2. BOOSTER PERFORMANCE AND PROJECTIONS[*]

The Booster accelerates protons from 400 MeV to 8 GeV (kinetic energy). Performance of the Booster has improved dramatically over the last few years following implementation of the Linac upgrade and new damping systems. The Booster recently delivered a total beam intensity of about 4.2¥1012 protons. At that intensity the beam transverse emittance filled the Main Ring aperture. Figure 2.1 shows the total intensity delivered from the Booster as a function of the intensity injected from the Linac. There is little evidence of roll-off with intensity. As a result, we expect that only modest improvements to the Booster will be required to meet the total intensity performance goal of 5¥1012 protons (6¥1010 protons/bunch) in Run II. These improvements are described in Sections 2.3-2.7 below, after present performance is reviewed in Sections 2.1-2.2.

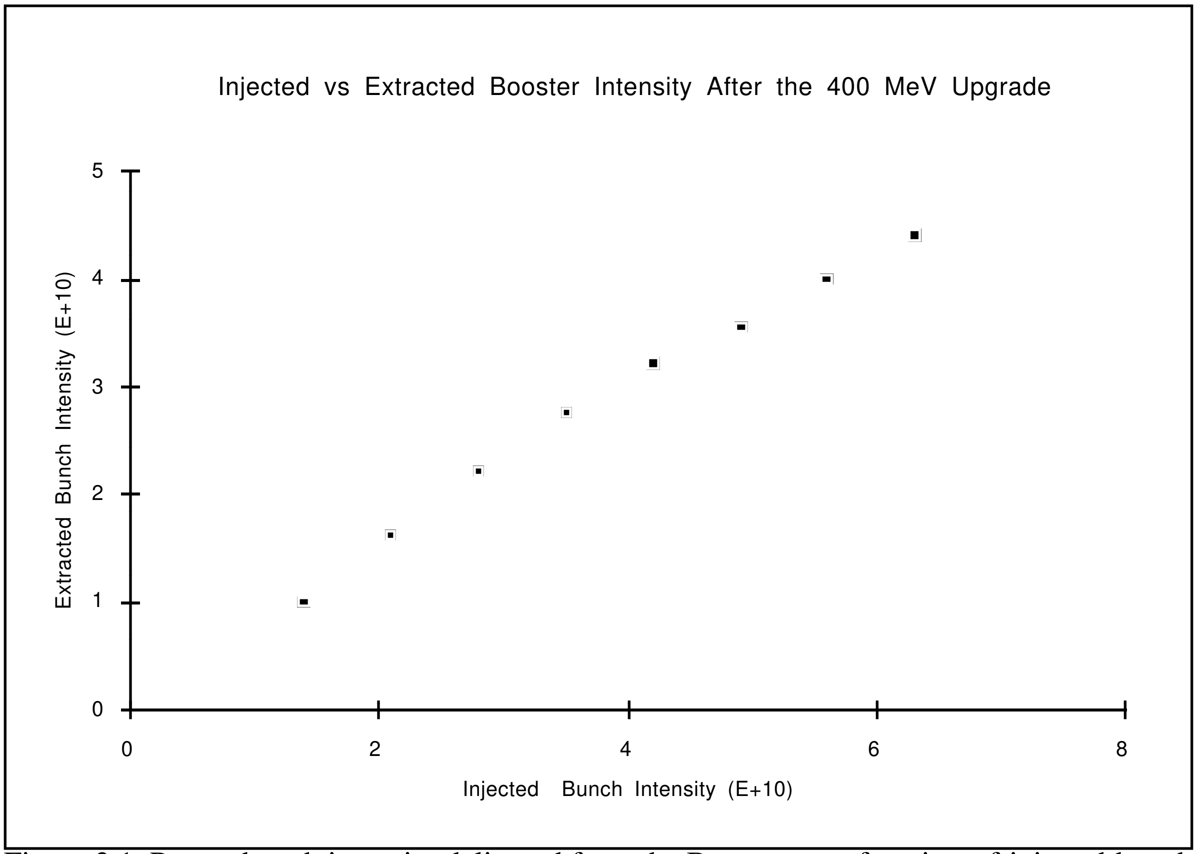

Figure 2.1. Proton bunch intensity delivered from the Booster as a function of injected bunch intensity for current operations.

