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STUDY OF ORBIT CORRECTION FOR eRHIC FFAG DESIGN*

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Abstract

The unique feature of the orbits in the eRHIC Fixed Field Alternating Gradient (FFAG) design is that multiple accelerating and decelerating bunches pass through the same magnets with different horizontal offsets. Therefore, it is critical for the eRHIC FFAG to correct multiple orbits in the same vacuum pipe for better spin transmission and alignment of colliding beams. In this report, the effects on orbits from multiple error sources will be studied. The orbit correction method will be described and results will be presented.

INTRODUCTION

Electron accelerators based on FFAG lattice are designed to be placed in the existing Relativistic Heavy Ion Collider (RHIC) tunnel for collision of electron and heavy ion beams [1]. The advantages of the FFAG lattice are in two aspects: the magnets are at fixed fields and there is strong focusing in the transverse planes. A machine with such lattice accepts beams over a large energy range. The dispersion function is very small ($\sim cm$) so that orbits of beams with different energies stay in the same vacuum pipe with small horizontal offsets. The orbits will be distorted differently if either the magnets are misaligned or there are magnet gradient errors. The misalignment and gradient errors in a FFAG lattice need therefore to be compensated locally to restore all the orbits to the design values. Dipole and quadrupole trims will be placed at each and every magnet center to correct the said errors. Considering the large number of magnets in the rings, a global correction scheme must detect local errors quickly and precisely. Furthermore, enough beam position monitors (BPMs) for beam position measurement is also critical to locate the errors effectively.

The lattice design has evolved much in the past year with optimization of linac size and synchrotron radiation [2, 3]. The orbit correction simulation will be presented in this paper is based on a single FFAG ring design, which accelerates electron beam from 1.9 to 10 GeV and decelerates the beam back to 1.9 GeV via energy recovery. The injected beam will be accelerated before entering the FFAG arc. Therefore, there are 9 accelerating beam passes and 8 decelerating passes through the FFAG arcs. As the beam gets accelerated, the betatron tune per FFAG cell changes from ∼0.44 to ∼0.1 in the horizontal plane and ∼0.3 to ∼0.04 in the vertical plane discretely [1].

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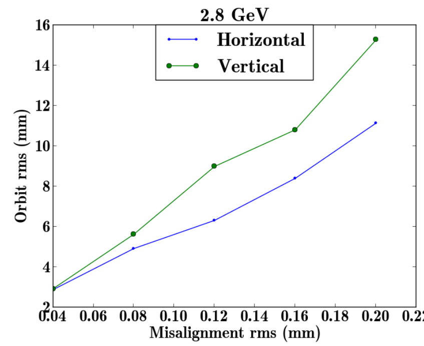

Figure 1: RMS of beam orbit distortion in eRHIC FFAG in both planes due to magnet misalignment errors, for the beam in the first pass with energy 2.8 GeV.

The measurement of beam positions is challenging for continuous bunch train with $\sim ns$ spacing between bunches. A gap in the electron beam bunch train, which coincides with the abort gap in RHIC, is necessary for ion clearing purpose. A diagnostic bunch will be put in the gap for routine monitoring of the beam positions continuously [4].

ORBIT DISTORTION DUE TO MISALIGNMENT AND GRADIENT ERROR

In the eRHIC FFAG design, the magnets are pure focusing and defocusing quadrupoles shifted horizontally in position relative to a circular orbit. The field experienced by the beam is $G * x$, G is the magnet gradient, x is the horizontal beam position relative to the magnet center.

The orbit distortion due to misalignment of magnets was studied in simulation. The orbit deviation root-mean-square (rms) in two planes for beam at $2.8 GeV$ is shown in Fig. 1 for a range of misalignment rms. The same orbit distortion due to misalignment erros were studied for the other 8 beam passes. The magnification factors, the ratio between orbit rms and misalignment rms, are compared for all passes. The magnification factor decreases with beam rigidity as expected in the horizontal plane, however not in the vertical plane. Analytical calculation of the magnification factor ($\propto \frac{\sqrt{\beta_1\beta_2}}{\nu\gamma}$, β_1, β_2 are the betatron functions at the magnets and BPMs, ν is the tune per cell, γ is the Lorentz factor) confirmed the count-intuitive behavior in the vertical plane, shown in Fig. 2.

