Proton Plan

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  - Jeff Spalding
  - Bruce Baller
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  - Dave Harding (TD)
  - Dan Wolf (EE)
  - Weiren Chou (Integration)
  - Peter Garbincius (Management)
  - Dave McGinnis (Management)
  - + others

Charge

- Develop a plan for a reasonable set of improvements and operational initiatives to maximize proton delivery to NuMI and the Booster Neutrino Beam (BNB) over the next ten years or so.
- Estimate the budget and timeline for these improvements.
- Estimate proton delivery to both beam lines if the Plan proceeds on schedule.
- Note: this plan is *exclusive* of the Proton Driver, which we assume will one day replace the existing Proton Source (Linac+Booster).

From the Executive Summary

- We present a three-year plan for increasing the proton intensity delivered to the two operational beam lines, with upgrades to the Linac, Booster and Main Injector. When the elements of this plan are completed, NuMI will accumulate approximately 3.4E20 protons per year. BNB will receive approximately 2.2E20 protons per year, however *the latter* estimate is highly dependent on the performance of the Booster and other efficiency factors.
- The preliminary estimate for the total cost of this plan, including 46% contingency, is $34M ($23M M&S, $10M labor SWF). The labor cost estimate includes technical, physicist and project management effort. Overhead is not included in these estimates.

Strategy

- **Increasing the proton delivery from the Booster to NuMI and MiniBooNE**
  - Increase maximum average Booster repetition rate.
  - Increase acceptance by improving orbit control and beam quality.
- **Increasing the beam intensity in the Main Injector for NuMI**
  - Main Injector multi-batch operation.
  - Slip stacking in Main Injector (requires RF upgrade).
- **Improving operational reliability and radiation limitations**
  - Linac quad supplies
  - Booster and Linac Instrumentation
  - Booster RF Upgrade
  - Investigate 7835 Problem

Breakdown of Plan

WBS	Description
1	**Proton Plan**
1.1	**Linac Upgrades**
1.1.1	Linac PA Vulnerability
1.1.2	Linac Quad Power Supplies
1.1.3	Linac Instrumentation Upgrade
1.2	**Booster Upgrades**
1.2.1	Determination of Rep Rate Limit
1.2.2	ORBUMP System
1.2.3	Corrector System
1.2.4	30 Hz Harmonic Upgrade
1.2.5	Gamma-t System
1.2.6	Alignment Improvements
1.2.7	Drift Tube Cooling
1.2.8	Booster RF Cavity #20
1.2.9	Booster Solid State RF PA's
1.2.10	Booster Instrumentation Upgrade
1.3	**Main Injector Upgrades**
1.3.1	Large Aperture Quads
1.3.2	Main Injector Collimator
1.3.3	NuMI Multi-batch Operation
1.3.4	Main Injector RF Upgrade
1.4	**Management**

Linac Projects

- 1.1: PA Vulnerability
  - Come up with a plan for dealing with the Linac Power Amplifier (7835) situation once and for all. Investigate:
    - Low Energy Linac replacement
    - Other tubes (e.g. Thales 629)
    - Other 200 MHz power (e.g. multi-beam klystrons)
    - In-house fabrication
    - Significant collaboration with Burle
  - Submit report to AD head by Feb, 2004.
- 1.2: Pulse Quad Power Supplies
  - Replace pulsed quadrupoles in the old Linac
  - Very similar to pulsed supplies in newer linac
- 1.3: Instrumentation Upgrade
  - Inadequate Linac instrumentation has led to extended periods of non-optimal running
  - Only 1/3 of BPM's instrumented.
  - Project started in 2004
  - Add 10 MHz digitizers to old linac RF stations
  - Move existing BPM digitizers to High Energy Linac
  - Instrument all BPM's with 10 MHz digitizers.

Booster Projects

- 2.1: Determine the Booster repetition rate limit
  - Once the other upgrades described here are complete, the Booster will be capable of extended running at 15Hz, *except* for the RF system.
  - The limit is believed to be 8-9Hz, limited by the main power, but this is not well understood.
  - Although the current scope of the plan does not require us to go beyond 9 Hz, we feel it is important to understand the limitation and what would be required to elimniate it.
- 2.2: ORBUMP System
  - Existing injection bump (ORBUMP) has two problems
    - Average repetition rate of the magnet and power supply is limited to 7.5 Hz by heating.
    - It lacks the power to move the beam out far enough at injection, resulting in a mismatch
  - Plan is to replace the (4) magnets and power supply
  - Magnet fabrication is under way, with the first magnet just completed.
  - Aim to put new system in place during 2005 shutdown.

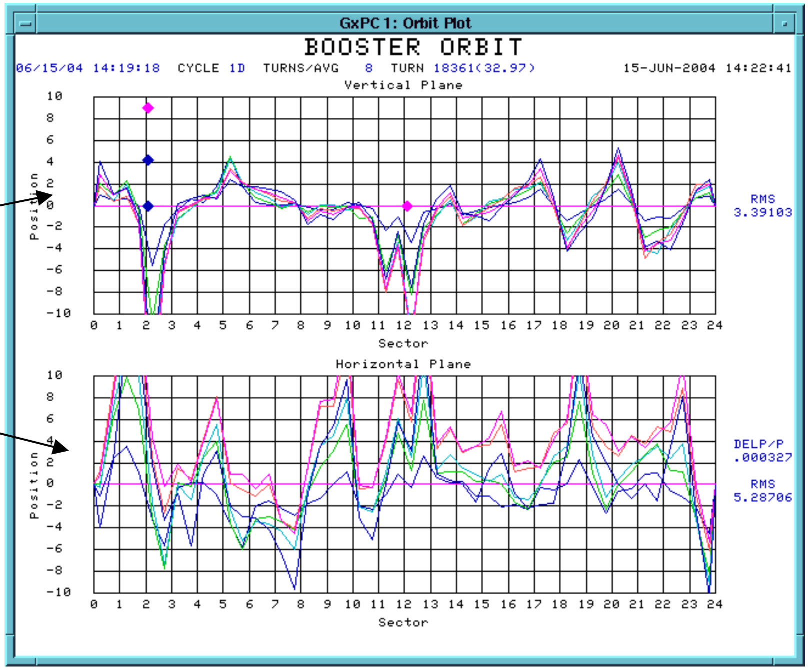
Booster Projects (cont'd)

- 2.3: Booster corrector system
  - Each of the 48 subperiods of the Booster have a trim package which contains H and V dipoles, as well as a quadrupole and a skew quadrupole.
  - These are not adequate to control beam position or tune through the cycle.
  - There would also be benefits to putting a sextupole in each package.
  - We are working with TD to design a new corrector package for the Booster, which will allow precise control of both beam position and tune throughout the cycle.

