OPTICS CORRECTIONS WITH LOCO IN THE FERMILAB BOOSTER *

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Abstract

The optics of the Fermilab Booster has been corrected with LOCO (Linear Optics from Closed Orbits). However, the first corrections did not show any improvement in capture efficiency at injection. A detailed analysis of the results showed that the problem lay in the MADX optics file. Both the quadrupole and chromatic strengths were originally set as constants independent of beam energy. However, careful comparison between the measured and calculated tunes and chromatcity show that these strengths are energy dependent. After the MADX model was modified with these new energy dependent strengths, the LOCO corrected lattice has been applied to Booster. The effect of the corrected lattice will be discussed here.

INTRODUCTION

The Fermilab Booster is the oldest circular machine in the Fermilab complex. It has been in operations since 1971 [1], but it was not until 2009 that new optics corrector pakages were installed between the gradient magnets that the ability to correct its optics for the entire ramp became available. Unfortunately, the initial attempt at correcting the Booster optics with LOCO (Linear Optics from Closed Orbits) [2] failed to achieve the goal of improving either the beam injection or ramp efficiencies despite correcting the beta beating to better than 5% on average. [3] For comparison, the normal HEP lattice has a beam ramp efficiency of 92% or better while the lattice with LOCO corrections has a maximum efficiency of 89%. The original goal, with LOCO corrections, was to achieve 92% or to improve on it, but we were unable to do it. Thus, a concerted effort was then made to discover the reason behind this failure.

But before we do that, we have to understand that one feature in the LOCO optics correction method is that it strongly depends on the accuracy of the optics model. Therefore, we had to spend time making sure that the MADX model was correct.

MADX MODEL PROBLEMS

We discovered through testing of the MADX model with measurements that it did not predict the chromaticities or the tunes correctly. Figures 1 show the extent of the problem where the predictions are not even close to measurements. These are two fundamental parameters of the any machine and if the model cannot predict these values, there is no hope for going any further with LOCO.

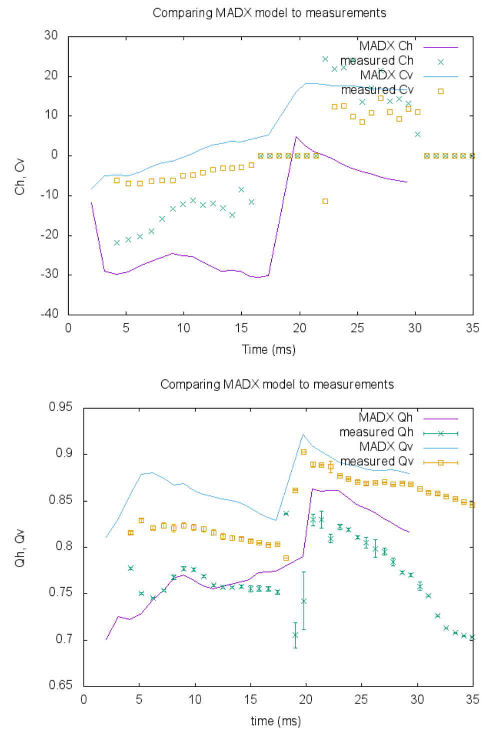

Figure 1: The chromaticities and tunes calculated by the MADX model compared to measurements as a function of the ramp time, i.e. energy of Booster. The model predictions are terrible.

Source of the Problem

The source of both the above problems can be traced to setting the sextupole and quadrupole focusing and defocusing components of the gradient magnets to constants, perhaps for convenience years ago, in the MADX model file. The setting of these components as constants is incorrect because from measurements done 2003 [4, 5] show that these components are a function of the ramp energy.

Correcting the Problem

We tried to use the magnet measurements done in 2003 in the MADX model but using these values in the model did not reproduce the measured chromaticities and tunes. As a consequence, we decided that a better way was to fit the sextupole and quadrupole strengths in the model to the measured values from beam measurements. When we did this, we could create a new set of sextupole and quadrupole strengths as a function of energy shown in Fig. 2. It is clear that this plot that the sextupole components can be parameterized in terms of a quartic polynomial while it is not possible to fit a low order polynomial to the quadrupole components as a function of kinetic energy (KE).