2.1 Transverse Emittance vs. Intensity

The Booster has been known for some time to operate in a regime in which the transverse phase space density is strongly influenced by space-charge forces at low energy. In the past the transverse emittance rose in direct proportion to the beam intensity at high intensity. This behavior has been interpreted as reflecting a space-charge tune shift limit of about 0.4. Raising the beam

[*] *This chapter was last revised on March 11, 1998.

brightness limit motivated the Linac upgrade, which increased the injection energy from 200 to 400 MeV in 1993.

Current performance is displayed in Figure 2.2. Measured horizontal and vertical emittances at 8 GeV are displayed as a function of bunch intensity. The difference between horizontal and vertical emittances may be entirely due to systematic errors in the normalization of the data. The emittances are seen to display a small linear dependence on intensity at the higher intensity levels. Based on extrapolation of the data in Figure 2.2, the transverse emittance delivered from the Booster at the specified Run II intensity of 6×10^{10} protons/bunch is thus expected to lie in the range 18-20π mm-mrad.

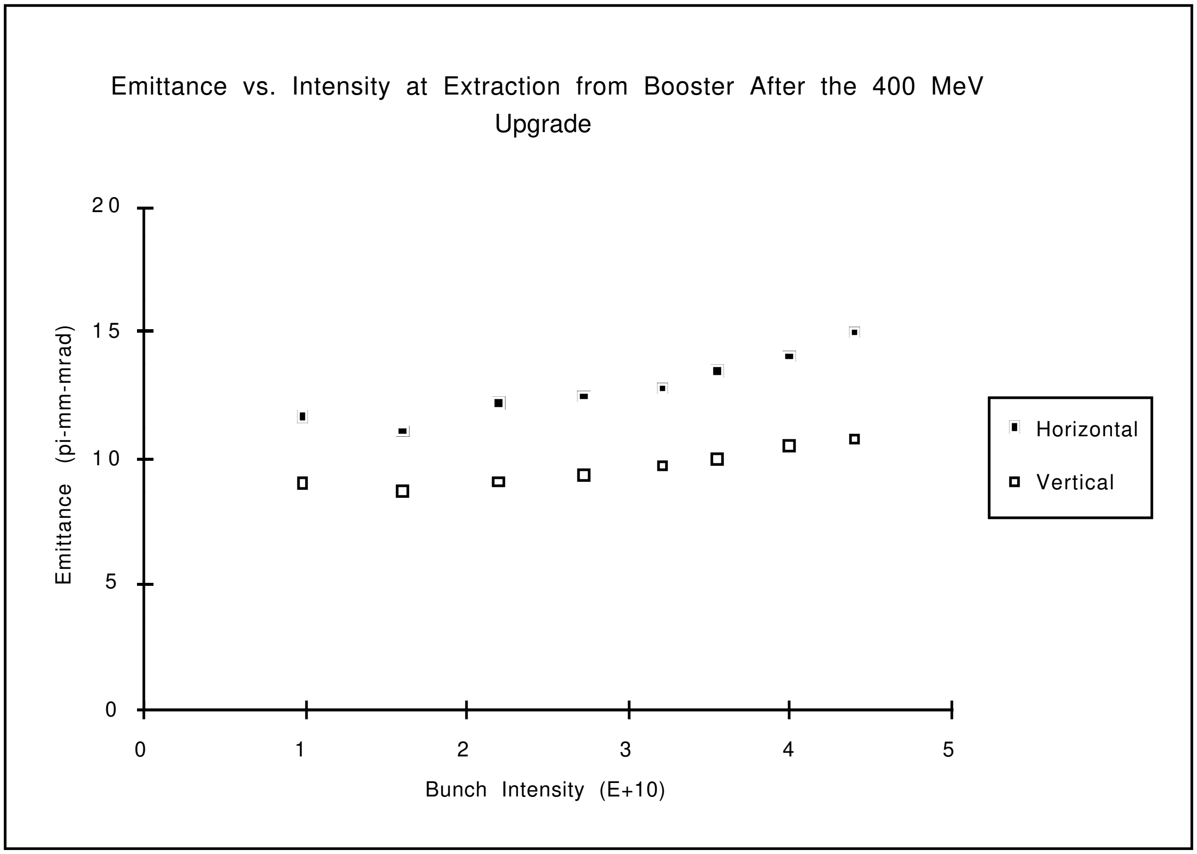

Figure 2.2. Measured 8 GeV transverse beam emittance delivered from the Booster as a function of beam intensity.

