BNL-79751-2008-CP

The EMMA Commissioning Procedure

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To appear in the proceedings of the FFAG Workshop '07, 5–10 November 2007, Kyoto University Research Reactor Institute, Osaka, Japan.

January 2008

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Abstract. I begin with a brief review of the goals of the EMMA experiment. I then describe two stages of EMMA commissioning. The first stage is simply to get the beam to circulate a full turn in the ring, and is done only once during the course of the experiment. The second stage will be repeated several times, at least once for each lattice configuration, and involves two parts: setting the required values for the machine parameters, and determining the tunes and time of flight as a function of energy.

Keywords: non-scaling fixed field alternating gradient accelerator, commissioning
PACS: 29.27.Bd

OPERATION OF EMMA

The goal of the EMMA experiment [1, 2] is to demonstrate that we understand the dynamics in linear non-scaling fixed field alternating gradient (FFAG) accelerators. In a linear non-scaling FFAG, both the tune and the time of flight in the machine vary strongly with energy (see Fig. 1). If the RF frequency does not vary during the acceleration cycle, the time of flight variation with energy causes the particles to leave the RF crest after a modest number of turns. Therefore a rapid acceleration rate is required. Since the tune varies with energy, many resonances will be crossed during the acceleration cycle (the term resonance is not completely correct due to the rapid acceleration rate [3], but one does see effects when one excites resonance driving terms [3–5]).

A number of different configurations will be set up in EMMA so that we may study how the behavior of the machine depends on the machine parameters [2, 6]. The tune range will be varied both to change which resonances are crossed during acceleration (see Fig. 2) as well as to see the effect on the longitudinal dynamics. The symmetry of the time of flight curve will be changed so as to see its effect on the longitudinal dynamics.

It is therefore important to know what the tunes and the time of flight are as a function of energy. Since our model of the machine will not be perfectly accurate, we will have to perform measurements to ascertain these functions. Furthermore, we will need to have a method for adjusting the machine parameters to achieve the desired configuration. This procedure will need to be repeated for each desired lattice configuration.

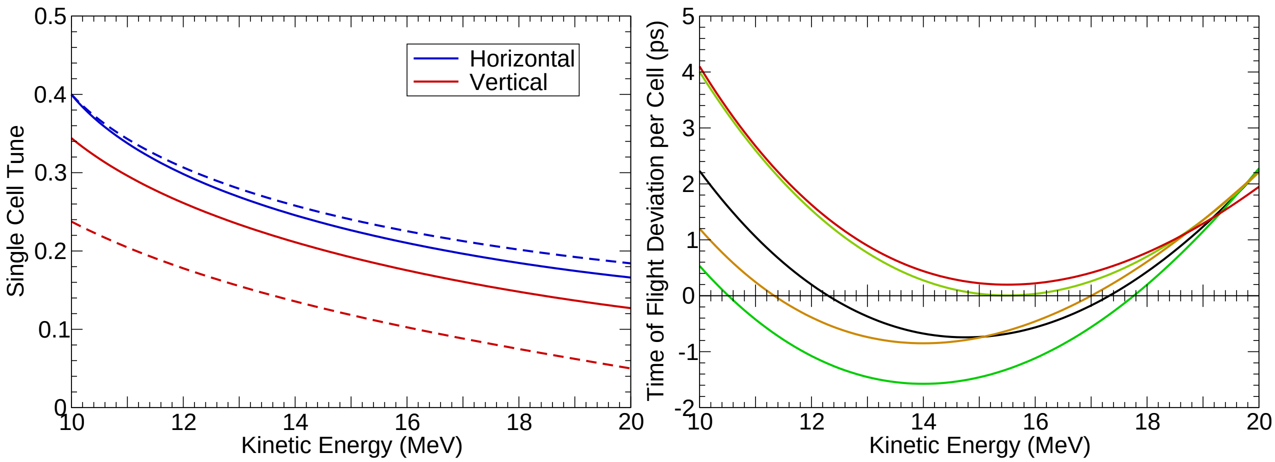

FIGURE 1. Left: tunes as a function of energy for two different configurations. Right: time of flight per cell as a function of energy for various configurations, relative to a time synchronized to 1.3 GHz RF.

