4. Performance Projection

Estimating proton delivery has always been one of the most important goals of the Proton Plan. In retrospect, it's clear that both the MiniBooNE and NuMI experiments were conceived and designed under rather unrealistic assumptions about proton rates, and experience from Run II has shown that in the long run, accuracy is more appreciated by experimenters than is extreme optimism.

From the beginning, we have tried to be as accurate and realistic in these projections as possible, but we have necessarily refined our expectations as we have gained experience. This writing represents the proton projections as prepared for the 2006 Director's Review. Specific improvements over previous projections include:

- More accurate handling of Booster batch sizes for single batch and slip stacked operation.
- Reduced up time of the NuMI line based on the first year of operating experience.
- A realistic asymptotic "ramp-up" following shut downs.
- Initial projections assumed that NuMI did not run during shot setup and fast transfers to the Recycler. In fact, they do, which has the effect of increasing protons to NuMI and reducing them to the BNB.

A comparison will be made of the refined projections and the projections as presented at the last Director's Review, in 2005.

4.1 Operating Modes

The proton delivery cycle encompasses the loading and acceleration cycle of the Main Injector. In this cycle two pre-pulses in the Booster are followed by a series of batches injected into the Main Injector. Once loaded and slip stacked these batches are accelerated. During Main Injector acceleration, the Booster is available to deliver batches to BNB, subject to the average repetition rate and radiation limits.

At present, it takes 1.37 seconds for the Main Injector to ramp from 8 to 120 GeV and back again. We count cycle time in units of Booster cycles, a cycle being 1/15 of a second, so the Main Injector ramp requires 21 cycles. The minimum Main Injector cycle time is then given by:

$$(21+nBatches+nSlip)/15$$

Where *nBatches* is the number of Booster batches loaded and *nSlip* represents any additional cycles required to slip stack batches together. Antiproton production for the collider requires a minimum cycle time of about two seconds.

As described in the introduction, there are two modes of NuMI operations:

- "2+5" – in which two batches are slip stacked together for antiproton production, followed by five batches for NuMI. All are accelerated together, and extracted to their respective destinations at 120 GeV.

- "2+9" – in which five batches are injected and accelerated slightly, followed by six batches which are slipped together. This results in five double batches – of which one is designated for antiproton production – and one single batch. All are accelerated to 120 GeV and extracted.

The time lines associated with these modes of operation are shown in Figure 4.1.1. In both cases, proton delivery is based on the Main Injector cycle time. The Booster is given the necessary conditioning prepulses, followed by the batches for antiproton production and NuMI. Additional batches are sent to the BNB line, up to the limits of the Booster output, as determined by either beam loss or total repetition rate.