2.2 Longitudinal Emittance vs. Intensity

Beam delivered from the Linac to the Booster is allowed to debunch prior to adiabatic capture by the Booster rf system. The bunches thus formed have a longitudinal emittance of less than 0.05 eV-sec. Historically, the Booster has suffered from strong longitudinal coupled bunch instabilities driven by modes in the rf cavities above transition. Implementation of narrow-band longitudinal dampers tuned to the most offensive modes has been effective at controlling growth at present intensities. Current performance is summarized in Figure 2.3. The longitudinal emittance delivered from the Booster is seen to be 0.1 eV-sec/bunch, nearly independent of intensity up to 4.5×10^{10} protons/bunch. Improvements to the damper systems, summarized in Section 2.4, are expected to allow maintenance of this longitudinal emittance in Run II.

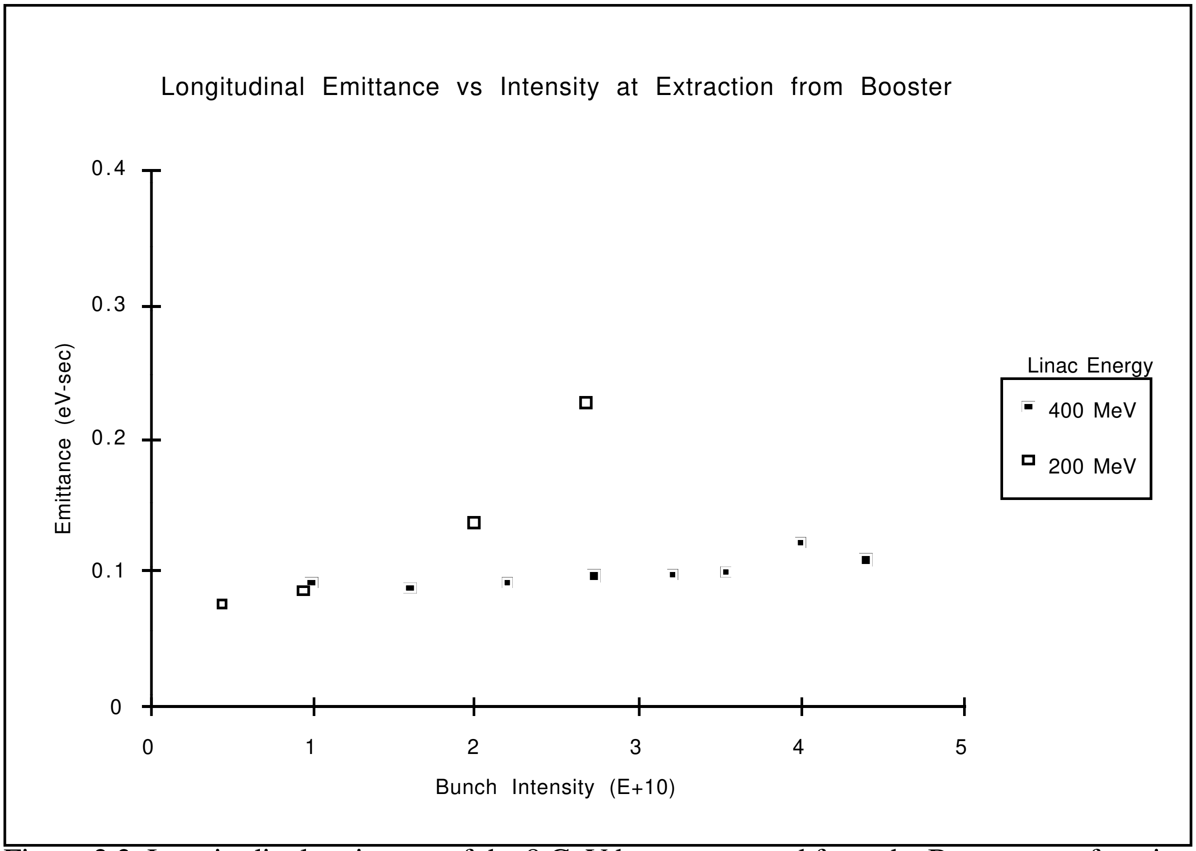

Figure 2.3 Longitudinal emittance of the 8 GeV beam extracted from the Booster as a function of bunch intensity. The points labeled "400 MeV" represent current performance.

