# FERMILAB BOOSTER ORBIT CORRECTION

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*Abstract*

The Fermilab particle physics program has recently expanded to include the MiniBooNE experiment in addition to the RunII program. As a result, the effective and reliable performance of the Fermilab Booster has become crucial to the lab. The Booster is an 8 GeV proton synchrotron and is a key element of the Fermilab accelerator chain. It must meet increasing demands for proton intensity and high repetition rates. One important requirement placed on the machine is low radiation levels. These levels are highly correlated with losses in the machine, and can limit Booster production. We will describe how a system of ramped dipole corrector magnets are being used to maintain orbital position throughout the acceleration cycle in order to minimize beam losses, maximize proton intensity, and maintain the required repetition rate.

## INTRODUCTION

Recently the physics program at Fermilab has grown to include a thriving group of accelerator based neutrino physics experiments. This is in addition to continued RunII operation of the Tevatron as the highest energy proton–antiproton colliding beam accelerator in the world. The neutrino program at Fermilab includes MiniBooNE [1], which began taking accelerator based neutrino data in late summer of 2002, and NuMI/MINOS [2], which is scheduled to come on line in 2005. Both of these experiments depend on massive amounts of protons from the Fermilab accelerator chain. In particular, MiniBooNE generates a neutrino beam that originates as an 8 GeV proton beam from the Fermilab Booster. The MiniBooNE baseline requirement is 5E20 p.o.t. (protons on target) per year; however, the Booster can currently deliver ~2E20 protons/year. This gives MiniBooNE only 40% of its baseline, although it receives roughly 12 times more protons than those used for RunII operations. Clearly, the demand on proton production from the Booster is significantly higher than it has been in the past, and it will continue to rise when NuMI/MINOS begins to take beam. By the year 2006, the Booster may be required to deliver 5 times what it produces now.

## THE FERMILAB BOOSTER

The Fermilab Booster [3] was originally built to provide protons to the Main Ring, and it first took beam in 1970. The Booster accepts the 400 MeV proton beam from the Fermilab Linac, accelerates it to 8 GeV, and sends it to MiniBooNE, the Main Injector for RunII, or the Radiation Damage Facility. The Booster is 472 m in circumference with a 24-fold periodic lattice. Each period has a 6 meter long straight and a 1.2 meter short straight drift section, and 4 combined function magnets, two horizontally focusing (F magnet) and two horizontally defocusing (D magnet) [4] (see Fig.1). These magnets cycle in a 15 Hz resonant circuit.

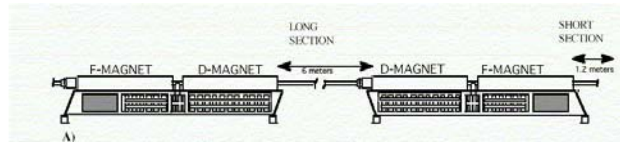


Figure 1: A Booster lattice cell [4], consisting of a focusing magnet, defocusing magnet, long drift, defocusing magnet, focusing magnet, and a short drift (FDOODFO).

In spite of its age, the Booster has been very reliable, maintaining an average uptime of over 90%. However, the machine is being pushed to run at record intensities and repetition rate. At present, the Booster can stably accelerate a *maximum* of 5E12 protons/pulse, and before the MiniBooNE era it typically ran at a repetition rate of ~2 Hz. In order to meet the new demand for protons, the current goal is to run steadily at 5E12 protons/pulse at a repetition rate of 7.5 Hz (5 Hz for MiniBooNE).

### *High Intensity Running*

There are many challenges involved in running the Booster at high intensity, including beam loss and radiation damage issues. Damage or activation of accelerator components in the tunnel is a serious concern. Damage to accelerator elements could increase failure rates, and activation makes it difficult to maintain machine components.

