MEASUREMENT AND CORRECTION OF THE FERMILAB BOOSTER OPTICS WITH LOCO*

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Abstract

The optics of the original Booster lacked the ability for full optics correction and it was not until 2009 when new optics corrector packages were installed between gradient magnets that this ability became available. The optics correction method that is chosen is called LOCO (Linear Optics from Closed Orbits) that measures the orbit response from every beam position monitor (BPM) in the ring from every kick of every dipole corrector. The large data set collected allows LOCO to not only calculate the quadrupole and skew quadrupole currents that both reduces beta beatings and corrects coupling, it also finds the dipole kicker strengths, BPM calibrations and their tilts by minimizing the difference between the measured and ideal orbit response of the beam. The corrected optics have been loaded into Booster and it is currently being tested to be eventually used in normal operations.

INTRODUCTION

The Fermilab Booster is a rapid cycling synchrotron that accelerates protons from 400 MeV to 8 GeV in 33 ms to supply beam to the rest of the complex for high energy physics. Booster has been operational since 1971 [1] but it was not until 2009 that new optics corrector packages were installed between the gradient magnets that the ability to completely correct its optics for the entire ramp became available. Fig. 1 shows an example of a corrector package that contains dipole correctors in both planes, a normal quadrupole, a skew quadrupole, normal sextupole, a skew sextupole, and beam position monitors in both planes.

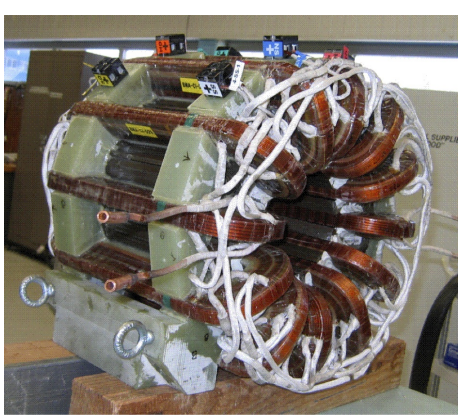

Figure 1: A Booster corrector magnet package before potting.

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The method that has been chosen to correct Booster optics is called LOCO (Linear Optics from Closed Orbits) and has been adapted to the peculiarities of Booster which will be discussed below. This method has been successfully used to correct the optics of other machines, for example the NSLS (National Synchrotron Light Source) X-Ray ring from which LOCO originated. [2]

BOOSTER LOCO

The principle of LOCO is the measurement of the orbit of the beam (i.e. orbit response) at every BPM as each dipole kicker in the ring is used to consecutively 1-bump the beam up the ramp at predefined breakpoints. Mathematically, the process can be parameterized as measuring the orbit response $\Delta x_i/\Delta\theta_j$ of the beam at BPM i due to the kick from kicker j of a fully decoupled machine at each breakpoint:

$$\frac{\Delta x_i}{\Delta\theta_j} = \frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu_x}\cos(|\psi_i-\psi_j|-\pi\nu_x) - \frac{D_i}{D_{\mathrm{RPOS}}}\frac{\sqrt{\beta_{\mathrm{RPOS}}\beta_j}}{2\sin\pi\nu_x}\cos(|\psi_{\mathrm{RPOS}}-\psi_j|-\pi\nu_x) \quad (1)$$

where $\Delta\theta_j$ is the size of the dipole kick from the jth kicker, Δx_i is the change in position at BPM i and $\beta_{i,j}$ are the beta functions at BPM i or kicker j respectively, $\psi_i-\psi_j$ is the phase advance between these two elements, and ν_x is the horizontal betatron tune. The RPOS device here is the radial feedback monitor. The beta function β_{RPOS} and dispersion D_{RPOS} (measured separately) at RPOS is required in the formula because Booster uses radial feedback and thus the dispersion function has a large efect on the response. The same formula without the dispersion term is used when the vertical plane orbit response is considered by appropriately replacing horizontal β's for vertical ones.

It is obvious that the same equation, Eq. 1, is found when the "measurement" comes from the lattice model. Clearly, both these methods will yield different values for $\Delta x_i/\Delta\theta_j$ and so a χ^2 error can be defined and it is

$$\chi^2 = \sum_{i,j}\left[\left(\frac{\Delta x_i}{\Delta\theta_j}\right)_{\mathrm{measured}} - \left(\frac{\Delta x_i}{\Delta\theta_j}\right)_{\mathrm{model}}\right]^2\frac{1}{\sigma_{ij}^2} \quad (2)$$

where σ_{ij} is the statistical error taken at the 95% confdence interval of the slope in the linear fit of the measured orbit response at the ith BPM from a set of kicks using the jth kicker. The use of slopes as the response rather than absolute positions is one reason why LOCO is a successful method.

