# BEAM TRANSFER LINE TUNING AND STEERING BASED ON MINIMIZATION MODEL TOOLS*

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*Abstract*

Accurate beam steering is crucial for transfers between different accelerators in the Fermilab accelerator complex.

During commissioning of the new 8-GeV beam transfer line from Fermilab Booster to Main Injector, we used a least square fit algorithm to achieve the desired beam line orbit. The program is based on the COCU orbit correction package used at CERN. The purpose and the need of this program is to keep the desired injection trajectories to the Fermilab Main Injector (FMI) constant and minimize the time required to tune the beam line. In addition, we performed a number of measurements to compare the optics of the line to the design values.

In this paper, we present the experience with the beam line steering in the 8-GeV line during commissioning and the results of detailed beam line studies.

## 1 INTRODUCTION

A new transfer line was built to transport $8.9\,\mathrm{GeV}$ protons from the Booster to the Fermilab Main Injector (FMI). The line is about $760\,\mathrm{m}$ long and is made from both permanent and conventional electromagnets [1]. The line was partly finished and tested in February 1997. After completion of the line, the final commissioning started in September 1998.

For regular operation, it is important to steer the beam through the line and into the Main Injector without losses, for which a good orbit is essential. This raises the need for a fast and convenient way to correct the trajectory to the desired reference.

## 2 ORBIT CORRECTION

The orbit correction that was implemented for the 8-GeV line is based on the MICADO algorithm [2]. It solves a system of linear equations

$$r = Ax + b \tag{1}$$

where $b$ is the vector of the BPM measurements, $x$ is the correction vector and $A = (a_{ij})$ the beam response matrix to a set of corrector excitations. The algorithm iteratively minimizes the norm of the residual vector $r$ using a least squares method. At each iteration, it finds the first best corrector excitation that yields the lowest residual r.m.s. BPM distortions. This corrector is appended to the corrector set, the residual distortion is reanalyzed and the next best corrector selected. The strengths of all correctors from previous iterations are recalculated. This is repeated for a number of correctors until the residual r.m.s. BPM distortions are as small as desired. The algorithm is fast and converges with a small number of corrector magnets.

Here, the MICADO algorithm is embedded in the orbit correction package COCU (Closed Orbit Correction Utilities) [3] which was developed at CERN. The package is capable of correcting the closed orbit, a trajectory in a circular accelerator or transfer line, and orbit or trajectory correction over a short range without affecting the rest of the machine. It also does calculation of bumps and simulation of the effects of correctors on the orbit. Calculations are based on the Twiss parameters which can be taken from simulations like MAD [4].

The COCU package had to be adapted for the use in the accelerator controls system at Fermilab. The existing code runs under HP-UX at CERN while the Fermilab controls system is based on VAX/VMS. Due to the complexity of the code it was decided not to port it to VMS but to run it under UNIX. The existing source could be compiled with minor changes under SunOS and Linux. An application program was written for the VAX control consoles. This program takes the beam position monitor (BPM) data and allows the selection of orbit correction type, plane to correct, number of correctors, etc. The BPM data and the correction commands are sent via TCP/IP to a server running on the UNIX side. The server program performs the data input to the COCU program, runs it and sends the predicted orbit and corrector excitations back to the console program. The console program shows the predicted orbit and corrector excitations and allows you to send the corrector excitations to the hardware.

The code is not particularly accelerator specific and can easily be extended to other transfer lines and circular machines. It will also be used for the transfer lines between Main Injector and Recycler and closed orbit correction in the Recycler Ring.

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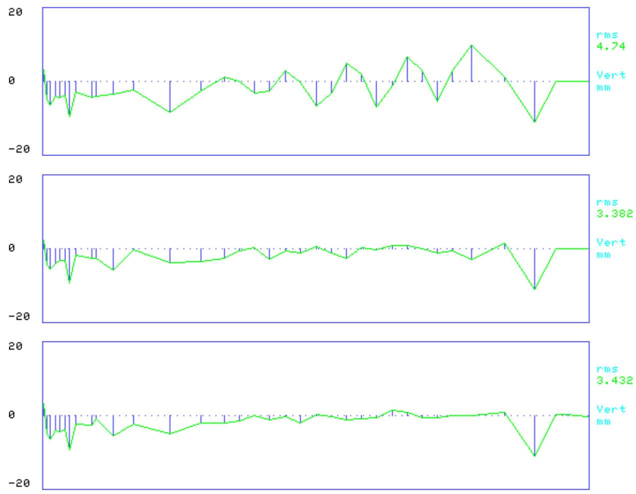


Figure 1: Vertical orbit data in millimeter as a function of the location. The upper graph shows the measured trajectory before correction. The center graph shows the predicted orbit for a short range correction where the injection trajectory into the Main Injector was kept constant. The lower graph shows the measured orbit after correction. It corresponds well to the predicted orbit.

