 6: Sinusoidal fits to measured data points for the reference momentum $p/p_0 = 1.0$.

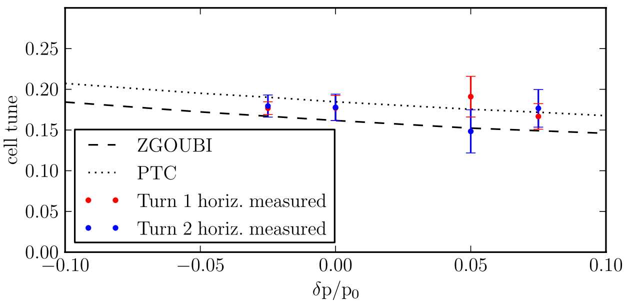

Figure 7: Measured horizontal cell tunes over 2 turns in EMMA.

Discussion of Results

The results presented here indicate that, for the most part, the simulated and experimental data for EMMA agree within error. The original low momentum tunes are considered to be unreliable, but later measurements show that the predicted and measured values are in good agreement. This work has been undertaken without the use of the electronic BPM readout system and further clarification of the tunes will be possible once this system is available. Further EMMA commissioning should also clarify the tunes as a function of momentum over the full momentum range and more precisely determine the extent of the agreement between the ZGOUBI model and the real machine.

IMPLICATIONS FOR PROTON NS-FFAGS

With regards to proton ns-FFAGs, these results indicate that a reasonable degree of confidence can be placed in the ZGOUBI code and that in practice the basic beam dynamics should not differ dramatically from the model. However, at this stage ZGOUBI does not incorporate space charge.

The incorporation of an approximate effect of space-charge in the ZGOUBI code has been considered elsewhere [6]. At this stage, there are a number of options for simulation codes for the development of high power proton ns-FFAGs. The first is a major upgrade to the ZGOUBI code to accommodate high intensity proton beams in a realistic way. Another option would be to benchmark the beam dynamics of EMMA using other simulation codes and proceed with the most realistic code that incorporates space charge. Approximation of space charge effects has also been looked at with COSY Infinity [15], making this a possible candidate.

SUMMARY AND FUTURE WORK

Initial experiments during the commissioning of EMMA have been used to compare the dispersion and betatron tunes predicted by the ZGOUBI simulation code to those of a real ns-FFAG. The results agree within error, indicating that a reasonable degree of confidence can be placed in the code for estimation of the basic beam dynamics of ns-FFAGs. However, the inclusion of space charge effects will be necessary to accurately model high power proton ns-FFAGs and future work will focus on identifying a suitable code for this purpose.

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