Status of the Fermilab Booster After the 400 MeV Upgrade

David McGinnis
Fermi National Accelerator Laboratory *

1. INTRODUCTION

The major emphasis in the Fermilab High Energy Physics program is the running of the TEVATRON in the proton-antiproton collider mode. One of the chief limits in the luminosity has been the number of antiprotons during a store. Antiprotons are produced at Fermilab by hitting a metal target (Nickel) with 120 GeV protons. The number of antiprotons produced are proportional to the number of protons targeted. The production ratio of the number of antiprotons collected to the number of protons targeted is about 17E-6.

Protons are first accelerated as H- ions in a 750 keV Crockoft-Walton accelerator. Before the Upgrade, the H- ions are then accelerated in a drift tube linac to a kinetic energy of 200 MeV. After the linac, the two electrons of the H- ions are stripped in a multi-turn injection process in the Fermilab Booster. The protons are then accelerated to a kinetic energy of 8 GeV and transferred to the Main Ring. The protons are finally accelerated to 120 GeV in the Main Ring before they are targeted towards the Antiproton Source.

Because of the low injection energy in the Booster, the beam in the Booster at injection suffers a large space charge tune shift (on the order of 0.35 for an injection intensity of about 3.0E+12 protons per Booster batch). Also, the Main Ring has an transverse injection aperture of about 14π mm-mrad (normalized, 95%). Coupled with this relatively small aperture and the large transverse emittance blowup due to space charge tune shift, the maximum number of protons targeted in a single Booster batch previous to September 1993 was about 2.0E+12.

To reduce the emittance increase at injection in the Booster, the injection energy of the Booster was doubled from 200 MeV to 400 MeV. This would allow an increase of intensity of 75% for the same space charge tune shift. The energy increase was accomplished by raising the average accelerating gradient of the last half of the Linac. The increase in accelerating gradient was achieved by replacing the last half of the drift tube Linac with seven sections of side-coupled cavities. Each section was powered by a 12 MW klystron.

A new transfer line was constructed between the Linac and the Booster that could transport H- ions without stripping. Also, the Booster injection region was redesigned with stronger pulsed local 4-bump magnets that did not require a costly redesign of the power supply. Special attention was paid to installing high quality diagnostics such as beam position monitors, multi-wire profilemeters and bunch length detectors.

This paper will concentrate on describing the Booster side of commissioning the 400 MeV upgrade.

*Operated by Universities Research Association under contract with the United States Department of Energy.

2. BOOSTER COMMISSIONING

2.1 Commissioning Milestones

Installation of the 400 MeV Upgrade followed the conclusion of the 1993 Collider Run (Run 1a) on June 1, 1993. The initial commissioning goal was to reach 2.0E+12 protons extracted at 8 GeV from the Booster in one batch by Oct. 1, 1993. The goals for Collider Run 1b which started Sept. 1, 1993 were to achieve 3.0E+12 protons on the Antiproton target for one Booster batch. A summary of the milestones achieved during the Booster commissioning of the 400 MeV Upgrade is summarized in Table 1. Note that items 8-10 in Table 1. are intensity records for Fermilab.

1.	June 1, 1993	Installation of the new Linac began.
2.	Sept. 10, 1993	First shot of beam into 400 MeV line
3.	Sept. 18, 1993	Beam reaches Booster injection girder.
4.	Sept. 24, 1993	First turn of beam in Booster.
5.	Sept. 24, 1993	Beam extracted at 8 GeV.
6.	Oct. 5, 1993	2.0E+12 protons extracted at 8 GeV.
7.	Nov. 9, 1993	3.1E+12 protons extracted at 8 GeV.
8.	Jan. 28, 1994	3.6E+12 protons extracted at 8 GeV
9.	Feb. 15, 1994	4.1E+12 protons extracted at 8 GeV
10	June 9, 1994	2.77E+12 protons extracted at 120 GeV

Table 1. Booster Milestones for 400 MeV upgrade.

