INCREASING THE INTENSITY OF THE FERMILAB BOOSTER

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Abstract

The Fermilab Booster is a fast-cycling synchrotron which accelerates protons from 400 MeV to 8 GeV of kinetic energy. Until recently, the primary demand for protons was for antiproton production, which typically uses about 7E15 protons per hour. Over the next few years, the Fermilab neutrino program will increase that demand dramatically, possibly beyond 1.8E17 protons per hour. This paper discusses the issues involved in reaching these intensities, and the plan for achieving them.

INTRODUCTION

Overview

The Fermilab Booster [1] is the synchrotron which takes 400 MeV protons from the Fermilab Linac and accelerates them to 8 GeV for use by all of the lab's physics programs. It is 472 m in circumference and has a harmonic number of 84. The 96 combined function magnets which form it's 24-fold symmetric lattice are configured in an offset 15 Hz resonant circuit.

Projected Proton Demand

Figure 1 shows the projected proton demand through the next few years. The primary users of protons are the two major neutrino experiments: MiniBooNE and NuMI/Minos.

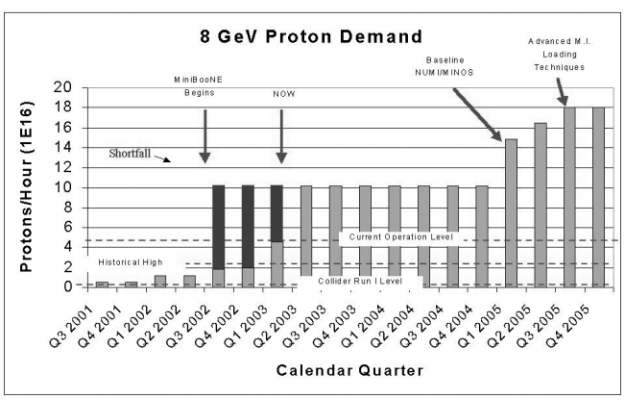

Figure 1: Projected Proton Demand

Limiting Factors

There are several factors that limit the total flux from the Booster:

- Maximum batch size: ~5E12 protons, limited by beam stability. At the moment, there is no plan for increasing this.
- Maximum average repetition rate: ~7.5Hz, limited by heating of the RF cavities and the magnets in the injection dogleg. This may have to be increased to 10 Hz or more by 2006 or so.
- Aboveground radiation: limited by shielding and the occupancy classes of the buildings above.
- Beam loss in the tunnel. This is discussed in detail shortly.

PREPARATIONS FOR HIGH INTENSITY

A great deal of work has been done to prepare the Booster for high intensity.

Longitudinal Damping System

At high batch intensities, coupled-bunch oscillations become a problem, so a longitudinal damping system [2] was developed which is crucial to high-intensity operation.

Shielding and Shielding Assessment

Initially, aboveground radiation was a severe limitation to total Booster flux, primarily because of the office space located above the ring. To address this problem, a large amount of shielding was added and a number of offices were moved and their space reclassified “minimum occupancy”.

As a result, we believe we can meet even the ultimate requirements of the Booster without exceeding the aboveground limits.

Extraction Septum

Formerly, heating in the Booster’s primary extraction septum limited the average repetition rate to about 2.5 Hz. Recently, both the septum and its power supply were replaced with a system which is capable of operating at the full 15 Hz rate.

MONITORING BEAM LOSS

The Booster is now physically capable of delivering the protons that are requested of it, and intensity is limited by the maximum acceptable beam loss in the tunnel. This is of concern both because of potential radiation damage to accelerator components and because activation of these components makes it difficult to service them.

We have generally attempted to keep the activation at key locations in the Booster tunnel to within a factor of two of what it was prior to the start of the neutrino program. Recall that we hope to achieve this while

ultimately increasing the total proton flux by more than a factor of 40.

We have two methods for monitoring beam loss during Booster operation. The first involves a system of 60 beam loss ionization monitors arranged around the ring. For each of these, a 100 second running sum is calculated, which is compared to a limit. Broadly speaking, limits have been set to be roughly twice the loss levels observed prior to the start of the neutrino program, but they have also been fine tuned based on observed activation in the tunnel. Booster operation is inhibited if any of these exceeds its limit.

In addition to the individual beam losses, the average beam power loss is calculated by measuring the derivative of he number of protons in the ring, weighting it by beam energy, and integrating it through the cycle Presently, we limit this power loss to 400W. The limit was chosen in similar manner to the individual loss limits, but it is remarkably close the 1W/m limit specified for the SNS.

KNOWN LATTICE PROBLEMS

Both of the Booster's extraction regions involve a four magnet dogleg to vertically steer the beam around the extraction septum during acceleration. These doglegs operate at fixed current, and bend the beam by 42 mr at injection. It has recently been discovered that edge focusing effects in these doglegs cause severe lattice distortions [3], which are worst at injection and fall off as $1/p^2$. Figure 2 shows the effect of these doglegs at injection. It is now believed that these lattice distortions are a major cause of losses early in the cycle.

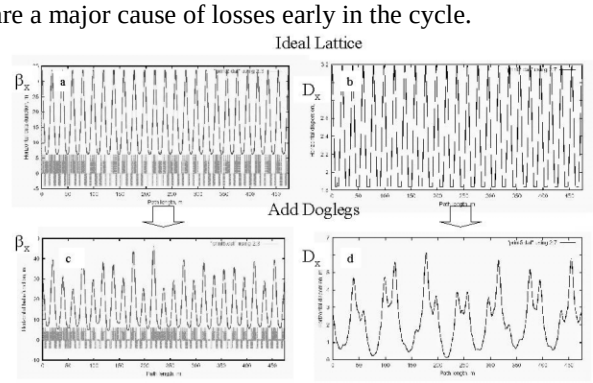

Figure 2: Lattice distortions due to the extraction doglegs. The ideal horizontal lattice functions are shown in (a) and (b), respectively, while (c) and (d) show these functions including the effects of the extraction doglegs.

RECENT PERFORMANCE

Figure 3a shows the output of the Booster in protons per minute starting in August, 2002. Although the proton flux has increased by more than a factor of 12 during this period, the average activation in the Booster tunnel has only increased by about a factor of two to three. This is illustrated in figure 3b, which shows the energy loss per proton over the same period. The primary reasons for this improved performance are increased attention to beam losses, and specific tuning to minimize the dogleg current.

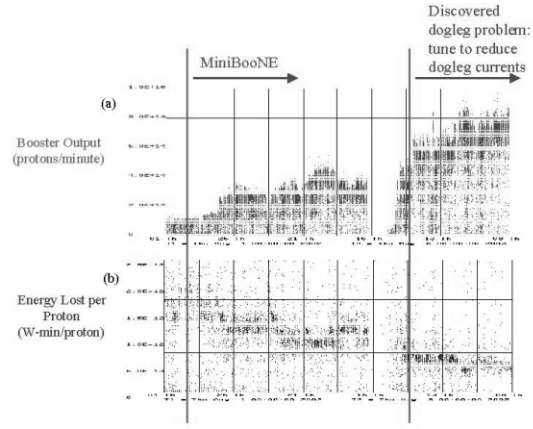

Figure 3: Booster performance since Aug. 2002.

MAJOR UPGRADE PROJECTS

Collimator Project

The biggest single project to increase the Booster intensity is the implementation of a collimation system [4]. Figure 4 illustrates the principle. High amplitude particles are intercepted by a thin primary foil, and subsequently absorbed by thick stainless steel secondary collimators. Each of the secondary collimators intercepts the beam on one edge in each plane.

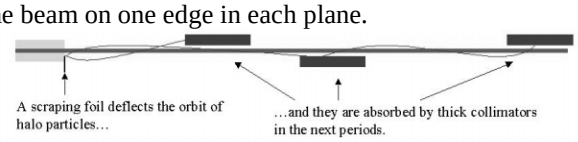

Figure 4: Collimation principle of operation.