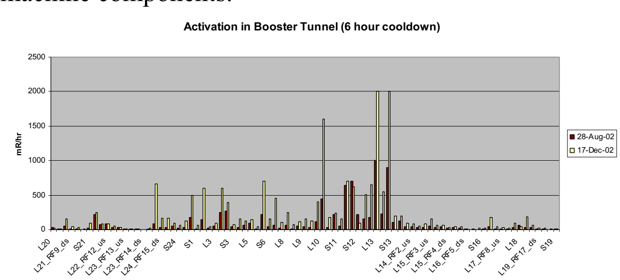


Figure 2: Booster tunnel radiation levels from radiation surveys performed in August 2002 and December 2002. Activation levels were significantly higher in December after MiniBooNE began routinely taking beam.

In December 2002, a radiation survey was done of the Booster tunnel (see Fig. 2). It became clear from the survey data that activation of tunnel components had significantly increased since the turn-on of MiniBooNE. Additionally, the personnel recording the data received a

20 mR radiation dose, and two technicians completing a minor high voltage cable repair in the tunnel received a 30 mR dose. After the survey, some of the beam loss limits in the Booster were lowered to reduce component activation in sensitive locations. Furthermore, reducing beam losses became a high priority in order to facilitate high intensity running of the Booster.

## BOOSTER ORBIT CORRECTION

The orbit correction project was designed to reduce beam losses in the Booster by controlling the beam orbit throughout the 33 msec acceleration cycle. This project makes use of the ramped dipole correctors, the BPM (Beam Position Monitor) system, and the extensive array of BLMs (Beam Loss Monitors) in the Booster.

### *Dipole Correctors*

Orbit correction is accomplished using the ramped dipole corrector magnets in the Booster. There are 2 such correctors in each lattice period, one horizontal and one vertical, for a total of 48. Each is located in its respective high beta region, with the vertical correctors in the long straight sections and the horizontal correctors in the short straights (see Fig. 3). We currently manipulate the orbit only in the vertical plane. It is possible to consider orbit correction in the horizontal plane, but there are complications involved in doing so. The Booster RF (Radio Frequency) system uses feedback from the horizontal beam position to determine the RF phase used for acceleration. Any external change to the horizontal beam position would need to accommodate this system in order to keep the machine functioning properly.

Originally, the correctors were run DC and were designed to introduce a separation of 1.4 cm at 10 meters (about half of a period) at the Booster injection energy of 400 MeV [4]. This meant that their impact on the orbit was reduced as the acceleration cycle progressed. Dramatic changes in the orbit position throughout the cycle were not uncommon. Recently, the ability to ramp the magnets was implemented. This enables us to affect the orbit throughout the entire Booster acceleration cycle.

### *Beam Position Monitors (BPMs)*

The Booster BPMs are also crucial to the orbit correction program, since they are used to measure the beam orbit position throughout the cycle. As with the dipole correctors, there are 48 BPMs in the Booster, located in each long and short straight section. These stripline devices measure beam position in both the horizontal and vertical planes with sub millimeter precision. They are also capable of measuring beam intensity.

### *Beam Loss Monitors (BLMs)*

There is an extensive array of BLMs in the Booster. They are located in each long and short straight section, with additional individual loss monitors at key positions around the ring for a total of 60. These ionization loss monitors are in the orbit correction project as a diagnostic. Beam losses with and without the orbit corrections are compared in order to understand how well the correction is working.

