EMMA – THE WORLD'S FIRST NON-SCALING FFAG

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EMMA Collaboration

Abstract

EMMA - the Electron Model of Muon Acceleration - is to be built at the STFC Daresbury Laboratory in the UK. It will demonstrate the principle of non-scaling FFAGs and be used to study the features of this type of accelerator in detail. Although a model of the muon accelerators in a Neutrino Factory, EMMA will have sufficient flexibility to study a variety of applications. It has been designed by an international collaboration of accelerator physicists and will be built as part of the CONFORM project using funds recently approved in the UK.

INTRODUCTION

Non-scaling FFAGs (NS-FFAGs) were invented at the end of the last decade [1], principally for the acceleration of muons in a Neutrino Factory [2]. They are ideal for this purpose as the fixed field nature allows rapid acceleration. Further, the non-scaling nature allows the manipulation of the particle orbits to produce a parabolic variation of the orbit length with energy. This gives a much smaller momentum compaction and hence a smaller orbit excursion than for a scaling FFAG, for example. A remarkable feature of these machines is this small orbit excursion can be achieved with linear magnetic fields. This gives them a large dynamic aperture and the ability to use higher RF frequencies than scaling FFAGs. In addition, it is possible to accelerate relativistic particles over a factor of more than 2 in momentum without changing the RF frequency (so-called asynchronous acceleration [3]), making CW operation possible for muon acceleration. For these reasons, NS-FFAGs have been selected as part of the baseline acceleration system for a Neutrino Factory.

More recently, due to their interesting properties, NS-FFAGs have been studied for other applications, in particular a high power proton driver for a Neutrino Factory [4] and for proton and carbon cancer therapy [5].

However, nothing comes for free and this type of machine also has three unique and potentially problematic features

- Due to the non-scaling nature, the tunes vary over a large range during acceleration. This means many resonances are crossed.
- The momentum compaction is much smaller than any similar machine ever built.
- Asynchronous acceleration has never been intentionally employed by any accelerator.

These features have been studied in some detail for muon acceleration and none appear to prevent NS-FFAGs from working. However, before a machine can be built for this or any other application, it is essential to build at least one proof-of-principle NS-FFAG to study these and all other features of this type of machine. This is the purpose of EMMA. The machine is being designed and built by an international collaboration from the following institutes: Brookhaven National Laboratory, CERN, Cockcroft Institute, Fermi National Accelerator Laboratory, Grenoble, John Adams Institute, Science and Technology Facilities Council and TRIUMF.

EMMA

Aims

The principle aim of EMMA is to demonstrate that non-scaling optics work and to make a detailed study of the features of this type of machine. In particular, a detailed investigation will be made of:

- Longitudinal dynamics, including the time-of-flight behaviour, the transmission and emittance growth as a function of parameter values, etc.
- Resonances, including emittance growth as function of acceleration rate and tune variation and the effect of errors.

In addition, much will be learnt from the construction of the first machine of this type.

Lattice

To reduce the cost, EMMA will use electrons to model the muon accelerators of the Neutrino Factory. The parameters of the machine, which have been appropriately scaled for the model, are listed in Table 1. A doublet lattice has been chosen, to minimise cost, and there will be 42 cells. Four cells are shown in detail in Figure 1 and the whole ring in Figure 2. Note that RF cavities will be installed in every other cell, except for around the injection and extraction regions. The other cells will be used for vacuum pumps, beam diagnostics and vertical orbit correctors.

Table 1: EMMA Parameters

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

To deliver the aims of the project, a number of different lattice configurations have been designed [6]. These impose a number of requirements on the hardware, in particular:

- Independently variable dipole and quadrupole fields in the magnets

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- Sufficient aperture in the magnets, RF and vacuum pipe to contain all orbits
- The ability to vary the RF frequency by -4.0 to +1.5MHz around 1.3GHz.
- A gain per cavity variable from 20kV to 180kV.
- The ability to be able to inject and extract at any energy.
- Sufficient diagnostic devices to be able to make detailed measurements of the beam.