2.2 Evaluating the Success of the Linac Upgrade

The goal of the Linac Upgrade was to increase the transverse phase space density at extraction in the Booster by 75%. Initially, the performance of the Upgrade was to be measured by the amount of beam accelerated in the Main Ring. This criteria was based on the assumptions that all the emittance growth in the Booster occurs at injection, the Booster has an injection aperture greater than 35π mm-mrad, and the Main ring has an injection aperture less than 14π mm-mrad.

However, in Run 1a and 1b, a number of measurements were made that suggest that a different criteria should be used for measuring the success of the Upgrade. First, aperture scans using very local four and five bumps were perfected for the Booster. These scans give a more accurate measure of the Booster injection aperture. The measurements indicated that the smallest aperture in the Booster was about 7π mm-mrad (which was vertical in nature and located near the extraction septum.) not 35π mm-mrad.

Second, an ion profile monitor that measures the transverse emittance on a turn by turn basis was developed during Run 1a. As shown in Fig. 1 about 50% of the emittance growth occurs at injection and the other 50% occurs elsewhere in the acceleration cycle (mainly at transition). With these two pieces of information, the success of the Linac Upgrade should be measured by the amount of beam in the Booster after about 1/3 of the way into the acceleration cycle.

As shown in Table 1, the Booster has achieved an intensity of 4.1E+12 protons. Above intensities on the order of 2.9E+12 protons, the beam in the Booster suffers from a number of coherent instabilities which will be discussed later. These instabilities make emittance measurements difficult to interpret. However for intensities less than 2.9E+12 protons, the beam is fairly stable. Emittance measurements now show that the emittance in the Booster is independent of intensity for stable Booster beams and that very little emittance growth occurs at injection.

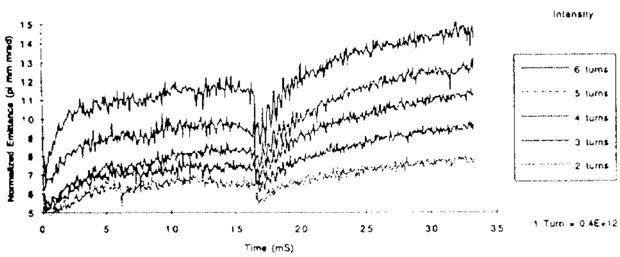

Figure 1. Emittance growth before the Upgrade.

2.2 *Obstacles Encountered During Commissioning*

Although the commissioning process went fairly smoothly, there has been a number of obstacles encountered that slowed the progress towards higher intensities. This section will discuss one of the more serious obstacles.

As stated earlier, the Booster uses a multi-turn injection process. A pulse of H- beam much longer than the Booster circumference is accelerated in the Linac and then overlaid turn by turn (A turn is one Booster circumference.) in the Booster by stripping the H- beam of its two electrons and combining the stripped beam with circulating beam at a local 4 bump. The intensity in the Booster is then proportional to the pulse length (or the number of "turns") accelerated in the Linac. A turn is about 0.42E+12 protons.

After the Booster had achieved its commissioning goal of 2.0E+12 protons at 8 GeV, it was found that as more turns were injected, the accelerating efficiency dropped so that only marginal intensity increases were obtained. It was found that the energy of the Linac pulse drifted linearly along the length of the pulse for pulse lengths greater than 2 turns. This momentum slew was on the order of about 0.06% per turn. The slew was the result of beam loading through the high shunt impedance of the side-coupled cavities.

Furthermore, the momentum spread of the beam due to the higher gradient of the new Linac was about 0.3%. This momentum spread is compressed with a "debuncher" cavity located in the 400 MeV transfer line 40m downstream of the end of the Linac. Because the new Linac operated at 805 MHz compared to the old frequency of 201 MHz, the maximum momentum spread that the debuncher cavity could compress was about 0.4%. The Booster can tolerate a momentum spread of about 0.1%, Coupled with the energy slew along the length of the Linac pulse and the larger momentum spread of the beam, pulse lengths greater than 6 turns had a momentum spread larger than the debuncher could compress. Thus the maximum intensity that the Booster could successfully accelerate was 2.4+E12 protons.

