A NOVEL BEAM STEERING ALGORITHM WITH ORBIT RESPONSE MATRIX

C. Wu *, E.H. Abed
Institute for Systems Research, University of Maryland, College Park, MD, 20742, USA.
B. Beaudoin, S. Bernal, K. Fuiza, I. Haber, R.A. Kishek, P.G. O'Shea, M. Reiser, D. Sutter
IREAP, University of Maryland, College Park MD 20742, USA.

Abstract

Beam centroid control is an important method for optimizing the performance for accelerators, including the University of Maryland Electron Ring (UMER), which is a scaled high-current(0.6-100 mA),low-energy (10 keV) storage ring. The conventional response matrix and singular value decomposition approach do not work well on UMER because of the unique ring structure. One of the purposes of this work is to verify that the beam centroid could be controlled in the presence of very strong space charge. In this paper, we present a novel algorithm which is based on the singular value decomposition, but uses a different response matrix. The response matrix is computed from the beam positions for the first four turns in the multi-turn beam circulation. Implementation of this algorithm leads to significant improvement on the beam positions and multi-turn operation.

ISSUES IN UMER CONTROL

UMER is a low-energy, high-current circular accelerator intended for the study of beam physics. This accelerator has been used for scaled studies that are applicable to many larger accelerators; this is especially so for space-charge studies [1, 2, 3]. A recent photograph of UMER is shown in Figure 1. The UMER beam current can be varied from 0.6 mA to 100 mA, which covers a wide range of space charge levels.

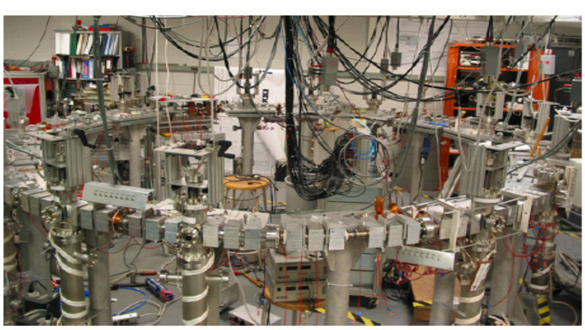

Figure 1: Photograph of the University of Maryland electron ring.

In order to conduct experiments with the space-charge beams at UMER, we need the beams to circulate around the ring with minimal beam loss and with desired beam size and angle. Thus, beam control is crucial to achieve the above goals. We want to optimize the beam quality in terms of several criteria: (1) minimizing particle loss; (2) achieving the highest number of turns or the highest current transmission rate; (3) keeping the beam size and emittance constant. These three criteria are equivalent in terms of beam control.

There have been many approaches for beam steering and control. Recently, the SVD and response matrix approach [4] has been widely used in many accelerators. In this approach, the response matrix was measured and compared with the model response matrix, and the required dipole currents were obtained. A quadrupole-scans assisted beam steering approach was tried on UMER [5]. Although the simulation was successful in this approach, the experimental application on UMER failed to offer a satisfactory result due to insufficient beam position data points.

Control of UMER beams, in simulation and experiment, has been addressed by other researchers [6, 7, 8]. Li [6] developed algorithms for beam steering and envelope matching before the UMER ring was closed. His control technique used linear optics theory and involved scanning the quadrupoles, taking beam photos at downstream phosphor screens, and computing resulting beam position changes. His solution achieves a local minimum of beam positions in BPMs with respect to half of the quadrupoles in the ring. Walter further developed this approach and set up solutions for multi-turn operations, but he found it difficult to implement it for closed-orbit correction [7]. The fast drop of beam current measured by the wall current monitor begs for the development of new control algorithms that improve multi-turn operation.

Beam steering is divided into injection line steering, ring steering and recirculation steering at UMER. Injection line steering is critical to the overall quality of multi-turn operation. However, we find there are coupling effects among the injection steering dipoles and misalignment and rotations in the quadrupoles. These complicate injection beam steering. In the ring, there are 36 horizontal and 18 vertical dipoles steering the beam. The problem is that not all the horizontal dipoles work exactly the same, nor the vertical dipoles. Moreover, the earth magnetic field, which contributes around 20% of bending force for beam steering, is not constant around the ring. The amplitude and direction of the earth magnetic field vary along the ring as shown in Figure 2 [9]. In this figure, at every 10 degree, there is a

* wuchao@umd.edu

horizontal dipole. For the recirculation steering, the pulses for the injection dipole (*PD_inj*) and recirculation dipole (*PD_rec*) have some jitter. This jitter add noise to the BPM signals, which makes the BPM measurement less reliable, especially for the pencil beam. Because of these problems, beam steering at UMER is very difficult.