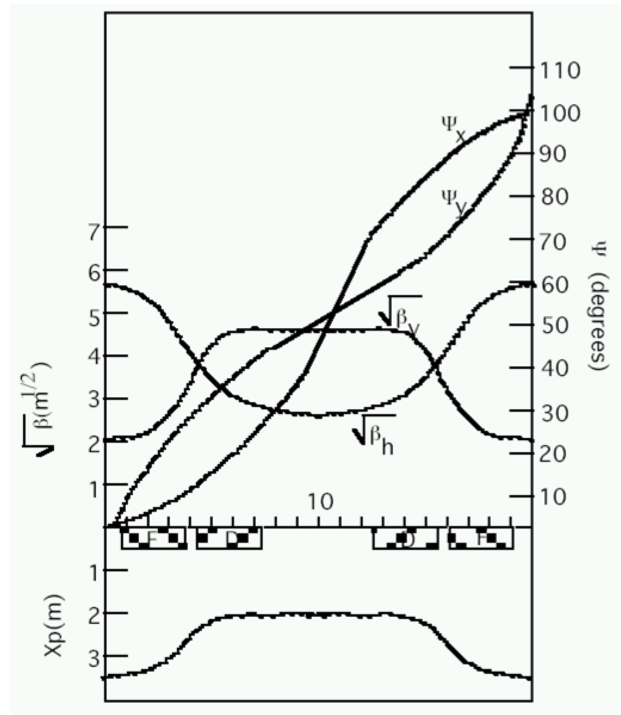


Figure 3: Booster lattice showing the correspondence between focusing and defocusing magnets and the horizontal and vertical beta functions. The vertical high $\beta$ region is in the long straight section, while the horizontal high $\beta$ region is in the short straight section [4].

### *Orbit Correction Procedure*

The orbit correction proceeds in several steps. First, the desired orbit is read either from a file or directly from a particular time during an active Booster cycle. In the latter case, an orbit shortly after injection is typically used. The orbit is measured as a function of time using the BPM system, and then the current ramps needed to hold the orbit at the desired point are calculated. There are 12 break points during the 33 msec Booster cycle at which the closed orbit current ramp is calculated. This is complicated by absolute current limits and a 600A/sec slewing limit between each time break for all correctors. The optimum corrections are calculated based on all active correctors, initially without regard to the limits. If any correctors are over the limit, then the quantity (D/L) is calculated for each, where D is the change in current since the last time break, and L is the distance to the limit for that magnet. All of the current changes are then scaled back such that the maximum value for (D/L) is 1, meaning that one corrector is at its limit. That corrector is set to the maximum, removed from the active list, and the orbit is reoptimized using the rest of the correctors. This process is repeated until no additional correctors hit their limits, up to a maximum of 15 iterations for each time break. Once the ramps are calculated, they are sent to the corrector magnets and implemented in the next accelerator cycle. There is also a steering interface, which enables the user to manipulate the orbit relative to the present desired orbit, and then recalculate the current ramps. This is used to steer the beam at unusual locations, such as extraction points or low aperture regions. Finally, the loss monitors are used to gauge the beam transmission through the machine once the ramps are activated.

### *Orbit Correction Results*

We have run the orbit correction program on Booster beam going to MiniBooNE, and can see a distinct difference in the beam position throughout the acceleration cycle due to the correctors. Figure 4 shows the vertical beam position with and without the ramped correctors at two different locations in the tunnel: long straight sections 13 and 24. At each location, we successfully held the orbit fairly flat throughout the cycle with the correctors. Long 13 is a special case because it is located at an extraction point which forces the beam position to be lower than might be expected.

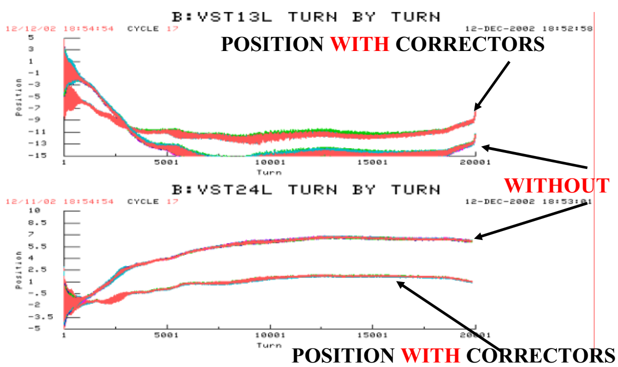


Figure 4: Vertical beam position at long straight section 13 (top) and 24 (bottom) as a function of time in the Booster cycle with and without the correctors.