The orbit distortion due to magnet gradient errors was studied in simulation as well. The orbit rms in the horizontal plane only for beam at 2.8 GeV is shown in Fig.3 for a

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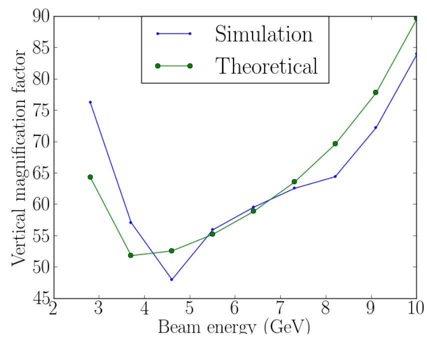

Figure 2: Misalignment magnification factor in the vertical plane for all passes from simulation compared with theoretical calculation.

range of relative gradient error rms.

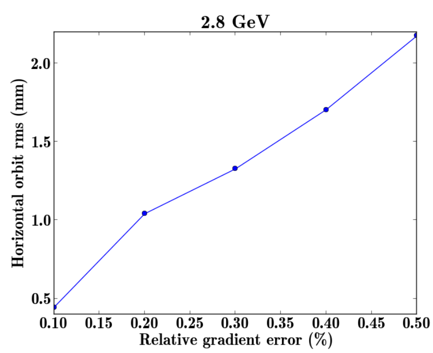

Figure 3: RMS of beam orbit distortion in eRHIC FFAG in horizontal plane due to magnet gradient errors, for the beam in the first pass with energy 2.8 GeV.

ORBIT CORRECTION ALGORITHM

For a linac machine with m BPMs and n correctors, the orbit response matrix is

$$R = \begin{pmatrix} R_{1,1} & R_{1,2} & R_{1,3} & \cdots & R_{1,n} \\ R_{2,1} & R_{2,2} & R_{2,3} & \cdots & R_{2,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{m,1} & R_{m,2} & R_{m,3} & \cdots & R_{m,n} \end{pmatrix} \quad (1)$$

where $R_{i,j} = \begin{cases} \sqrt{\beta_i \beta_j} * \sin(\phi_i - \phi_j) & \text{if } \phi_i > \phi_j \\ 0 & \text{if } \phi_i <= \phi_j \end{cases}$

The goal of orbit correction is to compensate the difference between measured and designed orbit [5],

$$\Delta Y = (Y_0 - Y) = R * \theta \quad (2)$$

Where Y_0 is the target orbit, Y is the measured orbit, R is the response matrix, and θ is the correction strength

Eq. 2 can be extended for the case of orbit correction using measurements from multiple passes,

$$\begin{pmatrix} \Delta Y_1 \\ \vdots \\ \Delta Y_2 \\ \vdots \\ \Delta Y_m \end{pmatrix} = \begin{pmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{pmatrix} * \theta, \quad (3)$$

m is the number of passes. The measured orbit could be available for any given number (from 0 to 8) of complete accelerating passes plus any fraction of the following pass in the stage of machine commissioning. Therefore, it is the difference between available measured orbit and corresponding design orbit on the left hand side, and corresponding response matrix on the right hand side of Eq. 3.

ORBIT CORRECTION RESULTS

We first tested the orbit correction scheme on a single pass. One BPM was placed after each and every magnet in eRHIC lattice so that local errors could be found properly. With only misalignment errors, orbit correction was performed for the first pass only to calculate dipole corrections. Then the same set of corrections were implemented in the lattice and residual orbit distortions for the other passes were examined. The orbit distortions for all the other passes were reduced under 1 mm peak to peak. This verifies that the local errors can be located by the correction scheme properly with 2 BPMs per FFAG cell. Correction strengths calculated for different passes independently are in good agreement, which indicates local errors can be well located.

It is costly to place BPMs with all magnets in the lattice. The length of a FFAG cell is 2.58 m because of strong focusing, therefore the total number of BPMs is unpractically high. We repeated orbit correction with 1 BPM per 2 FFAG cells. The corrections calculated for a single pass in this case didn't improve orbits for other passes. This means local errors can not be identified with the number of BPMs less than that of magnets if only the data from the first pass is used for the correction.

The tunes per cell variation for different energies is one of the reasons why orbits behave differently with errors in the lattice. On the other hand, beam position measurements for different passes all provide useful information about the sources of the errors. Therefore, one should be able to better localize the errors by correcting beam trajectories for multiple passes. The number of BPMs for an efficient orbit correction can be reduced as long as the number of measurements is greater than the number of error sources when correcting multiple orbits simultaneously.

