A ROBUST ORBIT-STEERING AND CONTROL ALGORITHM USING QUADRUPOLE-SCANS AS A DIAGNOSTIC

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Abstract

Beam based alignment and control has been a critical issue for many accelerators. In this paper, we've developed a new approach that can correct the beam orbit using a systematic quad-scan method, where there is an insufficient number of beam position monitors. In this approach, we've proposed a calibrated response matrix. This matrix takes consideration of the different sensitivities of different quadrupoles in the lattice. With the calibrated response matrix, we can greatly enhance our ability to control the beam centroid motion and reduce the control effort.

BEAM CONTROL AND STEERING TECHNIQUES

There have been many approaches for the beam steering and control for accelerators or storage rings. In [1], there is a very good discussion on the beam-based alignment techniques for accelerators. In general, we assume that if the beam passes through the center of a quadrupole, there is no deflection to the beam. Moreover, when the quadrupole's current is varied, the change of beam's position in the quadrupole is linearly proportional to the quadrupole's current change. One steering approach is the dispersion-free steering, which works by simultaneously varying all of the quadrupoles' currents by a fixed fraction of their nominal design values and measuring the beam centroid changes in the beam trajectory. Another approach is the ballistic alignment, which works by turning off some quadrupoles in a consecutive order and steering the beams to the resulting magnetic-free region. There is another popular approach for beam steering by using the orbit response matrix [2]. In this response matrix algorithm, the element in the matrix is defined as a linear response function between the change of the beam position and the change of the dipole current when the dipole current is varied. The approaches above work well in their corresponding applications.

However, not all the accelerators have the same diagnosis capability. For some accelerators, the beam position monitors are not enough, i.e., not every quadrupole having a BPM. Then, the above approach will not be able to work well since the beam position change due to the dipole current change cannot be effectively measured with the BPM far away from the quadrupole. In this paper, we proposed a robust orbit-steering and control algorithm to solve the problem. We provided simulation results based on the University of Maryland Electron Ring.

Introduction to the University of Maryland Electron Ring

The University of Maryland Electron Ring (UMER), as shown in Figure 1, has been a testbed for the low energy high current beam research [3, 5, 6, 7]. UMER models the transport physics of intense space-charge-dominated beams [8], employs real time beam characterization and control in order to optimize beam quality throughout the strong focusing lattice. Its current varies from 0.6mA to 100mA which covers a wide region from emittance dominated beams to space-charged dominated beams. Our past work has proven that UMER is providing fundamental beam physics research. Comparing to most big and costly accelerators, UMER has advantage over them in the cost and safety.

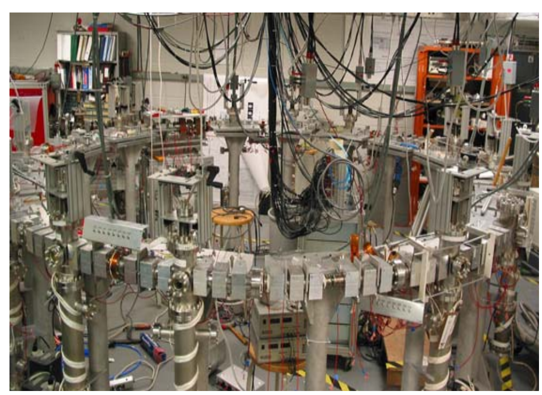

Figure 1: University of Maryland Electron Ring.

Beam alignment and control over a long distance has been a critical issue for all accelerators, including the University of Maryland Electron Ring. We require that the beam centroid trajectory deviate as little as possible from the design orbit, which is defined by the axes of the quadrupole magnets. In order to get a high quality beam for a single turn operation and for multi turn operation, we need employ advanced control techniques to achieve precise control on the beam centroid over the beam line. In UMER, the beam is focused by a set of quadrupoles and its

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trajectory is bent by a set of dipoles which keeps the beam turn around 360 degrees after one turn.

CALIBRATED CONTROL OF UNIVERSITY OF MARYLAND ELECTRON RING

There are two types of diagnostics using for control at UMER. One is the phosphor screens and the other is the beam position monitors (BPM). The phosphor screen can provide images of the beam with a detailed beam profile, such as phase space, emittance, etc, but it intercepts the beam. The BPM can capture the beam position without intercepting the beam. In the past beam control for UMER [9], Li relied on the phosphor screen for the beam control. This method is reliable but we needed to move the phosphor screen from one section to another section. Since the phosphor screen intercepts the beam, it cannot be used as diagnostics for beam's multi-turn operation. Thus, we are using the BPMs, instead of the phosphor screens to measure the beam positions [4], especially for the multi-turn operation.

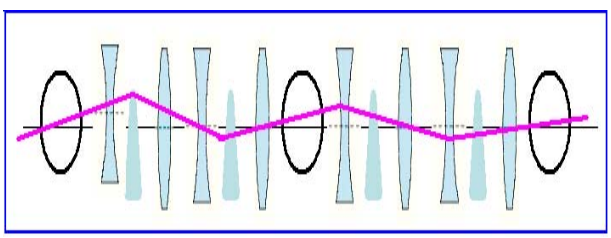

Figure 2: UMER chamber structure. Between every two BPMs, there are four quadrupoles and two dipoles. The distance between two neighboring quadrupoles is 16cm. The distance between the dipole and neighboring quadrupole is 8cm. The distance between the BPM and the quadrupole is 8cm.

