Proton Plan

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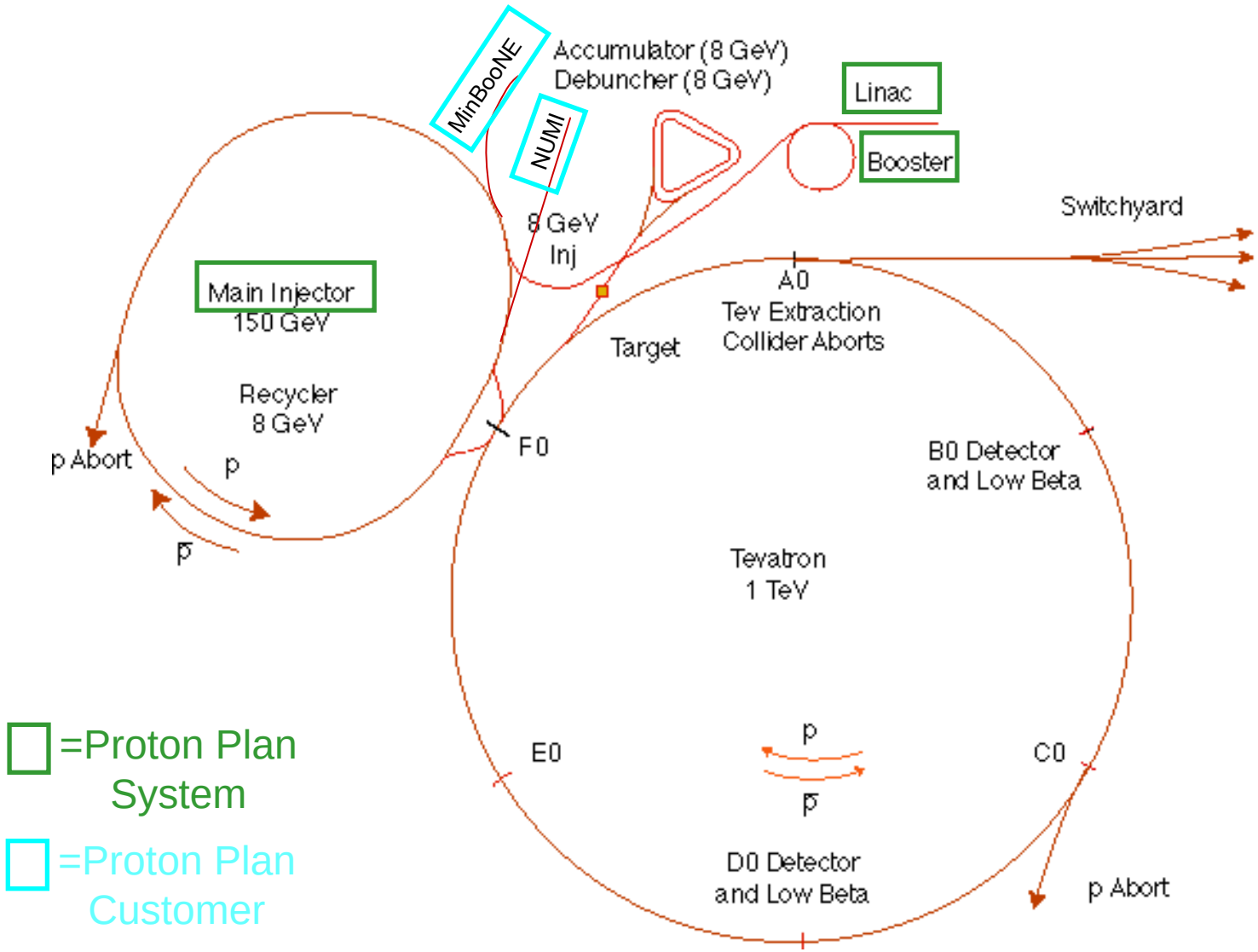
FNAL Accelerator Division

Outline

- Overview of the Proton Plan
- Progress since last review
- Plans for upcoming shutdown
- Projections and performance

The Fermilab Accelerator Complex



Proton Plan 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.

Very important

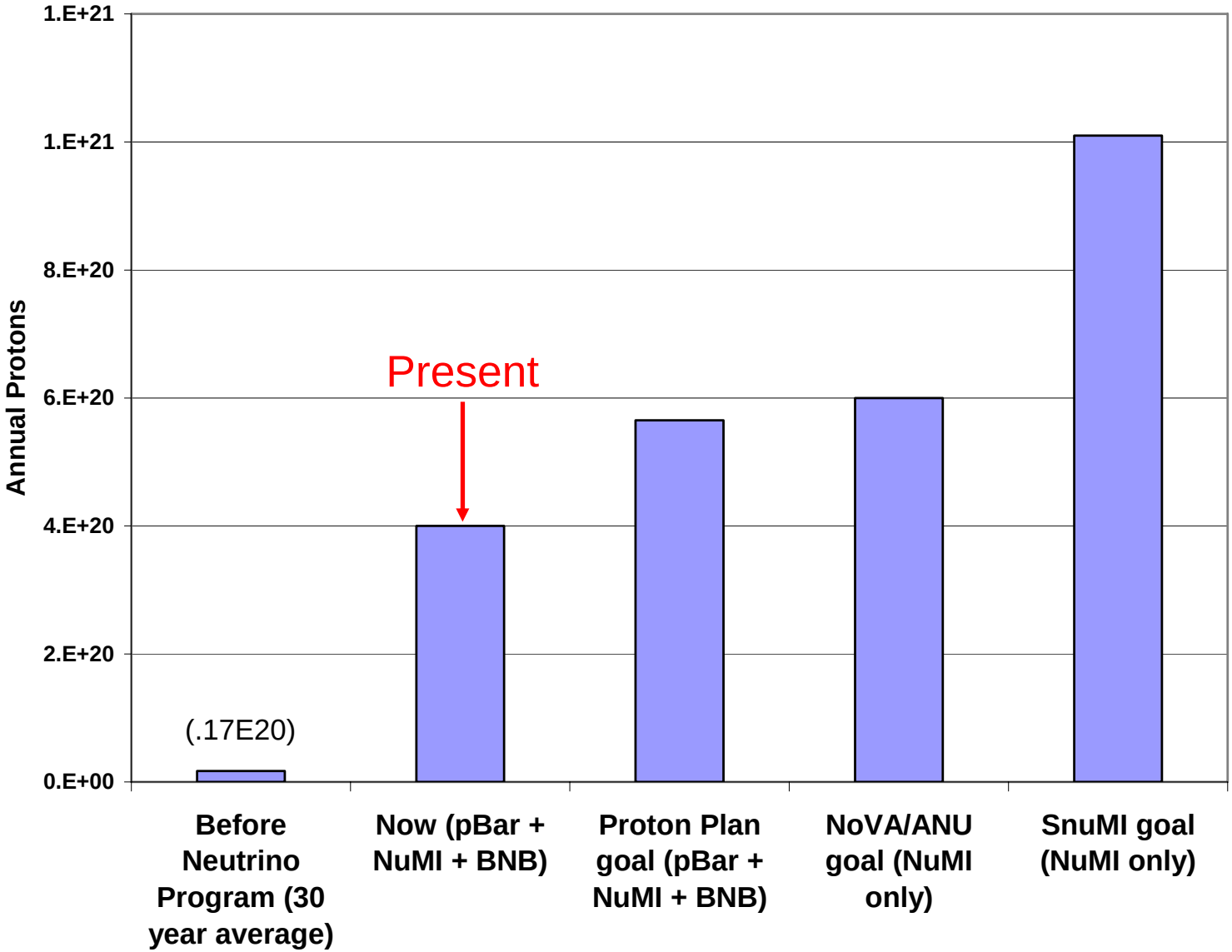
Staged Neutrino Program: What's in a Name?

- Current Proton Plan
  - A combination of Main Injector RF improvements and operational loading initiatives will increase the NuMI intensity to 4-5E13 protons to NuMI per 2.2 second cycle (~3E20 p/yr).
  - Ultimately 320 kW to NuMI (400 kW w/o pBar)
  - Runs through end of collider program

Scope of this talk

- ANU ("Accelerator NuMI Upgrades", combined with NOvA as per DOE directive)
  - Retask Recycler as a pre-loader to save proton loading time to the Main Injector
  - ~700 kW to NOvA
  - Presently being formalized and baselined
- SNuMI (formerly "SNuMI II")
  - Use pBar accumulator to momentum stack protons prior to boxcar stacking in the Recycler
  - Ultimately ~1.2 MW to NuMI
  - Still in the conceptual planning stage
- HINS (formerly "Proton Driver")
  - New 8 GeV proton Linac to Main Injector
  - Exploit synergy with ILC
  - ~2 MW to NuMI
  - Not part of our official planning at this point

Total Protons



Limits to Proton Intensity

- Total proton rate from Proton Source (Linac+Booster):
  - Booster batch size
    - ~4-5E12 protons/batch, depending on beam quality required.
  - Booster repetition rate
    - 15 Hz instantaneous
    - Currently ~9Hz, limited by RF system.
  - Beam loss
    - Damage and/or activation of Booster components
    - Above ground radiation
- Total protons accelerated in Main Injector:
  - Maximum main injector load
    - Six "slots" for booster batches (3E13)
    - Up to ~11 with slip stacking (4.5-5.5E13)
    - Beam stability (RF issues)
    - Beam loss concerns
  - Cycle time:
    - 1.4s + loading time (1/15s per booster batch)

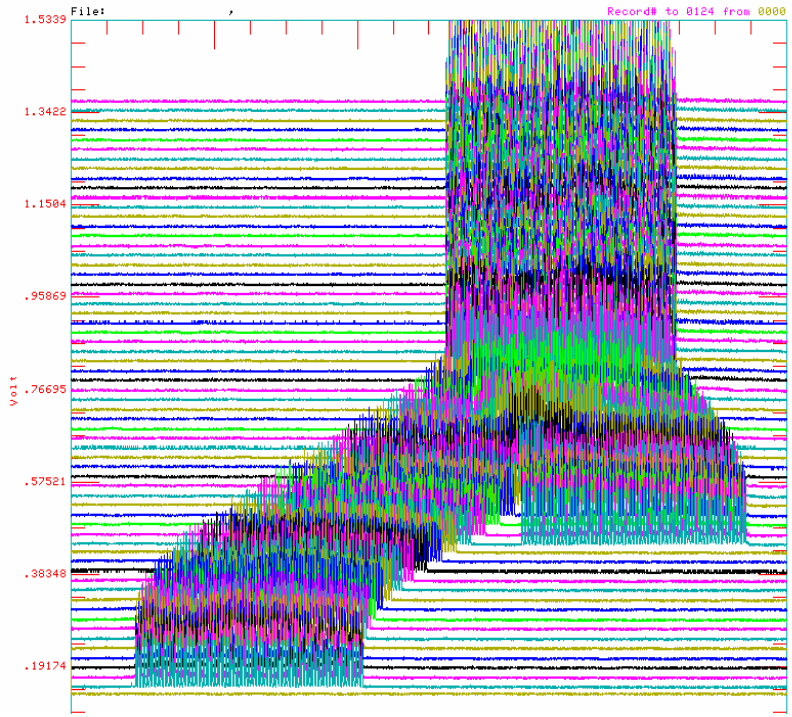
Historically our biggest worry

Critical path for NuMI/MINOS

Review: 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 an initial batch in the Main Injector is accelerated such that a subsequent batch will be at a slightly different energy.
- The two will then drift together and can be captured as a single batch (with at least twice the longitudinal emittance).

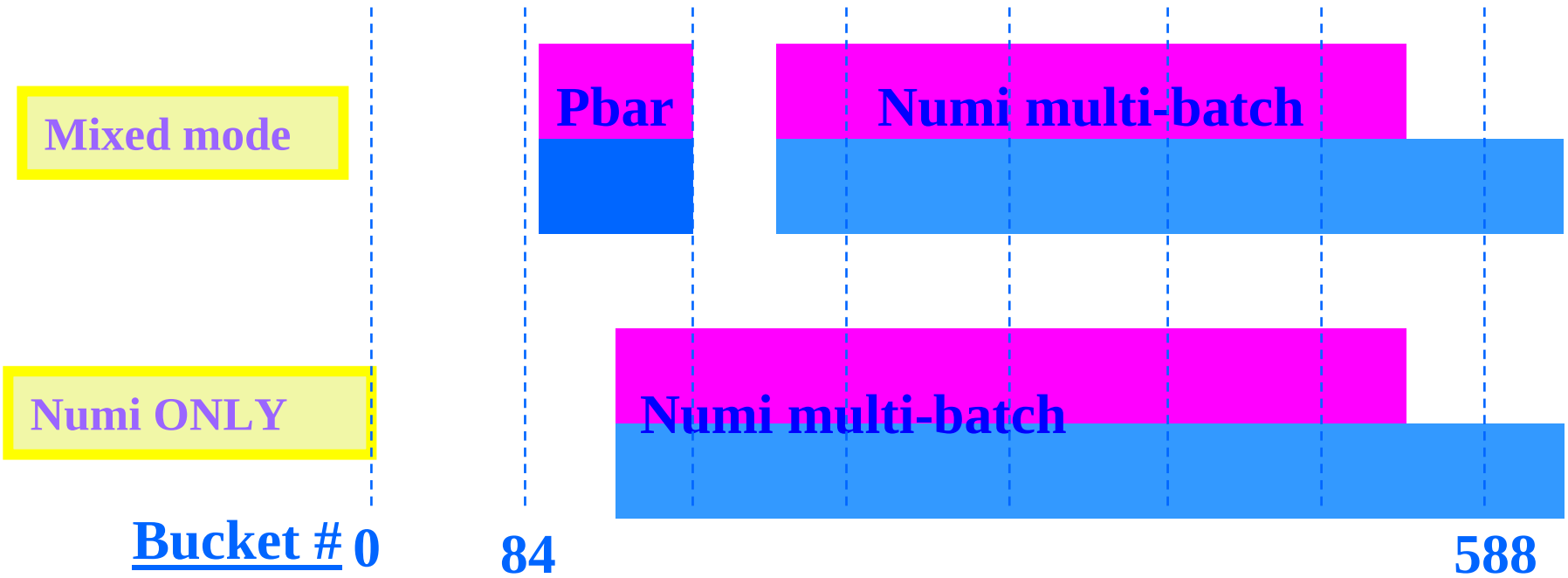


NuMI Operating Modes

- Present NuMI operation ("2+5"):
  - Two batches are slip stacked for antiproton production.
  - Five more batches are loaded for NuMI
  - All accelerated together.
  - pBar batches extracted, followed by NuMI batches.
  - For NuMI only operation all 7 batches are send to the NuMI target.
- 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.

Slip Stacking Goals

- Intensity:
  - 11 x 4.3E12 at injection
  - 11 x 4.0E12 at extraction
- Power
  - 80 kW -> pBar production
  - 320 kW -> NuMI



Plan Strategy

- Increase the total proton capacity of the
  - Increase maximum average Booster repetition rate.
  - Increase acceptance by improving orbit control and beam quality.
- Increase the beam intensity in the Main Injector for NuMI
  - Main Injector multi-batch operation.
  - Slip stacking in Main Injector.
- Improve operational stability and reliability
- Organized along the Run II model
  - "campaign" rather than "project"
- Budget ($K, loaded)

FY07	FY08 Preliminary	FY09 Request
$10,855.6	$3,941.9	$324.4

Summary: Significant Elements of Plan

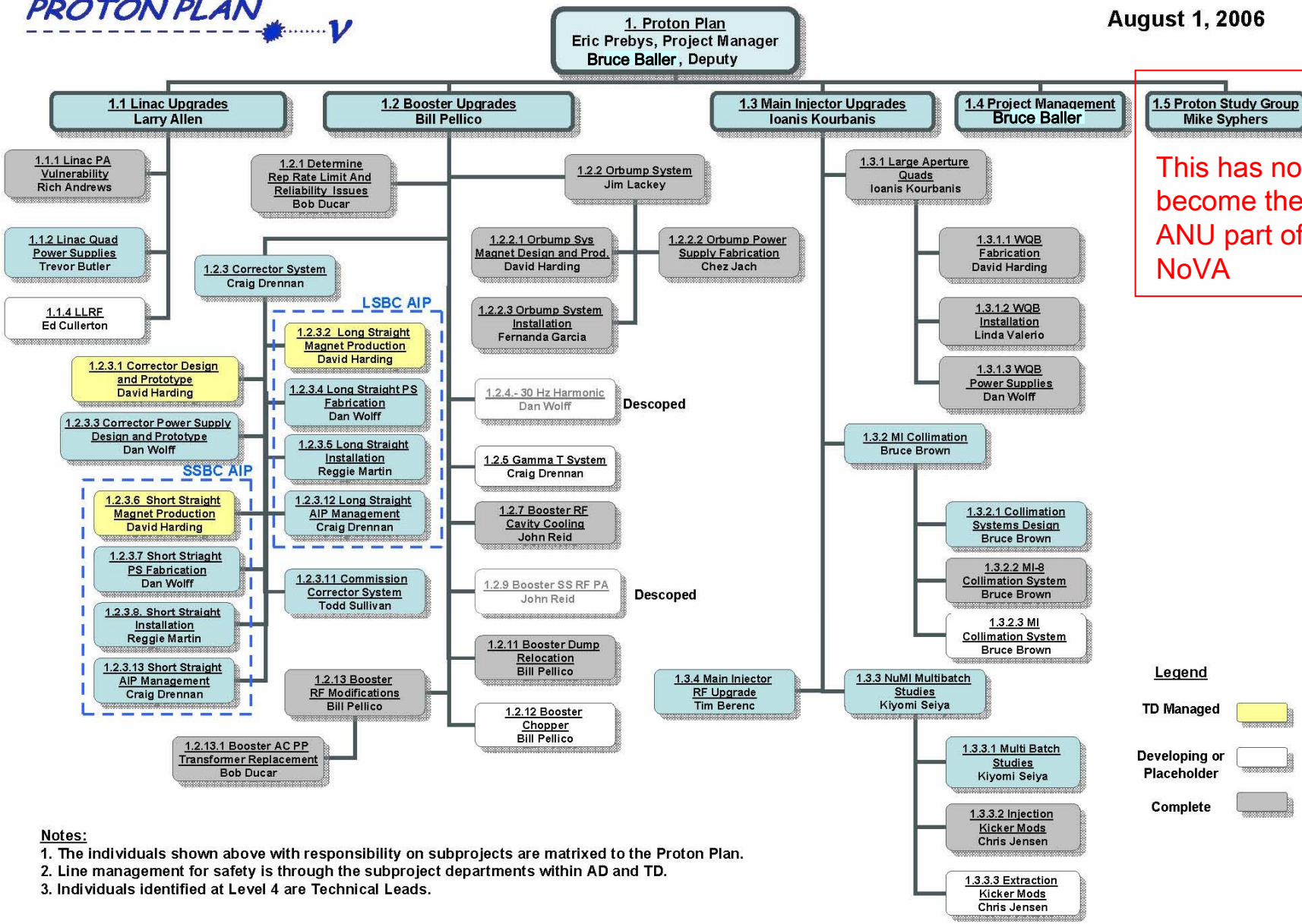
- Linac
  - Stockpile two year supply of spare 200 MHz power amplifier tubes (7835's), in the event of an interruption in supply
  - Characterize and improve Low Energy Linac Low Level RF
- