COMMISSIONING OF THE EMMA NON-SCALING FFAG

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Abstract

EMMA is the world's first non-scaling fixed field alternating gradient accelerator and is being constructed at the STFC Daresbury Laboratory. Experience from the initial commissioning phases (from early 2010) will be reported and lessons for future machines of a similar type will be discussed. The present experimental status and future plans will also be reported.

INTRODUCTION

The EMMA accelerator has been discussed in detail elsewhere at this conference [1]. Basically, it is a linear, non-scaling FFAG (ns-FFAG) which is being built to demonstrate and study in detail the unique features of this type of machine, in particular:

- the very small momentum compaction, approaching 0 in some regions of phase space
- the multiple resonance crossings during acceleration
- bucketless or serpentine acceleration for relativistic particles (see figure 1).

In addition, it will be used to benchmark the purpose-built or modified tracking codes that are being used to model this type of accelerator for this and a variety of other applications [2].

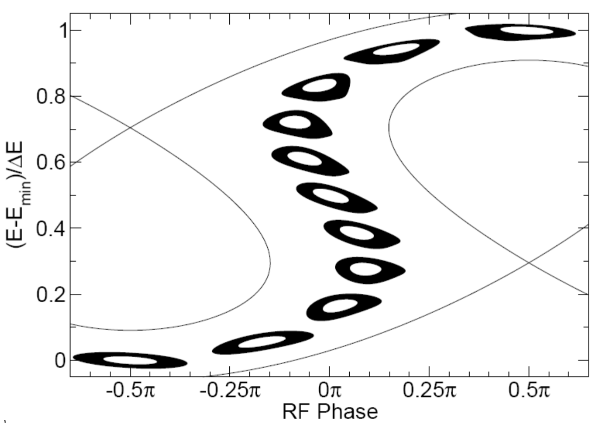

Figure 1: Serpentine acceleration: the phase of the beam is shown with respect to that of the RF system during acceleration.

EMMA is being built at the STFC Daresbury Laboratory and will accelerate electrons from 10 to 20 MeV. The parameters of the machine are summarised in table 1. It will use a doublet lattice and will have 42 magnetic cells. The electron beam will be provided by the existing ALICE accelerator [3] at the Daresbury Laboratory and a new injection line has been built to transport the beam to the EMMA ring. The layout of the facility is shown schematically in figure 2.

Table 1: EMMA Parameters

Energy range	10 to 20 MeV
Cell	Doublet
Number of cells	42
RF	19 cavities; 1.3 GHz
Cell length	394.481 mm
Ring circumference	16.57 m

EMMA LATTICES

As the primary purpose of EMMA is to study, as fully as possible, the beam dynamics of ns-FFAGs, 8 different magnetic lattices [4] have been created to probe the longitudinal and transverse phase space of the machine. The properties of these lattices are summarised in table 2. To achieve the aims of the project, they have been designed to have different tune footprints, and hence cross different major resonances (see figure 3). As EMMA is flexible enough to introduce known "errors", for example magnetic field errors in some magnetic cells, and asymmetries, e.g. the number of powered RF cavities, it will be possible to do detailed studies of the effect of the resonances as a function of the machine parameters. In addition, as the time-of-flight (ToF) in a non-scaling machine is not perfectly parabolic and symmetric about the central energy, it is important to check how the longitudinal beam dynamics change as the parabola changes. The lattices have been designed so that the position of the minimum in the ToF occurs at different energies and the ToF variation is different (see figure 4). The specifications for the machine have largely been determined by the needs of these 8 lattices.

Table 2: Properties of the 8 EMMA lattices

Lattice	ToF minimum	Resonances crossed		
		$3\nu_x=1$	$\nu_x+2\nu_y=1$	$\nu_x-2\nu_y=0$
070221b	Symmetric	Yes	Yes	No
070221c	Symmetric	Yes	No	No
070221d	Symmetric	No	No	No
070221e	Symmetric	Yes	No	Yes
070221f	14 MeV	Yes	Yes	No
070221g	15.5 MeV	Yes	Yes	No
070221h	14 MeV	Yes	No	Yes
070221i	15.5 MeV	Yes	No	Yes

EXPERIMENTAL PROGRAMME

The experimental programme is broken into two parts: (1) commissioning, and (2) experimental studies. Each of

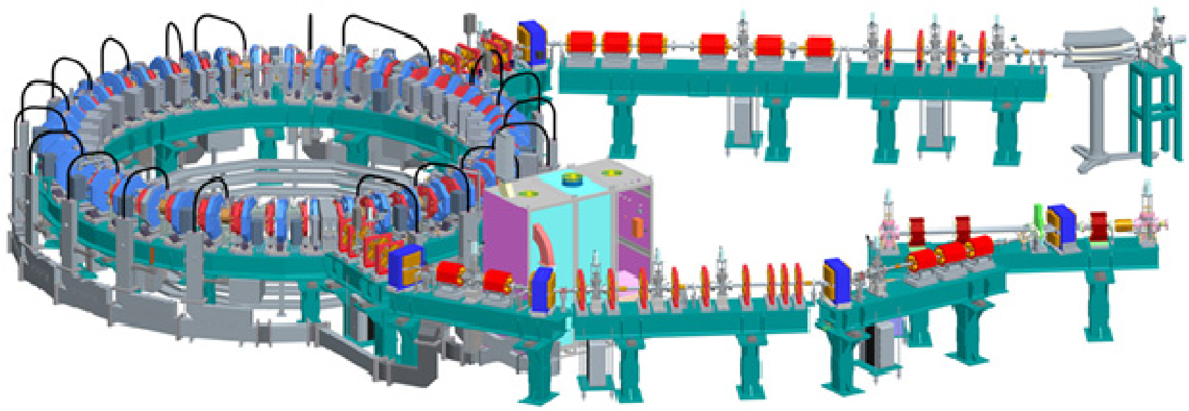

Figure 2: The layout of EMMA. Shown is a short section of the ALICE machine, with a new dipole magnet to steer the beam into the injection line (bottom of the picture). The EMMA ring, showing the 42 cells, is on the left and the diagnostics beam line at the top.

these is discussed in more detail in the following sub-sections.

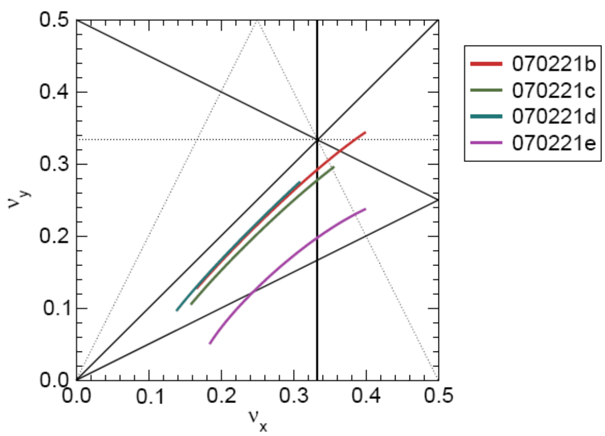

Figure 3: Single cell tune footprint over the full energy range for each lattice. Straight lines are single-cell resonance lines up to third order, solid lines are upright driven (except the linear coupling resonance).

Commissioning

The commissioning of the EMMA has been planned in several stages, as follows:

- As beam is required from ALICE between 10 and 20 MeV and it does not usually run at these energies, some setting up and optimisation is required. In addition, measurements of some the beam properties in ALICE, e.g. emittance, are required.
- Commissioning of the injection line. The beam must be transported to the end of the line and measurements made of the beam properties.
- Injection into the EMMA ring. It is currently planned to inject into 4 out of the 7 EMMA girders, otherwise known as 4 sector commissioning. This will enable a number of measurements to be made without the beam making a complete turn.
- Complete ring commissioning, with all 7 girders in place, but without acceleration.
- Acceleration commissioning.
- Extraction line commissioning, including the diagnostic devices in this line and the first measurement of the extracted beam parameters.

Although some parts of the experimental programme described below will be undertaken during these commissioning phases, the full programme will only be possible once all the phases have been completed.

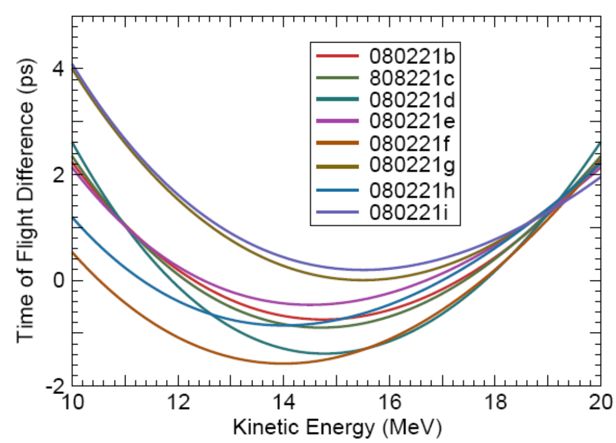

Figure 4: Time of flight as a function of energy for the different lattices.

Experimental programme

The experimental programme will also proceed in a number of stages. The first will be to measure the tunes and time-of-flight as a function of beam energy. Several methods for making these measurements have been proposed and will be studied during the commissioning phase. These measurements, in comparison to the expectations from a computer model in the Zgoubi code [5], will allow the tuning of the lattice to the baseline lattice initially required (070221b above). Once this is established, the next step will be to demonstrate serpentine acceleration and verify that this behaves as expected.

Once these phases have been completed, the true experimental programme can commence. The first step in this will be to scan the longitudinal phase space in both phase and energy, measuring the beam distributions and any emittance distortion in the process. These will be compared with the computer model. The second step will be to vary the RF frequency and voltage and check the effect on the serpentine channel, in particular this channel closing. Again, the beam distributions and any emittance distortion will be measured as a function of these parameters and compared with the model. The third step will be to investigate the transverse dynamics of the accelerator. In particular, this will include measuring the dynamic aperture versus energy, as a function of phase, RF frequency and voltage, and the time-of-flight as a function of the beam transverse amplitude. Any differences in the longitudinal behaviour as the beam is accelerated at larger transverse amplitudes will also be measured.

The next step will be to investigate in more detail resonance crossings for the baseline lattice. There are several ways in which this can be done. As already discussed above, it is possible to introduce significant artificial errors in EMMA and modelling has already shown that these can generate measureable effects even at the normal acceleration rates (see figure 5). However, the preferred method of study is to slow down the acceleration rate to study the emittance distortion as a function of acceleration. What will be achievable will only be known once the experimental programme has started.

The final step will be to repeat these measurements with the other 7 lattices. This will allow a study of how the crossing of different resonances affects the accelerator performance, in particular the dynamic aperture and the transverse emittance growth. It will also show how changes to the time-of-flight curve affect the longitudinal beam dynamics. A detailed comparison of the results with one or more computer models will bring a better understanding of how linear, non-scaling FFAGs work and benchmark these codes for other applications.

EMMA STATUS

Being the first machine of its type, there have been significant challenges in the design and construction of EMMA. Further, the compactness of the machine has made some components very difficult to design and build, in particular the injection and extraction systems. The result of this is the machine is not as advanced as had been hoped and commissioning of the ring has not yet started. The current status of the machine is shown in figures 6 and 7 and summarised below.

As of the middle of May 2010, the injection line is complete and the first measurements of the beam in this have been made. These will be presented below. Four of the 7 EMMA girders are complete and in place in the experimental hall. The fifth and sixth girders were installed in the middle of May 2010 and this will be followed by about a month of cabling up, testing, etc. Once this is complete, 4 sector commissioning will start. The last girder will be completed and installed later in 2010 and this will be followed by the other commissioning steps and the experimental programme described above.

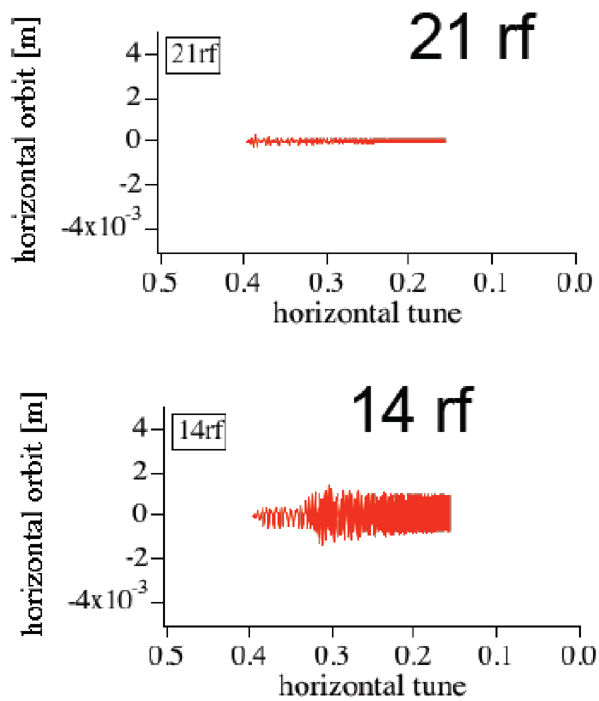

Figure 5: Horizontal orbit errors for 21 (top) and 14 (bottom) RF cavities. Note that the increased asymmetry with 14 cavities excites the third integer resonance.

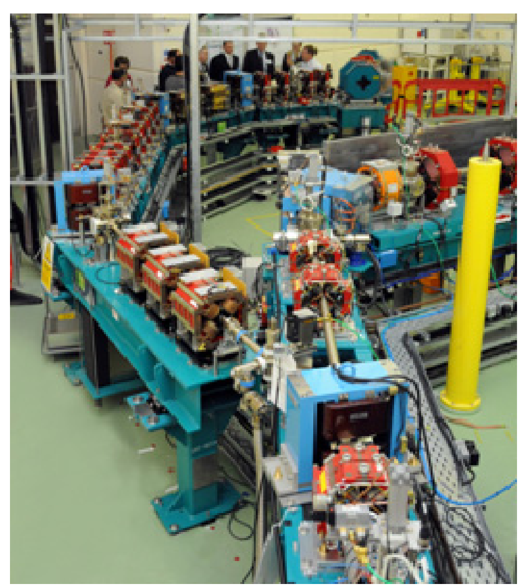

Figure 6: Part of ALICE and the EMMA injection line.

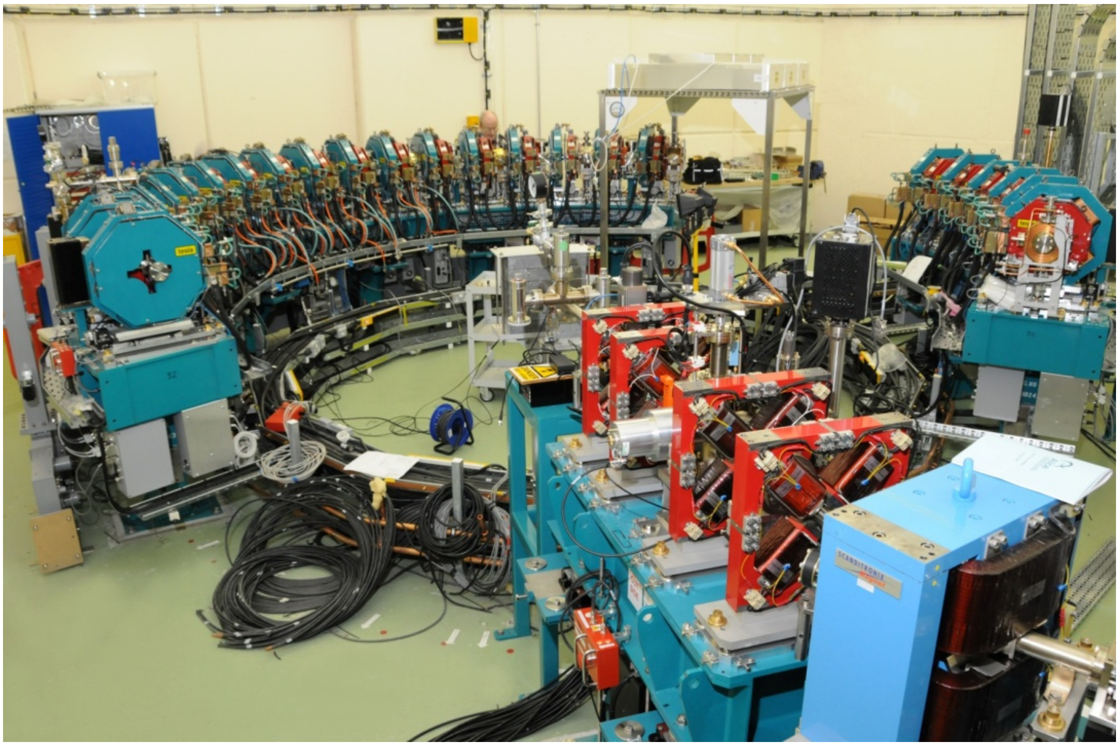

Figure 7: EMMA as of the beginning of 2010. This shows the end of the injection line and the 4 (out of 7) ring girders in place at the time.

COMMISSIONING STATUS

As explained above, EMMA commissioning has only recently started and only the first two bullet points above have been possible. This work is on-going and short running periods have been possible during the EMMA installation process. Only some very preliminary measurements are included here from the first attempt to pass beam through the injection line.

There are 6 YAG screens in the injection line and figure 8 shows images from the first and last screens in the line. An initial analysis has started of the beam energy spread and emittance in this line, as this information is very important for beam loading and space charge effects in the ring. The energy spread is being measured from the beam size on a screen in a region of high dispersion and, although the analysis is very preliminary, the result obtained is consistent with expectations. The emittance is being determined from the Twiss parameters measured in the injection line "tomography" section. This work is not yet complete.

CONCLUSIONS

The EMMA non-scaling FFAG is being constructed at the STFC Daresbury Laboratory. Due to significant technical difficulties that have been encountered during the construction is this unique accelerator, there have been delays in starting commissioning. Nevertheless, the machine is now well advanced and measurements have been made of the beam in the injection line. These measurements are on-going and it is believed that injection into the first part of the EMMA ring should begin in the near future.

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