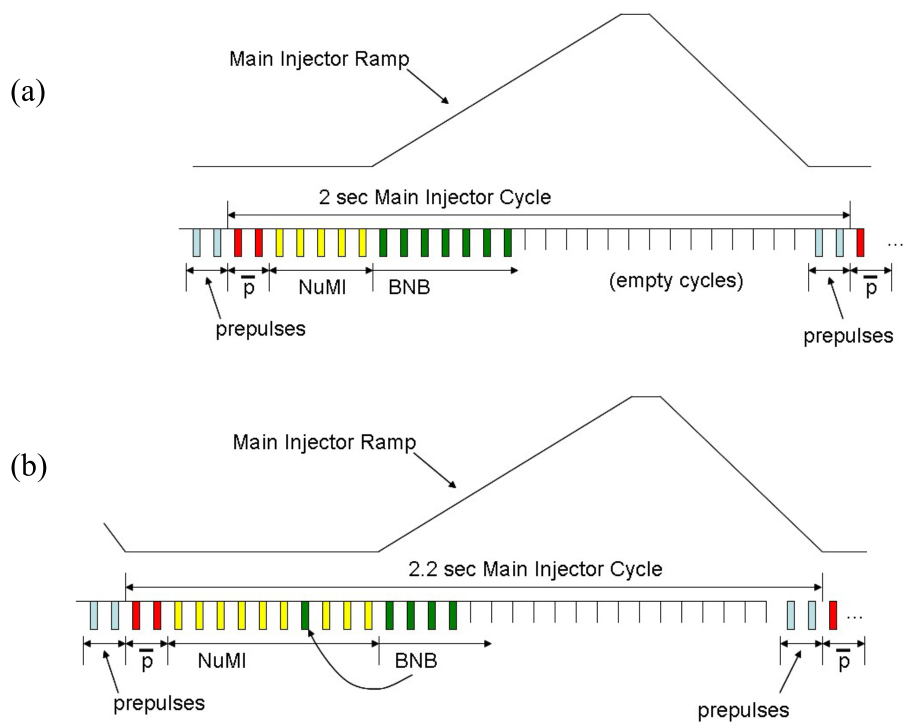

FIGURE 4.1.1: Proton timelines. The tick marks represent 15 Hz Booster cycles. The Phase I and II loading schemes are shown in (a). After two pre-pulses, two antiproton and five NuMI batches are sent to the Main Injector. While these are accelerating as many batches as possible are sent to BNB, subject to the limits of average repetition rate and Booster losses. Phase III running is shown in (b). The number of NuMI batches is increased to nine. In addition to the regular BNB batches, some BNB batches may be inserted during NuMI loading if slipping time is needed.

At the time of this writing, "2+5" has been the standard mode of operation for over a year. Following the 2006 shutdown, the injection kicker to the Main Injector is capable of running at the sustained rates needed for "2+9" operation; however, beam loss in the

Main Injector will likely prevent full scale slip stacked operation until the installation of a collimation system, currently scheduled for summer 2007.

4.2 Booster Radiation Limit and Booster Batch Size

One of the goals of this plan is to steadily reduce uncontrolled losses in the Booster, allowing a higher operational limit for proton throughput. The first major step in reducing uncontrolled beam loss in the Booster was the intallation of a collimation system during the 2004 shutdown. Prior to that shutdown, the Booster had demonstrated 8E16 protons per hour and was regularly operating at 7E16 protons per hour, so we set this as our starting point at the beginning of 2005. However, even at these rates, we were still seeing a significant reduction in activation around the Booster. Figure 4.2.1 shows the change in activation around the Booster, relative to the levels before the collimators were installed. There was a 40% reduction around most of the ring. Based on this, we are confident that after a reasonable period of optimization, the collimators have given the Booster the capability of delivering peak intensities of at least 1E17 protons per hour without exceeding the activation which was seen prior to the collimators.

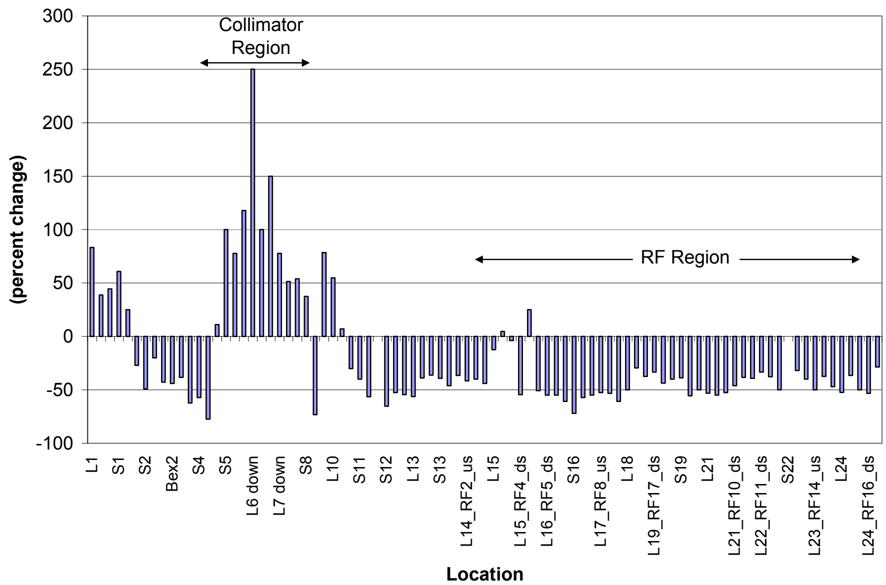

FIGURE 4.2.1: The effect of collimator system on activation around the Booster ring.

In order to estimate the benefit of various improvements, we will calculate the relative increase in acceptance due to each of them. We will focus on the horizontal plane. The aperture needed by the beam is:

$$A = \delta A + \sqrt{\frac{\beta_T \varepsilon_{\max}}{\beta\gamma} + \left(D\frac{\Delta p}{p}\right)^2}$$

where δA represents aperture loss from all causes and the other variables have their usual meaning, and the second term represents the beam size due to transverse and longitudinal emittance. This can be used to calculate the acceptance as:

$$\varepsilon_{\max} = \frac{\beta\gamma}{\beta_T}\left((A - \delta A)^2 - \left(D\frac{\Delta p}{p} \right)^2 \right)$$

We use the fractional change in acceptance as an estimate of increased beam capacity for each of the proposed improvements.

