AN INJECTION/EXTRACTION SCENARIO FOR EMMA

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Abstract

EMMA is an experiment to study beam dynamics in a linear non-scaling fixed-field alternating gradient accelerator (FFAG). It accelerates an electron beam from 10 to 20 MeV kinetic energy. To optimally perform these studies, one must be able to inject the beam at any energy within the machine's energy range. Furthermore, because we wish to study the behavior of large-emittance beams in such a machine, the injection systems must be able to inject the beam anywhere within a transverse phase space ellipse with a normalized acceptance of 3 mm, and the extraction systems must be able to extract from that same ellipse. I describe a computation of kicker and septum fields to achieve all of these requirements, and discuss how this interacts with the hardware constraints.

INJECTION/EXTRACTION SYSTEMS

In any FFAG, injection and extraction is one of the most challenging aspects of the machine. Requirements for the symmetry and compactness of the lattice make the requirements on the kicker hardware very challenging. Since the purpose of the EMMA experiment is to perform detailed studies of beam dynamics in a linear non-scaling FFAG, the requirements for the injection and extraction systems are significantly more extensive. The injection system must be able to inject the beam at any energy within the operating range of the machine (10 to 20 MeV kinetic energy) so that the fixed-energy lattice parameters can be measured as a function of energy. One must also be able to extract at most energies to study beam properties during the acceleration cycle. To examine the behavior of the machine at large transverse amplitude, a small probe beam will scan the transverse phase space. The injection system will be used to accomplish this in the horizontal plane, and the extraction system must reverse this to guide the beam into the extraction line (whose transverse acceptance is significantly smaller than that of the EMMA main ring). The lattice of the main ring will be varied [1], and the injection and extraction systems must accomplish all of these tasks for the range of possible lattice configurations.

The injection region for the EMMA ring is shown in Fig. 1. It consists of a septum and two kickers, all placed in successive drifts. These choices were made for several reasons. We wanted to avoid intervening RF cavities between elements of the injection system, with the constraint that we would try as best as we could to place a cavity in every other cell [2]. Given the space constraints, the maximum integrated kicker strength was around 7 mT-m [3], meaning that a two kickers would be needed. The extraction

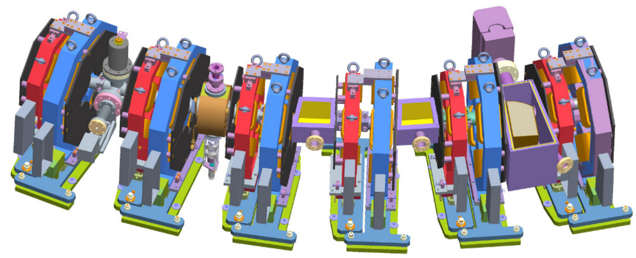

Figure 1: Injection region of EMMA, showing, right to left, the injection septum and two kickers.

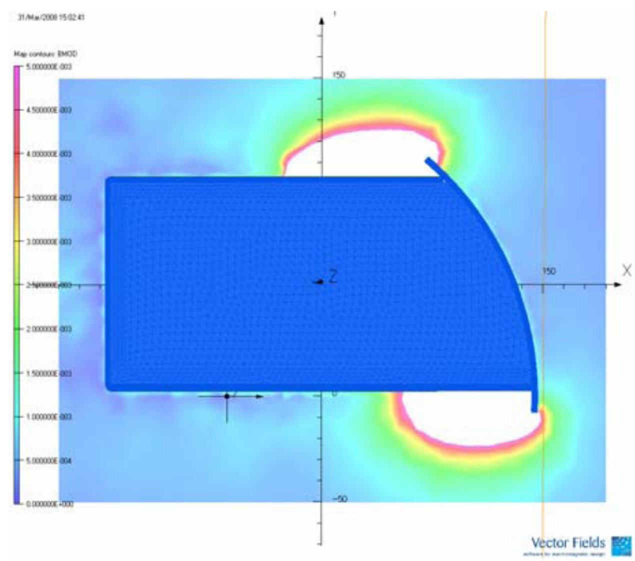

Figure 2: Septum, showing magnetic field magnitudes [5]. Transition to white is at 5 mT.

system is essentially a reflection of the injection system.