During initial commissioning of the 8 GeV transfer line between Booster and Main Injector, the steering of the beam was done manually using 3-bumps to zero the orbit at the BPM locations. After implementation of the COCU package, it was tested and used.

The program successfully corrected the trajectory. It allowed a much faster, deterministic way of trajectory correction. An example of the measured, predicted and corrected orbit is shown in Fig. 1. The program has shown particularly useful to correct to a previous reference trajectory after changes in the Booster extraction orbit. It converges very fast, one iteration usually is sufficient. This indicates that the beam optics is close to the design optics.

Fig. 2 and Fig. 3 show examples of the corrected trajectory in the horizontal and vertical plane, respectively. The trajectory is well corrected to a few millimeter, except for the beginning of the beam line. The trajectory there results from Booster extraction orbit with no corrector magnets at upstream locations in the transfer line. This orbit excursion is not critical since it does not create beam loss. The transmission through the beam line obtained during the commissioning was 96-97%.

## 3 TRAJECTORY ANALYSIS

The effectiveness of the orbit correction strongly depends on the correspondence between the model and the actual machine. To verify the optics of the 8-GeV line, we studied the effect of single corrector excitations on the trajectory.

The COCU package has the feature to predict the effect of single corrector kicks on the BPM readings. This was used to calculate the deviation of the measured BPM data

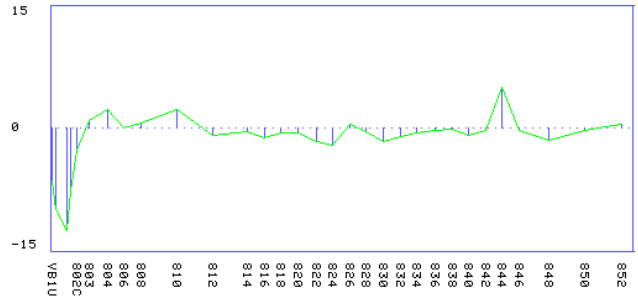


Figure 2: Horizontal BPM display in millimeter as a function of the BPM position. The orbit is well corrected except for the beginning of the beam line. The excursions there result from Booster extraction with no upstream corrector magnets in the transfer line. The apparent excursion at the 844 location results from a bad BPM reading.

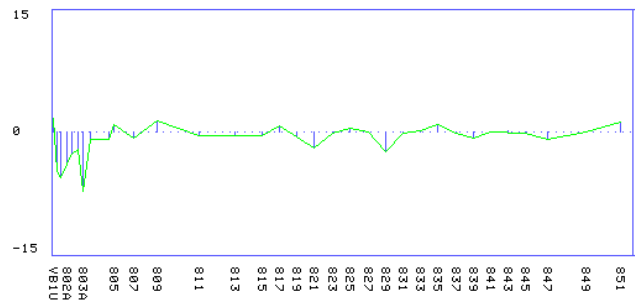


Figure 3: Vertical BPM display in millimeter as a function of the BPM position. The excursion at the upstream end cannot be corrected due to missing correctors.

from the expected trajectory for the design optics. A reference orbit was saved, a corrector magnet changed and the difference trajectory to the reference was recorded. The analysis of the difference orbit has the advantage that absolute BPM position errors do not influence the results. An example for the horizontal plane is shown in Fig. 4.

The graph shows that the difference trajectory from a kick at corrector HT802 corresponds to the theoretical expectation down to the BPM HP806. An oscillation is visible downstream of that location. An orbit correction with COCU was performed to find the origin of the kick and kick strength. The result shows that this oscillation can be corrected with one single kick at the 806 location, indicating an error in the quadrupole strength $k_1$. The gradient error $\Delta k_1$ was estimated from the calculated correction kick $\Delta\theta$ and the BPM reading $x_{\mathrm{BPM}}$ at this location as $\Delta k_1 \cdot L = \Delta\theta / x_{\mathrm{BPM}}$ where L is the length of the magnet.