It is also possible to look at the loss monitor results both with and without the ramped correctors. Figure 5 shows the normalized loss pattern in the Booster as a function of the position around the ring *without* using the ramped correctors. Figure 6 shows the normalized losses *with* the correctors on and actively controlling the vertical beam position. While the overall magnitude of the losses remains similar, the loss distribution was successfully changed. Beam losses at Long 22 and Long 24, where sensitive RF cavities are located, were dramatically improved.

## CONCLUSIONS

Demand for proton production at Fermilab has significantly increased, forcing the Booster to run at record intensity and repetition rate. Unfortunately, beam losses create challenges to achieving the new production goals. The orbit correction project has successfully controlled the beam orbit throughout the entire Booster cycle. As a result, beam losses have been significantly improved near sensitive equipment. Work on this project continues in order to reduce overall Booster losses throughout the ring, thus enabling consistent high intensity running of the Booster.

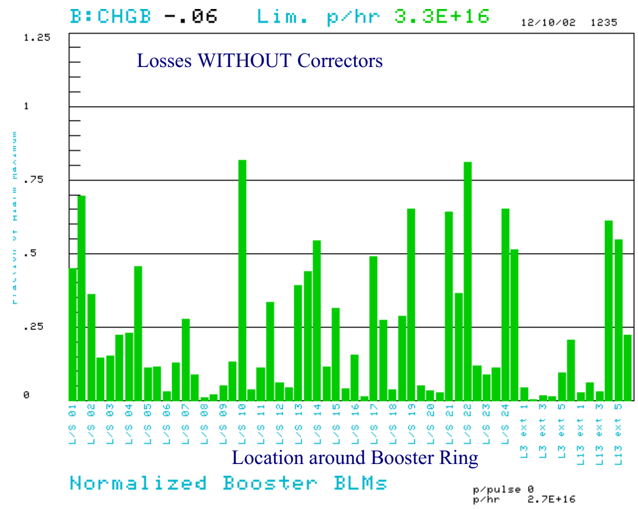


Figure 5: Normalized Booster losses as a function of position around the ring without using the ramped correctors. Note the high losses around L/S 22 and 24 to the right of the plot.

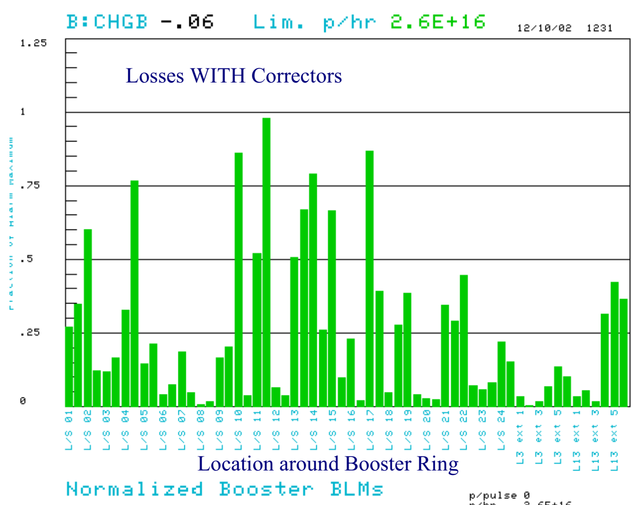


Figure 6: Normalized Booster losses as a function of position around the ring WITH ramped correctors to change the vertical beam position. Note that the losses around L/S 22 and 24 have been significantly reduced.

## REFERENCES

[1] E. Church, et al., "A Proposal to Measure $\nu_\mu \rightarrow \nu_e$ Oscillations and $\nu_\mu$ Disappearance at the Fermilab Booster: BooNE", Fermilab Proposal 898 (1997).
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[4] B.Worthel, Booster Rookie Book, (1998).