Beam position around ring, relative to injection, at various times in cycle

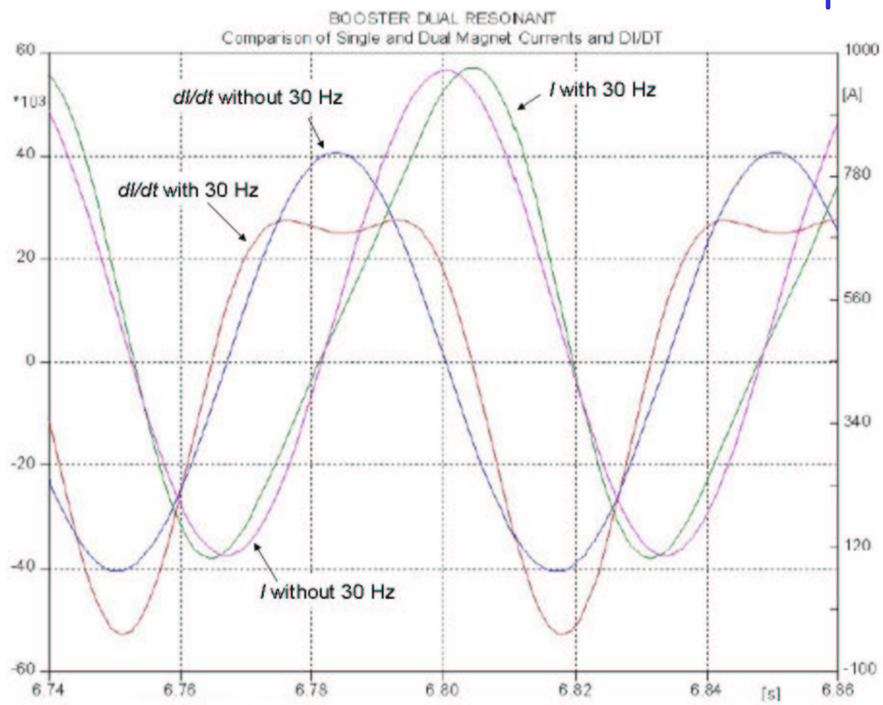
V

H



Booster Projects (cont'd)

- 2.4: 30 Hz harmonic
  - The booster lattice magnets operate in a 15 Hz offset resonant circuit.
  - By modifying the magnet girdirs to ad a 30 Hz component, we could reduce the maximum acceleration rate, which is equivalent to increasing RF accelerating voltage
  - This would allow us to accelerate more beam per batch.



Booster Project (cont'd)

- 2.6: Gamma-t System
  - The booster transition jump system has a long history.
  - May be necessary to fully take advantage of other upgrades to increase batch intensity.
  - It suffers from misalignment problems and exacerbates coupled bunch instabilities, so we don't use it.
  - Will schedule a series of studies to make a either make it work or decide to abandon it within a year.
- 2.7: Alignment
  - The Booster has never been properly aligned
  - Made significant progress in the vertical plane and with RF cavity alignment over the last year.
  - Over the shutdown, did a TeV style 3D laser tracker network and as-found.
  - Will use this data to form a plan for girder moves over the next year or so.

Booster Projects (cont'd)

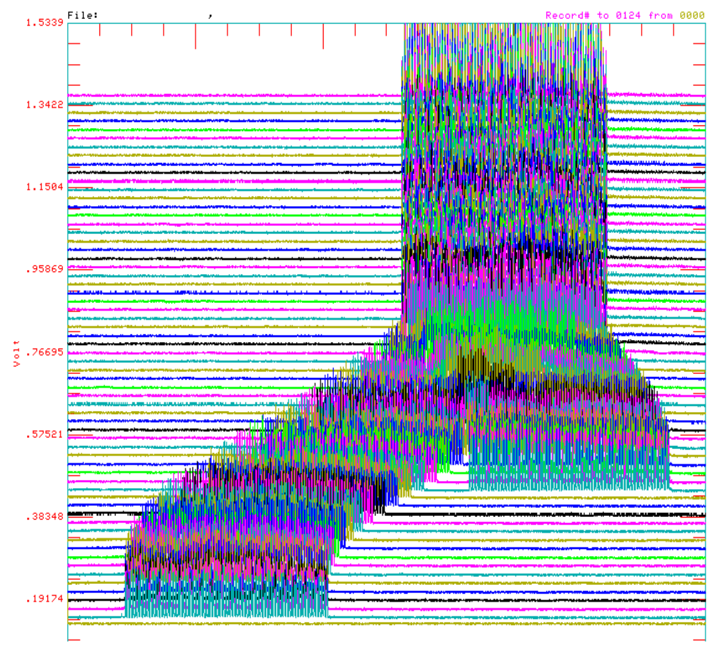
- 2.8: RF Drive tube cooling
  - Once the ORBUMP project is complete, the next rate limit comes from heating of the RF cavities.
  - The cavities contain internal cooling channels, which are no longer used because some of them leak.
  - We are building water cooled slip rings, which can be installed in cavities during normal maintenance.
  - Once this is done, the cavities themselves should be good for 15 Hz.
- 2.9: RF Power Amplifier Upgrade
  - The booster RF Power amplifiers are our highest maintenance item.
  - Servicing them results leads to some of the higher radiation exposures at the lab (typically 100-150 mRem/quarter).
  - These can be replaced with Main Injector style solid state drivers, which have a MTBF of three to four times longer.
  - This is expensive, but the cost is offset by the $400K we currently spend on tubes for the existing PA.