2.3 Aperture

The Booster aperture was restricted in the vertical plane by the two extraction septa, one used to transfer the beam to the Main Ring (at long 13) and the other to the AP-4 dump (at long 3). These septa remain in place for operation with the Main Injector although their roles change. The septa were obstructing the top part of the aperture in the extraction regions. There was a set of four bending magnets in each of the two regions that displace the beam away from the septum in a double dogleg configuration. However, the displacement was small because the magnets are not strong enough. The septa had to be vertically positioned to strike a compromise between the aperture requirements of the circulating beam and the extracted beam. The vertical acceptance in the extraction regions at injection energy was approximately half of that available elsewhere in the Booster. The old dogleg magnets gave a normalized vertical aperture of ~12πmm-mrad for circulating beam at injection and a normalized vertical extraction channel acceptance of <20π-mm-mrad for the 8 GeV extracted beam.

A new set of dogleg magnets has been installed for Run II to remove the vertical restriction in the extraction regions. The new dogleg systems are designed for a normalized vertical aperture at the septa of 40π-mm-mrad throughout the acceleration cycle and a full normalized 40π-mm-mrad 8-GeV extraction aperture. Early measurements indicate that the doglegs are functioning as expected.

Aperture scans using 400 MeV circulating beam show that at both of the extraction straight sections the transverse apertures in both planes are as large effectively as any corresponding straight section in the machine. The extraction septa have been effectively eliminated as aperture restrictions. The measured beam position at 400 MeV under the septa show the beam to be at the correct position to achieve a 40π mm-mrad (normalized) aperture.

Rather than ramping the dogleg magnets a set of ramped high field corrector magnets was installed that ramps the orbit at the extraction septa. The combination of the ramped orbit plus the deflection of the doglegs keeps the beam at the correct position (with respect to the septum) to achieve a 40π mm-mrad (normalized) aperture throughout the cycle. This position appears to be adequate, but no serious effort has yet been made to determine the optimum beam position.

Early measurements of vertical extraction apertures show that at Long 13 the extraction aperture is very large, much larger than the beam itself. At Long 3 the aperture is still limited. The reason for this is being investigated. It may simply be an alignment error of the septum or of the upstream Booster magnet. Whatever the cause, it should be possible to adjust the septum to compensate.

Outside the extraction regions, the Booster acceptance is determined by the apertures of the combined-function magnets and rf cavities and by their alignment. Misalignment of the magnets or rf cavities results in a reduction of the available aperture. The most serious vertical misalignments were removed in the last few years by moving some of the magnets and rf cavities. After the new dogleg magnets are in place in the extraction regions, the quality of the alignment of guide-field magnets and rf cavities will be critical in achieving the (normalized) design values of 27π mm-mrad in the vertical plane and 62π mm-mrad in the horizontal plane. It is anticipated that it may be particularly difficult to achieve the large horizontal aperture because of inadequate field quality in the gradient magnets and because of the difficulty in eliminating coupling between the horizontal and vertical betatron motion. Fortunately, a modest improvement in the vertical aperture will be sufficient to meet the Run II goals.

2.4 Damper Requirements

Achieving intensities of $\geq 6\times 10^{10}$ protons/bunch will require both transverse and longitudinal dampers. The transverse dampers used during Run Ib can also be used for Run II with very little modification, but more significant upgrades will be required for the longitudinal dampers.

The Booster produces beam with a horizontal emittance of $<17\pi$ mm-mrad and a vertical emittance of $<12\pi$ mm-mrad When the dampers are operating and the Booster is properly tuned, the emittances of the extracted beam show no effects of horizontal or vertical coherent instabilities at present intensities. This shows that the dampers currently have enough gain under these conditions to overcome the instability growth rates. The growth rate is proportional to the beam intensity and the proposed intensity is 1.2 dB higher than the current operating intensity. Provided that no new instabilities appear, the existing dampers will suppress coherent instabilities if the gain is increased proportionally. There are several simple options for increasing the gain of the system by another 1.2 dB; therefore there is no need for any major changes or additions to the transverse system.

The amplifiers for the longitudinal system are already saturated by longitudinal instabilities, so the gain cannot be increased as easily as the gain on the transverse system. Also, the longitudinal system only damps four specific coupled-bunch modes, and it is unclear how many additional modes would become unstable with the increase in intensity.

A wideband, high-level amplifier and longitudinal kicker should be designed and constructed in order to meet the longitudinal emittance specifications for the Booster. This will make it possible to increase the gain of the current system and add other modes to the damper system if the new intensity requires it. The power amplifiers being used now are already saturated by the common mode signal, and although there is a strong effort to achieve better common mode rejection at the front end, it is doubtful that it can be improved to the level needed for the proposed intensities.