The algorithm for our current beam control and steering is based on the conventional response matrix and singular value decomposition [2, 10, 12]. In this algorithm, we assume there is a linear response between the change of the beam centroid position and the change of the dipole current. Based on this assumption, we build the conventional response matrix and invert that matrix such that we can get the corresponding kick force if the beam has some offset and is not in alignment in the quadrupoles. In general, this approach works well for large accelerators, for example, MIT-Bates Linear Accelerator and Stanford Linear Accelerator [11] or Indiana University Cyclotron Facility Cooler Ring [10]. For those big accelerators or storage rings, they have one BPM for each quadrupole. However, due to the space constraint and other considerations for a highly space-charged beam [5], the density of magnets on UMER is much higher than that of the average ring. UMER's ring beam line has 72 quadrupoles, 36 dipoles, 14 BPMs. There exist ambient fields (including earth magnetic field, environment magnetic field) which make beam control more difficult. As in Figure 2, between every two BPMs, there are four quadrupoles and two dipoles. 14 BPMs are not enough measurements for beam control. Our current approach on beam centroid steering and control is to apply directly the response matrix algorithm. However, the control result is limited such that we have difficulty to transport the beam over one turn around the ring without beam loss.

Recently, we discovered that due to the insufficient number of BPMs, we should not directly apply the conventional response matrix algorithm. In each chamber, the distance from different quadrupoles to the same BPM is different such that the sensitivity is different. In the conventional response matrix approach, the same sensitivity factor is used because each quadrupole has its own BPM. However, in UMER, we should not use the same sensitivity factor as the structure is not uniform for a quadrupole and its BPM. We did a modification by taking consideration of the sensitivity–we call it the calibration factor. It is defined as following

$$CF_{ij} = \frac{\partial X_{B_i}}{\partial I_{Q_j} \partial X_{Q_j}} \quad (1)$$

where CF_{ij} is the calibration factor relating to BPM i and quadrupole j, ∂X_{B_i} and ∂X_{Q_j} are the beam centroid displacements in BPM i and quadrupole j and ∂I_{Q_j} is the current change in quadrupole j.

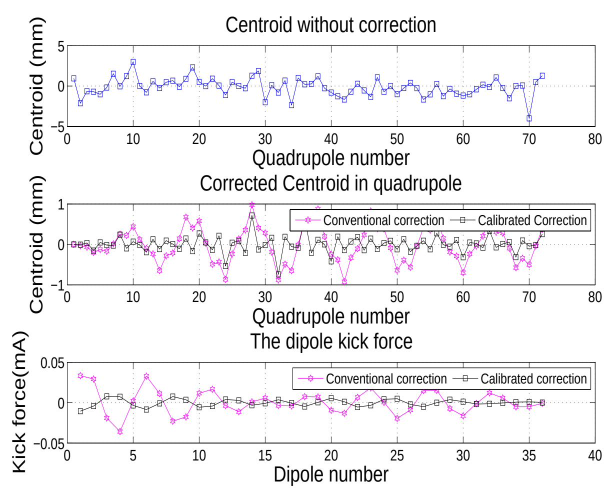

Figure 3: Beam centroid correction with earth field. In the upper figure, we assume there is a random error in the quadrupole center. The center figure shows the corrected beam centroid with conventional control and the calibrated control. The bottom figure shows the bending force required in each dipole.

The conventional calibrated response matrix is expressed as following

$$R_{ij} = \frac{\partial X_{Q_j}}{\partial I_{B_i}} \quad (2)$$

where R_{ij} is the element relating to quadrupole j and dipole i, ∂X_{Q_j} is the beam centroid displacement in quadrupole j, and ∂I_{B_i} is the current change in dipole i.

The new calibrated response matrix R^* is defined as

$$R^* = R/CF \tag{3}$$

By adding the calibration factor to the response matrix, we are actually considering a weighted response matrix–quadrupoles with different distances to the same BPM having different weighting factors in the response matrix.

We use the WARP PIC [13] codes for simulation to get the calibration factors and the response matrix. Since UMER beam is a low-energy electron beam such that it is very sensitive to the earth field. We consider the cases with/without the influence of the earth magnetic field. Assuming the beam has some random offsets in the quadrupoles, the controlled beam centroid in the center of quadrupoles and the control signals required for each dipole are shown in Figure 3 and 4. By comparison, we have a better corrected beam centroid under the calibrated control technique. At the same time, the required control effort is much smaller, which has a substantial advantage to the power supplies and magnetics.

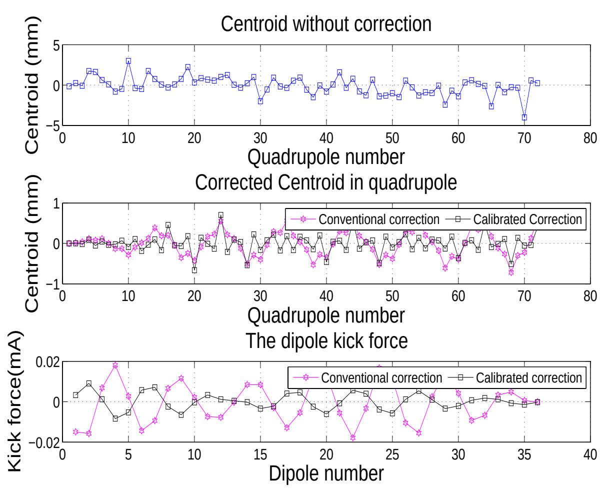

Figure 4: Beam centroid correction without earth field. In the upper figure, we assume there is a random error in the quadrupole center. The center figure shows the corrected beam centroid with conventional control and the calibrated control. The bottom figure shows the bending force required in each dipole.

CONCLUSIONS

We have greatly improved the beam steering and control performance by the calibrated response matrix approach. The control effort is much smaller comparing to the conventional response matrix approach. We are currently working on experimentation of this algorithm on UMER.

ACKNOWLEDGMENTS

We thank the U.S. Department of Energy for their support with grant numbers DE-FG02-94ER40855 and DE-FG02-92ER54178, the Office of Naval Research and the Joint Technology Office.

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