For our purposes, the following remain fixed:

- $\beta\gamma \approx 1$
- A (aperture). Given the lack of understanding of the details of beam shape and halo composition, rather than use the physical aperture of the machine, we use an effective 95% aperture based on a 15π mm-mr acceptance prior to the start of all Booster improvements, with all of the slewing and lattice parameters set at their initial values. This corresponds to
    - o 3.7 cm horizontally
    - o 2.3 cm vertically
- $\frac{\Delta p}{p} \approx 0.13\%$ (measured)

The aperture reduction is currently about one centimeter at injection, due to (1) ORBUMP slewing, (2) alignment problems, and (3) inadequate beam control.

In addition to the aperture reduction, acceptance has been reduced because of the parasitic focusing due to the extraction chicanes ("dogleg effect") [13], which increases the maximum beta function and dispersion in the horizontal plane. One of the extraction regions were modified in 2003 and the second in the 2004 shutdown.

Table 4.2.1 shows the calculated improvement in acceptance for each of planned upgrades.

Improvement	**Date**	δA_x (mm)	$\beta_{x,\max}$ (m)	$D_{x,\max}$ (m)	δA_y (mm)	$\beta_{y,\max}$ (m)	ε_x (π-mm-mr)	ε_x (π-mm-mr)	Rel. total	Incr.
Initial	---	10	45.8	6.2	4	24	15.0	15.0	85.3%	
Dogleg 3 Fix	10/03	10	40.8	4.5	4	24	17.6	15.0	100.0%	17.3%
Dogleg 13 Fix	10/04	10	36.1	3.8	4	24	20.2	15.0	114.6%	14.6%
Extraction 13 Removal	6/06	10	34.9	3.5	4	24	21.0	15.0	119.1%	4.0%
ORBUMP/400 MeV upgrade	6/06	5	34.9	3.5	4	24	29.5	15.0	167.8%	40.9%
Correctors (dipoles)	8/07,8/08	2	34.9	3.5	2	24	35.4	18.3	245.6%	46.3%

TABLE 4.2.1: The effect of various improvements on acceptance. The "Relative total" column shows the cumulative effect relative to the state of the machine prior to the 2004 shutdown, and the final column shows the incremental effect of each improvement.

In addition to these effects, we consider the following:

- It is believed that losses at the Long 13 extraction region are preventing the collimation system from operating at its full potential; however, this is hard to quantify, so we will base projections on merely eliminating the measured loss at that location by relocating the Booster Dump, which will result in roughly a 3% increase in beam.
- It is estimated that having sextupoles at only discrete locations around the ring results in about a 5% emittance growth in each plane, so we could potentially get 10% more beam when the new corrector packages are in place. It is also very likely that we will benefit from the improved ability to control third order resonances, but this is difficult to quantify.

In the following section, we project proton delivery for each of the beamlines. In the "Design Projection" we assume (1) a base performance of 1E17 protons per hour prior to these improvements, (2) that actual improvements are degraded by a factor of two from these calculated values, and (3) that it takes a year to gain the maximum benefit from each improvement. A "Base Projection" is also presented using a base of 9E16 and assuming that each improvement has only 25% of the calculated effect. This leads to the intensity limits shown in Table 4.2.2.

Date	**"Design" Limit (1E16 p/hr)**	**"Fallback" Limit (1E16 p/hr)**	**Comment**
1/2006	10.7	9.3	Effect of collimators, dogleg fix, plus some alignment
6/2007	13.6	10.6	ORBUMP, and L13
8/2009	18.9	13.0	New corrector system

TABLE 4.2.2: Intensity Limits reached at the end of each year for the Design and Fallback Projections.

The Booster intensity limit is linearly interpolated between these yearly values, as shown in figure 4.2.2.

