Chapter 3: Centroid Steering

3.1 Motivation

3.2 Considerations for low-ridgidity electron beam

3.3 Prior Approach

This note describes the quad-as-BPM measurement procedure and a new steering algorithm designed to horizontally center the beam in the quadrupoles. The quad-as-BPM measurement, described in Section **??**, was developed by Kiersten and Irv and measures the position of the beam on the first turn using quad scan data. The horizontal steering algorithm, Section **??**, is a methodical, "front to back" approach that first minimizes the position of the beam in the quadrupoles on the first turn then minimizes orbit deviations in subsequent turns. This is proposed as a alternative to the response matrix steering algorithm [**?**], and may be more useful for applications where orbit centering in the quadrupoles is essential.

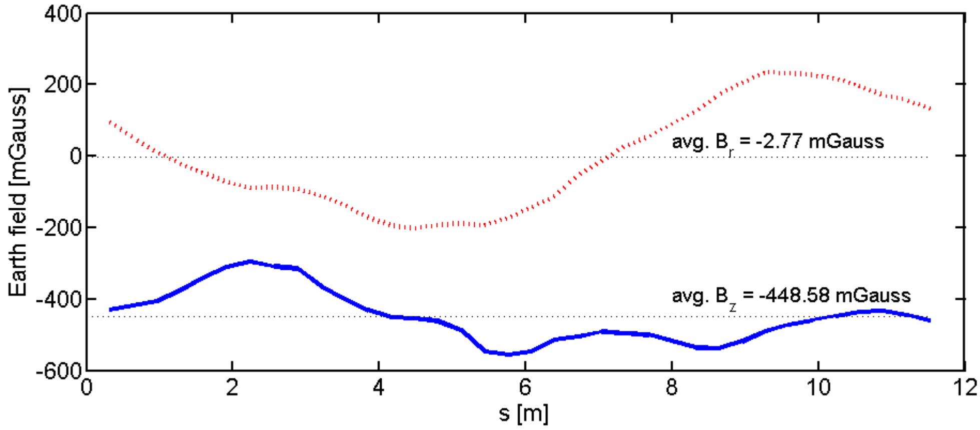

Fig. 3.1: Measured Earth field, from Dave Sutter measurements 6/1/2010. Red dashed = radial field (positive = outward direction). Blue solid = vertical field.

3.4 Quadrupole as BPM technique

The quad as BPM method is a way to measure the beam orbit in the first turn. We calculate the beam position at the center of each quadrupole by measuring the change in beam position due to a perturbation in the quadrupole current. This is an essentially identical method to that described by Kamal Poor Rezaei in an earlier technical note [**?**], with the main difference being the use of the VRUMER beam tracking code to calibrate position, rather than a transfer matrix calculation.

In the work described here, calibration of quadrupole response (measured directly at nearest downstream BPM) is accomplished using VRUMER. VRUMER, described in detail in Appendix [TBD], is a simple orbit integrator written in Matlab, originally developed by Irv Haber to model transverse beam centroid behavior and test UMER-specific steering algorithms. The model used here includes the measured background earth field, applied as a continuously acting, lab-frame-position dependent force based on linear interpolation between measurement points at the 36 dipoles. This model does not include centroid kicks as a result of magnet fringe fields or the steering effect of the offset YQ magnet, although the framework can support these refinements.

3.4.1 Avoiding null points

Generally, the quad as BPM measurement uses response data from the nearest downstream BPM. However, for certain quad-BPM pairs this may not be appropriate due to the BPM being located near a null point of the betatron oscillation.

There are two reasons why the BPM response will be very flat: the beam is near the center of the quadrupole, or quad-BPM separation is close to $n\frac{\lambda}{2}$ for integer n, where λ is the betatron wavelength. The beam transformation in VRUMER is not exactly equivalent to the transformation in UMER (VRUMER does not include edge focusing, SC effects, etc). Therefore, quad-BPM separations near $n\frac{\lambda}{2}$, the BPM response slope will be small in both VRUMER and UMER but not identical. (This is true for all quad-BPM pairs, but will generally be a small error).

At an operating point of 1.826 A, the UMER 6 mA beam has $\nu_x = 6.636$, $\nu_y = 6.752$ [**?**]. This corresponds to betatron wavelengths $\lambda_x = 1.736$ m, $\lambda_y = 1.706$ m. In the VRUMER simulation, horizontal and vertical tunes are equal (no edge focusing), $\nu = 6.293$, equivalently $\lambda = 1.83$ m. This is consistent with the simplifications made in VRUMER.