2.5 Booster Extraction to the Main Injector

Booster extraction in the Main Injector era will not be dramatically changed. Beam will continue to be extracted using a kicker/pulsed septum vertical extraction scheme from both areas. The functionality of the existing extraction regions will be interchanged: Long Straight Section 3 will become the extraction area for high energy physics, and beam to be dumped will be extracted at Long Straight Section 13. The dump will be used for studies, for short batch extraction, and for disposal of beam if an abort condition is detected prior to extraction at Long 3.

The extraction kickers in Long Straight Section 2 were modified for Run II so that both extraction areas could be operationally independent. The modification consisted of adding 1 additional kicker magnet at Long Straight Section 2 and 2 PFN (Pulse Forming Network) modulators. The modulators became available when the Main Ring was decommissioned. The Long 2 Kickers are now functionally identical to the Long 12 Kickers.

The present extraction kickers are essentially the same as those originally commissioned in the Booster. Their effective rise time is too slow, resulting in a 2% to 5% beam loss on the extraction septum each pulse. The measured kicker rise time is 50 to 60 nsec, far too slow for a full Booster ring with 19 nsec bunch spacing. The kicker dc high voltage power supplies will be replaced with resonant charging supplies of the Main Injector type. This change will allow the thyratron operating point to be changed so that a rise time of 30 nsec can be achieved. The resonant supplies should be installed and commissioned in summer 1998.

Further improvements in the rise time can be made by splitting the 20 nsec fill-time kicker modules in half to achieve a 10 nsec fill time, reducing the inductance in the thyratron cabinet, and possibly by using pulse sharpeners. The decision whether to proceed on these improvements will be made based on early commissioning experience with Run II.

2.6 Booster Losses

High intensity Booster operation results in beam loss of about 20%. The losses can be grouped into the following categories

1. Normal injection losses. These losses are probably caused by resonances driven by space charge forces and possibly by non-linearities in the magnet fields.
2. Normal extraction losses. These losses are probably due mostly to the inadequate rise time of the kicker (see section II.2.5) but the small aperture in the vicinity of the septum may also play a role (see sectionII.2.3).
3. Abnormal losses. These losses are typically caused by misadjustment of the Booster or the failure of some component.

During normal operation most of the beam loss occurs at injection with a few percent loss at extraction. The injection losses will be attacked by trying to increase the 400 MeV aperture by moving magnets and by possibly improving the compensation of the low order resonances. It is not clear how much progress can be made without major modifications, but the Run II goals do not require any performance improvement in the Booster at 400 MeV. The extraction losses should be reduced by the improved aperture management that will be possible with the new dog leg magnets and particularly by the faster rise time kicker. In addition, we plan to operate the Booster with a missing bunch so that the kicker rise time requirement is reduced to about 30 nsec. The synchronization of the Booster gap with the Main Injector marker will be one of the challenges of operating the Booster with a gap in the beam.

Experiments on Booster losses were in progress when this was written (December 1997). Early measurements of extraction losses using the "notcher" (to create the gap in the beam) are encouraging. Long 13 losses at low intensities are nearly zero. At Long 3 the losses are reduced by over 90% with the beam gap. There are however known timing jitter problems the new Kickers at Long 2 and, as mentioned above, the extraction aperture still appears to be limited at Long 3. Nonetheless, losses at Long 3 should ultimately be as low as they are at Long 13.

2.7 Booster Shielding

The Booster Shielding is currently inadequate to fully contain the showers from loss of the 8 GeV proton beam, particularly in the vicinity of the Booster Tower Buildings. Fortunately, the shielding is adequate to contain the injection losses at 400 MeV. However, improvements to the shielding must be made to allow operation with the Main Injector and to support future projects like NUMI. A particular concern is that the extraction losses which formerly occurred on the septum at Long 13 when extracting to the Main Ring, will appear at Long 3 underneath the West Booster Towers. The plan to ameliorate the inadequate shielding has not been finalized but is likely to include the following:

1. Minimizing normal losses to the extent possible as outlined in section II.6
2. Adding steel shielding above the extraction septum at Long 3 inside the Booster Tunnel.
3. Adding steel shielding above the extraction septum at Long 3 outside the Booster Tunnel. This shielding requires a major excavation prior to installation.
4. Adding more interlocked detectors to protect against accident conditions
5. Modifying the aperture and/or orbit so that losses tend to occur at locations where the shielding is thickest (*i.e.*, not under the Booster Towers).

It appears that this combination of measures will be more than adequate for Run II (one Booster pulse every 1.5 sec) and may be adequate for continuous operation of the Booster at 15 Hz.