THE EMMA LATTICE DESIGN

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Abstract

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). This paper describes the design of the EMMA lattice. We begin with a summary of the experimental goals that impact the lattice design, and then outline what motivated the choice for the basic lattice parameters, such as the type of cells, the number of cells, and the RF frequency. We next list the different configurations that we wish to operate the machine in so as to accomplish our experimental goals. Finally, we enumerate the detailed lattice parameters, showing how these parameters result from the various lattice configurations.

PURPOSE OF EMMA

EMMA will be the first non-scaling FFAG ever built. Its purpose will be to study the dynamical properties that are important in a highly relativistic linear non-scaling FFAG.

In a linear non-scaling FFAG, the tune depends strongly on energy. In most machines, this would lead to substantial beam loss due to resonance crossing. Substantial dynamic aperture over the entire energy range is maintained because

- The lattice consists entirely of simple cells (doublets for EMMA) which are made as identical as possible. Computing resonances for a single cell thus gives all important resonances for the machine.
- Only linear magnets are used, minimizing nonlinear driving terms.
- Acceleration is rapid, so that the remaining weak resonances, due to nonlinearities, primarily arising from magnet ends, and linear lattice imperfections, are crossed rapidly.

EMMA will attempt to study the importance of all of these conditions. It will be capable of breaking the machine symmetry. The acceleration rate will be varied. Finally, the range of resonances which are crossed in the machine will be modified, and individual resonances will be studied.

The time of flight also depends on energy. For highly relativistic machines, such as EMMA, one can choose a single energy where the machine is locally isochronous. Using fixed-frequency RF cavities, one expects to eventually lose synchronism with the RF, and therefore to no longer accelerate. There are three methods for addressing this:

- Vary the RF frequency to match the time of flight as one accelerates.
- Use a fixed RF frequency, but make the harmonic number change by (approximately) an integer on each turn [1, 2].
- Use a fixed RF frequency, and complete the acceleration before the bunch is too far off crest.

We will examine the latter acceleration scenario, which has never been used in an accelerator before. EMMA will vary the parameters that determine the longitudinal dynamics to insure that our understanding of this mode is correct. In principle, a later upgrade of EMMA could look at one of the other acceleration scenarios as well.

THE BASIC MACHINE PARAMETERS

EMMA is similar in design to a muon accelerator FFAG. Its parameters are based on those designs [3].

EMMA should be able to accelerate by a factor of two in momentum, which is a minimum desirable amount of acceleration for a machine. An energy range of 10 to 20 MeV was chosen for the machine based on a compromise between the desire to keep the beam highly relativistic and the cost benefits of a smaller, lower energy machine.

The number of cells in the machine times the number of turns required for acceleration characterizes the performance of the machine. This number should be high, since it means that less RF voltage will be required to accelerate for a given ring circumference, and acceleration will be more adiabatic. Making the number of cell-turns larger in the accelerating mode used here, however, generally requires more cells in a ring, shorter cell lengths, and lower RF frequencies. Typical muon acceleration rings have between 500 and 1500 cell-turns; to keep costs down, our goal is to achieve 500 cell-turns for reasonable longitudinal phase space acceptance, defined as an a parameter of $1/12$ [4].

A triplet lattice will give the optimal performance in the chosen acceleration mode for a given number of cells and

Table 1: Basic machine parameters.

Minimum kinetic energy	10 MeV
Maximum kinetic energy	20 MeV
Approximate RF frequency	1.3 GHz
Lattice cells	42
RF cavities	19
Lattice type	Doublet
Normalized transverse acceptance	3 mm
Nominal long drift length	210.000 mm
Nominal short drift length	50.000 mm
Nominal D magnet length	75.699 mm
Nominal F magnet length	58.782 mm

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fixed cell length. However, since a triplet lattice requires three magnets per cell and an additional inter-magnet drift, and the end magnets will need to be very short, a doublet lattice is preferred.

We choose between two readily available RF frequencies, 1.3 GHz and 3 GHz. Using 3 GHz would require substantially more lattice cells to achieve our goals, and would have lower stored energy per cavity cell than 1.3 GHz RF (important since beam loading effects should be small). While RF power transport is more expensive for 1.3 GHz than for 3 GHz, that is not enough to overcome the advantages of the smaller ring.

The machine has 42 lattice cells. Using fewer cells would require shortening the already short magnets and increasing their fields substantially. The number of cells is kept as small as possible to reduce the cost and ring size.

Ideally, we would fill every other cell with an RF cavity, leaving remaining cells open for diagnostics and injection/extraction hardware. Two additional cavities must be removed for injection and extraction, leaving 19 cavities in the ring. Filling every third cell instead of every second increases the RF power requirement and creates larger betatron oscillations due to the discrete nature of the acceleration and the nonzero dispersion in the cavities.