We can see that the quad-BPM separations for which unusually high x_q, y_q

Tab. 3.1:

Quad #	Nearest BPM	$\Delta S_{Q\rightarrow BPM}$ [m]
QR14	RC5	0.88
QR32	RC11	1.84
QR38	RC11	0.88
QR62	RC17	0.88
QR70	RC1 (turn 2)	0.88

values appear (Table **??**) are close to the the VRUMER wavelength $\lambda = 1.83$ m, $\frac{\lambda}{2} = 0.92$ m. There are two inaccuracies that may result from this:

- Quad-BPM separation is close to UMER betatron wavelength (a null in the actual ring). VRUMER sees a small $\frac{\partial x_{BPM}}{\partial I_Q}$ slope and predicts $x_q \sim 0$, while in reality x_q could be fairly large. This is hard to discern from the data, and may artifically obscure bad first-turn steering.

- Quad-BPM separation is close to VRUMER betatron wavelength. If BPM response slope is not very flat (but VRUMER thinks this should be a null point) the VRUMER calculation for x_q blows up. This can be seen in Fig. **??**, where QR14, QR32 and QR62 in particular have unphysically large x_q.

In subsequent quad as BPM data in this note, QR14, QR32 and QR62 use the BPM response in the next nearest downstream BPM to avoid artificial blow-up or suppression of x_q and y_q. This effect should also be (but is not currently) included in the calculation of errorbars for the quad as BPM data.

3.5 Ring steering

3.5.1 Horizontal Steering Procedure

3.5.2 Vertical Steering Procedure

3.6 Injection and Recirculation Steering

3.6.1 Injection

3.6.2 Recirculation

3.7 Comments on steering the Alternative Lattice

3.8 implementation

The quad as BPM measurement is controlled by UMER control script kiersten_quad_scan_v2.m. In this procedure, the current in each ring quadrupole (RQ2-RQ71) is independently scanned about it's nominal operating point. The horizontal and vertical position of the nearest downstream BPM is recorded. This data is fitted to a linear curve, using the linear least squares method. The fitted slope is the BPM response to the quad scan, $\frac{\partial x_{BPM}}{\partial I_{quad}}$, equivalently the uncalibrated position in the quad. The errorbars are defined as the 95% confidence interval of the slope coefficient.

To calibrate the position in the quad, I use the VRUMER code to determine what initial condition in the quadrupole gives the appropriate BPM response. I first choose an arbitrary starting position $x_{0,q}$, $x'_{0,q}$ and simulate a quad scan. I then apply the Newton-Raphson method to determine the appropriate x_q to give the desired (measured) BPM response, $m_{sim} = m_{data}$ (where $m_{data} = \frac{\partial x_{BPM}}{\partial I_{quad}}$):

$$\mathrm{x}_q = x_{0,q} - (m_{sim} - m_{data}) \left(\frac{dm_{sim}}{dx_q}\right)^{-1}$$

This allows us to define a calibration factor between the BPM response and the position at the center of each quadrupole,

$$\mathrm{x}_q = C_{q,BPM} \times \frac{\partial x_{BPM}}{\partial I_{quad}}$$

While this factor will not change for a static version of VRUMER, the kiersten_quad_scan_v2.m procedure is set up to do the Newton-Raphson calculation for every set of quad scan data. This was mainly a matter of convenience at the time, as having a lookup table for the calibration factors would result in slight decrease in run time and a loss of flexibility (changes to ring operation would require recalculation of the look-up table, etc). Running VRUMER takes $\sim$ 0.06 seconds, so even for the an entire quad scan (9 points) repeated twice for the Newton-Raphson calculation VRUMER costs $\sim$ 1 second per quad.

This is a description of the horizontal steering method I used to steer the 6 mA beam on November, 2015. The final solution was saved as settings file kiersten_6mA_151116.csv.

The procedure for horizontal steering attempts to steer the beam as close as possible to the center of the quads in the first turn, and use two dipoles at the end of the ring to close the orbit. I generated this solution using an existing solution with many turns, but it should be possible to apply this method to a ring with "no-steering" (significant current loss in the first few turns). The procedure is as follows:

1. Set last 2 injection dipoles by scanning currents and identifying smallest rms deviation in first two RQ's after injection. Time: 1 hour.

2. Steer through RQ3 (first turn) by setting current in D1; Repeat injection scan if change was significant. Time: 10 minutes + 1 hour if repeating injection scan.

3. Steer through quads in first turn, setting dipoles D2-34 in order and using quad-as-BPM method to measure position in quads. Time: 2 1/2 hours ($\times 2$ for best results).

4. Close orbit by scanning D34 and D35 currents. Time: 30 minutes

5. Verify orbit quality by running quad scan for 1st turn quad-as-BPM data, and look at multi-turn BPM data to estimate orbit excursions from closed orbit. Time: 30 minutes.

Total (minimum) time for steering: ≈ 6 hours. Time estimates are for total measurement/ beam-on time, more time should be added for trouble-shooting and general unruly behavior.