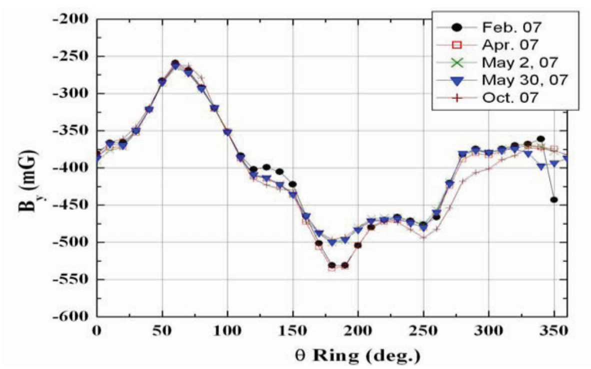

Figure 2: Measured laboratory magnetic earth field around the ring in 2007.

ITERATIVE BEAM STEERING WITH THE ORBIT RESPONSE MATRIX

Beam centroid control based on the orbit response matrix has been widely accepted in the accelerator community. This approach is easy to be understood and applied. Assume we obtain a orbit response matrix R, then the dipole currents I are given by:

$$I = invR \times x_0 \tag{1}$$

Note that, x_0 are the beam positions measured when the ring dipoles run at some currents.

However, the general orbit response correction method does not work well for UMER because of several difficulties. First, there is an insufficient number of Beam Position Monitors (BPMs). Second, beam steering in the injection line must use the beam position monitors in the ring to assist beam position measurement, since there is only one BPM in the injection line. This makes the injection steering and ring steering coupled. Nevertheless, our new approach takes advantage of this coupling. Third, there is a complicated Y section which focuses and bends the beam, coupling beam matching and steering.

Thus, we propose an iterative beam steering technique using the orbit response matrix which is illustrated in Figure 3. We notice the dark-blue area covers response matrices of R_1 and R_2 since we use BPMs in the ring when we measure the injection response matrix. And the steering procedures are described as follows.

1. Measure the initial beam positions;
2. Construct the injection line orbit response matrix R_1 and use it to steer the beam in the injection line;

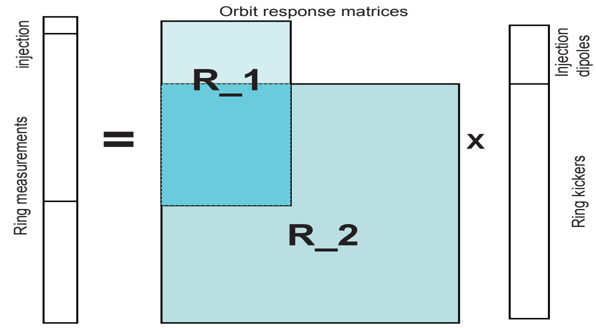

Figure 3: UMER control schematic.

3. Construct the ring orbit response matrix R_2 and use it to steer the beam in the ring;
4. Repeat above procedures until we get the optimal multi-turn operation and the closed orbit.

The optimal multi-turn operation means that there is minimal beam loss from turn to turn. This can be judged from the turn by turn signals on the wall current monitor.

Besides the iterative steering approach above, we proposed a new orbit response matrix. Instead of using the conventional response matrix, we used the closed orbit response matrix. Here, the element in the closed orbit response matrix is different from the coventional response matrix where only the first turn beam position changes are considered. It is defined as the following

$$R_{ij} = \frac{\text{horizontal closed orbit change } \Delta x \text{ at BPM } i}{\text{current change } \Delta I \text{ at horizontal dipole } j} \tag{2}$$

where the closed orbit is computed using the four-turn beam position data as the following equation

$$x_{co} = \frac{x_2^2 - x_3^2 + x_2 x_4 - x_3 x_1}{3(x_2 - x_3) + x_4 - x_1} \tag{3}$$

where x_1, x_2, x_3 and x_4 are the BPM readings of the first four consecutive turns at the same location. This formula was taken from [10].

Figure 4 compares the singular values for these two response matrices. It is clear that in the closed orbit response matrix, the ratio of largest singular value to smallest singular value is larger than the ratio in the conventional response matrix. That means in the closed orbit response matrix, the resulting control solution is more sensitive to the beam position change.

The advantage of this approach is that it directly minimizes the closed orbit distortion. The conventional orbit response matrix only minimizes the first turn beam positions. However, the closed orbit is affected by not only the first turn beam positions, but also beam positions of the other three subsequent turns. By relating with beam positions of the other three turns, we are able to minimize the centroid oscillations along all the beam position monitors. In the steering process, we first use the conventional

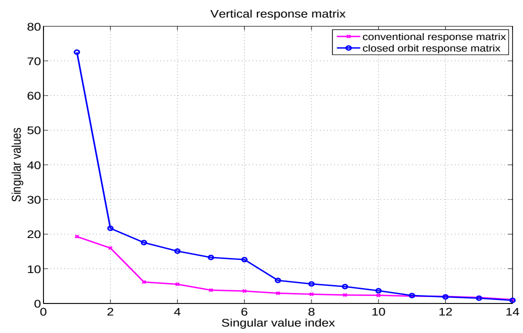

Figure 4: Singular values for two vertical response matrices (7 mA beam).

response matrix, then use the closed orbit response matrix until we get a satisfactory steering results. For more detailed discussions, please refer to [11].

