FIRST COMMISSIONING RESULTS FROM THE NON-SCALING FFAG ACCELERATOR, EMMA

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Abstract

The first results from commissioning EMMA - the Electron Model of Many Applications- are summarised in this paper. EMMA is a 10 to 20 MeV electron ring designed to test our understanding of beam dynamics in a relativistic linear non-scaling fixed field alternating gradient accelerator (FFAG). EMMA will be the world's first non-scaling FFAG and the paper will outline the characteristics of the beam injected in to the accelerator as well as summarising the results of the 4 sector 'gantry-type' commissioning which took place at Daresbury Laboratory. The paper will report on recent progress made with the full EMMA ring commissioning, giving details of tune and orbit measurements as well as their correction to the desired lattice series.

INTRODUCTION

EMMA is an accelerator currently being commissioned at Daresbury Laboratory, UK, to demonstrate the world's first operation of a new concept in accelerators called a non-scaling FFAG, (ns-FFAG) [1,2]. First conceived to provide very rapid acceleration for high energy muons, and now adopted in the baseline design of an international neutrino factory design [3], ns-FFAGs are perceived to have a wide range of potential applications ranging from cheap, simple and compact proton/carbon cancer therapy machines e.g. the PAMELA project [4], to highly reliable powerful proton accelerators producing neutrons to drive sub-critical nuclear reactors [5].

THE EMMA EXPERIMENT

EMMA's purpose is to study beam dynamics in linear ns-FFAGs. By using a high-frequency RF system, the machine will focus on dynamics that can be studied in an FFAG that accelerates rapidly. Two particular areas are of interest: the (rapid) crossing of resonances (though "resonance" might not be the best term [6]), and "serpentine" acceleration, a mode of acceleration particular to nearly isochronous linear non-scaling FFAGs [7].

The EMMA ring accelerates electrons from 10 to 20 MeV in kinetic energy. The beam is provided by ALICE (née ERLP) [8,9]. It uses the small ALICE beam to scan a significantly larger phase space (3 mm normalized transverse emittance). We can extract the beam at any point in the acceleration cycle to examine its properties in a diagnostics line.

The main ring lattice was designed to support these goals. It consists of 42 identical quadrupole doublets, where the quadrupole positions (individually) and gradients (for each family) can be varied. This permits independent control of the dipole and quadrupole gradient for each magnet type, which permits us to tune the lattice to a desired configuration, and to modify the tunes and time of flight of the lattice to study the dependence of the machines behaviour on lattice parameters [10]. Making the cells identical eliminates systematic resonances other than those associated with a single cell, preventing undesired orbit distortion and emittance growth [3].

Both the injection and extraction systems [1] consist of a septum and two kickers in successive cells. This configuration permits us to inject and extract a beam at any energy within the energy range of the machine and at any transverse amplitude of interest [11]. We can use this to measure the (fixed energy) tunes and time of flight (ToF) as a function of energy, which is essential for determining the properties of our lattice. We can also inject and extract the beam at any point in an acceleration cycle.

The ring contains 19, 1.3 GHz RF cavities which can create up to 2.3 MV of acceleration per turn [9]. The cavity frequency can be varied over a range of at least 5.6 MHz. The ability to control the RF voltage and frequency allows us to explore the parameters of the serpentine acceleration mode [4].

ENGINEERING & CONSTRUCTION

The construction methodology has been to assemble accelerator components into subsystems offline to enable integration and system testing of modules prior to installation, allowing early detection of problems and minimising assembly work within the working accelerator area. The extremely compact nature of the EMMA lattice has been very challenging for the engineering design and construction, particularly for the injection and extraction fast pulsed magnets. After a poor response from suppliers the design and construction was carried out in-house.

Seven support girders with six lattice cells each are employed to ensure the stable support of the accelerator components in an integrated way, as shown in Figure 1.

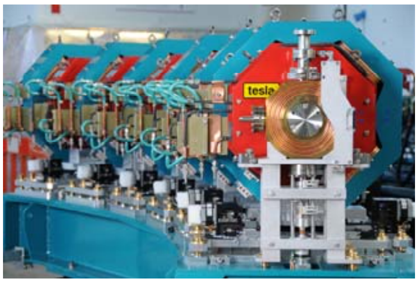

Figure 1: An EMMA girder assembly, 1/7th of the ring

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The requirement to deliver close to identical magnetic fields in every cell, places a stringent alignment tolerance of ±50 µm (1σ), ½ for transferring the magnetic centre to the local fiducials and ½ for alignment errors. This is achieved through a series of precision design, engineering and alignment control processes implemented throughout the magnet measurement, assembly and survey procedure.

COMMISSIONING OF THE RF SYSTEM

The EMMA RF system, Table 1, consists of 19 cavities, a waveguide distribution system, an amplifier and a single LLRF control system, see Figure 2, [12].

Table 1: EMMA RF Parameters

Machine Parameters	**Values**	**Units**
Frequency	1.3	GHz
Frequency range	-4.0 to 1.5	MHz
Acceleration per cavity	120	kV
Upgrade acceleration	180	kV
Beam Aperture	40	mm
RF Pulse Length	1.6	ms
Amplitude Control	0.3	%
Phase Control	0.3	Degrees

The cavities have been manufactured by Niowave Inc, USA. To distribute RF power to 19 RF cavities in such a compact ring, a novel waveguide distribution system has been designed and built by Q-Par Angus Ltd, UK. An IOT amplifier, through a cascaded network of hybrid power splitters, delivers power to each cavity. A high power phase shifter is included in each hybrid to provide independent cavity control, with reflected power being dissipated in reject loads. In acceptance tests a tuning range of 196 ° was achieved and 0.01mm, movement in the tuner motor gave a resolution of 0.1°. Isolation tests between ports showed better than 42 dB. Forward and reverse directional couplers showed a directivity of > 41 dB (spec. >40 dB). CPI's VIL409 HeatwaveTM IOT-based RF high power amplifier (RF HPA) has demonstrated up to 90 kW of pulsed power centred at 1.3 GHz over a broad bandwidth of ± 4 MHz.

Figure 2: The EMMA RF System Installation

The Instrumentation Technologies, Libera LLRF system has to synchronise with the ALICE injector, set initial cavity conditions and control the cavity amplitude/phase to ensure stable acceleration in EMMA. It has substantial diagnostic capabilities allowing it to calibrate and monitor the cavity field probe signals, forward and reflected power to each cavity, the IOT power levels before and after the circulator and control the tuner motors and phase shifters installed before each cavity input. In addition it provides closed loop control of both cavity frequency and inter cavity phase.

To cover the frequency range with respect to the ALICE carrier frequency of 1.3 GHz, requires a novel solution whereby the system synchronises itself every pulse to deal with timing jitter contributions from the photo-injector system. To set an offset frequency while maintaining synchronisation, a 'virtual reference' is created that tracks the 1.3GHz and is retimed after each timing signal. The phase relationship between the two machines is maintained even though the frequencies are effectively slipping in time.

Commissioning of the EMMA RF system has commenced. The EMMA cavity frequencies have been adjusted to 1.3008 GHz and the RF output power increased to 40 kW producing an overall accelerating voltage of just under 1 MeV/turn. With the LLRF loop closed, a global phase change has been applied to all the cavities via the LLRF system allowing the phase to each of the cavities to be adjusted from 0 to 360°.

Timing system

The timing system for EMMA is based around two eight channel Quantum Composers 9530 pulse generators. These units are aimed at providing timing and synchronisation for laser applications. A trigger pulse is received from the ALICE photoinjector 20mS before beam is generated. The timing channels have a resolution of 250pS in both delay and width and better than 50pS jitter. An EPICS interface enables remote control of the unit from the control room. The EMMA kickers, septum magnets, high power RF and LLRF are all timed in sequence and adjustable using the quantum pulse generators.

BEAM COMMISSIONING

A staged commissioning methodology has been employed. The injection line from ALICE to EMMA was commissioned with 1st beams on 26th March 2010. Initial matching of the line and diagnostic commissioning has been carried out. The primary diagnostic is a phase space tomography section, consisting of three YAG screens and two FODO cells that have already been used to make a preliminary reconstruction of the transverse phase space.

On 22nd June 2010, first injection into 4 of 7 sectors was achieved allowing an early opportunity to set up injection system and measure cell tune and the dispersion. On completion of the whole ring, on August 13th, parameters such as revolution time and closed orbit became available.