We wish EMMA to have similar levels of nonlinearities to a muon machine. The relative importance of nonlinearities in our case is related to the fraction of the magnet aperture occupied by the beam and the angles that the beam makes with respect to magnet ends and axes. A simple scaling argument says that, assuming that the beam occupies a similar fraction of the magnet aperture in both cases and that the lattices have similar numbers of magnets, that the scaling of emittances should be proportional to the cell lengths. Thus, since 30 mm normalized acceptance is desirable for the muon machines [5], a normalized acceptance of 3 mm is our goal for EMMA.

To create the combined dipole and quadrupole fields required for the lattice, we have chosen to use displaced quadrupoles positioned on precision sliders which will allow the dipole field to be varied relative to the quadrupole field. The dipole and quadrupole fields can thus be varied independently, while using quadrupoles which are fairly straightforward to build.

To make the pole tip fields in the magnets similar, to leave adequate space for RF cavities, to leave sufficient room between magnets, and to keep a reference lattice synchronized appropriately with 1.3 GHz RF, the lengths shown in Tab. 1 have been chosen. All magnets are treated in initial studies as being rectangular, and having a constant field within the "nominal length" indicated in Tab. 1. End fields initially are treated as being "hard edge," with a multipole symmetry, using techniques similar to those described in [6, 7]. Subsequent studies will use more realistic fields (using ZGOUBI [8] or other codes). The sequence consisting of an RF cavity, an F magnet, and a D magnet in that order have their axes aligned parallel to each other for ease of construction; there is little penalty for doing so.

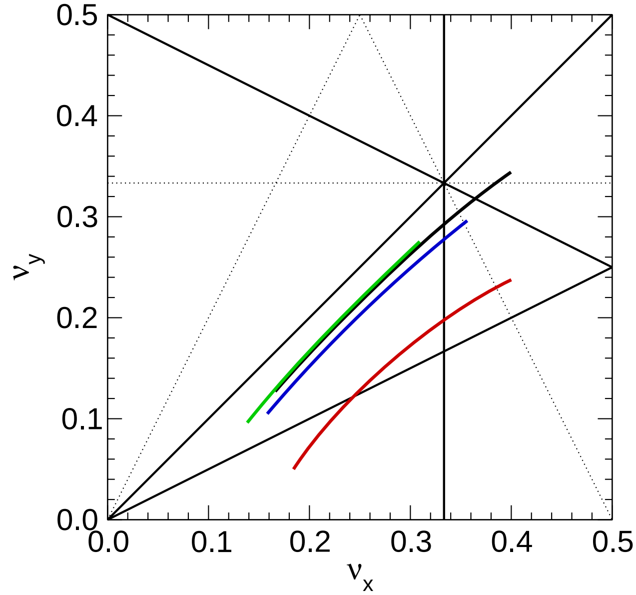

Figure 1: Single-cell tune for all energies for four different lattice configurations. Low energy has higher tune.

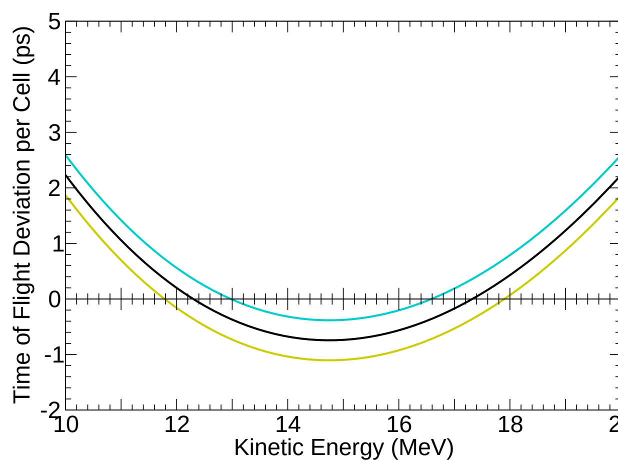

Figure 2: Time of flight as a function of energy for three different RF frequencies. Zero time of flight deviation is when the particle on the closed orbit at that energy is synchronized with the RF. The actual time of flight doesn't change between curves, only the RF frequency changes.

LATTICE CONFIGURATIONS

To establish the range of parameters for the magnet fields and displacements, the RF cavities and power sources, and the vacuum chamber aperture size, we examine several possible machine configurations.

We will vary which resonances the beam passes through during acceleration. We have chosen four configurations based on which of the nonlinear resonances generated by sextupoles to first order the machine crosses during acceleration, as shown in Fig. 1. The configuration with the lowest horizontal tune requires the largest horizontal aperture.

We want to study the effects of varying the time of flight

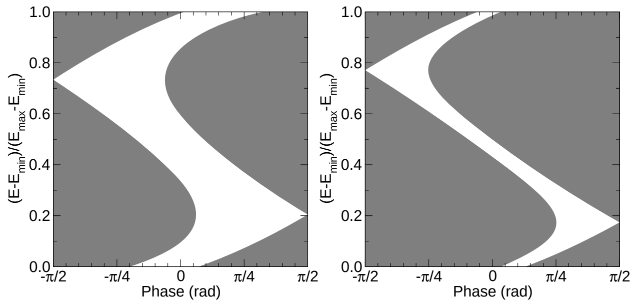

Figure 3: Longitudinal phase space for two lattices which differ only in their RF frequency. Particles are accelerated from the minimum to the maximum energy through the white area.