Booster Projects (cont'd)

- 2.10: Instrumentation Upgrade
  - The Booster instrumentation is largely antiquated.
  - There are a large number of ramped devices, which are difficult to monitor in our existing alarms and limits system
  - A software package has been developed to automatically monitor ramped devices in the Booster, but it is limited by the existing instrumentation.
  - Also, our BPM system, while adequate, is becoming difficult to service.
  - We plan to install a new readout system based on the Hotlink Rack Monitor (HRM) standard, which will allow much more reliable, high rate data acquisition from the Booster.

Main Injector Loading

- The Main Injector has six usable “slots”, into which Booster batches may be placed.
- More batches may be loaded, using “slip stacking”, in which batches are injected at slightly different energy, drift together, and are captures as one batch (with at least twice the longitudinal emittance).



Main Injector Loading (cont'd)

- Initial NuMI operation ("2+5"):
  - Two batches will be slip stacked for antiproton production.
  - Five more batches will be loaded for NuMI
  - All will be accelerated together.
- Ultimate NuMI operation ("2+9"):
  - Five batches will be loaded into the Main Injector, leaving one empty slot.
  - Six more batches will be loaded and slipped with the first to make two for antiproton production and 9 for NuMI.
  - This is beyond the capacity of the current RF system.

Main Injector Projects

- 3.1: Large Aperture Quadrupoles
  - A number of the existing quadrupoles cause losses near injection and extraction Lambertsons.
  - These will be replaced with larger aperture quads designed as part of the Proton Driver R&D.
  - The fabrication is already under way.
- 3.2: Main Injector Collimation System
  - It is possible that the large amount of beam being transported and the increased longitudinal emittance of slip stacking may result in unacceptable losses and activation in the MI.
  - This may require a collimation system, similar to the Booster.
  - We will investigate the need for such a system, and determine the cost if it proves to be necessary.

Main Injector Projects (cont'd)

- 3.3: Main Injector Multi-Batch Operation
  - This item comprises the studies and development time necessary to operate NuMI in a multi-batch operation, as described earlier.
    - Initial 2+5 operation
    - Slip stacking for 2+9 operation
- 3.4: Main Injector RF Upgrade
  - The existing RF system can accelerate about 4E13 protons
  - This is enough for 2+5 operation (~3.5E13 protons), but not enough for 2+9 (~5.5E13).
  - Each RF station has a port for a second PA.
  - The plan is to verify that this will provide enough power to accelerate 7E13 protons, then proceed with procurement to add a second PA.
  - This is the most expensive part of the plan and the most vital to NuMI operation.
  - It would require new modulators, which would make the old ones available for the Booster RF upgrade (2.9)

Cost and Schedule

- Methodology.
  - Establish total costs based on best available estimates on individual components.
  - Assign contingency to individual components as:
    - Recent experience or direct quote: 20%
    - Similar experience, rules of thumb, etc: 50%
    - Good faith estimate: 100%