A particular challenge is posed by the septum. Stray fields from the septum are significant (see Fig. 2): integrated fields as low as 20 μT-m can lead to significant orbit distortions [4]. The septum must thus be placed a significant distance from the beam, ideally at least 1 cm away. Due to the wide range in positions of the circulating beam that we will be trying to inject or extract, the septum was designed to be moved horizontally to maintain the required separation while preventing a large distance to the septum from making injection or extraction unnecessarily difficult.

A doublet lattice is not reflection symmetric. So one must choose whether the horizontally focusing (F) or horizontally defocusing (D) magnet will immediately follow the injection septum, realizing that the magnet immediately before the extraction septum will be the other one. Assuming horizontal injection, injection is simper when the D magnet is adjacent to the septum: the D magnet pushes

* Work Supported by the United States Department of Energy, Contract No. DE-AC02-98CH10886.

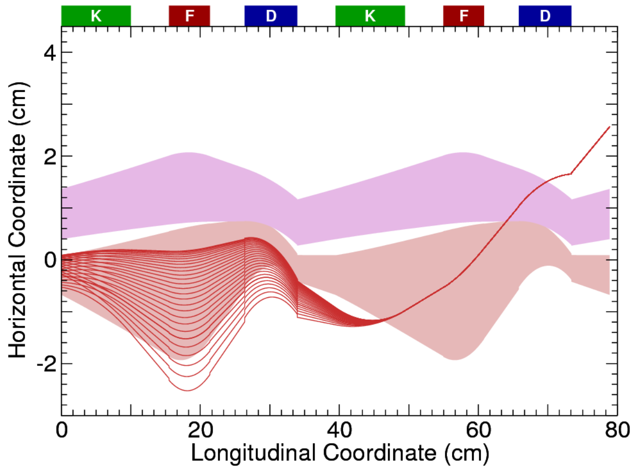

Figure 3: Injection of 10 MeV beam into EMMA, for the 070221f lattice configuration described in [1]. The beam goes from right to left in the drawing. The last value plotted on the right is where the beam exits the septum. Different lines are for different beam positions on the outer edge an ellipse with a 3 mm emittance. The top of the graph shows the magnets: D and F for the two displaced quadrupoles, and K for the kickers. The filled areas are the paths traced out by 3 mm emittance beams circulating at 10 MeV (below) and 20 MeV (above). Positive horizontal coordinates are toward the outside of the ring.

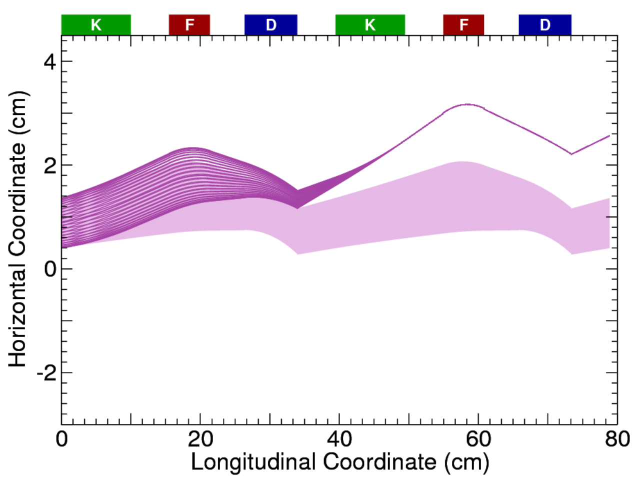

Figure 4: Injection of a 20 MeV beam into EMMA. Everything is as in Fig. 3, except only the 20 MeV circulating beam is shown.

the beam out of the ring and will generally have a beam with a small size and smaller excursions (compare Figs. 3 and 6, for example). We chose to put the D magnet immediately after the injection septum since we wanted to insure that we could inject at every energy. Also, for injection, the septum needs to be outside the highest energy orbit (since the beam's energy will increase and therefore move the beam to the outside), whereas for extraction, the septum could be moved nearer to the circulating beam at