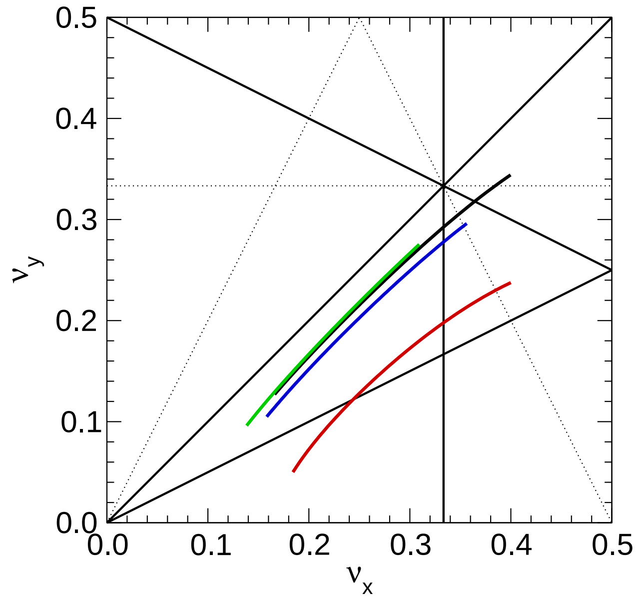

FIGURE 2. Range of single cell low-amplitude tunes for several lattice configurations. Straight lines are resonances up through sextupole order. Dotted lines are skew sextupole driven.

The process is simplified somewhat by an important property of linear non-scaling FFAGs, namely that the lattice consist entirely of simple, identical cells. Any breaking of the symmetry drives resonances, and leads to closed orbit distortion, mismatched beams, and potentially emittance growth [3]. In the case of EMMA, the cell is a combined-function doublet lattice, where the combined-function magnets are displaced quadrupoles. We are capable of adjusting the horizontal position of the displaced quadrupoles, and thus we can vary the dipole and quadrupole fields independently.

In this paper I will begin to outline the commissioning process for EMMA. Commissioning will occur in two stages. The first stage will occur only once, and requires that the machine be aligned to an initial reference position so that the beam can make one turn around the ring. The second stage, which must be repeated for each configuration, is the process of setting the machine parameters that achieve the desired machine configuration, and measuring the tunes and time of flight as a function of energy for that configuration.

THE FIRST TURN: ALIGNMENT

All machines must face the problem of making the beam complete its first turn. In our case, our goal is to have the beam follow exactly the same trajectory in every cell. Determining that this occurs will be complicated by a number of factors.

First of all, it is difficult to ensure that the beam is following the closed orbit. For conventional synchrotron lattices, this would be more straightforward since the closed orbit passes through the center of quadrupole magnets. Determining that the beam follows the same trajectory when the quadrupole is powered and when it is not therefore provides alignment information for the magnet or trajectory. In our case, both magnets bend the trajectory, at least for most energies. While in principle there is a single energy in some configurations where the beam is not bent by the F magnet, the lattice is probably not tuned to the configuration that does so at the computed energy, due to uncertainties in the modeling.

Furthermore, the BPMs are not in the same position in every cell (see Fig. 3; there are two sets of BPMs per cell). Cells with cavities in the long drift have insufficient space to also have BPMs [7]. However, the two sets of BPMs are more effective if they can be placed immediately adjacent to different magnets [8]. Therefore, the BPMs are placed differently in every other cell. Furthermore, there may be difficulties placing the BPMs in the cells with the septa [9]. Thus, one cannot simply search for identical readings in every BPM; at best one can achieve this in every other BPM.