In principle, LOCO minimizes the χ^2 error, but in practice Eq. 2 is not directly used in the algorithm as the measure. An equivalent measure is defined instead so that a linear algebra

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problem can be constructed. The details of this measure and the method used for inverting the Jacobian that minimizes this measure can be found here [3].

Booster Model Lattice

The Booster lattice consists of 24 periods of FOFDOOD cells. These cells are formed from combined function magnets and so the quadrupole components are already incorporated into these magnets and scale according to the dipole current. Therefore, in a perfect machine, these magnets have been designed to give a perfect periodic lattice without any corrector quadrupole, skew quadrupole or sextupole magnets. See Fig. 2.

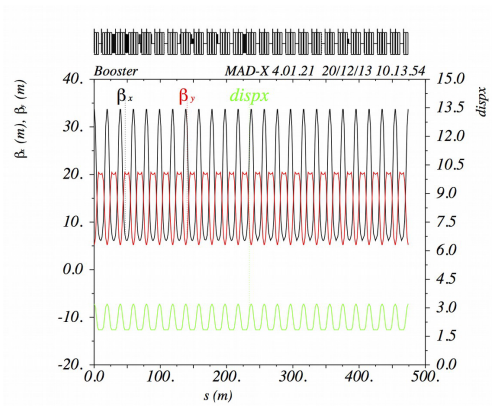

Figure 2: The ideal Booster lattice without errors. The combined function magnets provide the focusing and defocusing required for a periodic lattice. All the corrector elements have zero current.

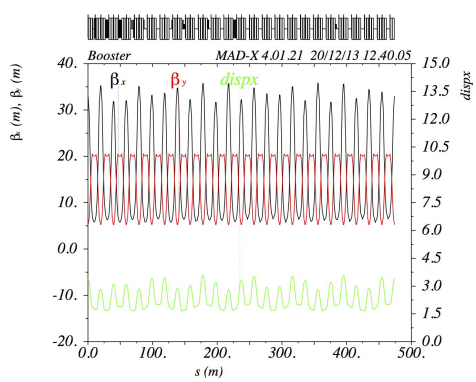

Figure 3: The Booster lattice at injection with the extraction dogleg in the *vertical* plane turned on, and it is clear that the lattice in the horizontal plane is distorted.

However, in normal operations, the DC vertical dogleg that is used for extraction, distorts the lattice in the horizontal plane. See Fig. 3. Therefore, even for a lattice that does not have any other errors, the introduction of the dogleg creates beta-beating that requires optics correction. It is important to note that LOCO *cannot* take out the error from the dogleg because it will fit the corrector quad currents to match the lattice shown in Fig. 3 because the dogleg is "on" in the Booster MADX model file. Therefore, the solution is to take out the effect of the dogleg by hand and recover the ideal lattice. This will be discussed in the next section.

Correcting the Effects of the Dogleg

In order to recover the ideal Booster lattice from the effects of the dogleg, a subset of the available corrector quadrupoles around the dogleg have been optimized so that this error can be taken out. The strengths of these quadrupoles are shown in Table 1. Of course, these strengths are dependent on the strength of the dogleg and beam energy. In this case, the dogleg current is 293.4 A and for any other current these quadrupole strengths will need to be rescaled. The dogleg corrected lattice is shown in Fig. 4. It is clear from this figure that the correction is not perfect — there is still a small distortion around the dogleg.

Table 1: Quadrupoles Used for Dogleg Correction

Quadrupoles	Gradient (T/m)
QS24	0.403011
QS01	0.298202
QS02	0.185324
QS03	0.290666
QS04	0.372706
QS05	0.4282
QS06	−0.0412226

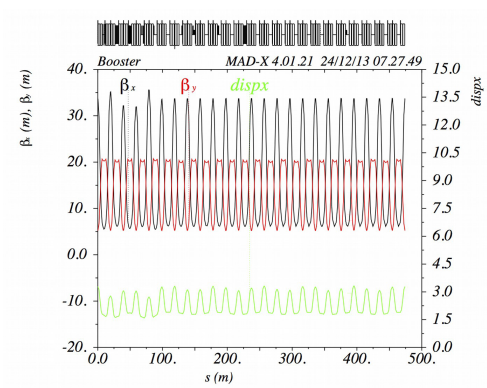

Figure 4: After using a subset of the corrector quadrupoles around the dogleg, the optics can be mostly corrected. There is still a small distortion around it.

