FIRST RESULTS FROM THE EMMA EXPERIMENT

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on behalf of the EMMA collaboration

Abstract

Commissioning of a linear nonscaling Fixed Field Alternating Gradient (FFAG) accelerator is underway at the Daresbury Laboratory in the UK. It has shown stable orbit and optics with very small dispersion function, acceleration in the serpentine channel outside the rf bucket, and no significant growth of betatron oscillation amplitude when a beam goes through several integer tunes during acceleration. We will discuss the recent results of this new type of FFAG accelerator.

INTRODUCTION

More than 10 years ago, a Fixed Field Alternating Gradient (FFAG) accelerator was proposed as a muon accelerator for the Neutrino Factory and Muon Collider [1-3]. The muon beam emittance is very large, roughly 30,000 π mm mrad (normalized), because it is produced as a tertiary particle after a proton beam hits a target. Muons have a lifetime of 2.2 μs in their rest frame. The fixed field nature of the FFAG accelerator can potentially shorten the acceleration time, only limited by the available rf voltage. While there had been development and construction of scaling type FFAGs in Japan, their main motivation has been for use as a high current proton accelerator [4]. Work on nonscaling (NS) type FFAGs, which was initially more focused on applications to muon acceleration, remained at the design stage [5]. There are a few reasons. The NS FFAG relies on high symmetry of the lattice to realize very strong focusing and make the dispersion function small. For example, there could be 84 identical cells for a muon accelerator from 10 to 20 GeV/c [6]. Consequently, the circumference tends to be large even for a scaled down model. In particular for muon acceleration, the novel acceleration scheme using a 'serpentine channel' was proposed [7-12]. This requires that the beam should be already ultra-relativistic at the injection energy. The cost of the injector even for an electron model tends to be high. Finally the total voltage has to be large (more than MV per turn) to open the serpentine channel.

Discussions began in the early 2000's whether we could find a site to build an electron model of a NS FFAG which mimics a muon acceleration. After some discussion it turned out that ALICE (Accelerators and Lasers In Combined Experiments), the electron accelerator at the Daresbury Laboratory in the UK, could provide an ideal electron beam [13]. The momentum could be changed from around 10 to 35 MeV/c. There was space available to accommodate a reasonable size ring downstream of the ALICE area. With funding from EPSRC in the UK, the construction of a linear NS FFAG accelerator started for the first time in the world (Fig. 1). The new machine was christened EMMA; Electron Model for Many Applications [14,15]. Parameters are listed in Table 1.

Three main goals of EMMA were set. First, EMMA should prove that the beam quality would not deteriorate through the crossing of several integer tunes. Excursion in the total tune space by several units is a consequence of an absence of chromaticity correction in this linear NS FFAG as shown in Fig. 2. Secondly, we should prove that the novel use of the serpentine channel for accelerating a beam would work as expected (Fig. 3). The lattice is adjusted to be almost isochronous and has two stable fixed points, one near the injection and the other near the extraction momentum. Thirdly, we should show that EMMA has large dynamic aperture so that a large beam, like a muon beam, could be accommodated. One of the main reasons to adopt a linear field instead of a more elaborate scaling field profile is the removal of nonlinearity so that beam stability could be assured in a more extensive region.

Table 1: Principal Parameters.

momentum	10.5 to 20.5 MeV/c
circumference	16.57 m
number of cells	42
focusing	doublet
nominal integrated Q field	0.402/-0.367 T
rf frequency	1.301 GHz
number of rf cavities	19
tune shift for the momentum range	0.3 to 0.1/cell
acceptance (normalized)	3 π mm rad

COMMISSIONING WITH FIXED MOMENTUM BEAM

Commissioning started in June 2010 when the construction had almost finished. We decided to carry out the commissioning in stages, first only 4 sectors out of 7, mainly to study the injection system and to make sure the orbit and optics with extremely small dispersion function work. By using YAG screens as a diagnostics device and taking two kickers (its strength) and septum (its strength, position and rotation) as parameters, we succeeded in getting a beam through the 4 sectors as shown in Fig. 4.

In August, the whole ring with 7 sectors was completed and the circulating beam was observed for three turns first

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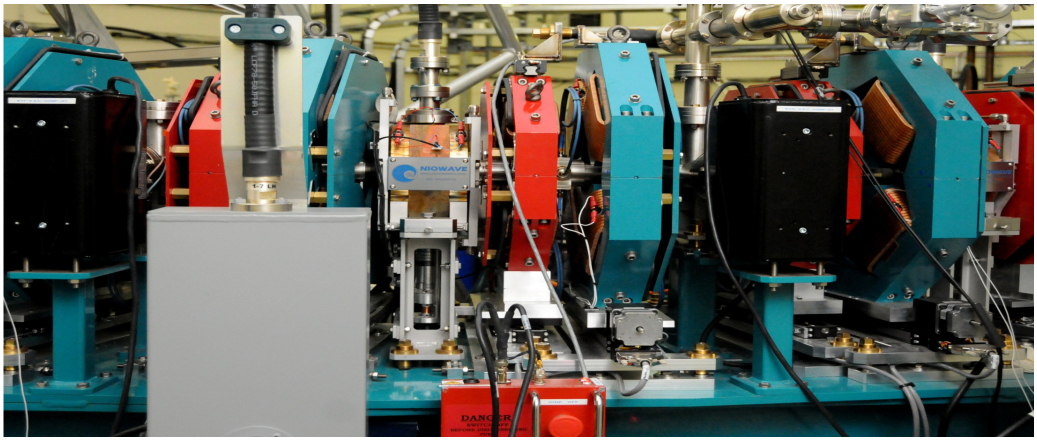


Figure 1: One cell of EMMA lattice. Red and blue magnets are focusing and defocusing quadrupoles, respectively. rf cavities are in every other long straight section. The length of a cell is 0.395 m.

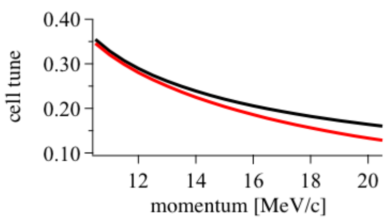


Figure 2: Cell tune as a function of momentum. Black curve is horizontal and red is vertical.

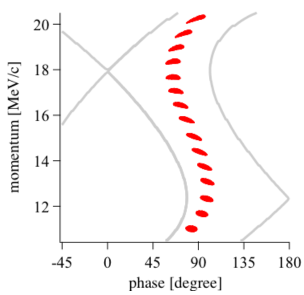


Figure 3: Serpentine channel acceleration shown in longitudinal phase space.

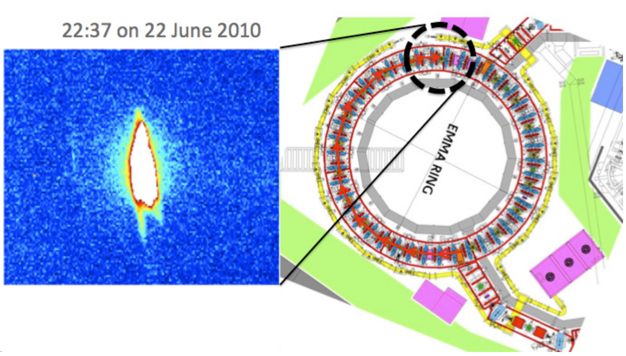


Figure 4: Screen image at the end of the 4 sectors.

and for thousands of turns a few days later (Fig. 5). Note that ALICE is an electron machine with different programmes running one by one so that there was not much beam time between June and August and progress was really fast.

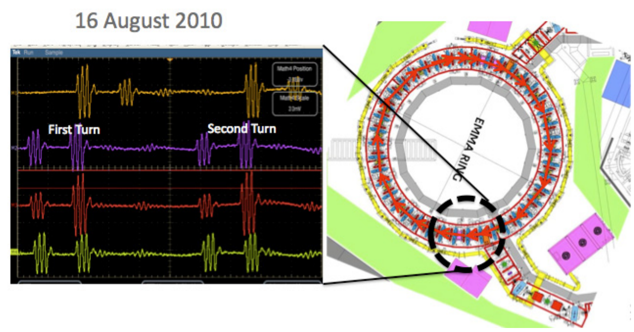


Figure 5: BPM signal of a circulating beam.

Once we had a beam circulating for thousands of turns, it became possible to measure machine properties such as orbital period, closed orbit distortion, transverse tune and dispersion function.

Unlike a synchrotron and a scaling FFAG, the properties of a linear NS FFAG depend on beam momentum; in order to measure their dependence, the ALICE injector could be adjusted to cover the whole momentum range from injection at 10.5 MeV/c to extraction at 20.5 MeV/c. However, we changed the strength of the main magnets instead of changing the injection beam momentum (fixed at 12.5 MeV/c) because it was easier and the orbit and optics should be identical in both ways except for orbital period. We call this "measurement with the equivalent momentum".

Figure 6 shows the orbital period in the momentum range. It shows an almost parabolic behaviour, as was expected from the model and simulation.

Figures 7 and 8 show horizontal and vertical orbit positions and horizontal and vertical cell tunes respectively as a function of beam momentum. Cell tunes were calculated by NAFF [16] using oscillating orbit positions within 21 neighbouring cells.

At this point, we faced two major problems. One was the large closed orbit distortion and the other was the rf phase alignment of 19 cavities. As Fig. 9 shows, both horizontal and vertical closed orbit distortion (COD) have

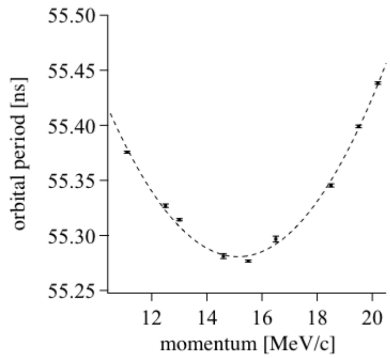


Figure 6: Orbital period as a function of momentum. Markers are after correction of velocity between real and equivalent momenta.

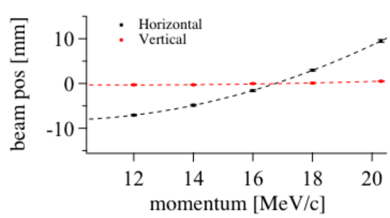


Figure 7: Orbital position as a function of momentum.

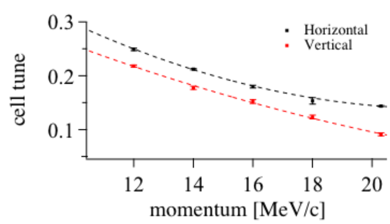


Figure 8: Cell tune as a function of momentum.

amplitudes of around +/-5 mm. With an alignment accuracy within +/-0.05 mm, the expected COD should be less than +/-1 mm. Although some magnet misalignments were found to be larger than expected, after re-alignment there still remained a COD of similar size in both horizontal and vertical planes.

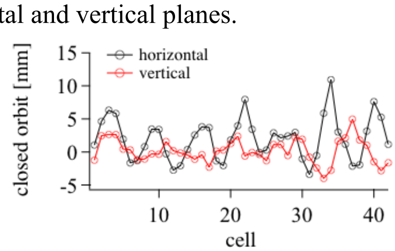


Figure 9: Measured COD in horizontal and vertical.

It was found later that a major source of the horizontal COD was a septum stray field (Fig. 10). This was first identified when the septum for extraction was excited. Comparison between a simulation with two localized dipole kicks at the septa positions and measured COD explained the horizontal COD. On the other hand, it is not yet clear what causes the large vertical COD.

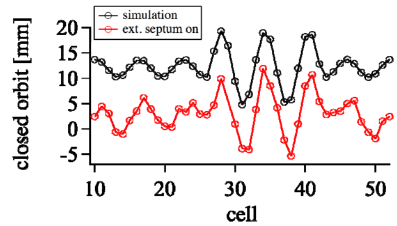


Figure 10: Measured and simulated COD with septum stray fields. Injection septum is located at cell 1 (or 43) and extraction septum at cell 27.

The other problem is the phase adjustment of 19 rf cavities. The initial setup exhibited phase offset of the cavities, but the synchrotron oscillation measurements within a small bucket indicated that the vector sum of the voltage was not the simple sum of individual voltages.

We then found that the cavity monitor showed a beam loading signal (Fig. 11). Although the accuracy was not high, we could align the rf phase by which all the cavities (except one or two) showed the energy gain or loss at the same time. After this adjustment, the vector sum voltage was only around 10% less than expected according to the synchrotron oscillation measurement.

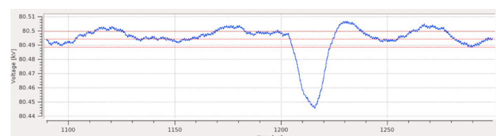


Figure 11: Beam loading signal when a beam gains energy.

SERPENTINE CHANNEL ACCELERATION

Measurement of orbit position and cell tune as a function of momentum gave us all the information to calibrate beam momentum when a beam is accelerated. One remaining measurement was the timing offset between an injected beam and rf phase. We needed to know at which rf phase a beam was injected. A stable fixed point can be found by observing synchrotron oscillations in a small bucket. As shown in Fig. 12, the stable fixed point was around 280 degree. We confirmed that the phase offset was independent of rf voltage so that a beam could be injected at the right phase after the rf buckets were merged and the serpentine channel appeared.

With 1.9 MV per turn, the orbit in the horizontal plane moved outwards while it stayed zero in the vertical plane, as shown in Fig. 13. At the same time, the cell tunes in both horizontal and vertical planes were decreasing as shown in Fig. 14.

All of these observations qualitatively indicated the monotonic increase of beam momentum. Furthermore, by combining phase information of a beam relative to the rf and by calibrating momentum in three different ways (namely, with horizontal orbit, horizontal and vertical cell tunes) the trajectory in longitudinal phase space could be reconstructed as shown in Fig. 15. Trajectories with five different initial phases clearly indicated that a beam was accelerated in the serpentine channel.

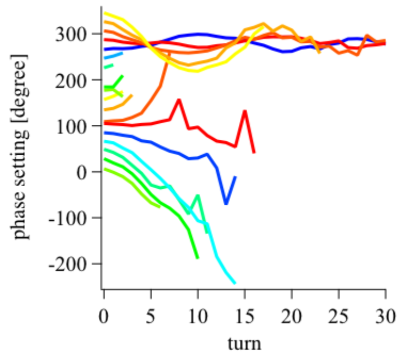
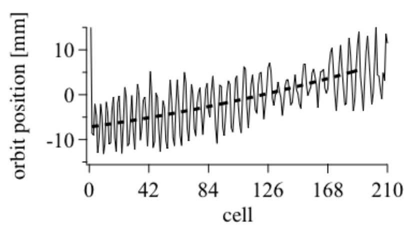
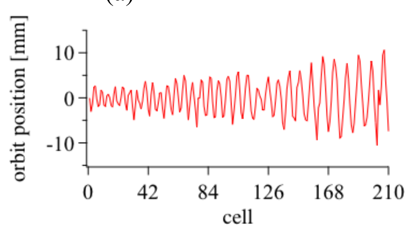


Figure 12: Measured phase oscillations.

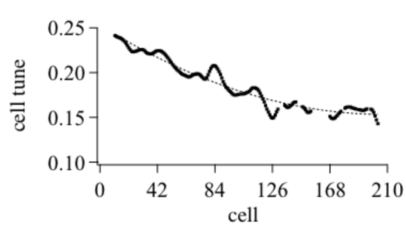


(a)

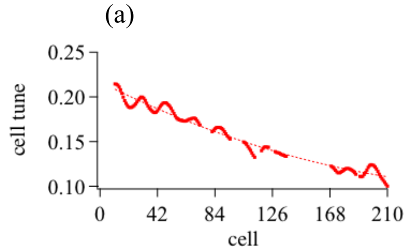


(b)

Figure 13: Horizontal and vertical orbit position when a beam is accelerated. x-axis is cell number a beam passed. One turn corresponds to 42 cells.



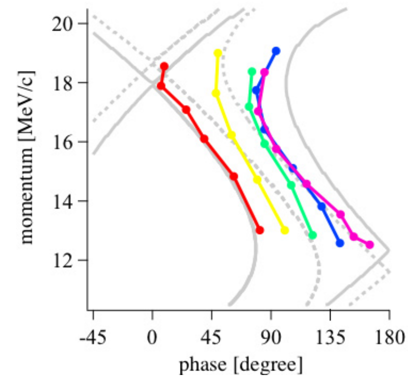
(a)



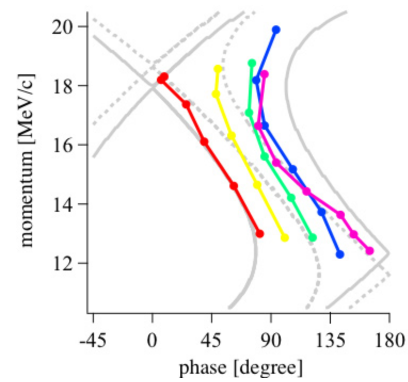
(b)

Figure 14: Horizontal and vertical cell tune when a beam is accelerated. x-axis is cell number a beam passed.

We concluded that an electron beam injected at 12.0 MeV/c was accelerated beyond 18.0 MeV/c in the serpentine channel [17]. The momentum measurement for the extracted beam using a dipole and two screens before and after the dipole confirmed the acceleration as well (Fig. 16). The beam momentum was estimated as 18.4+/-1.0 MeV/c.



(a)



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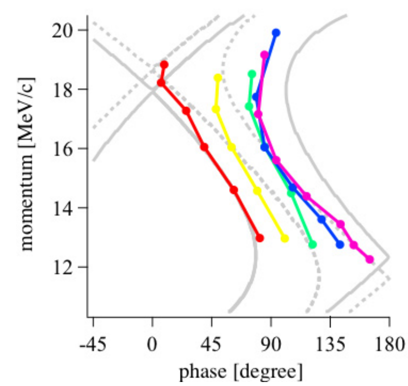

(c)

Figure 15: Longitudinal trajectories reconstructed by three different momentum calibrations; (a) with horizontal orbit, (b) with horizontal tune, and (c) with vertical tune. Solid and dashed grey curves are separatrices of upper and lower bounds considering the systematic errors of Fig. 6

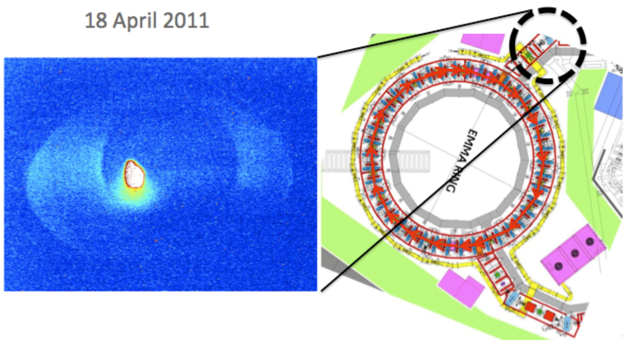

Figure 16: Screen image in the extraction beam line.

As shown in Fig. 17, there was no significant increase in betatron oscillation amplitude although the beam went through several integer tunes during acceleration.

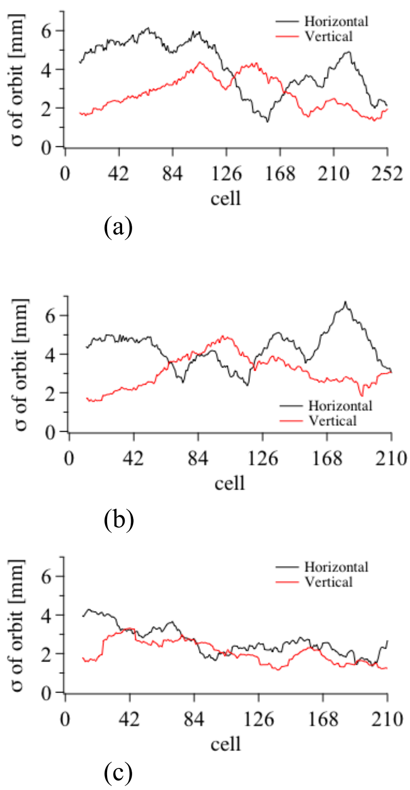

Figure 17: Standard deviation of orbit with neighbouring 21 cells. (a) beam with red trajectory in Fig. 15, (b) one with green trajectory in Fig. 15, (c) one with magenta trajectory in Fig. 15.

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