Cost

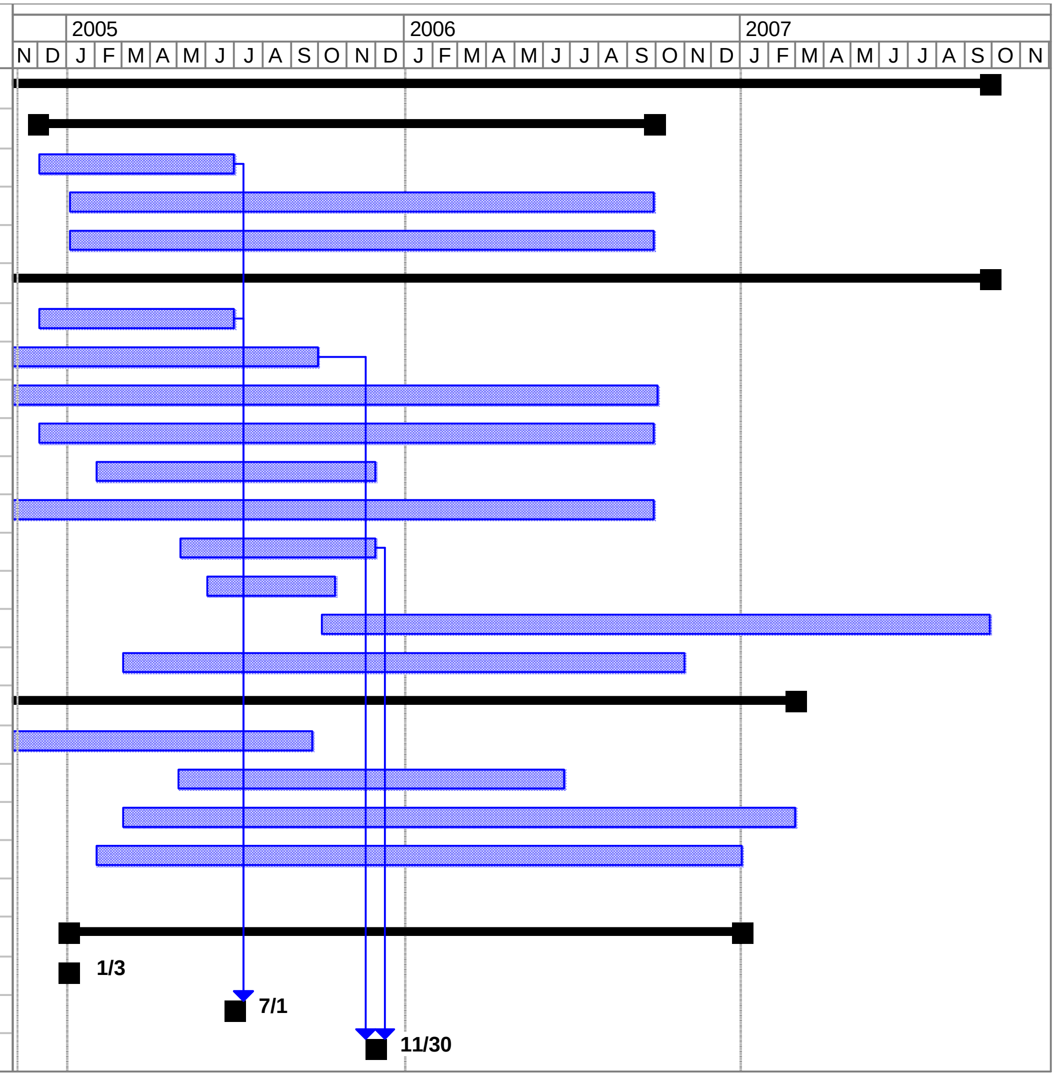
WBS	Description	M&S Base	M&S Cont	M&S Total	SWF Base	SWF Cont	SWF Total
1	**Proton Plan**	**16,513**	**42%**	**23,486**	**6,648**	**57%**	**10,419**
1.1	**Linac Upgrades**	**2,705**	**86%**	**5,039**	**981**	**65%**	**1,622**
1.1.1	Linac PA Vulnerability	2,000	100%	4,000	300	100%	600
1.1.2	Linac Quad Power Supplies	617	50%	925	628	50%	942
1.1.3	Linac Instrumentation Upgrade	88	30%	114	53	50%	80
1.2	**Booster Upgrades**	**6,499**	**35%**	**8,765**	**2,777**	**54%**	**4,262**
1.2.1	Determine Rep Rate Limit	0	0	0	110	50%	165
1.2.2	ORBUMP System	256	42%	364	231	47%	338
1.2.3	Corrector System	629	58%	995	715	57%	1,124
1.2.4	30 Hz Harmonic	1,031	35%	1,388	279	60%	447
1.2.5	Gamma-t System	0	0	0	50	100%	100
1.2.6	Alignment Improvements	0	0	0	60	50%	90
1.2.7	Drift Tube Cooling	10	50%	15	10	50%	15
1.2.8	Booster RF Cavity #20	300	50%	450	120	50%	180
1.2.9	Booster Solid State RF PA's	4,200	30%	5,460	960	50%	1,440
1.2.10	Booster Instrumentation	73	27%	93	242	50%	363
1.3	**Main Injector Upgrades**	**7,294**	**32%**	**9,661**	**2,026**	**60%**	**3,239**
1.3.1	Large Aperture Quads	194	50%	291	406	50%	609
1.3.2	Main Injector Collimator	200	100%	400	150	100%	300
1.3.3	NUMI Multi-batch Operation	0	0	0	250	100%	500
1.3.4	Main Injector RF Upgrade	6,900	30%	8,970	1,220	50%	1,830
1.4	**Management**	**15**	**32%**	**20**	**864**	**50%**	**1,296**

Cost by Year

WBS	Description	Base Estimate: M&S and SWF				Total with Contingency
		FY05	FY06	FY07	Total	
1	**Proton Plan**	**8,341**	**10,965**	**3,854**	**23,161**	**33,904**
1.1	**Linac Upgrades**	**1,039**	**2,097**	**550**	**3,686**	**6,661**
1.1.1	Linac PA Vulnerability	650	1,100	550	2,300	4,600
1.1.2	Linac Quad Power Supplies	248	997	0	1,245	1,867
1.1.3	Linac Instrumentation Upgrade	141	0	0	141	194
1.2	**Booster Upgrades**	**1,945**	**4,718**	**2,613**	**9,276**	**13,027**
1.2.1	Determine Rep Rate Limit	110	0	0	110	165
1.2.2	ORBUMP System	486	0	0	486	702
1.2.3	Corrector System	583	761	0	1,344	2,119
1.2.4	30 Hz Harmonic	146	1,165	0	1,310	1,835
1.2.5	Gamma-t System	50	0	0	50	100
1.2.6	Alignment Improvements	30	30	0	60	90
1.2.7	Drift Tube Cooling	20	0	0	20	30
1.2.8	Booster RF Cavity #20	420	0	0	420	630
1.2.9	Booster Solid State RF PA's	0	2,680	2,480	5,160	6,900
1.2.10	Booster Instrumentation	100	82	133	315	456
1.3	**Main Injector Upgrades**	**5,010**	**3,860**	**450**	**9,320**	**12,900**
1.3.1	Large Aperture Quads	600	0	0	600	900
1.3.2	Main Injector Collimator	250	100	0	350	**700**
1.3.3	NUMI Multi-batch Operation	50	150	50	250	500
1.3.4	Main Injector RF Upgrade	4,110	3,610	400	8,120	**10,800**
1.4	**Management**	**348**	**290**	**241**	**879**	**1,316**

Time Table

WBS	Task Name
1	**Proton Plan**
1.1	**Linac Upgrades**
1.1.1	PA Vulnerability
1.1.2	Linac Quad Power Supplies
1.1.3	Linac Instrumentation Upgrade
1.2	**Booster Upgrades**
1.2.1	Booster Rep Rate Limit
1.2.2	ORBUMP System
1.2.3	Corrector System
1.2.4	30 Hz Harmonic
1.2.5	Gamma-t System
1.2.6	Alignment Improvements
1.2.7	Drift Tube Cooling
1.2.8	Booster RF Cavity #20
1.2.9	Booster Solid State RF Drivers
1.2.10	Booster Instrumentation
1.3	**Main Injector Upgrades**
1.3.1	Large Aperture Quads
1.3.2	Main Injector Collimator
1.3.3	NUMI Multibatch Operation
1.3.4	Main Injector RF Upgrade
1.4	Management
1.5	**Major Milestones**
1.5.1	Start Phase I
1.5.2	Scope Decision WBS 1.1.1 and 1.2.1
1.5.3	Start Phase II



Proton Projections

- Phases of Operation
  - Phase I
    - After this shutdown
    - Dogleg problem ameliorated
    - Booster limited to 7.5Hz total repetition rate
    - Main Injector limited to 4E13 protons (2+5 operation)
  - Phase II
    - After 2005 shutdown
    - ORBUMP replaced
    - RF cooling finished
    - Booster capable of 9Hz operation
    - MI still limited
  - Phase III
    - After 2006 shutdown
    - MI RF upgrade complete
    - 2+9 operation to NuMI

Evaluate Effect of Booster Improvements

- Calculate effect of various improvments based on increased acceptance (a la McGinnis):
- Use:

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

Effective aperture reduction

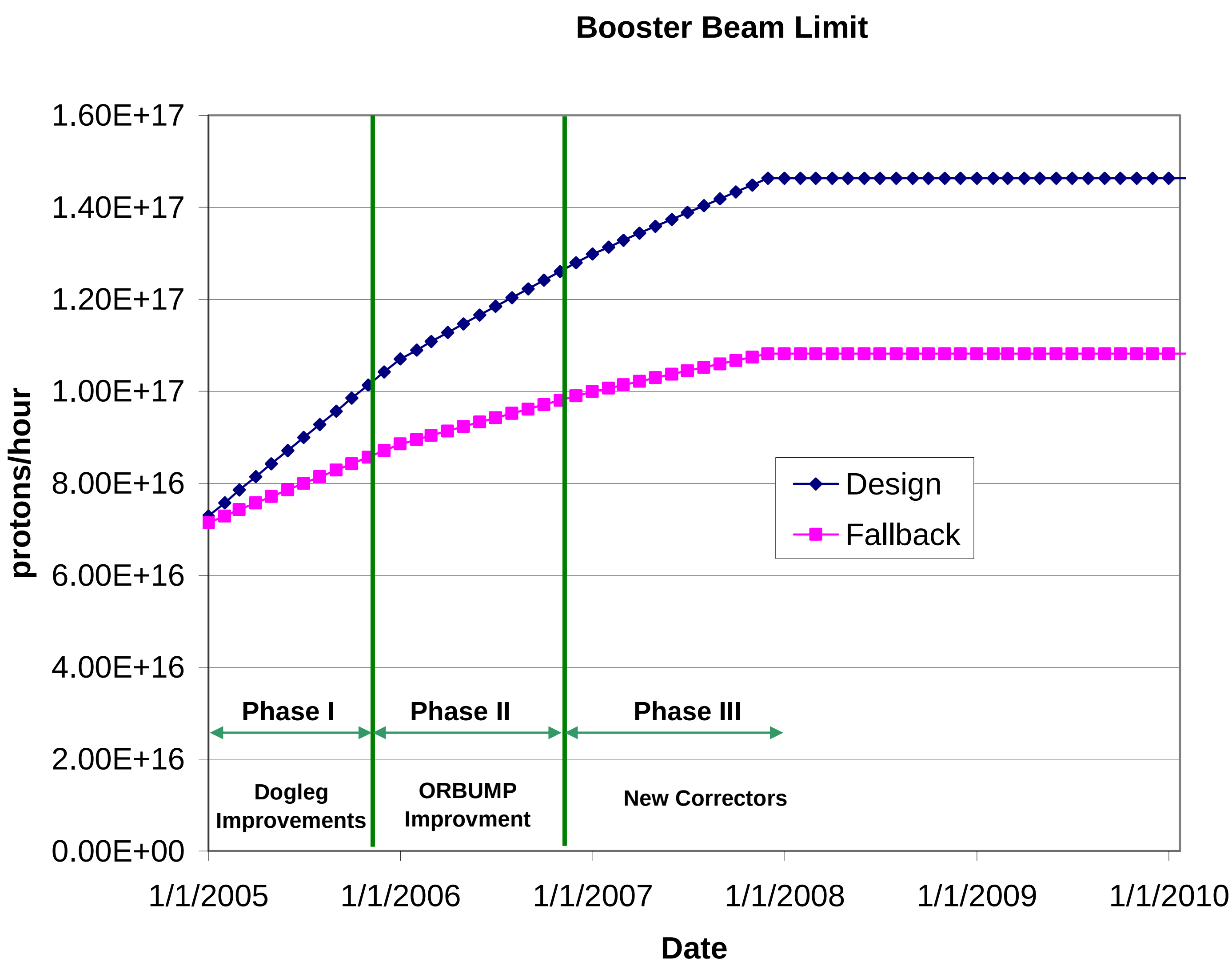
Condition	Date Completed	δA (mm)	max D (m)	max beta (m)	Acceptance (π-mm-mr)	Relative Increase (%)
Start of MiniBooNE	---	10	6.2	45.8	15.7	-15
Dogleg 3 Fix	Oct-03	10	4.5	40.8	18.4	0
Dogleg 13 Fix	Oct-04	10	3.8	36.1	21.0	14
Alignment	Oct-05	8	3.8	36.1	24.3	32
ORBUMP	Oct-05	5	3.8	36.1	29.5	60
correctors	Oct-06	2	3.8	36.1	35.2	92
Ideal	---	0	3.19	33.7	42.3	130

Effect on Max Proton Intensity

- Prior to this shutdown, regularly delivering 7.5E16pph with ~40% reduction in activation around most of the Booster.
  - Assume after another year of tuning and collimator optimization, we could have hit 1E17 pph with no other improvments ("fallback" = .9E17).
- Operational experience: tuning asymptotically approaches benefit of a particular improvement:
  - Assume after one year of tuning, 50% of the benefit of a particular improvement is realized (fallback = 25%).

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
1/2007	13.0	10.4	Alignment and ORBUMP
1/2008	14.6	11.0	New corrector system

Predicted Proton Intensity Limits



Estimating PoT

- Even the fallback proton scenario accommodates NuMI operation.
- Total proton output continues to be limited by radiation losses, rather than Booster repetition rate.
- We assume:
  - NuMI and antiproton production get what they need
  - The BNB gets whatever it can beyond that, within the total output limit of the Booster
- This is a programmatic decision:
  - Protons can be diverted from NuMI to the BNB, but not the other way around.
- The BMB PoT estimates are extremely sensitive to the total proton limit, which is uncertain.