The design of the hardware has taken these requirements in to account and is now far advanced. The main components of the machine are described in following section.

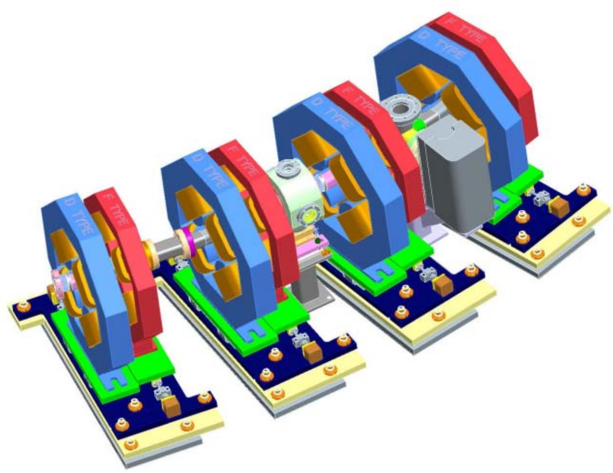

Figure 1: Four EMMA cells, showing the magnets mounted on sliders. Between the middle two cells is an RF cavity. The left gap has a resistive wall monitor and the right an ion pump.

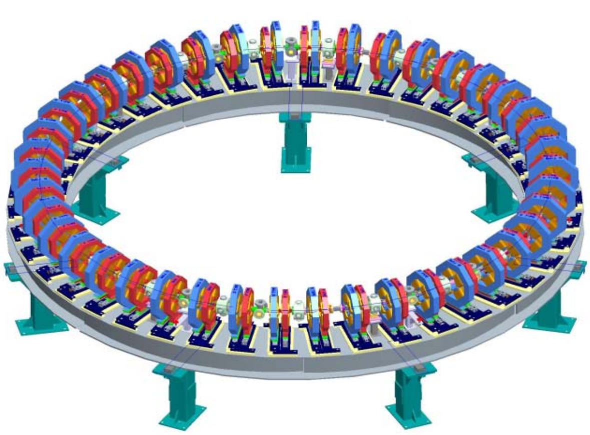

Figure 2: The complete EMMA ring.

Location

Two further requirements had to be met before the design of EMMA could advance: (1) a flexible injector, with sufficient space in the same hall, had to be found, and (2) the funding for construction had to be obtained. The injector needs to be able to provide a beam over the full energy range of EMMA, to allow detailed probing of resonances. It must be able to provide at beam with the right time structure and with sufficient intensity for the EMMA diagnostics.

Such a machine now exists at the Daresbury Laboratory, the Energy Recovery Linac Prototype (ERLP) [7]. Construction of this machine has recently finished and commissioning has started. Further, there is sufficient space in the hall for EMMA.

To obtain the funding, the CONFORM consortium (COnstruction of a Non-scaling Ffag for Oncology, Research and Medicine) was formed [8]. This submitted a proposal for funding to build EMMA and to study NS-FFAGs for hadron therapy and other applications. The proposal was successful and the funding started on 1st April 2007. Work on EMMA had, however, already started much before this.

EMMA HARDWARE

The design of the hardware for EMMA is still on-going, though some aspects are advanced and prototypes are ordered. Here, we will discuss only the three main components of the machine: magnets, RF and diagnostics.

Magnets

Due to the relatively large ring circumference compared to the electron energy, the combined function magnets for EMMA would actually have much bigger quadrupole components than dipole. As a result, it was decided to build the magnets as quadrupoles and obtain the dipole component by using them off-centre. The independent variability of these components is obtained by mounting them on sliders, so that the position of the beam within the magnet can be changed. This scheme is demonstrated by figure 1. Note that field clamp plates will be mounted either side of the doublet to prevent magnetic interaction with, for example, the kicker magnets for injection and extraction.