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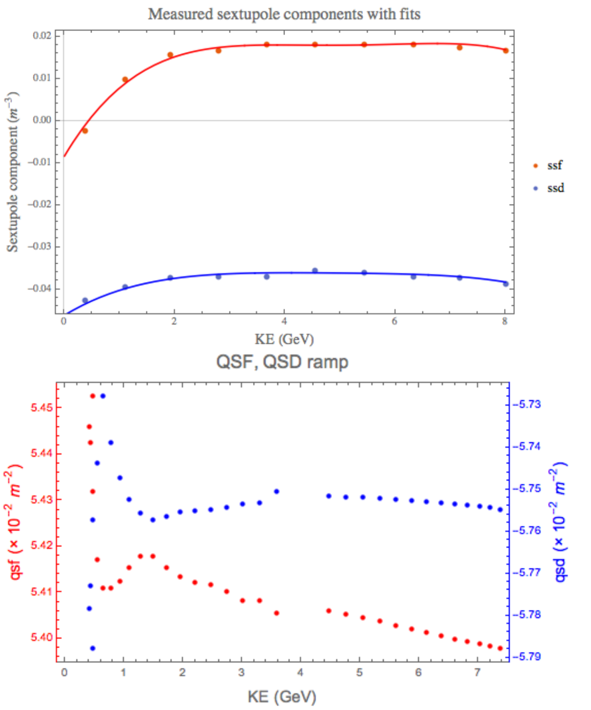

Figure 2: The sextupole and quadrupole components found from fitting the model to measurements.

NEW MADX MODEL

Using the new sextupole and quadrupole strengths that are energy dependent in the MADX model allowed us to successfully predict both the tunes and chromaticities. Figure 3 shows the results. This new model allowed us to continue work on optics corrections.

LOCO CORRECTED OPTICS

We decided to use the new MADX model to correct Booster optics from 2.9 ms to 6.50 ms (KE from 410 MeV to 670 MeV) rather than the entire ramp as a test of the method. Unfortunately, we found that when we applied 100% correction, the beam transport efficiency was reduced to below 90%. Therefore, we decided to be less ambitious and applied partial optics corrections. We found that a 75% correction from 2.9 ms (410 MeV) to to 6.5 ms (670 MeV) and with the rest of the ramp unchanged kept the beam efficiency above 90% and just 1% below the normal HEP lattice. See Fig. 4

The details of how we applied LOCO is discussed in Ref. [6]. For example, the as found and corrected optics at 3.05 ms (KE = 413 MeV) in Booster are shown in Fig. 5 after 6 SVD iterations. We can see that even with 75% correction, the beta beating is well under control.

Tuning to Recover 1%

We tuned the Booster to try to recover the 1% loss. Orbits, tunes and chromaticities were checked. There were very small changes from the lattice change, for example, Figure 6 shows the tunes before and after correction. The horizontal tune remains the same while the vertical tune has a very

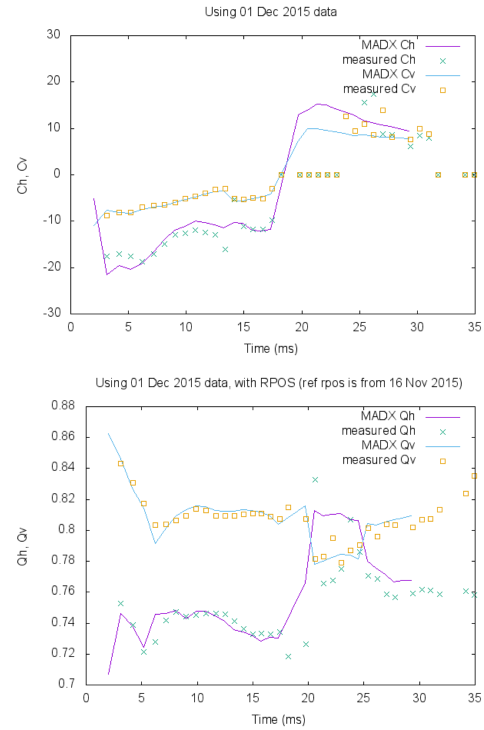

Figure 3: The chromaticities and tunes calculated by the improved MADX model compared to measurements as a function of the ramp time, i.e. energy of Booster. This time the model predictions match measurements.

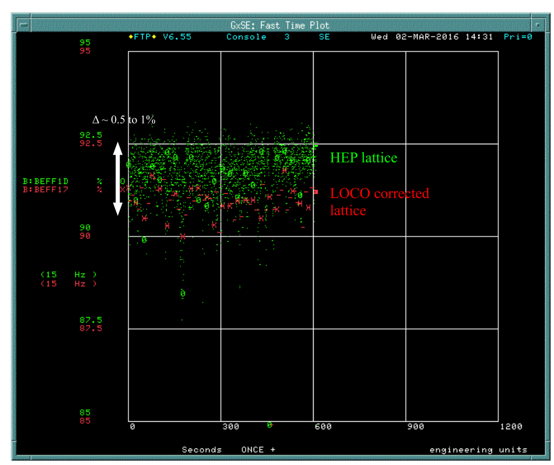

Figure 4: The transport effiency between the HEP lattice and the 75% corrected lattice from 2.9 ms to 6.50 ms. The LOCO corrected lattice has an effiency that is between 0.5 to 1% less than HEP.

small shift of 0.004. Unfortunately, we were unable to recover the 1% during the machine studies period. We also opened up the aperture at the collimator locations to see if the larger beta's from the corrections caused the loss as well as measuring emittances. These measurements did not show any smoking gun.