The quadrupole strength was changed and the measurement was repeated. After final adjustment, the measured trajectories almost correspond to the theoretical design within the noise of the BPM system. Fig. 5 shows an example of a single horizontal kick trajectory after quadrupole adjustments.

A similar measurement for the vertical plane was performed by changing the strength of the Booster extraction

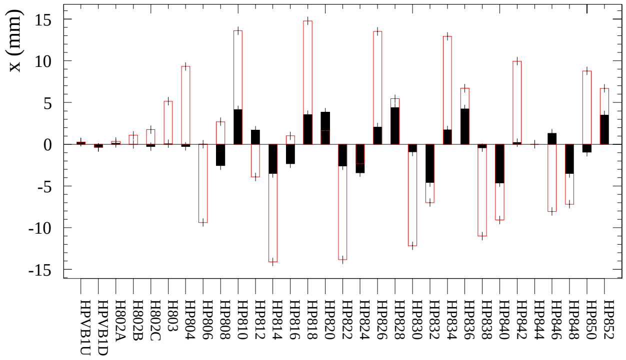


Figure 4: Horizontal BPM readings. The open data shows the measured trajectory difference for a single correction coil (HT802) excited. The filled data shows the difference between theoretical prediction and measured data. An oscillation starting from BPM HP808 is clearly visible.

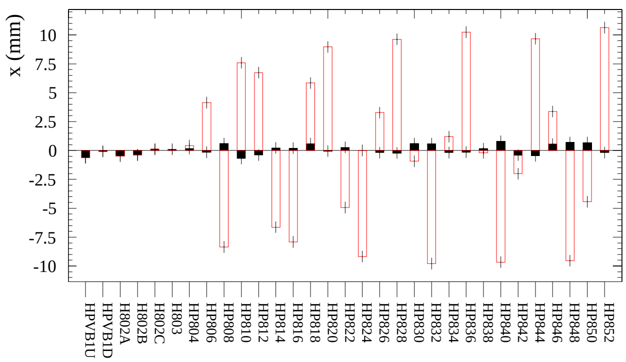


Figure 5: Horizontal BPM readings as in Fig. 4 after adjusting the quadrupole strength of Q806. The trajectory results from excitation of the single correction coil HT804. It corresponds well to the predicted trajectory for the quadrupole strengths as designed.

septum magnet (see Fig. 6). The results indicate that a few quadrupole magnets do not run at their design strength and have to be adjusted. The analysis will be repeated after adjustments made to the vertically focusing quadrupoles and also for kicks on the first corrector in the horizontal plane to diagnose the quadrupole strengths of the first magnets in the beam line. A more detailed analysis of the 8 GeV transfer line including lattice functions, dispersion, emittance propagation and matching to the Main Injector can be found in [5].

## 4 CONCLUSION

The COCU orbit correction package was successfully implemented at Fermilab and used during commissioning of the 8 GeV transfer line. The application program can easily reduce the time required to optimize the beam trajectory. It helped to achieve a transmission of 96-97% through the transfer line.

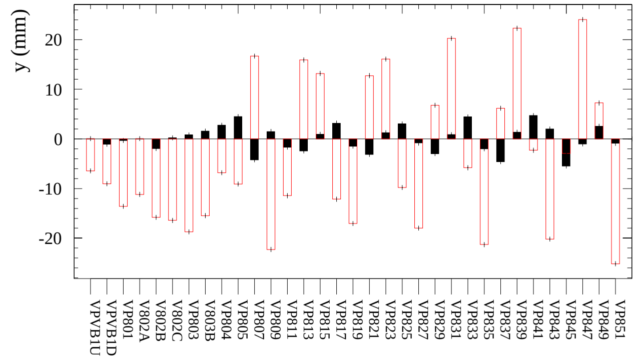


Figure 6: Vertical BPM readings. The trajectory results from a current change in the Booster extraction septum magnet MP02. Open data is the measured data, the filled data shows the difference from the predicted trajectory for the design optics.

The COCU package was also used to compare the trajectory of orbit kicks to the design and helped to find quadrupole strength errors. The transfer line optics in the horizontal plane corresponds well to the design. A few gradient errors are still present in the vertical plane and will need further investigation.

## 5 ACKNOWLEDGEMENTS

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