It is thus likely that initial commissioning will rely on having good reproducibility from magnet to magnet, and

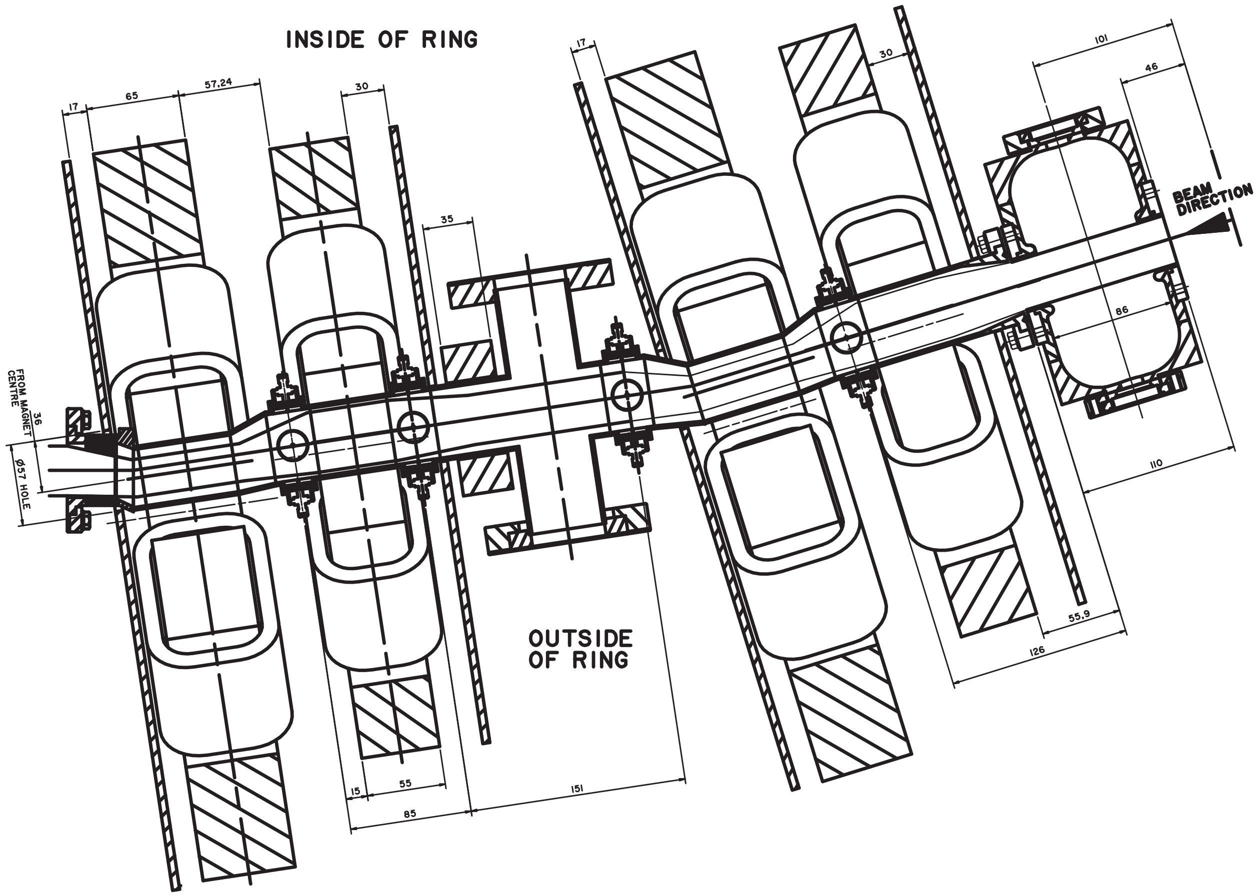

FIGURE 3. Two cells of the EMMA lattice, viewed from above.

accurate initial alignment of the magnets and the BPMs. The BPM readings themselves are likely to be the only point of reference for the beam measurements.