The number of BPMs in the following simulation was set as 1 BPM per 2 FFAG cells. We assumed 100 μm rms misalignment error, 0.05 $mrad$ rms for roll, pitch, yaw angles. The orbit correction was simulated based on six FFAG arcs in sequence with 172 cells per arc. The residual orbit errors at the end of each pass is assumed to be corrected by the

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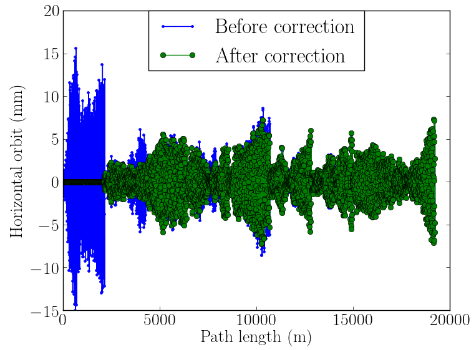

Figure 4: Horizontal orbits for 9 passes without (blue) and with (green) orbit corrections implemented for the first pass.

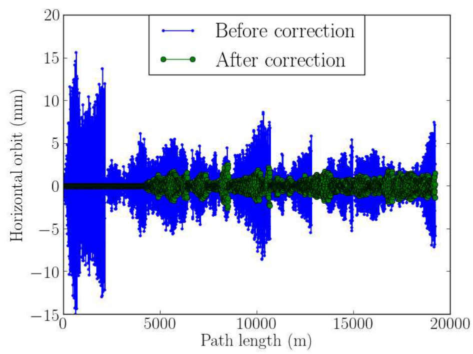

Figure 5: Horizontal orbits for 9 passes without (blue) and with (green) orbit corrections implemented for the first two passes.

separate beam lines in the spreader/combiner section [6], however, not perfectly. To account for the imperfect correction, initial errors of $\delta x = 0.5\ mm$, $\delta x' = 0.08\ mrad$ were assumed at the start of each pass. All magnets were assigned with relative gradient errors, whose rms is 0.2% [7]. Random errors in [-20, 20] μm range were applied to BPM measurements.

In Fig. 4, orbit correction was applied for the first pass, however, orbits of the other passes were not improved. With corrections for the orbits of the first two passes, the orbits of the other passes were improved substantially, shown in Fig. 5. Further improvement were made by correcting the orbits of the first four passes, shown in Fig. 6. By correcting all 9 passes, the orbit deviations of all 9 passes can be reduced to $\sim 50\ \mu m$ peak to peak (Fig. 7) except at the beginning of each pass because of the assumed initial angle and position errors.

SUMMARY

The orbits of multiple passes in an early stage eRHIC FFAG design were studied. The orbit distortion due to misalignment and magnet gradient errors were simulated. It was concluded that the misalignment errors is the dominating source for orbit distortion. Orbit correction scheme

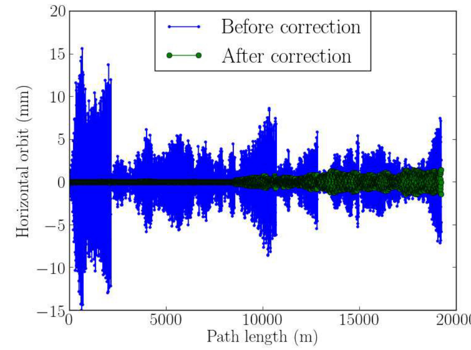

Figure 6: Horizontal orbits for 9 passes without (blue) and with (green) orbit corrections implemented for the first four passes.

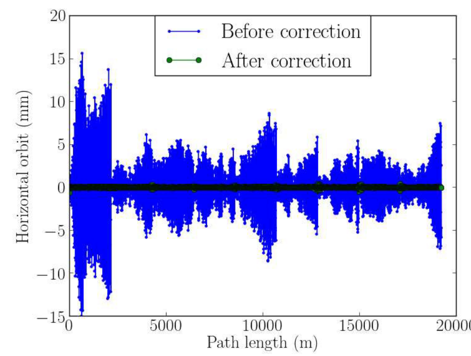

Figure 7: Horizontal orbits for 9 passes without (blue) and with (green) orbit corrections implemented for all the 9 passes.

for the eRHIC FFAG design was proposed and verified in simulation.

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