

EMMA

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On behalf of EMMA collaboration

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Abstract. EMMA stands for Electron Model for Many Applications and is expected to demonstrate the novel concept of a non-scaling Fixed Field Alternating Gradient (FFAG) accelerator. A non-scaling FFAG accelerator was originally invented to accelerate muons up to a few tens of GeV energy range although it is now hoped to have a wider variety of applications such as a proton driver for Accelerator Driven Sub-critical Reactor (ADSR). We will report the recent developments of the EMMA experiment, with more emphasis on acceleration of a muon beam.

1. Introduction

The accelerator for a muon beam has different requirements from that for a conventional particle beam such as protons and electrons. Acceleration has to be very quick because of its lifetime in the rest frame which is $2.2 \mu\text{s}$. Acceptance should be large enough to accommodate the large muon beam emittance, which is true even after the ionisation cooling. A linear accelerator (or linac) could satisfy the requirements because it is basically a sequence of accelerating units and its aperture could be as large as the muon beam emittance. One drawback of a linac for muon acceleration is the cost. Using an acceleration unit only once for each beam pulse is the most inefficient way of transferring energy to the beam. In order to reach the final energy, the total sum of the gap voltage over all the acceleration units must at least be equal to the final energy.

Circular accelerators like the cyclotron and synchrotron use their acceleration units repeatedly for the same beam pulse in order to minimize the required rf voltage and reduce the total machine cost to achieve the final energy. However, the cyclotron does not work as a muon accelerator because muon beams are in the ultra-relativistic regime. The synchrotron has a problem as well because of its slow repetition of acceleration. As a hybrid type of accelerator between linear and circular ones, a re-circulating linear accelerator (RLA) had been proposed [1]. It utilizes a linear accelerator as an accelerating unit but with the several arcs of 180 degree bending at the end of the linac so that multiple passes through the linac can be realized. In practice, however, more than 4 or 5 re-circulations is not feasible because the separator/combiner between the linac and the arc becomes increasingly complicated.

A Fixed Field Alternating Gradient (FFAG) accelerator is a circular accelerator with a strong focusing lattice like a synchrotron [2]. However, as its name implies, the guiding magnetic field is

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constant in time and the time required for acceleration is determined only by the available rf voltage. For example, if we could provide 1 GV rf voltage per turn, 10 GeV energy gain would be possible in 10 turns within a few micro seconds. Considering the lifetime of muons which is Lorentz boosted, acceleration in a few micro seconds is still fast enough. If large physical and dynamic aperture are assured, a FFAG accelerator becomes a very promising candidate for muon acceleration with relatively low capital cost.

Proposal of muon acceleration with a FFAG has been published first at Nufact01 workshop [3]. It assumed a scaling FFAG in which the lattice magnets have transverse field profile of r^k so that the transverse tune stays constant through the acceleration. Constancy of tune is essential for more conventional acceleration where a beam circulates in an accelerator for a few tens of thousands or even more turns. If tune changes during acceleration by more than a unit, a beam will cross dangerous integer and half-integer resonances which are excited by imperfections of lattice magnets and misalignments. However, the resonance is an accumulative phenomenon and it may not affect a beam if it circulates in an accelerator for only 10 turns.

If constancy of transverse tune is eliminated, the lattice magnets can be simpler and, more importantly, becomes more compact, which further enhances the advantage of a FFAG accelerator. That is a non-scaling FFAG which uses linear quadrupole magnets instead of more complicated magnets with nonlinear fields [4]. For acceleration of a muon beam within around 10 turns, particle tracking simulation shows that it is indeed possible to use the non-scaling FFAG without deterioration of beam quality [5]. A neutrino factory design with a non-scaling FFAG as the main muon accelerator becomes now a baseline [6].

2. Goals of the experiment

The idea of a non-scaling FFAG seems feasible by paper, but it certainly needs an experimental demonstration. Fortunately, a project was approved and a small-scale model using 10 to 20 MeV electron beams from ALICE (Accelerators and Lasers in Combined Experiments) facility [7] was constructed at Daresbury Laboratory in the UK. With more applications of this new type of accelerator in mind, the model accelerator is named Electron Model for Many Applications (EMMA).

Table 1. Principal parameters of EMMA.

	Value	Unit
Momentum	10.5 to 20.5	MeV/c
Circumference	16.57	m
Number of cells	42	
Focusing	focusing/defocusing quadrupole doublet	
Nominal integrated quadrupole gradient (QF/QD)	0.402/-0.367	T
Radio frequency	1.301	GHz
Number of radio frequency cavities	19	
Tune shift for the momentum range above	~0.3 to ~0.1/cell ~12 to ~4/ring	
Acceptance (normalized)	3	π mm rad

The construction of the major parts has completed by June 2010 and the beam commissioning started right after. The main parameters are listed in Table 1.