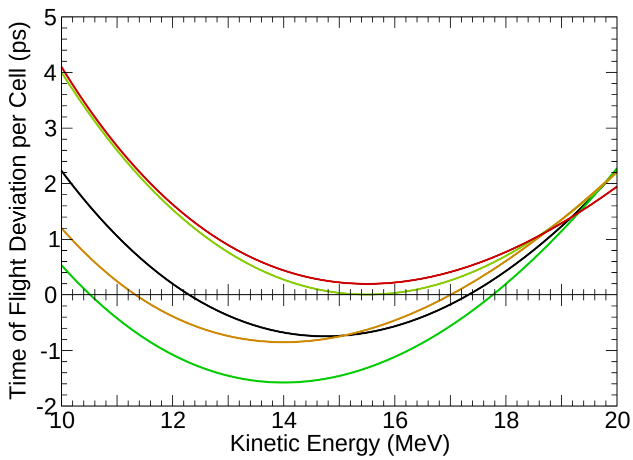

Figure 4: Time of flight as a function of energy for lattices where the minimum in the time of flight is moved to either 14 MeV or 15.5 MeV. The RF frequencies are identical in all cases.

as a function of energy to study its impacts on the longitudinal dynamics. One would like to vary the energies at which the RF is synchronized to the fixed-energy closed orbit (this varies the b parameter in [4]). This is accomplished by adjusting the RF frequency (see Figs. 2 and 3). In addition, one would like to study the effect of varying the position of the minimum of the time of flight. The time of flight is not a symmetric function of energy, and therefore the optimal transmission is not obtained when the minimum is at the central energy or when the times of flight at the minimum and maximum energies are identical. Furthermore, because of the dependence of the time of flight on transverse amplitude [9, 10], the optimal energy for the minimum must take into account all transverse amplitudes. We will modify the magnetic lattice so that the minimum of the time of flight is as low as 14 MeV and as high as 15.5 MeV kinetic energy (see Fig. 4). We will only do this for the two lattices with the highest horizontal tunes, since doing so for the lattices with lower horizontal tunes would require significantly increased apertures.

During commissioning, we will want to run at fixed energies. This will be essential for mapping out tunes and the time of flight as a function of energy. Doing so will require that the time of flight at the energy in question be equal to a multiple (72 in our case) of the inverse of the cavity resonant frequency. This requires an even wider range of cavity frequency variation than the aforementioned study of the longitudinal dynamics.

Table 2: Range of machine parameters required for all configurations.

	D	F	Cavity
Central axis shift			
Minimum (mm)	28.751	4.903	0.439
Maximum (mm)	48.559	10.212	0.439
Aperture radius (mm)	55.975	31.850	34.751
Vacuum chamber apertures			
Minimum horiz. (mm)	-7.416	-21.638	-16.936
Maximum horiz. (mm)	18.789	20.700	17.814
Half height (mm)	11.676	8.906	10.571
Max. gradient (T/m)	-4.843	6.847	—
RF parameters			
Min. freq. offset (kHz)	—	—	-4019
Max. freq. offset (kHz)	—	—	1554
Max. ring voltage (kV)	—	—	2286

The RF voltage in the lattice will be varied to explore its effect on the longitudinal phase space. We need sufficient voltage to have enough phase space volume to easily accelerate the beam ($a = 1/12$), and then some excess voltage to study the effect of voltage variation.

REFERENCES

[1] A. A. Kolomenskii, Zh. Tekh. Fiz. **30**, 1347 (1960) [Sov. Phys. Tech. Phys. **5**, 1278 (1961)].

[2] A. G. Ruggiero, Phys. Rev. ST Accel. Beams **9**, 100101 (2006).

[3] J. S. Berg, in *The International Workshop on FFAG Accelerators, October 13–16, 2004, KEK, Tsukuba, Japan*, edited by S. Machida, Y. Mori, and T. Yokoi (2005), p. 1, URL http://hadron.kek.jp/FFAG/FFAG04_HP/. Report NFMCC-doc-309-v1, URL http://nfmcc-docdb.fnal.gov/cgi-bin/DocumentDatabase/

[4] J. S. Berg, Phys. Rev. ST Accel. Beams **9**, 034001 (2006). See references therein for earlier studies.

[5] J. S. Berg *et al.*, Phys. Rev. ST Accel. Beams **9**, 011001 (2006).

[6] J. S. Berg, in *Proceedings of EPAC 2004, Lucerne, Switzerland* (EPAC and European Physical Society Accelerator Group, 2004), p. 2236.

[7] É. Forest and J. Milutinović, Nucl. Instrum. Methods A **269**, 474 (1988).

[8] F. Méot and S. Valero, report CEA DSM DAPNIA-02-395 (2002).

[9] S. Machida, Phys. Rev. ST Accel. Beams **9**, 104002 (2006).

[10] J. S. Berg, Nucl. Instrum. Methods A **570**, 15 (2007).