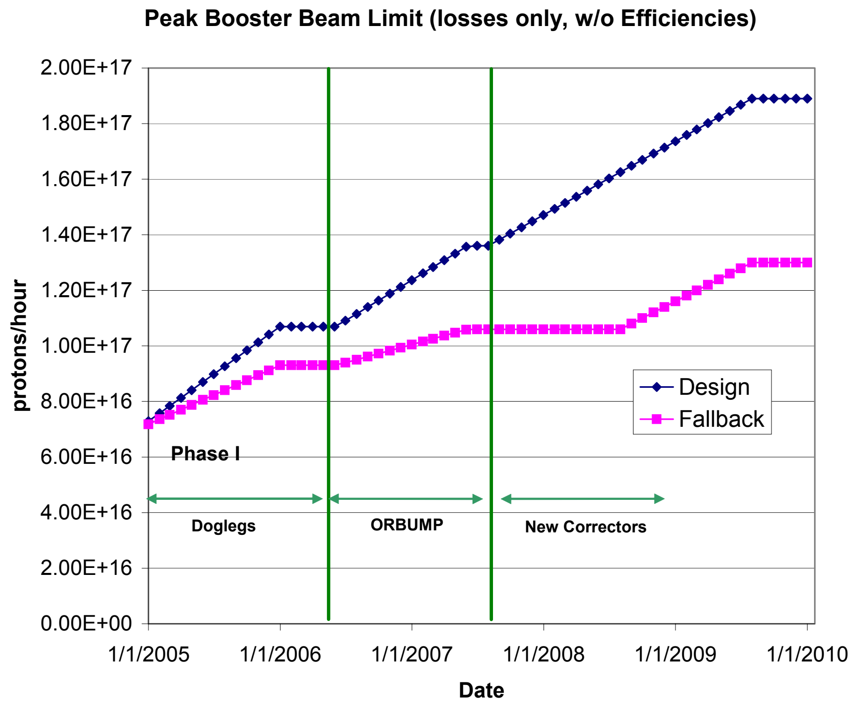

FIGURE 4.2.2: Booster output limit which is used as a basis for proton projections.

Because there is still a great deal of uncertainty in the exact loss mechanisms early in the Booster cycle, Booster batch sizes have been conservatively calculated based only on the increased efficiency represented by the above improvements. Based on demonstrated performance, the increased efficiency would lead us to expect at least 5.5e12 over the next several years for single batches. Using the normal recipe, the design scenario has the single batch size rising steadily from 4.5e12 to 5.25e12 over the period from 1/2004 to 1/2009. The base scenario has the batch size remaining at 4.5e12.

Because slip stacking requires excellent beam quality, the maximum batch size used for slip stacking will always be smaller than the batch size for single batches. Based on demonstrated performance with antiproton production, the design scenario has the slip stacked batch size increasing from 3.5e12 to 4.3e12 over the period from 1/2004 to 1/2009, while the base scenario has it increasing from 3.5e12 to 4.0e12 over the same period.

Multi-batch operation to the Main Injector requires the Booster to be “cogged”, or synchronized to the Main Injector. This must be done so that the extraction “notch”, created early in the cycle, is in the correct place for beam extraction after acceleration. The process by which this is done manipulates the radial position of the Booster beam during acceleration to fix the total acceleration time. This results in somewhat increased beam loss and therefore a reduced total number of protons. For the purposes of projection, it is assumed that cogged cycles lose 20% more energy per proton than uncogged cycles.

4.3 PoT Projection

We present here a model that delivers the planned intensity for antiproton production and maximizes the PoT for NuMI. BNB then receives the residual capacity of the proton source. Reducing the PoT for NuMI and providing additional protons to BNB is an option within the overall program.

In addition to the Booster output and batch sizes, we include the following effects:

- Booster average to peak ratio: This is the ratio between the peak booster output and the average output. It has been initially set at 86%, based on MiniBooNE running experience. Because this is at least partially due to energy fluctuations from the Linac, the design scenario has this rising to 90% in the year following the 2007 shutdown, during which Linac LLRF improvements are scheduled to be made. The base scenario has it remaining at 86%
- BNB Uptime: This is the total uptime outside of annual shutdowns during which MiniBooNE takes beam. This is set at 81% in the design scenario, based on initial MiniBooNE running experience. The base scenario is 78%, which assumes one unscheduled horn replacement every two years.
- NuMI uptime: In initial projections, this was set equal to BNB uptime; however, in the first year of operation, that has proven to be an overestimate. The new projection has the design up time set at 80%, while the base scenario has it at 70%, which is similar to the up time observed from startup to the 2006 shutdown.
- NuMI slip stacking ramp up: This assumes that following the 2007 shutdown, we begin to operate "2+9" slip stacked operation, but with a batch size that initially delivers the same number of protons as "2+5" operation. This will then ramp up over the next three months to full slip stacked operation. The base scenario assumes that slip stacking doesn't work at all.
- NuMI slip stacking efficiency: We have this rising steadily from 85% to 95% from the start of 2006 to the middle of 2007. The base scenario has it rising only to 90%.
- NuMI average to peak efficiency: This is an overall 90% factor to account for any non-optimal running.
- Post shutdown ramp-up: Assume all proton delivery ramps up as $(1-\exp(-t/\tau))$ following a shutdown, with τ=2 weeks.