The effect of the dogleg diminishes as the beam energy increases. It scales as (p/c) and thus the strength of these quads will be reduced proportionately up the Booster ramp.

MEASURING AND CORRECTING THE BOOSTER LATTICE

The measured Booster lattice at injection, after the coupling is corrected with LOCO, is shown in Fig. 5. It is clear from this figure that when compared to the model Booster

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lattice shown in Fig. 3, there are other errors besides those from the dogleg.

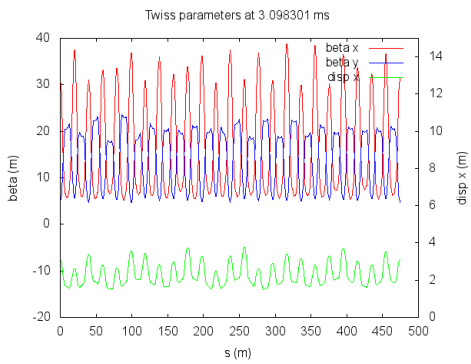

Figure 5: The measured Booster lattice at injection before correction.

The process for correcting the as found lattice is to first put in the quadrupole values that correct for the dogleg error and then applying LOCO to find the values of the corrector quadrupoles that removes the remaining errors.

Data Collection and Analysis

The Booster ramp is divided into 32 time break points and for each break point, the orbits are measured 6 times to get a good mean and standard deviation of the orbit. There are 96 corrector dipoles in one plane and for each of these dipoles, three 1-bumps are applied. Finally, not every Booster ramp can be used to take data because high energy physics is taking place during the measurements. The study events occur every 1.67 s. Putting all these numbers together, and assuming that it takes zero time to retrieve the data from the 96 BPMs, it takes, theoretically, 48 min to complete taking data for one plane. In practise, it takes about 2 hours to complete data taking for both planes.

The LOCO analysis of the data collected is a large memory problem because of the large number of BPMs and dipole kicks and fit parameters (tilts and calibrations of corrector dipoles, BPMs and quadrupoles) used. In fact, there are 4.3×10^6 elements in the Jacobian for every breakpoint! When LOCO is run on a single processor machine, it takes about 1.5 hours to do the complete analysis. In order to speed up the analysis, LOCO has been parallelized. The result is a 6× increase in speed, with the complete analysis taking 15 min, when 30 processors are used. See [4].

After Correction

The corrected lattice at injection is shown in Fig. 6. It is clear that the corrected lattice is a lot better than the as found lattice shown in Fig. 5. There is still some beta-beating but whether this can be completely corrected will need to be studied further.

CONCLUSION

Of course, the entire exercise of optics correction is to apply the corrected optics to operations. However, the operational optics have been tuned extensively over decades and so to get the LOCO corrected lattice to the operational efficiency still requires betatron tune and chromaticity changes especially at injection. Fig. 7 shows the difference in efficiency between the two lattices. There is a 2% drop in ramp efficiency with the LOCO lattice compared to the operational lattice. Thus, there is an ongoing effort to increase the efficiency of the LOCO lattice so that it can become operational. It is planned to have this lattice used for operations some time this year.

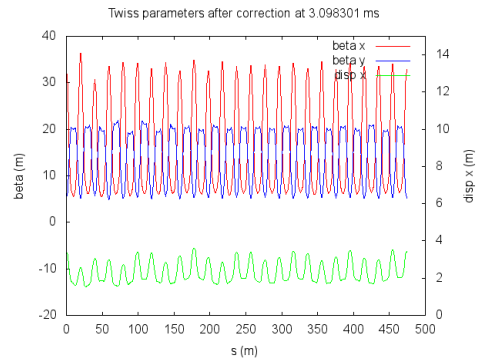

Figure 6: The measured Booster lattice at injection after LOCO correction.

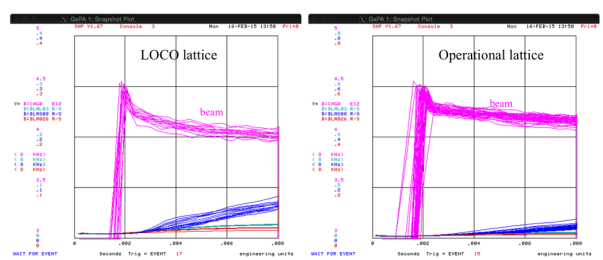

Figure 7: This is a comparison of the beam capture efficiency between the LOCO lattice and the operational lattice. There is a 2% drop in efficiency with the LOCO lattice.

ACKNOWLEDGMENTS

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