The otherwise simple design is complicated by the need for fairly extensive shielding of the secondary collimators. We lack a quantitative model for Booster beam loss, so the shielding needs were calculated based on the assumption that the collimation system would intercept more or less all of the beam which is currently observed to be lost during the acceleration cycle. For the sake of calculation, the loss was taken to be 30% of the beam at injection energy (400 MeV) and 2% near extraction energy (8 GeV) with the Booster delivering the maximum proton flux which is forseen.

This leads to a shielding requirement of about 4' long steel 2' thick around each of the three secondary collimators. To avoid the need for moveable parts or vacuum seals in the extreme radiation environment inside the shielding, we settled on a design in which the secondary collimator jaws are fixed within monolithic steel shielding blocks. Each block is attached to the beam pipe on either end with bellows, allowing the *entire assembly* to move over the range required by collimator operation.

The design of the collimator system is more or less complete and construction is underway. Installation is planned for the 2003 summer shutdown.

Large Aperture RF System

The 18 cavities of the Booster RF system have 2¼" drift tubes. This aperture restriction is of particular concern because it results in activation of the cavities themselves, which are a high maintenance item.

A powered prototype of a new cavity with a 5" aperture was built and tested last year. Based on the success of these tests, work is proceeding on two vacuum prototypes. In order to reduce the cost of these cavities and expedite the fabrication, a substantial number of the parts have been machined at universities involved in the lab's neutrino program.

All the major parts have now been completed and assembly of the cavities has begun. We are on schedule to replace two of the existing cavities with these new cavities on the summer shutdown. Based on our evaluation of the effectiveness of these prototypes, we will make the decision whether to proceed with the complete replacement of the RF system over the next few years.

Extraction Dogleg Improvements

As mentioned before, ameliorating the dogleg problem has become one of our primary goals.

In the fairly near term, there's a plan to stretch out the distance between the magnets of the doglegs. Over the summer shutdown, we hope to increase the distance between the dogleg magnets of the primary extraction region from 18" to 41". Because the effect goes as the square of the bending angle, this will be almost a factor of five reduction for this dogleg. Ultimately, we hope to do the same for the second extraction region.

We are also considering ways to completely eliminate the need for the doglegs. These include:

- Putting large aperture lattice magnets upstream of the extraction septum, so that the septum blade may be moved completely out of the beam.
- Adding a pulsed bump within the extraction period which is only energized near extraction time.
- Develop a septum that mechanically moves into the beam near extraction. This would involve motion of about 2-3 cm at 15 Hz.

Beam Orbit Control

While the main lattice elements of the Booster ramp sinusoidally, the correction dipoles have historically been operated DC. This means that the beam position moves on the order of several millimeters over the acceleration cycle. Among other things, this will complicate the use of the collimation system.

A system has been designed to use ramped current controllers to maintain beam position during acceleration. Details are described elsewhere [5], but the basic idea is that beam positions will be measured at discrete times in the cycle and corrections will be calculated to move these orbits to the ideal orbit, subject to the limitations of the power supplies.

This system is currently in the commissioning phase.

Lattice Improvements and Space Charge Mitigation

Recently, there has been a dramatic increase in the effort to accurately model the Booster, with particular interest in space charge issues [6].

One immediate result of the improved model was the discovery of the dogleg problems.

This effort continues on a number of fronts, which are too numerous to mention here, but we have hopes that other problems and solution will be found.

CONCLUSIONS

The 30 year old Fermilab Booster has made impressive progress toward meeting the demands of the Fermilab neutrino program. The proton flux has increased by roughly a factor of 12 over that prior to the start of the MiniBooNE experiment in August, 2002. This has been accomplished with only roughly a factor of two increase in the activation of tunnel components.

On the other hand, we are still delivering only about 45% of the MiniBooNE baseline request. With this, the turn-on of the NuMI beamline in 2005, and proposed increases in the needs for antiproton production, the Booster flux will have to increase by about another factor of five over the next few years.

A number of improvements are planned which make us optimistic that we can reach these goals.

ACKNOWLEDGEMENTS

These dramatic improvements in Booster performance would not have been possible without the efforts and dedication of the Fermilab operations department and technical support departments.

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