

# LINEAR OPTICS CALIBRATION AT THE MIT-BATES SOUTH HALL RING\*

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## Abstract

The MIT-Bates South Hall Ring has been successfully commissioned for internal target experiments. More than 150 mA of stored beam has been circulated through a 40 cm long 1.5 cm diameter internal target cell. The ring has also been tuned for the first experiment on an external target using a resonantly extracted high duty factor beam. Beam-based measurements of the ring optics by means of analyzing the beam orbit response matrix, and comparing the results with models, have produced much needed information to set up the ring optics. Efforts have been made to improve the measurement precision, and to put the entire process on-line for use during machine operation.

## 1 INTRODUCTION

The MIT-Bates South Hall Ring (SHR) is designed to serve medium energy nuclear physics experiments. The ring is composed of four achromatic bending sections which form a pair of symmetry corrected second order achromatic  $180^\circ$  bends. There are two long straight sections, one for injection and the internal target, the other for extraction and the installation of a new spin rotator to maintain beam polarization[1]. Adjusting ring chromaticity does not disturb the symmetry corrected second order centroid shifting aberrations at the extraction and internal target locations. The design does require a relatively large number of independent quadrupole families. There are 81 quadrupoles, of 19 different gradient values, organized into 34 groups by power supply.

A discrepancy between the design optics and that achieved by setting the quadrupoles to their calculated values has been noticed for some time. Initially, correction was made by increasing all quadrupole strengths about one percent, and using the extraction straight section quadrupoles for fine adjustments. This method could bring the betatron tunes to design values, but distortions in the  $\beta$  amplitude functions were significant. This was particularly a problem in the two long straight sections, where specific Twiss parameters are required.

Beam based determination of the ring linear optics was considered a realistic and precise way to correct the optics. The idea of beam based measurements of the optics by means of analyzing the beam orbit response matrix is illustrated in [2], and the computer code LOCO (Linear Optics from Closed Orbits) has been used for modeling. The

beam orbit response matrix is defined as

$$\begin{pmatrix} x \\ y \end{pmatrix} = \mathbf{M} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix} \quad (1)$$

where  $\theta_x$  and  $\theta_y$  are the angles imparted to the beam by steering magnets, and  $x$  and  $y$  are the resulting orbit perturbations at the ring beam position monitors (BPMs).  $\mathbf{M}$  is an  $l \times m$  matrix, where  $l$  is the number of BPMs, and  $m$  is the number of steering correctors. The LOCO code adjusts the parameters (quadrupole gradients, etc.) of an optics model to fit the model response matrix to the measured response matrix. Assuming the deviations between the model and measured matrices are linear functions of a set of the  $n$  varied parameters  $\vec{X}_n$ , then the minimization of the deviations is to solve the linear matrix equation

$$\mathbf{A} \Delta \vec{X}_n = -\vec{V}. \quad (2)$$

where  $A_{i,n} = (\partial V_i / \partial X_n)$ .  $\mathbf{A}$  is an  $(l \cdot m) \times n$  matrix, and  $\vec{V}$  is an  $l \cdot m$  vector which represents the element deviations between the model and measured response matrices. The LOCO analysis involves solving an over-constrained problem, fitting many self-consistent constraints. In addition to the quadrupole gradients, BPM and steering corrector gains are treated as fit parameters. Also the beam energy shift associated with the deflection by a horizontal steering magnet is included.

In the SHR model, there are 187 independent variables: 34 quadrupole groups, 60 BPM gains, 62 steering magnet gains, and 31 energy shifts caused by horizontal steering magnets.  $\mathbf{A}$  is then a  $3720 \times 187$  matrix. Without  $x$ - $y$  coupling, half of the elements of  $\mathbf{A}$  will be null.

## 2 CALIBRATION PRECISION

The precision of the quadrupole gradient determination can be estimated by comparing the LOCO analysis results from repeated beam response matrix measurements. The factors that appear to determine the precision are the BPM resolutions, the sensitivity of the ring optics to the parameters being varied, and beam conditions. The accuracy of the modeling is verified by independent measurements of the optical parameters, such as betatron tunes,  $\beta$  amplitude functions, dispersion, and so on.