Figure 4.3.1 shows the implications of these projections in terms of machine loading. Note that under the design scenario, total repetition rate becomes the limiting factor in the Booster, rather than beam loss.

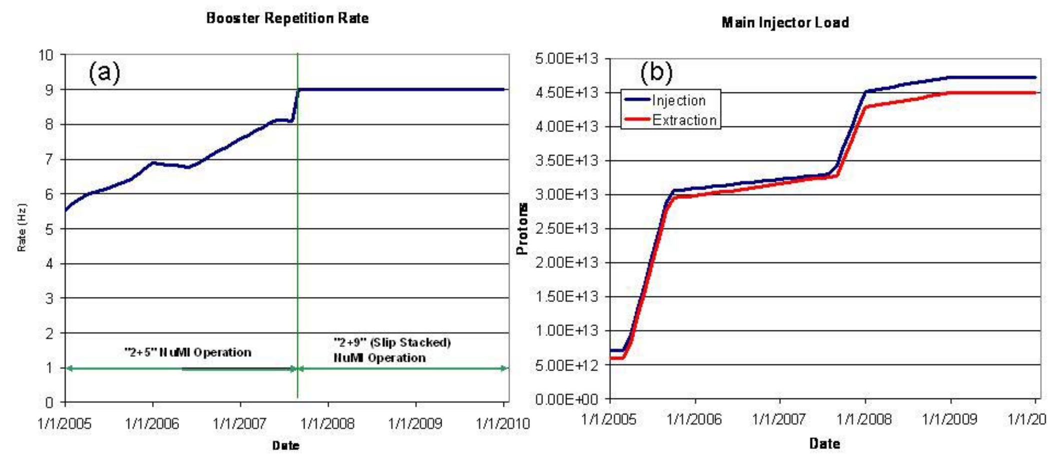

FIGURE 4.3.1: Projected performance in terms of (a) the average Booster repetition rate, and (b) Main Injector intensity. The strange structure in the repetition rate is due to the fact that we assume that during the commissioning of NuMI slip stacking, we will send a large number of small batches to Main Injector.

Figure 4.3.2 shows success in total proton predictions to date for fiscal year 2005, which corresponds to predictions from the original proton plan document, and fiscal year 2006, which corresponds to the predictions of the first Director's Review. In particular, note that the turn on after the 2006 shut down was significantly slower than planned. Figures 4.3.3 shows predictions for NuMI. As can be seen, NuMI proton delivery was dominated by unforeseen down time, which led to the reduced up time values for the new projections. In general, the MiniBooNE experiment benefited from these down times, as shown in Figure 4.3.4.