Calculating NuMI PoT

- Even the fallback scenario accommodates NuMI operation.
- Assume the following
  - Booster batch intensity rises steadily to 5.5E12 over the next three years.
  - Ramp up to full 2+5 operation by April 2005
  - Ramp up to full 2+9 batch slipstacked operation a few months after MI RF upgrade.
  - 90% efficiency for slip stacking.
  - 10 month operation each year.
  - 81% total uptime for remainder of year
    - based on MiniBooNE. Includes scheduled and unscheduled downtime
  - 90% avg/peak operating efficiency
  - 10% down time for shot setup
  - 5% down time for fast Recycler transfers
  - 5% down time during 2005 for Ecool accesses.

Calculating BNB PoT

- Trickier:
  - Still limited by beam loss, NOT rep. rate.
  - Assume antiproton and NuMI have priority, so
  - BNB VERY sensitive to proton limit and its fluctuations.
- Use:

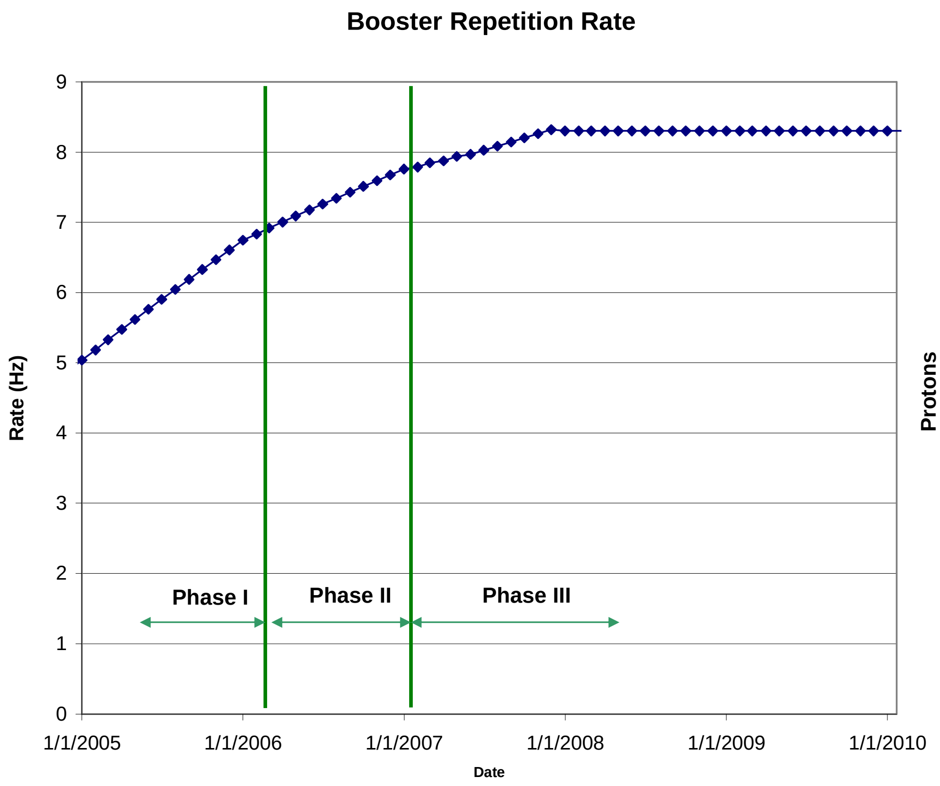
$$(\text{avg pph}) = (\text{pph lim.})^{*}\eta - (\text{NuMI pph}) - (\text{pbar pph})$$

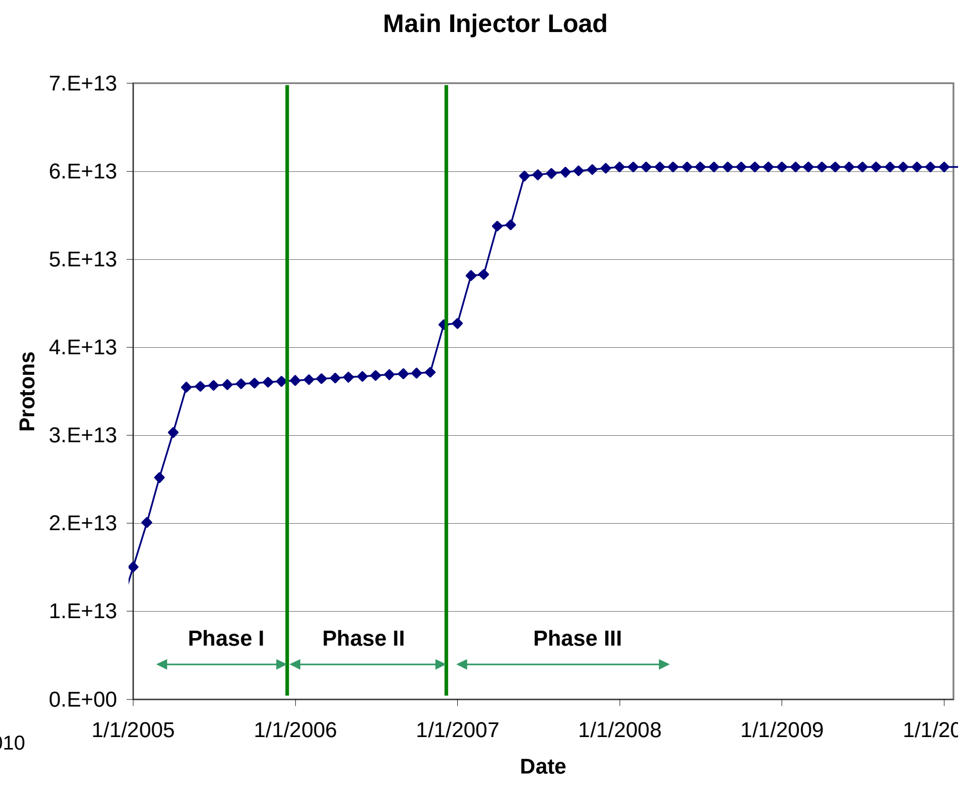
Booster output limit, as discussed

Avg/pk ~ 86% from July 2004 MiniBooNE operation

- Also assume:
  - 10 month operation
  - 81% up time (based on 2004)
  - BNB gets all the beam during shot setup (10% of the time)