### 2.1 BPM Resolution

The original ring BPM system[3] was aimed at fast turn-by-turn beam position measurement. The system used 8

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bit flash ADCs and had a position measurement resolution of 0.1 mm. The measured RMS BPM noise level was about  $40 \mu\text{m}$ , consistent with the  $78 \mu\text{m} / \text{bit}$  ADC digital resolution. It was concluded after early beam response matrix measurements and optics modeling, that the ADC resolution was the main obstacle to achieving a more precise linear optics measurement[4]. To alleviate this, a parallel signal processing system was added. Now the 60 BPM signals are multiplexed to eight ADC channels via an existing video switch board. The signals are integrated over  $62 \mu\text{s}$  (95 turns), held, and then digitized by an 8 channel, 12 bit VMIC 4514 ADC card. Data acquisition is under the newly installed EPICS system, with an update rate up to 60 Hz. Under this new BPM system, the measured BPM noise level without beam is down to about  $5\text{-}10 \mu\text{m}$ . This is closer to, but does not reach, the desired  $\pm 2.4 \mu\text{m}$  ADC digital resolution. The measured BPM noise level with beam was about  $5\text{-}10 \mu\text{m}$  in the horizontal plane, but 2-3 times larger in the vertical plane.

## 2.2 Optics sensitivity

The precision of the quadrupole gradient measurement by LOCO depends on how the quadrupoles are grouped, the quadrupole gradients, and the ring optics.

A simulation was done to examine the details of these effects. The extent the optics change for a change in an individual parameter is related to the overall RMS BPM response, which is the RMS average of the change in all the BPM readings, for beam deflections by all the steering correctors. Table 1 lists the RMS BPM response for a 0.5 % gradient change in eight of the thirty-four quadrupole groups. The steering magnet deflection is chosen to produce  $\sim 0.8 \text{ mm}$  RMS closed orbit perturbations.

Table 1: RMS change in orbit response matrix ( $\mu\text{m}$ ) for quad  $\Delta k/k = 0.005$

Q group	Storage mode			Extraction mode		
	$k (1/m^2)$	$\delta x$	$\delta y$	$k (1/m^2)$	$\delta x$	$\delta y$
QSW3	2.0011	22.3	11.8	2.0011	21.8	7.8
QSW8	-1.1281	12.7	37.4	-1.281	13.4	24.4
QS2F	3.1284	41.3	17.8	3.1284	47.1	11.3
Q26	4.3156	1.7	0.9	4.3156	1.5	0.6
Q40	2.5521	17.3	7.3	2.8189	21.7	5.2
Q41	-1.8327	5.2	8.9	-2.4326	6.4	8.3
Q44	1.6950	10.3	2.8	0.9177	9.6	4.8
Q45	-1.8807	3.1	11.7	0.2342	3.1	0.2

From Table 1, if the BPM resolution is in the  $2\text{-}4 \mu\text{m}$  range, it is possible to determine the quadrupole gradient of groups such as QSW8 or QS2F to better than 5 parts in 10,000. However, for a “weak” quadrupole group, such as Q26, the gradient prediction precision will be in the  $5 \times 10^{-3}$  range, or even a few percent.

There are other effects which may limit the precision of the measurement. The model averages over all gradients of each quadrupole group, and does not include possible errors in the ring dipole gradients (expected field index  $n = 0.539$ ).

Because of how some quadrupoles are grouped, it is possible for a change in one quadrupole to be compensated by changes in others, leaving the ring optics almost the

same. An example of this is the extraction straight section, when operated in pulse stretcher mode. For the same response matrix measurements, but slightly different dispersion measurements, different optical solutions were obtained which had Q45 gradient variations of up to 6%. These variations were compensated by changes in other quadrupoles. The resulting lattices had identical tunes and almost the same betatron amplitudes. The overall horizontal RMS  $\beta$  amplitude differences were less than 0.05 m. The maximum  $\beta_x$  difference of 0.5 m occurred at a high  $\beta_x$  (50 m) location. The vertical RMS difference was three times smaller. We have tried using piecewise fitting to limit these “optical uncertainties”. The procedure is to determine the settings for the quadrupoles which have better measurement precision, fix these settings (do not vary them in later fitting), and then do a second fit to find the values for the less well determined quadrupoles. This technique met with some success in storage mode when working with the 8 bit BPM ADCs. In a future run, it will be tested for the poorly determined extraction section quadrupoles in pulse stretcher mode, after setting up the better known quadrupoles in the rest of the ring.

## 2.3 Beam condition effects

The quality of the linear response matrix measurement is closely related to beam conditions. The dominant beam instability observed for some time has been a persistent vertical betatron oscillation with large amplitude (several millimeters in some locations) and varying amplitude modulation frequency. The measured BPM noise in the vertical plane is always 2 to 3 times larger than in the horizontal. The oscillation was eventually eliminated by changing the vertical tune, based on a proposal[5] which suggested the oscillation may be excited by ions, and could be suppressed by setting the vertical tune to a proper value. Whether the vertical BPM noise level will be reduced now that this persistent betatron oscillation has been eliminated, will be carefully tested in the next ring run.