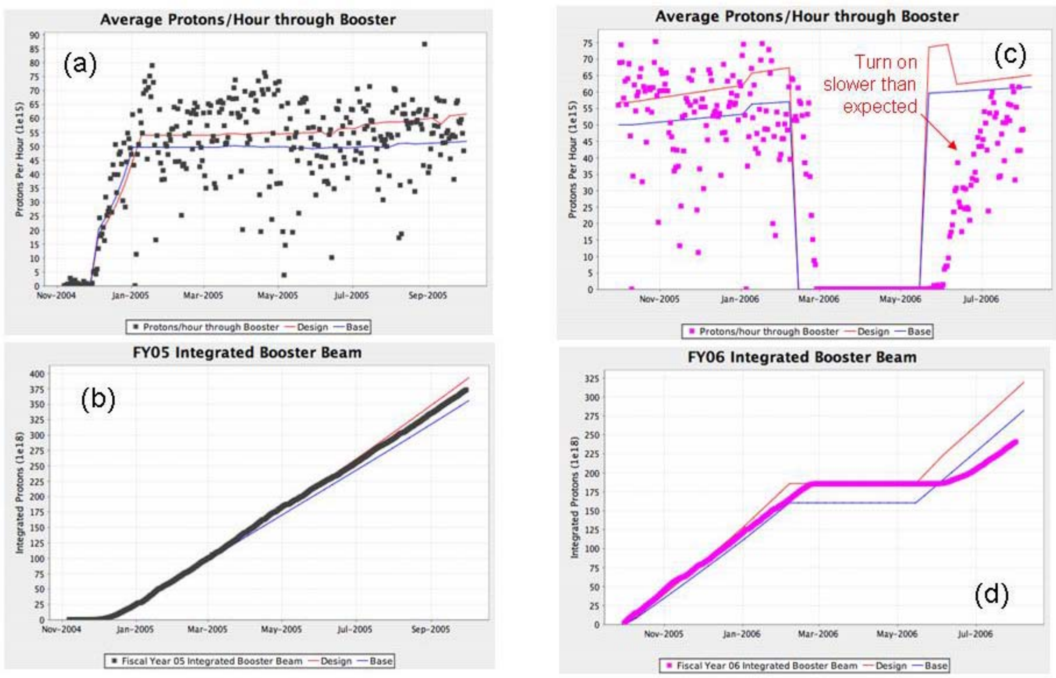

FIGURE 4.3.2: Total proton delivery versus design (red) and base (blue) projections. (a) and (b) show average hourly and integrated total for fiscal year 2005, while (c) and (d) show the same thing for fiscal year 2006 so far

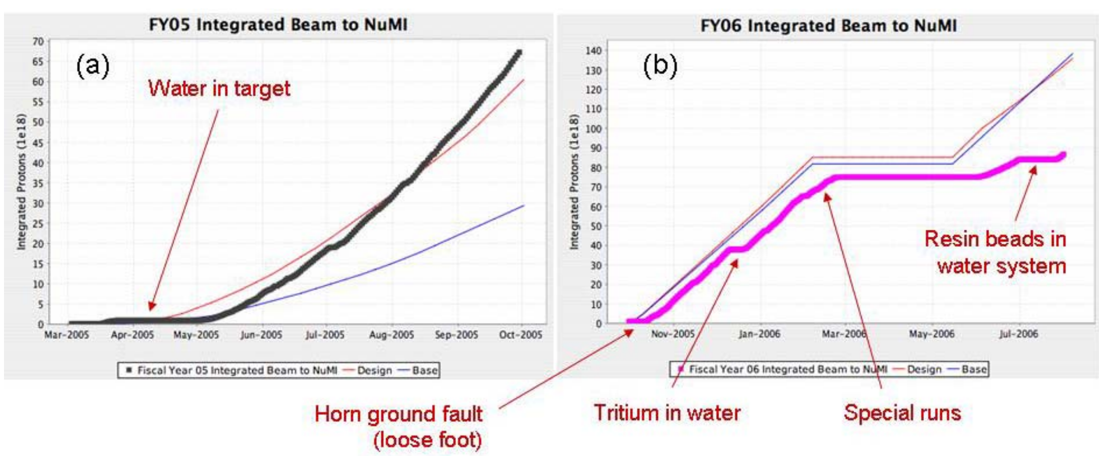

FIGURE 4.3.3: Total proton delivery to NuMI versus design (red) and base (blue) projections. (a) shows fiscal year 2005 and (b) shows fiscal year 2006 so far. Also indicated are the reasons for various down times which dominated beam delivery.