However, the new Linac has incorporated feedforward learning algorithms in the low level RF control system specifically designed for compensating beam loading of the side-coupled cavities. When the feedforward algorithms were re-programmed, the beam loading and hence the energy slew were compensated. Shortly afterwards, an intensity of 3.1E+12 protons at 8 GeV was achieved in the Booster. (Milestone 7 in Table 1.)

3 INSTABILITIES

The major impediment to obtaining the goal of 3.0E+12 protons on target has been the occurrence of transverse instabilities in the Booster that cause the beam emittance at extraction from the Booster to be too large for the Main Ring injection aperture. The onset of the instabilities occur when the Booster extraction intensity becomes greater than 3.0E+12 protons.

3.1 *Transverse Instabilities*

The only instabilities observed in the Booster during Collider Run 1b have been horizontal in orientation and occur only after transition. (Transition in the Booster occurs about half way through the acceleration cycle.) The instabilities occur after transition because of the short bunch length (hence the large line charge density) in the Booster after transition. The growth rate of the instabilities can be reduced by mis-timing transition so that the longitudinal emittance after transition becomes larger.

The horizontal orientation of the instabilities is probably the result of a negative horizontal chromaticity after transition. Because of the fast cycle rate, the chromaticity in the Booster is difficult to measure. However, chromaticity measurements of the Booster when the accelerating ramp is turned off (E_k = 400 MeV) show a large negative uncorrected horizontal chromaticity (~ -22 Units) and a large positive vertical chromaticity (~ +10 Units). The positive vertical chromaticity before transition is easily corrected by air-core ramped sextupoles. However, the present horizontal air-core sextupoles are not strong enough to correct the horizontal chromaticity after transition.

The strongest horizontal instability occurs at the lowest betatron sideband (180 kHz) and is probably due to the increased driving term of the resistive wall at low frequencies. The growth rate of this mode can be reduced by changing the horizontal radial position of the beam. The reason for this behavior is thought to be that the relatively large octupole component of the Booster combined function magnets act as a position dependent sextupole.

However, attempts to increase the Booster extraction intensity above 3.0E+12 protons were met with large beam loss at high field in the Booster. Because the growth rate of this instability is so fast, a wideband active damper does not have enough gain to suppress the instability. A relatively straight forward narrowband damper that works on the lowest frequency betatron sideband is shown in Fig. 2. The system incorporates two pickups located 100° apart in betatron phase. The system is phased by making a beam transfer function measurement and maximizing the negative real part of the transfer function by adjusting the relative gain of the pickups. The gain of each pickup can be changed as a function of time in the acceleration cycle giving a time dependent phase shift. To phase this system takes about 4500 Booster pulses. With the narrowband system commissioned, beam intensities well over 3.6E+12 protons could be accelerated. (Items 8-9 in Table 1.)

However, with the fast growing mode removed with the narrowband damper at high intensities, the rest of the betatron sidebands became unstable. Although the growth rate of these bands are relatively slow compared to the narrowband mode, the emittance growth as a result of these modes was still to large to fit into the Main Ring for Booster intensities above 3.0E+12 protons. The major difficulty for building a wide band damper for the Booster is the large swing in the revolution period from 2.2 uS at injection to 1.6 uS at extraction. This swing in revolution period requires a damper with a variable delay. Switched coaxial cable dampers have proved to be too noisy to work for fast growing instabilities. The Booster department at Fermilab is in the process of commissioning an 8 bit digital delay damper. The design of this damper system is complex. The relatively large cable delays and large revolution period swing require that the A/D and the D/A clock somewhat asychronously to each other. This requires the use of fast dual port memory.

Because the commissioning process of the digital damper is anticipated to be rather long, a fixed coaxial cable delay damper has been commissioned. The revolution period changes only by 0.25% during the last 1/3 of the acceleration cycle. This margin is small enough for a fixed delay damper to be stable. The damper signal is down converted to DC and a high pass filter is applied to remove the large common mode signal of the fundamental RF beam harmonic. With this damper, a stable operating intensity of 3.3+E12 protons with an emittance less than 14π mm-mrad can be extracted at 8 GeV from the Booster. At this intensity a Main Ring intensity record of 2.77E+12 protons at 120 GeV was set (Item 10 in Table 1).

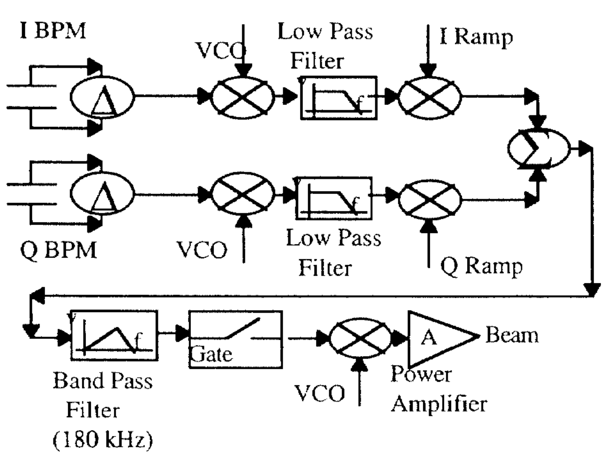

Figure 2. Narrow band Transverse Damper

3.2 Longitudinal Instabilities

Above extracted Booster intensities of 3.3E+12 protons, longitudinal coupled bunch modes in the Booster diminish the injection efficiency of the Main Ring. These coupled bunch modes are derived from the higher order mode impedances of the Booster accelerating cavities. The modes that are excited are the dipole modes 34-36. (The harmonic number of the Booster is 84.) Although this cavity mode has passive higher order dampers (HOMs) installed, the mode does not tune and therefore the sweeping revolution harmonics still see the same order of shunt impedance as if the HOMs where not installed.

The growth rate of these modes is on the order of 5 mS. For this growth rate, the electronic gain of a damper chain would have to be about 90 dB for a 50Ω kicker. This gain is difficult to achieve with a wideband damper system. However, since the mode frequency of the cavity is well known, a set of narrowband active dampers can be fed into an appropriate coupling loop of a single cavity. The electronic gain needed for the narrowband dampers reduces to about 70 dB. The type of narrowband damper used is a sweeping single sideband notch filter similar to the dampers used for the CERN PS Booster developed by F. Pederson. As shown in Fig. 3, this damper eliminates the longitudinal instability for Booster intensities less than 3.3E+12 protons. At higher intensities more gain is needed and this has yet to be accomplished.

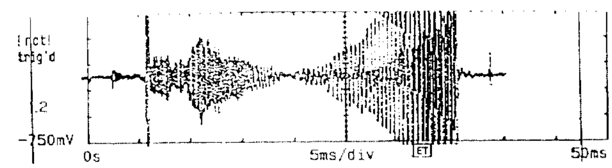

Figure 3a. Longitudinal error signal with damper off.

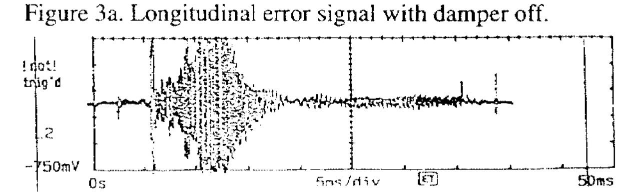

Figure 3b. Longitudinal error signal with damper on.

4. FUTURE WORK

The Booster is accelerating 3.3E+12 protons to 8 GeV. The injection efficiency is 95% and the accelerating efficiency is 80%. The extracted transverse emittances are less than 14π mm-mrad and the longitudinal emittance is about 0.06 eV-sec. It is estimated that the Booster will need to accelerate 3.7E+12 protons to 8 GeV to accomplish its goal of 3.0E+12 protons on the antiproton target. The major tasks yet to be accomplished are:

1. Commission the digital transverse dampers.
2. Increase the gain of the narrowband longitudinal dampers
3. Increase the strength of the horizontal sextupoles.
4. Move combined function magnets for larger aperture.
5. Redesign extraction septum for larger aperture.