The beam current and lifetime also affect the measurement. The better measurements have been conducted at low stored current levels (5-40 mA). At higher currents, the measured BPM responses contain larger, possibly systematic, errors. Some measured BPM positions drifted during the noise measurement period (a few minutes). We suspect current related phenomenon such as synchrotron radiation effects on some BPM horizontal pickups. In storage mode, at low currents and very long lifetimes, the measurement results were reproducible. However in extraction mode, where the horizontal tune is closer to half integer resonance, minimal effort has been made to improve the closed orbit so as to achieve a long lifetime. There, with a beam lifetime of  $\sim 200 \text{ s}$ , the position “drift” on a number of BPMs was observed even at low current. Beam scraping may be contributing to the problem.

### 3 ON-LINE APPLICATION

It is important for commissioning to make this calibration process an on-line, real-time operational application.

For the SHR, the beam response matrix measurement typically takes about 10 minutes, being mainly limited by the steering magnet setting time, plus the analog signal switching control rate (4Hz). Computation time for the LOCO analysis depends on the details of the parameters being optimized. A workstation with a 450 MHz Pentium II processor is dedicated to the LOCO analysis. It takes less than 3 minutes to make one LOCO analysis iteration, for the 34 quadrupole groups in the model, and about 10 minutes for the entire calculation. The most difficult and time consuming process during commissioning is determining the quality of raw measurement data.

For the entire measurement and analysis process, a semi-interactive application has been created on a local web site. This has proven efficient for data analysis, and flexible for development. The application consists of measurement set-up and model initialization, the actual measurement, raw data display and analysis, LOCO analysis and display of those results, and generation of a script with new quadrupole settings to achieve the model optics. Most of the data transfer, analysis, and display are done on-line. A Java applet has been developed to handle graphical display. To avoid security issues, some of the actual ring hardware operation commands are required to be made locally under a machine operations account. The site also provides additional data analysis tools.

The raw beam response measurement data analysis and display are extremely helpful. Ordinary mistakes like control system misconnections to BPMs and steering coils can be detected immediately. It has also been useful to help solve more complicated problems, such as video switch hardware and software troubles. Under normal operations, the entire LOCO process can be done in half an hour. Usually several measurements are made and analyzed before a solution is adopted to correct the optics. The analysis and measurement can be done in parallel.

### 4 RESULTS AND PLAN

The beam-based linear optics calibration has been applied on-line, during the last ring commissioning run, for setting up both the storage and extraction optics. Independent optics measurements and ring performance proved the optics corrected by LOCO were close to the design model. In storage mode, the RMS errors of quadrupole gradient predictions were in the  $5 \times 10^{-4}$  and  $5 \times 10^{-3}$  ranges (for different quadrupole groups). In extraction mode, the errors were typically 2 to 3 times larger than in storage mode, and even worse for some quadrupole groups. Further improvement of the BPM resolution and beam conditions are needed. Figure 1 shows  $\beta_x$  before and after one iteration of correction, in extraction mode. The LOCO determinations of  $\beta_x$  are very close to those obtained by quadrupole

gradient ( $k$ ) modulation techniques. Deviations in  $\beta_y$  after correction were much less. Although the measurement precision in extraction mode was limited, the solution of the first LOCO iteration was sufficiently close to the model optics to give us good resonant extraction. This allowed us to measure our first coincidence spectra with high duty factor beam, on an external target[6].

An advantage of having the response matrix measurement and analysis running as an on-line application, is that it is also an effective tool to help diagnose BPM system performance, and expose beam related problems.

Future ring plans call for installation of superconducting solenoids, plus associated skew and normal quadrupoles, for spin control. This will necessitate changing the LOCO model to include  $x$ - $y$  coupling. To improve the measurement precision, we will reduce the noise on the BPM electronics, and operate at a tune with no persistent  $\beta_y$  oscillations. As part of the conversion of the ring controls and instrumentation, the response matrix measurement programs will be moved to EPICS. More work will be done with the piecewise fitting approach. Finally, shunts will be added to many of the quadrupoles which are powered in groups, to allow us to verify the  $\beta$  functions at more locations.

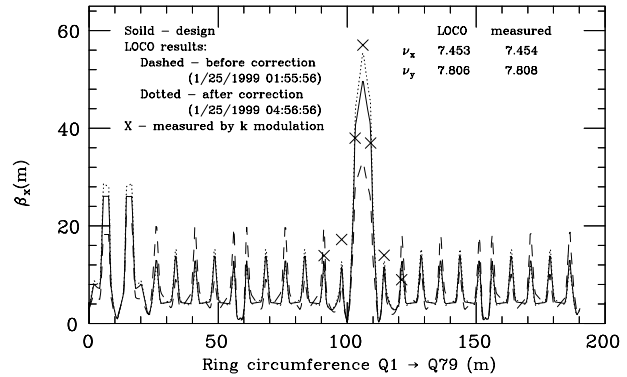


Figure 1:  $\beta_x$  before and after LOCO correction.

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