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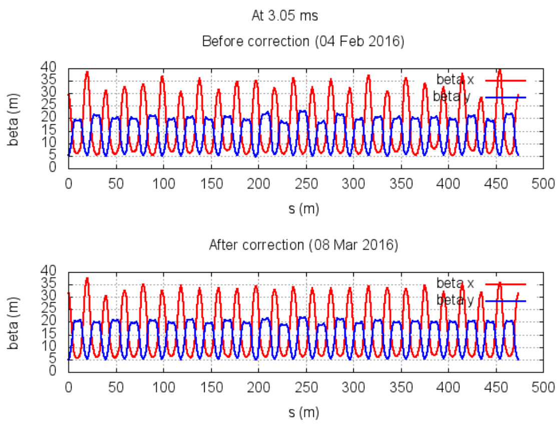

Figure 5: The optics before and after correction at 3.05 ms. The beta beating is mostly corrected after 6 SVD iterations.

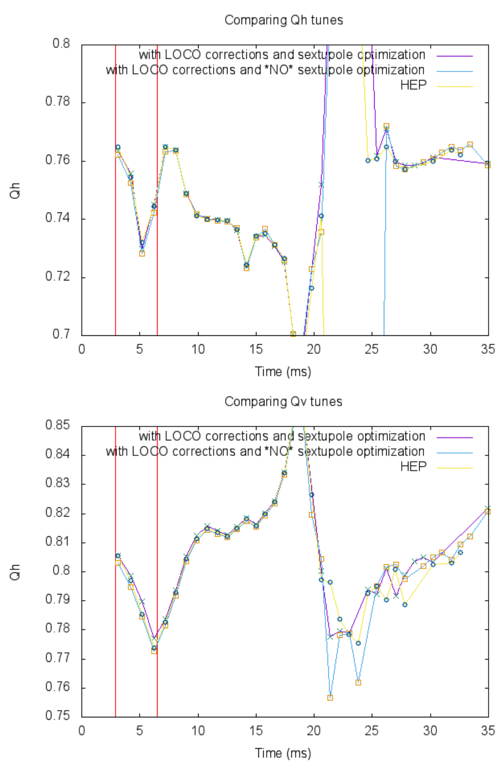

Figure 6: The tunes before and after 100% lattice correction between the two red vertical lines are compared. There is a small vertical tune shift by 0.004 due to the correction.

Tune Space

One hypothesis for correcting the lattice is that the tune space should be improved. We did a tune scan to see whether this was the case. Unfortunately, we did not see any improvement. In fact, we saw a reduction in tune space instead. The tune scans done at 3 ms into the ramp with normal HEP intensities ($\sim 4.5 \times 10^{12}$ protons) are shown in Fig. 7. It is clear from this figure that the tune space is reduced with the LOCO lattice. This reduction in tune space can explain the

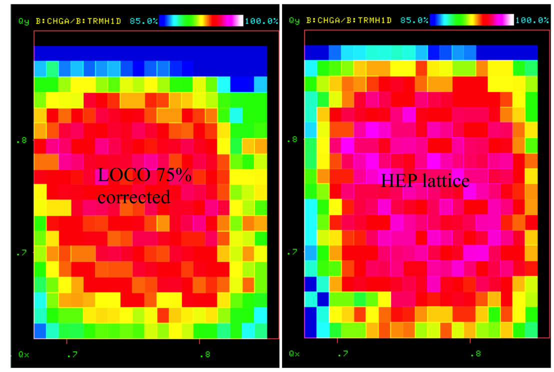

Figure 7: The tune space betweeen the 75% corrected lattice and the HEP lattice taken at 3 ms into the ramp are shown here. It is clear that there is a reduction in tune space with the LOCO lattice.

inefficiency of the LOCO corrected lattice when compared to the HEP lattice.

CONCLUSION

There is a 1% drop in ramp efficiency with the LOCO lattice compared to the HEP lattice when only 75% of the corrections are applied between 2.9 ms to 6.5 ms (410 MeV to 670 MeV). Tune scans show that there is a loss in tune space with the corrected lattice. More work will need to be done with simulations to understand why there is a reduction in tune space as well as how much improvement is to be expected.

ACKNOWLEDGMENTS

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