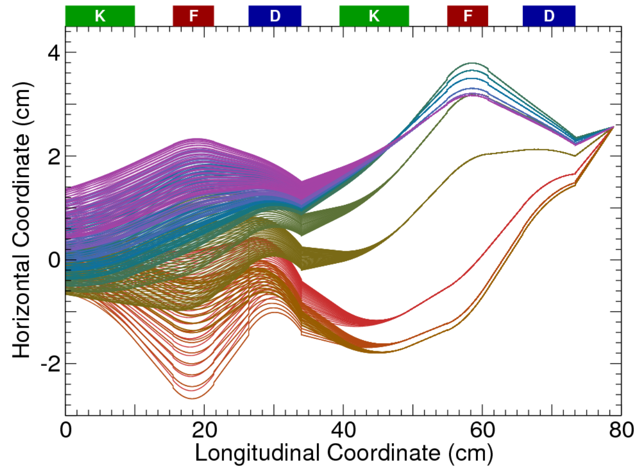

Figure 5: Injection of beams of various energies into EMMA. Energies are from 10 to 20 MeV in 1 MeV steps. Each color is a different energy: violet, toward the top, is the highest energy, and red, toward the bottom, is the lowest. For a given color, different lines are different initial conditions on the edge of an ellipse as in Fig. 3.

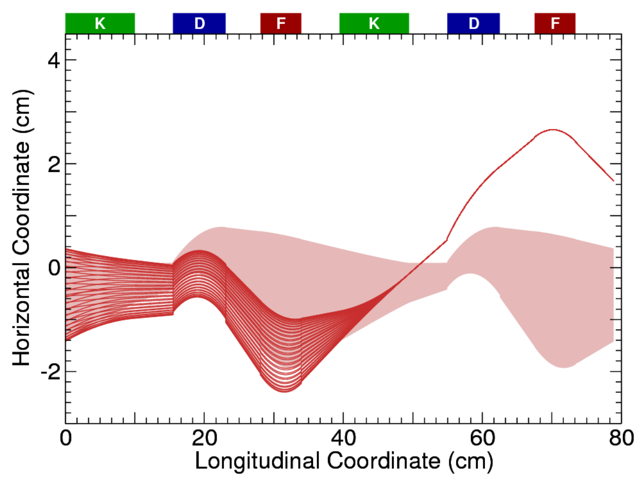

Figure 6: Extraction of 10 MeV beam from EMMA. The beam goes from left to right in the drawing. The last point plotted on the right is where the beam enters the septum. Only the 10 MeV circulating beam is shown. Everything else is as in Fig. 3.

the desired extraction energy, since the beam would never be outside that point. Injection is thus inherently more difficult, so it is important to choose the lattice symmetry to ease injection.

In this paper, I will describe the results of using these hardware constraints to choose parameters for the injection and extraction kickers so as to be able to inject and extract at every energy from 10 to 20 MeV, as well as to be able to scan a horizontal phase space with a normalized acceptance of 3 mm. I will discuss some of the difficulties of the resulting system and how they can be addressed.

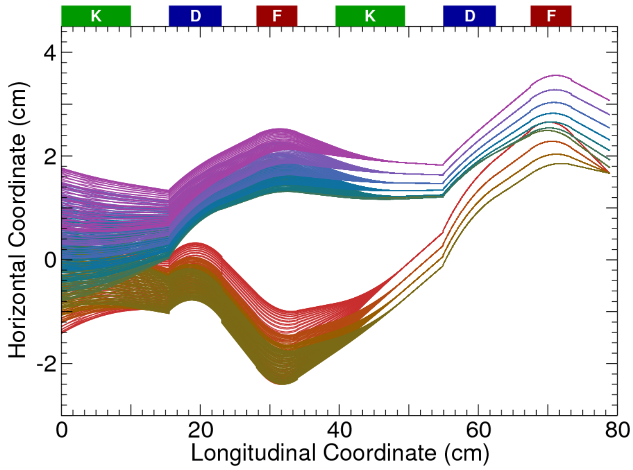

Figure 7: As in Fig. 5, but for extraction as in Fig. 6.