Due to the very strong focusing in this ring, it is likely that as long as the beam is injected into the dynamic aperture of the machine (which should be relatively large), the beam will make it around at least once. From that point, one can search for closed orbits at various energies, and then minimize the closed orbit distortion via magnet alignments. Horizontal misalignments are easily corrected by horizontal displacements. One should insure that vertical alignments can be corrected through some fine adjustment, which in principle need not be made very often (ideally only once).

SETTING MACHINE PARAMETERS, MEASURING LATTICE FUNCTIONS

To determine the properties of a configuration and to ascertain whether we have reached the proper configuration, one must find the tunes and the time of flight as a function of energy. More precisely, at a number of different energies, one will find the closed orbit, measure the time of flight on that closed orbit, and measure the beam tunes by inducing small oscillations in the beam. Ideally one would like the tunes to about 1% accuracy and the time of flight per turn to better than 10 ps. One should be able to compute these quantities at a relatively modest number of energies (10–20 at most) and use a least-squares spline interpolation to determine the functional dependence at any energy. Finding the closed orbits accurately will not be possible near an integer tune, and the tunes will be difficult to determine near half integer tunes.

To obtain the times of flight and tunes, one must store the beam for a number of turns at fixed energy. Because of beam loading, the beam will gradually lose energy to the cavities. This will happen slowly at first, but the total energy loss will be quadratic in the number of turns if the beam frequency and the cavity frequency are the same, and will

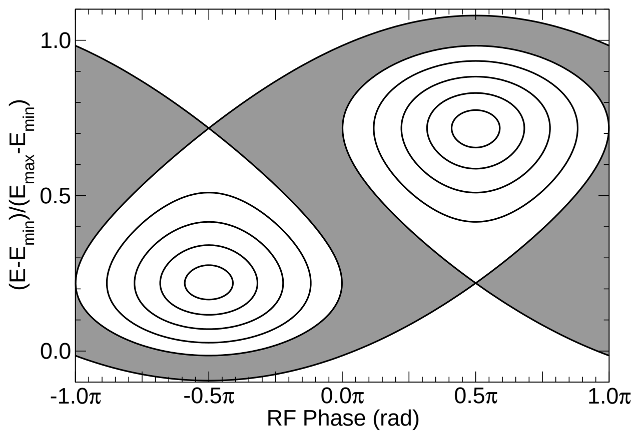

FIGURE 4. Longitudinal phase space, showing the stable buckets (at the lower left and upper right) and the phase space region through which particles are accelerated in the accelerating mode (shaded grey).

eventually become significant. Instead, one can fill the cavities and time the beam to arrive at the zero crossing of the RF. The absence of synchrotron oscillations indicates that the time of flight of the beam corresponds to the RF frequency. In this mode, one is operating at one of the stable fixed points in the longitudinal phase space (see Fig. 4) instead of accelerating in the channel between the buckets surrounding these fixed points. This will not work near the minimum of the time of flight, but one can interpolate from values that can be measured to compute the time of flight there. The frequency of the RF cavities must be variable over a sufficient range to be able to synchronize with the beam at any energy in any configuration. Other techniques, such as detuning the RF cavities from the beam frequency, may also be viable. One may not even need very many turns if the time of flight can be measured accurately in a single turn (or a small number of turns), and if the large number of BPMs can be used to determine the tune rapidly. One will, however, need a sufficient number of turns to ensure that one has found the closed orbit, since time of flight measurements should be made with no transverse amplitude (although it is interesting to have the time of flight measurements for a nonzero transverse amplitude as well [10, 11]).

Setting Machine Parameters

Each configuration is defined by three relations: two involving the tunes, one involving the time of flight [12]. The relations involving tunes either specify the tunes at the minimum and maximum energies or relate the distances of the tunes at the minimum and maximum energies from low-order resonance lines. The relations involving times of flight either relate the times of flight at the minimum and maximum energies or specify the energy of the minimum in the time of flight. In addition, one must attempt to center the beam in the the beam pipe, or alternatively ensure that the minimum and maximum excursions of the beam are equidistant from their nearest beam pipe walls. This gives a total of four constraints that one is trying to satisfy (two tunes, one time of flight, one position) for each configuration.