Machine Loading

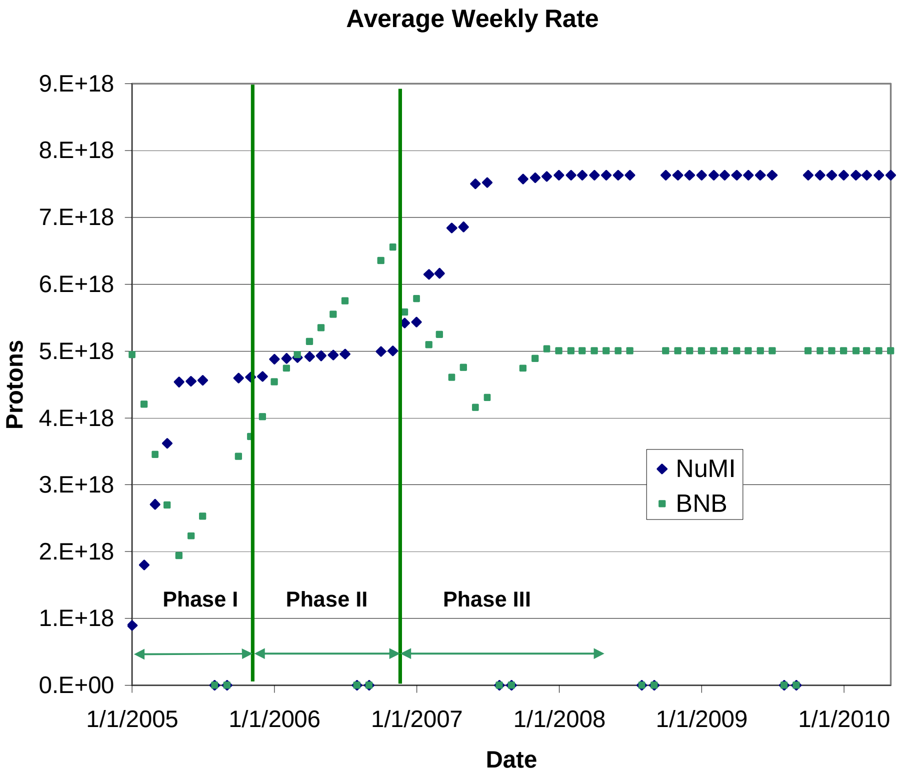


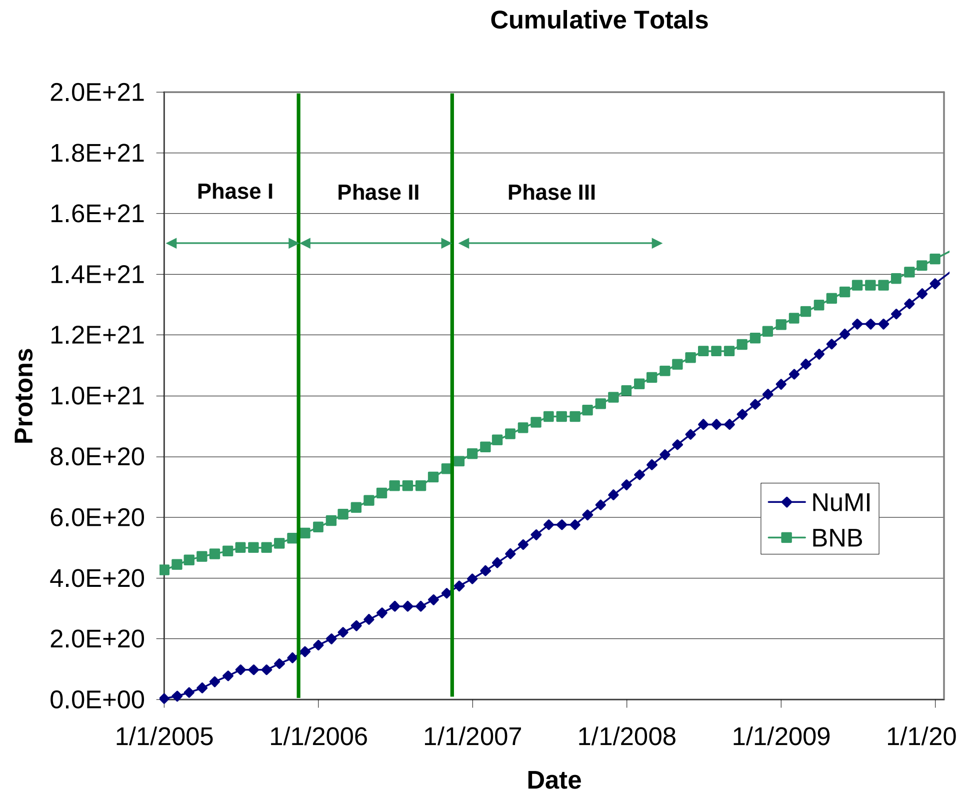


"Design" PoT

	Booster Batch Size	Main Injector Load	Cycle Time	MI Intensity	Booster Rate*	Total Proton Rate	Annual Rate at end of Phase	
		(AP + NuMI)	(sec)	(protons)	(Hz)	(p/hr)	**NuMI**	**BNB**
Actual Operation								
July, 04	5.0E+12	1+0	2.0	0.5E+13	5.1	0.8E+17	0	3.3E+20
Proton Plan								
Phase I	5.10E+12	2+1→2+5	2.0	3.6E+13	6.3	1.0E+17	2.0E+20	1.5E+20
Phase II	5.3E+12	2+5	2.0	3.7E+13	7.5	1.2E+17	2.2E+20	2.8E+20
Phase III	5.50E+12	2+9	2.2	6.0E+13	8.3	1.5E+17	3.4E+20	2.2E+20
Beyond Scope of Present Plan								
11 Hz	5.50E+12	2+9	2.2	6.1E+13	11.0	2.0E+17	3.4E+20	5.0E+20