The parameters of the magnets are summarised in Table 2. Due to their aspect ratio, proximity and the fact that the particle orbits extend far from the central axis, detailed 3D modelling is currently being undertaken. An order has been placed for prototypes of each magnet to verify the modelling and to measure field uniformity, etc.

Table 2: F and D magnet parameters

	D	F
Separation	50mm	
Yoke lengths	65mm	55mm
Inscribed radii	51mm	36mm
Displacement at reference energy	34.0mm	7.5mm
Minimum shift	28.8mm	4.9mm
Maximum shift	48.6mm	10.2mm
Aperture (h)	26.2mm	42.3mm
Aperture (v)	23.4mm	17.8mm
Max. field (T)	0.44	0.48

The number of power supplies to be bought for the magnets is still under study. The ideal situation is to have

84 supplies, one for each magnet, but this will be expensive. The cheapest option is to have two: one for the F's and one for D's. However, this will exclude individual control of the fields in the magnets. This will be necessary in at least a few to allow known field "errors" to be introduced. The likely solution is to measure all the magnets on delivery and use individual supplies for those which fall outside the required uniformity for the magnets, ±0.05%.

As well as the main magnets, 16 vertical correctors will be placed in available cells without RF cavities for vertical orbit correction.

Injection and extraction from EMMA has been studied in detail [9]. Injection is required at all energies to allow a detailed probe of resonances. Extraction at all energies is required because some of the diagnostics can only be mounted in an diagnostics extraction line. Thus, it must be possible to kick across the entire EMMA aperture in both cases. Tracking studies suggest this is possible using a septum and two kickers in adjacent cells. It is for this reason that it is not possible to have RF cavities in the injection and extraction regions.

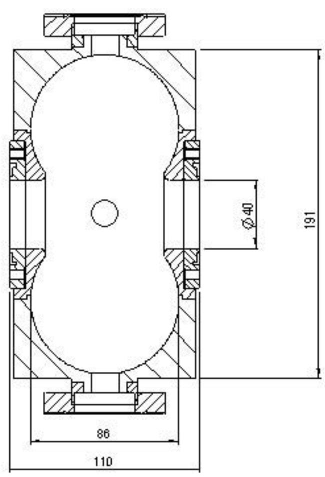

Figure 3: The RF cavity model

Designs for the injection and extraction lines themselves are currently under study. As far as possible, these will re-use magnets from the Synchrotron Radiation Source (SRS) at Daresbury, which is soon to be closed down.

RF Cavities

There will be 19 cavities in EMMA, one every other cell, except for around injection and extraction. They must fit into a slot length of 110mm and have an aperture of 40mm. As the RF power sources are the most expensive item in EMMA, considerable effort has gone in to modelling the cavities to maximise shunt impedance. The resulting design is shown in Figure 3. This is estimated to have a shunt impedance of 4.3MΩ, though it is likely that only 3.4MΩ will be achievable in practice. The thermal and structural analysis of this cavity is now underway. The aim is to have a prototype available for measurements during the autumn.

With this expected shunt impedance, the total RF power required is 116kW, including a 30% overhead. This can be delivered in two ways: using IOTs or via a single klystron using the SRS power supply. The best option will depend to some extent on the actual performance of the prototype cavity. The low-level RF and distribution systems are still being designed.

Diagnostics

As EMMA is an experimental machine having sufficient diagnostics is crucial. The current requirements and how they will be met are summarised in Table 3. The details of the hardware are currently being worked on.

Table 3: The diagnostics requirements of EMMA. The last three measurements will be made in the extracted beam line.

Measurement	Device	Number
Beam position	4 button BPM	84
Beam profile	OTR screens & wire scanners	Not decided
Beam current & phase wrt RF	Resistive wall monitor, Faraday cup	4
Beam loss	Beam loss monitor	4
Emittance	Screens	3
Momentum	Spectrometer	1
Long. Profile	Cavity and screen	1

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