In the EMMA experiment, we set three main goals. One is the rapid acceleration with large tune shift during acceleration, which is inevitable due to lattice focusing with linear quadrupole magnets. In the accelerator terminology, the accelerator is operated with natural chromaticity over a wide momentum range ($\pm 33\%$). Figure 1 shows the horizontal and vertical tune per ring as a function of beam momentum from 10.5 to 20.5 MeV/c. The total ring consists of 42 identical doublet focusing cells. The cell tune can be defined as the ring tune divided by the cell number of 42. Therefore, the cell tune is within 0 and 0.5, meaning that there is no systematic integer and half-integer resonance lines crossed during acceleration. However, a beam must traverse non-systematic integer and half-integer resonances. The experiment should show whether those non-systematic resonances can be safely avoided with rapid acceleration.

Second goal is to demonstrate acceleration in a serpentine channel. We need an explanation of the serpentine channel here. In order to minimize the orbit excursion in horizontal direction from the lowest to the highest momenta, the dispersion function everywhere in the ring is minimized. This leads to the minimum variation of the orbital length in the whole momentum range and the orbital length has a parabolic dependence as a function of momentum. In the momentum range of 10.5 to 20.5 MeV/c for electrons, it is already ultra-relativistic so that the orbital period also has a parabolic shape as a function of momentum. This means that the accelerator is operated almost on the isochronous condition, but not exactly. In other words, a beam goes through the transition energy at the middle of acceleration. When we choose the rf frequency such that it synchronizes at one momentum below the transition, this implies that there is a corresponding synchronous momentum above the transition. In the longitudinal phase space, two stable fixed points appear slightly below and above the transition energy whose phase position is 180 degree apart. Now if we keep increasing the rf voltage, the rf bucket size increases until its separatrix merges with the unstable fixed point associated with the other bucket. The longitudinal phase space geometry suddenly changes and the continuous channel starting in the area below the lower stable fixed point to the one above the higher stable fixed is created [8]. The beam is injected outside of the separatrix, but it gained energy at almost fixed rf phase. It was reported that similar acceleration dynamics had been observed in a cyclotron where the isochronism was not exactly satisfied [9]. Figure 2 shows the evolution of a beam in longitudinal phase space in the serpentine channel.

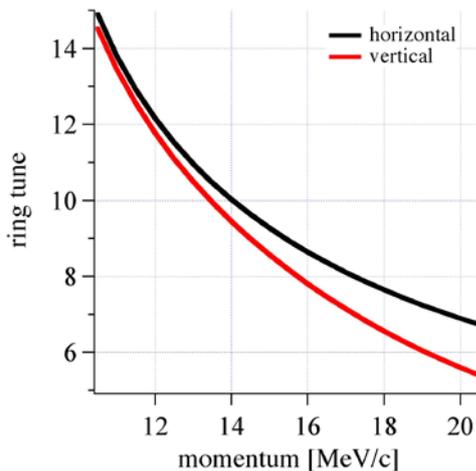


Figure 1. Tune shift during acceleration. The ring consists of 42 identical cells so that cell tune is $1/42$ of ring tune.

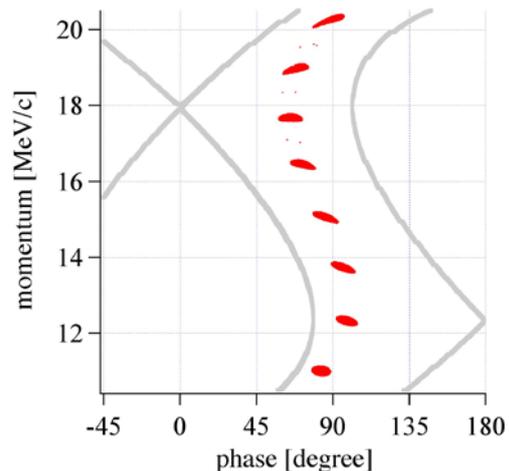


Figure 2. Beam (red bunch) is accelerated in serpentine channel. Grey curve shows separatrix.

The third goal is to show large acceptance. Since the lattice focusing magnet has no nonlinearity, dynamic aperture is expected to be large and simulation study confirms it. However, it is necessary to demonstrate that is the case experimentally.

3. Experimental observation

The beam commissioning started last summer in 2010 and it continues until next year in 2012. The recent development will be published in a conference proceedings [10] and a paper [11].

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