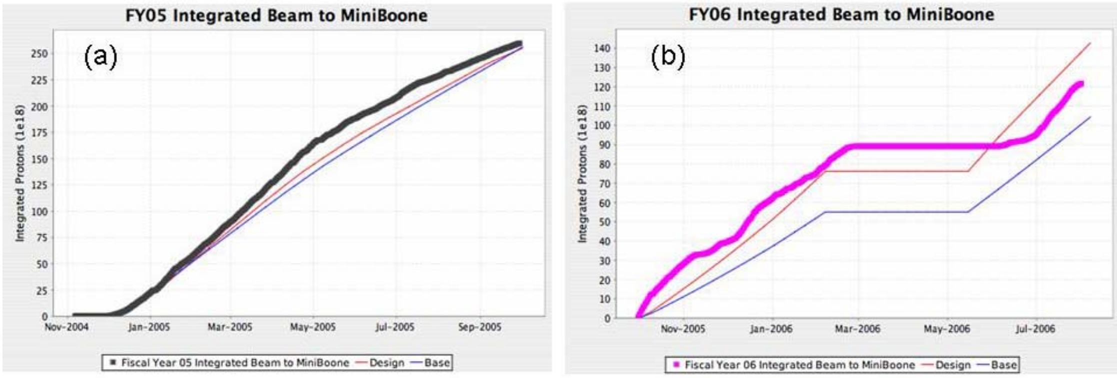

FIGURE 4.3.4: Total proton delivery to the BNB versus design (red) and base (blue) projections. (a) shows fiscal year 2005 and (b) shows fiscal year 2006 so far. As can be seen, the 8 GeV neutrino program benefited from NuMI down times.

The experience that has been gained has led to some of the refinements that are now in the proton projections. The revised projections are shown in figure 4.3.5 for the NuMI and BNB lines. These start with the actual delivered proton totals as of 8/1/06. For comparison, the proton projections are shown as of the 2005 Director's review.

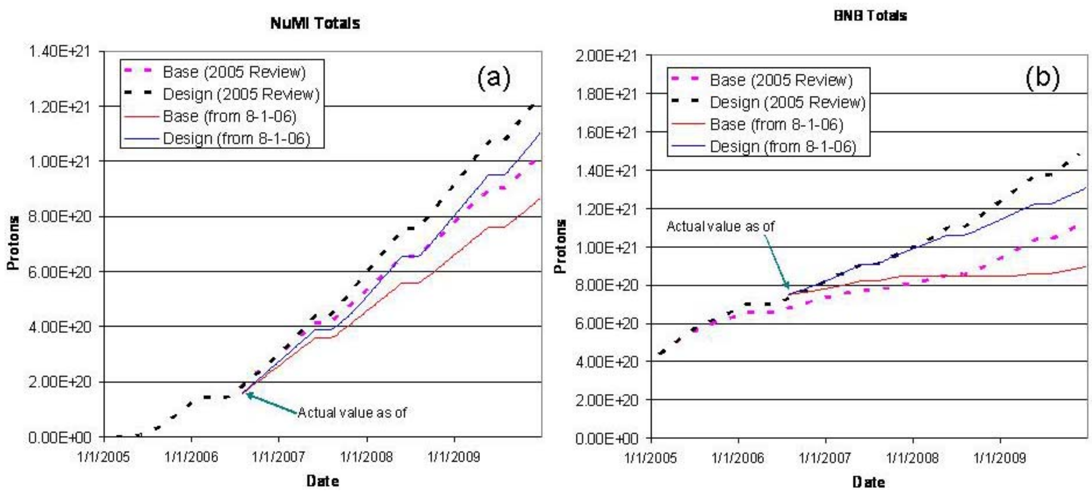

FIGURE 4.3.5: This shows the total revised proton projections to NuMI (a) and the BNB (b) to the end of 2009. The NuMI design scenario is lowered somewhat by later slip stacking and more realistic assumptions about batch size and turn on, while the base scenario assumes to slip stacking and a lower up time. The BNB design scenario is a bit lower because of turn on, as well as allowance for cogged cycle energy loss. The base curve assumes that NuMI is operating at design, including during shot setup, but that the Booster is only at base performance.

The decrease in the NuMI design curve comes primarily from a somewhat smaller batch size while the lowered base curve shows the effect of reduced up time. The reason that the BNB base curve is lower is that the old projection assumed that under any scenario, the BNB could continue to run during shot setup. It is now assumed that NuMI will continue to run for shot setup. That means that under a scenario where NuMI is operating at design, but the Booster output is at base, there is a situation where there will not be enough spare protons to make the 8 GeV program viable. If this situation arises, it will obviously fall to Program Planning to make a decision as to priorities.

The projections are summarized in Table 4.3.1 as of the end of 2009, at which point it's assumed that the Proton Plan has completed all of its projects, and that the collider program is at an end.

Experiment	**Total Protons (10^{20})**		**Rate (10^{20} per 44 week year)**	
	Design	**Base**	**Design**	**Base**
NuMI	11.0	8.7	3.2	2.2
BNB	13.1	9.0	1.8	0.75

TABLE 4.3.1: The ultimate goal of the Proton Plan to the end of 2009 for both the NuMI and the BNB lines.