Available diagnostics

To investigate the beam dynamics, beam position monitors are essential in measuring and understanding the orbit. For the 42 cells, a total of 81 horizontal and vertical button pickups are available. Front end processing of these turn-by-turn pickup signals takes place in the electronics distributed along the ring, and the results are fed through individual cables into VME BPM cards. The digitised signals then go through a mapping algorithm, which calculates horizontal and vertical beam positions. This data is then made available through the EPICS control system.

In the front end electronics, pairs of button signals, e.g. left-right or up-down, are time-multiplexed onto a single cable, with a fixed time gap corresponding to a quarter of the revolution period (13.8ns). The BPM system is described in more detail in [13].

For the data reported here, the full complement of VME cards was not yet available, and the signals from the front end electronics were viewed directly on an oscilloscope in the control room. An example of a two-turn signal, showing the left and right signals in four cells from 12 to 15, is shown in Figure 3

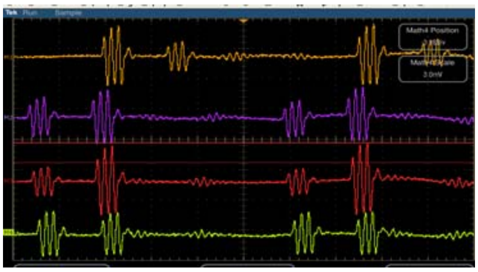

Figure 3: Left-right pickup signals for turns 1 and 2

Equivalent beam momentum

EMMA is designed to inject and extract a beam with energy region from 10 to 20 MeV. For commissioning at this stage, however, magnetic field is lowered to simulate a higher energy beam operation with a fixed energy beam from ALICE. Beam energy is 15 MeV and the nominal magnetic field is lowered by a factor of 15.5/18.5 to make the operation with 18 MeV equivalent energy. The operation with equivalent energy will give the same orbit and optics as that with real energy except time of flight (ToF). Slight difference of ToF due to particle speed is depicted in Figure 4..

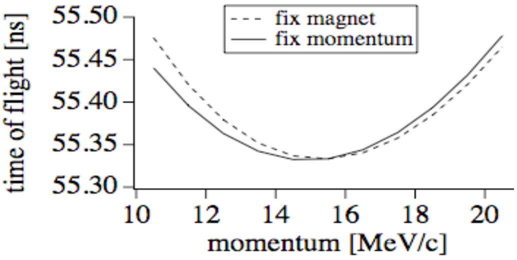

Figure 4: ToF with momentum with fixed field (dashed line) and fixed momentum 15.5 MeV/c (solid line).

Orbit at Injection Region

A beam is injected into the ring with a septum and two kickers. The septum is a quite unusual eddy-current-type devices providing a large, 65^{o} bend angle within less than 10 cm. The septum is capable of translation (towards the machine centre and away from it) and rotation around a moving pivot point to ensure the desired beam position and angle in the entire energy range of interest. A number of tests were performed on the injection septum in the very early stages of the commissioning work.

Orbit position and angle into the septum are monitored by means of the beam position at the last quadrupoles before the septum. We can tell a deviation from the design value each time ALICE and the injection line are setup. They are always within 1 mm in horizontal and a few mm in vertical.

To make sure that position and angle after the septum is more or less repeatable, they are measured with two BPMs right after the septum. Without quadrupole excitation, beam position at two locations in free space can be measured. So far we have been unable to adjust the position and angle at the exit of the septum to the design values. The septum itself seems to be functioning as we expected. An effective magnetic length of 90.9 mm has been determined from BPM measurements of the beam angle before and after the magnet [14]. The value of the same parameter, determined from direct Faraday probe magnetic measurements is 91.4 mm, Figure 4. The good agreement shows that the septum performs as designed.

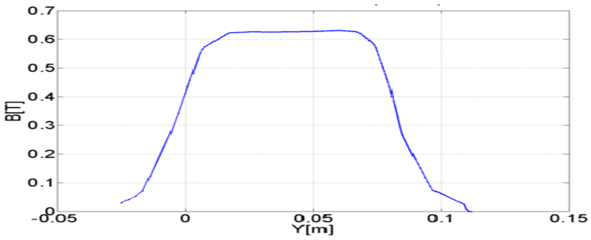

Figure 4: Septum field distribution from probe

One possible reason for miss steering is that position and angle into the septum is not as designed, although the position at the last two quadrupoles is correct. Later we will try to adjust the steering in the EMMA injection line to obtain the desired orbit values at septum exit.

At the position and angle we measured, the strength of two kickers are calculated to take the beam on to the design orbit as shown in Figure 5. The calculated kicker strength is not exactly the same as the determined values but is similar.

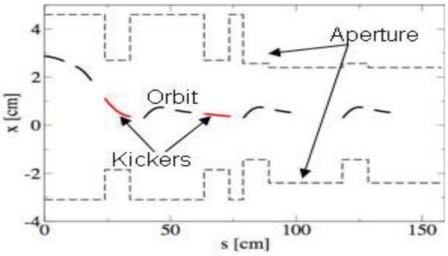

Figure 5: Injection region orbit, 2 normal cells

The kicker waveform has a large undershoot, which kicks the beam when it comes back after one turn. The waveform is adjusted such that the time difference between the first peak and the zero crossing point is around one revolution time. However, it is slightly longer. Therefore, a beam is actually kicked before the crest with increased kicker current to avoid the second kick.

Tune measurement

With seven BPMs consecutively located at the middle of doublet quadrupoles, we measured cell tune. One example of measured position is shown in Figure 6. The main frequency component is calculated with least square fit method and shown in Figure 7. The uncertainty in the individual BPM readings is 0.5 mm. The average chi2 per degree of freedom for the fit is 4.

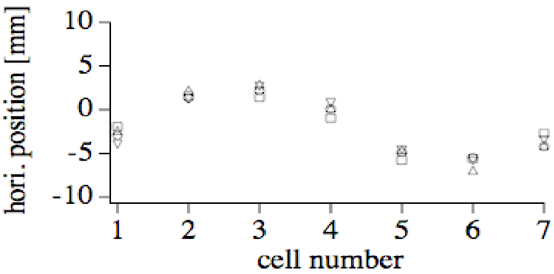

Figure 6: Beam position at seven consecutive cells

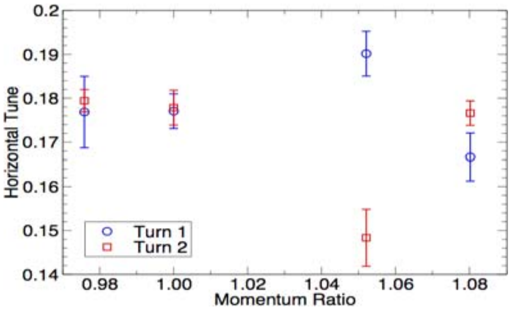

Figure 7: Tunes resulting from a fit of the data from 7 consecutive BPMs to a sinusoidal oscillation.

Dispersion function

To avoid the complexity of retuning the injector for different energies, we change the quadruple current keeping the QD/QF ratio strength ratio constant to simulate different momentum optics whilst keeping a fixed momentum beam from ALICE.

From measuring the horizontal beam position at each of seven consecutive cells (cells 12 to 18), it was possible to fit a sine function to the betratron oscillation and deduce the mean beam position across the cells. An example of this is shown above in Figure 6. Note that seven cells approximately covers a full betratron cycle..

From the mean beam position and the effective momentum, the dispersion function could be plotted, and this is shown in Figure 9 below.

The calculated dispersion values at 100% effective momentum (15.5 MeV/c) from this data are 82mm horizontally, and 3mm vertically. These values are for the BPM positions of S=0.29m within each cell, and are consistent with the base-line EMMA model.

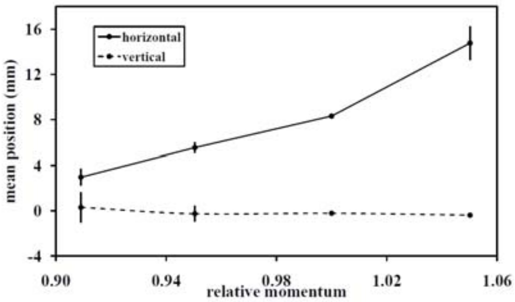

Figure 9: Mean beam position vs relative momentum

Time of flight measurement

Time of flight is measured as a revolution time. From differential signal of one of BPM electrode, see Figure 10 time when a bunch passing a BPM is determined and intervals of consecutive signals are obtained. The precision of the measurement is mainly determined by sampling rate of the oscilloscope, that is 50 ps. Preliminary results show the revolution time at 18.5 MeV/c, equivalent momentum is “55.3+/-0.1 ns”.