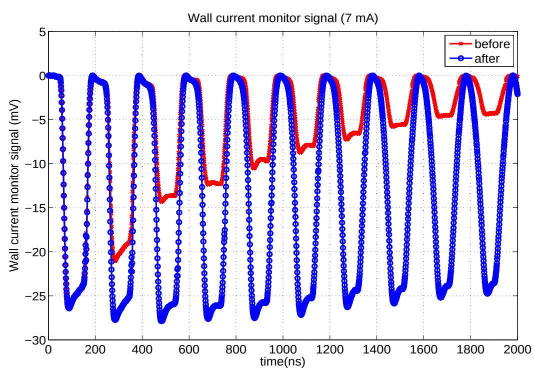

Figure 5: Comparison of wall current monitor signals before and after steering (7 mA beam).

For simplicity, we just compare the wall current monitor signals (Figure 5) from previous steering solution and the new steering solution. The wall current monitor signal is proportional to the beam current in the ring. We see that with new steering solution, there is almost no beam lost for the first ten turns, while there is less than 10% current maintained at the tenth turn with the old steering solution. Before the correction, the rms deviation of the closed orbit from the design orbit was more than 4.0 mm, after steering, it is below 2.0 mm.

With the new steering solutions, we have achieved significant improvement in beam steering for all five UMER beams, from low space charge to intense space charge. For the pencil beam, we have achieved 250 turns with little beam loss. For the 100 mA beam, we can maintain 70% of beam current at the tenth turn. This represents a significant achievement for the space-charge-dominated UMER beams and largely fulfils the commisioning goals we have set.

CONCLUSIONS

We have presented a new iterative steering method based on response matrix for accelerators which have coupling between injection line and ring, and have fewer number of BPMs. This method proves very successful in terms of minimizing closed orbit distortion and improving multi-turn quality.

ACKNOWLEDGMENTS

This work is funded by the US Dept. of Energy Offices of High Energy Physics and High Energy Density Physics, and by the US Dept. of Defense Office of Naval Research and Joint Technology Office.

REFERENCES

[1] M. Reiser, *Theory and Design of Charged Particle Beams*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2004.

[2] M. Reiser, et.al., *"The Maryland Electron Ring for Investigating Space-Charge Dominated Beams in a Circular FODO System,"* Proceedings of the 1999 IEEE Particle Accelerator Conference, New York City, NY, 234, 1999.

[3] R.A. Kishek, et.al., *"The University of Maryland Electron Ring (UMER) Enters a New Regime of High-Tune-Shift Rings,"* Proceedings of the 2007 IEEE Particle Accelerator Conference, Albuquerque, NM, ed. C. Petit-Jean-Genaz, IEEE Cat. No. 07CH37866, 820, 2007.

[4] J. Safranek, *"Linear Optics from Closed Orbits (LOCO)–An Introduction,"* Beam Dynamics Newsletter, No. 44, International Committee for Future Accelerators, Issue Editor A. Ghodke, Editor in Chief: W. Chou, Dec. 2007.

[5] C. Wu, et.al., *"A Robust Orbit-Steering and Control Algorithm Using Quadrupole-Scans as a Diagnostic,"* Proceedings of the 2007 IEEE Particle Accelerator Conference, Albuquerque, New Mexico, 2007.

[6] H. Li, et.al., *"Beam Control and Matching for the Transport of Intense Beams,"* Nuclear Instruments and Methods in Physics Research Section A, 544, pp 367-373, 2005.

[7] M. Walter, et.al. , *"Multi-turn Operation at the University of Maryland Electron Ring (UMER),"* Proceedings of the 2007 IEEE Particle Accelerator Conference, Albuquerque, New Mexico, 2007.

[8] H. Nishimura and M. Walter, *Notes on a Measured Smatrix*, UMER Technical Notes, UMER-LON-001, Sept. 12, 2005.

[9] D. Sutter, Priviate Communication, 2009.

[10] J. Koutchouk, *"Trajectory and Closed Orbit Correction,"* Frontiers of Particle Beams: Observation, Diagnosis and Correction, Proceedings, Anacapri, Isola di Capri, Italy, (Lectures Notes in Physics 343, M. Month, S. Turner Eds), p 46, 1988.

[11] C. Wu, *Precision Control of Intense Electron Beams in a Low-Energy Ring*, Ph.D. Dissertation, Department of Electrical and Computer Engineering, University of Maryland, 2009.