DESIGN METHOD

There are a number of constraints on the system. The beam must not stray outside of the beam pipe. Based on hardware considerations [6] the geometric constraint is that the horizontal beam position would remain in the range of -26 mm to +44 mm within the quadrupole magnets, and -18 mm to +26 mm within the kicker magnets (these are coordinate values relative to the polygon defining the EMMA coordinate system [1]). The maximum kicker strength cannot exceed 7 mT. I assumed that the horizontal phase space scanning would occur entirely using the kickers, and that therefore the septum position and field strength would remain fixed. I attempted to design a system which would maximize the distance between the extracted beam at the end of the septum within the ring and the circulating beam given these constraints.

An example of the results of these studies in shown in Figs. 3–7. For injection, the extracted beam must always lie outside the 20 MeV circulating beam (see Fig. 3), even when injecting at 10 MeV. The 20 MeV beam is injected at the same position as the 10 MeV beam is (Fig. 4). Figure 5 shows the beams at several energies. Every beam can be extracted to the same position, though every energy arrives with a different angle. Every transverse amplitude can be guided onto the same orbit for a given energy since two kicker strengths are sufficient to describe an arbitrary horizontal phase space coordinate.

There are two types of motion in the injection region, depending on the beam energy: either the beam is pushed out then pulled in by the two kickers (Fig. 3 and the lower energies in Fig. 5), or the beam is pushed out by both kickers (Fig. 4 and the higher energies in Fig. 7). The difference is whether the phase advance per cell is greater or less than 0.25. For energies where the phase advance per cell is near 0.25, injection is in fact most challenging since only one kicker can contribute to displacing the beam in that case.

Similar results apply to extraction (Figs. 6–7). In this case, the septum can be moved to be closer to the extracted orbit. However, it should always be placed outside the injected orbit, which is the reason that the extraction position is the same for all of the lowest energies in Fig. 7.

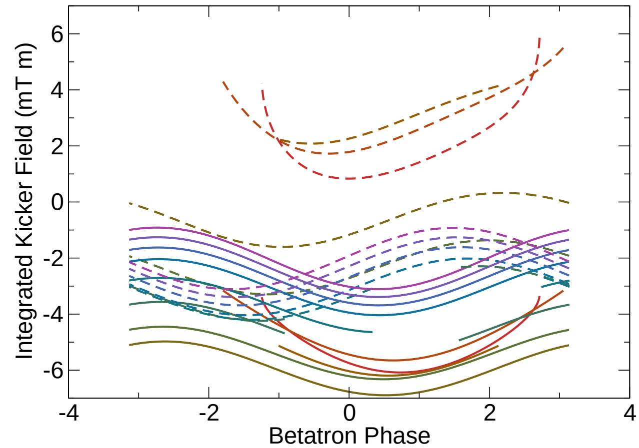

Figure 8: Integrated kicker fields for different betatron phases on the 3 mm normalized horizontal ellipse. Different colors are for different energies. Solid lines are for the kicker closest to the septum, dashed are for the other.

CHALLENGES

For injection at the lowest energies, the inner beam pipe wall prevents the entire 3 mm horizontal phase space ellipse from being scanned. The inner constraint is necessary since the magnets are quadrupoles displaced to the outside of the ring [1], and thus the physical constraint is on the inside of the ring. However, one can scan approximately one half of the ellipse, which is sufficient since the transverse amplitudes are approximately equivalent in the other half of the ellipse.

Kickers cannot have arbitrarily small strengths [6]. Unfortunately, the optimization method here has chosen kicker strengths which, even for a given energy, span a wide factor in values (see Fig. 8). This will require adjusting the method in some way: one could do something other than minimizing the required kicker strength, or one could include the field of the septum in the parameters that one adjusts. Further study of this issue is needed. The kickers are being designed to work with two ranges of maximum strength, and their polarities can be adjusted manually [7].

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