Assuming that every cell is identical, there are four machine parameters that one can set to meet these specifications: two quadrupole displacements and two quadrupole strengths. Simplistically, the quadrupole strengths change the tunes, the average of the quadrupole displacements changes the displacement in the beam pipe, and the difference in the quadrupole displacements changes the energy of the time of flight minimum. In reality these are highly coupled. One can use Newton's method to predict how the machine parameters should be adjusted from their current values based on the most recent lattice function measurements to obtain new machine parameters that will result in lattice functions that are closer to those desired for the configuration. One can use a model to obtain an initial guess for the derivative of the lattice functions with respect to the machine parameters which should be sufficiently accurate. One can even use various methods to update the derivative based on the measurements (Broyden's method [13] being the most popular; see [14] for some others).

CONCLUSION

I have given a basic outline of the commissioning process for EMMA. There are clearly details which still need to be worked out in the procedure. In particular, one must specify precisely how one will determine the machine settings in the initial commissioning stage, and one must compute how many turns will be needed to obtain the beam quantities to sufficient accuracy. The answer to this latter question may impact how one runs the machine to ensure that the beam stays at a fixed energy.

ACKNOWLEDGMENTS

Discussions with Shinji Machida and Shane Koscielniak have been particularly useful in my thinking about beam loading and its effect on the fixed-energy beam runs. This work has been supported by the United States Department of Energy, Contract No. DE-AC02-98CH10886.

REFERENCES

1. R. Edgecock, "EMMA–The World's First Non-Scaling FFAG," in [15], pp. 2624–2626.
2. J. S. Berg, "The EMMA Experiment," in *ICFA Beam Dynamics Newsletter No. 43*, edited by C. R. Prior, and W. Chou, ICFA, 2007, pp. 60–74.
3. S. Machida, and D. J. Kelliher, *Phys. Rev. ST Accel. Beams* **10**, 114001 (2007).
4. J. S. Berg, et al., *Phys. Rev. ST Accel. Beams* **9**, 011001 (2006).
5. S. Y. Lee, et al., *New J. Phys.* **8**, 291 (2006).
6. J. S. Berg, et al., "The EMMA Lattice Design," in [15], pp. 3181–3183.
7. N. Bliss, Cell engineering update (2007), URL `https://www.conform.ac.uk/documents/emma/ec%20-%20emma%20collaboration%20meetings/Mtg3-2007-mar-13/conform-emma-ec-mtg3-talk-0004v1.0-cell-engineering-update-Neil-Bliss.ppt`, presentation at the EMMA phone meeting, 13 March 2007.
8. D. Kelliher, Optimial positions of BPMs (2007), URL `https://www.conform.ac.uk/documents/emma/ec%20-%20emma%20collaboration%20meetings/Mtg2-2007-feb-9/BPM_optimal_position.ppt`, presentation at the EMMA phone meeting, 9 February 2007.
9. N. Bliss, EMMA injection devices progress 17.10.07 (2007), URL `https://www.conform.ac.uk/documents/emma/ec%20-%20emma%20collaboration%20meetings/Mtg11-2007-oct-18/conform-emma-meng-talk-0001v1.0-EMMA-injection-concept.pdf`, presentation at the EMMA phone meeting, 18 October 2007.
10. S. Machida, *Phys. Rev. ST Accel. Beams* **9**, 104002 (2006).
11. J. S. Berg, *Nucl. Instrum. Methods A* **570**, 15–21 (2007).
12. J. S. Berg (2007), URL `http://www.conform.ac.uk/documents/emma/acc%20-%20accelerator%20physics/lattice.html`.
13. C. G. Broyden, *Math. Comp.* **19**, 577–593 (1965).
14. V. Eyert, *J. Comput. Phys.* **124**, 271–285 (1996).
15. C. Petit-Jean-Genaz, editor, *Proceedings of PAC07, Albuquerque, New Mexico, USA*, IEEE, Piscataway, NJ, 2007.