"Design" Totals



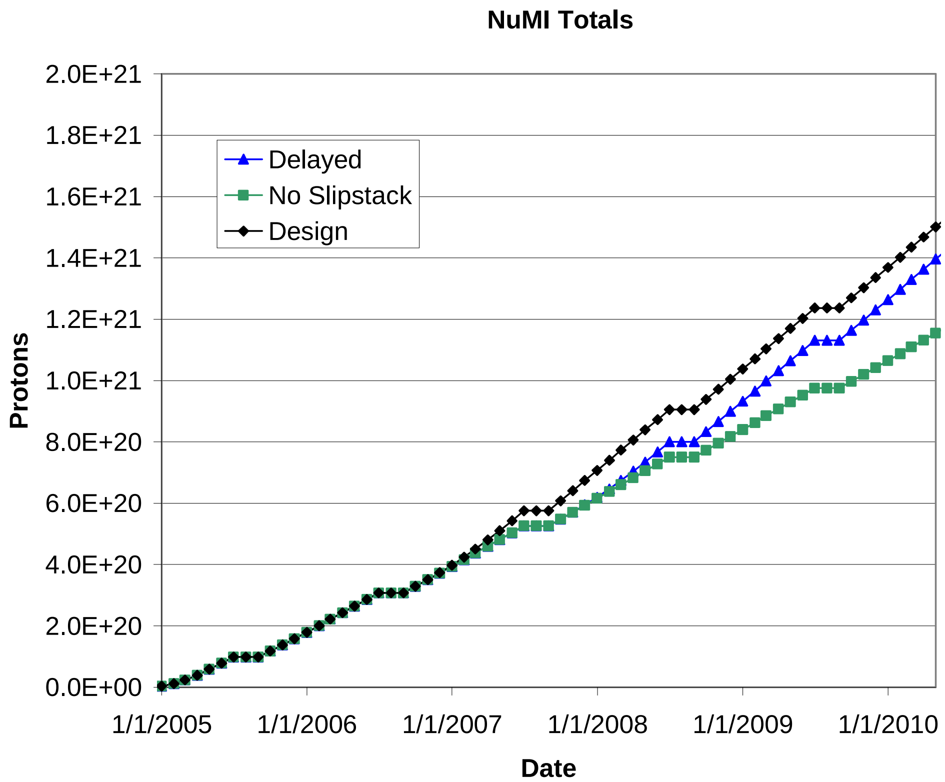


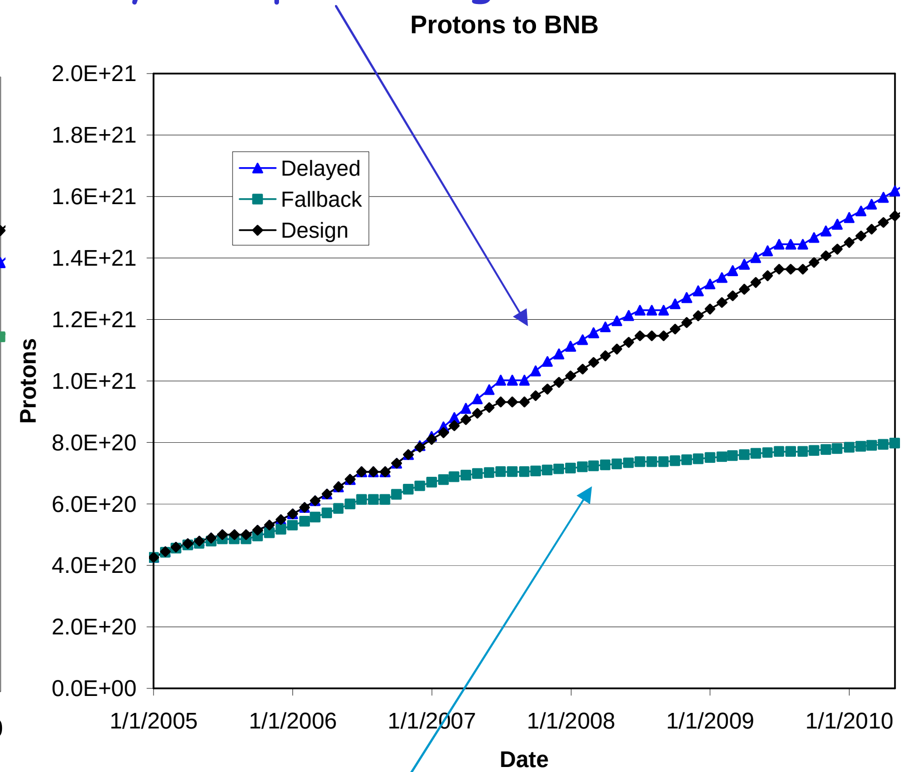
Fallback Scenarios

- NuMI
  - Project totals if the MI RF upgrade is delayed by a year.
  - Project totals if slip stacking fails entirely for one reason or another.
- BNB
  - Project totals if both the MI RF upgrade and the corrector upgrade are delayed by a year.
  - Project totals if the aperture improvements have only 25% of their calculated benefit.

Fallback Projections

BNB *benefits* from delayed slip stacking





BNB only during shot setup

Summary

- We have a three year plan for a set of improvements to maximize proton delivery to NuMI and the BNB for the forseeable future.
- We have made an attempt to estimate the benefits of these improvements.
- NuMI proton delivery will be determined by how successful we are with the RF upgrade and the implementation of slip stacking.
- BNB proton delivery will depend on the total proton output capacity of the Booster, and is therefore still highly uncertain.