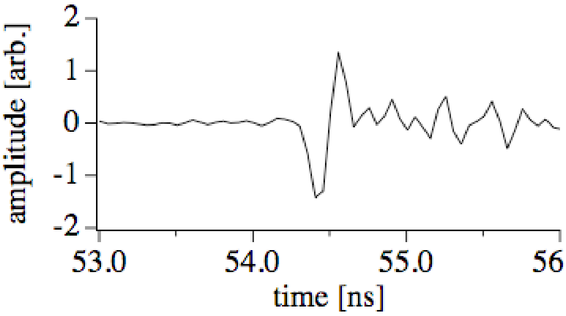

Figure 10: Beam signal to determine ToF.

Transverse stability

Without RF, a beam is circulating for more than 1000 turns, Figure 11. The source of gradual loss is unknown. It could be initial optics mismatch, beam energy loss due to beam loading at cavity, or scattering with residual gas.

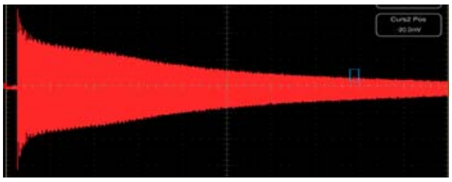

Figure 11: BPM signal with 4 μs/dev.

COMMISSIONING PLANS

Our current commissioning shifts are focussed on setting up the cavity tuning and phase to verify that the LLRF system is fully functional and capable of providing the required phase and amplitude stability, specifically at the ALICE matched frequency and over the required range of frequencies. On achieving this, it is then hoped that a verification of successful accelerator, evidence of energy gain from acceleration inside and then outside of the bucket would follow relatively quickly.

The next steps are to get a measurement of tune and time of flight as a function of energy with the RF cavities turned off. We will initially continue on our current course of simulating different energies by using a fixed-energy beam from ALICE and scaling the magnet fields. We will set the magnet fields to simulate injecting the beam over the full energy range of EMMA (ideally in 1 MeV steps), and find the injection system parameters to inject the beam on the closed orbit for each case and allow the beam to circulate for a large number of turns. We will measure the time of flight on the closed orbit. We will then inject the beam slightly off this orbit to measure the tune. We will do this at a number of amplitudes, and measure the time of flight at those amplitudes as well. Having ~1/2 of the BPMs, i.e. those located inside the doublets, instrumented will be important for the accuracy of these measurements.

We will repeat the above process with the magnet fields fixed and varying the energy of the ALICE beam. ALICE will be tuned to supply a beam for each energy for which we generated a simulated energy in the earlier process.

The closed orbit position as a function of energy will also be used to construct a mapping from energy to position so that we can monitor the energy during the acceleration cycle without extracting the beam. We would also like to extract the beam, and we will thus find the extraction system parameters to extract the beam from the closed orbit at different energies. We will measure the energy of the extracted beam.

Once we have the tune, time of flight, and orbit position as a function of energy, we will adjust the main ring magnet parameters to bring those curves closer to the desired values, and repeat the process of finding the tune and time of flight as a function of energy.

We will set RF frequencies and phases to be synchronized with the beam at some number of energies. We can then measure synchrotron oscillations. This will also give us a time of flight measurement which can be compared to time of flight measurements made without the RF system.

We will then accelerate the beam in the serpentine acceleration mode with the RF cavities powered. We will begin with a relatively large RF voltage to have a large region of phase where we can accelerate the beam. We will using the mapping of orbit position to energy to show the bunch motion in longitudinal phase space, and will extract the beam at various turns to compare the energy measurement in the extraction line to the energy determined from the orbit position.

SUMMARY

Through innovative design, the world's first non-scaling FFAG has been realised at Daresbury as a highly sophisticated accelerator research tool. The initial ring commissioning is underway in parallel to the final system installation and testing. Next steps are the demonstration of acceleration, followed by a systematic set of experiments designed to comprehensively characterise this unique accelerator and it operation.

ACKNOWLEDGEMENTS

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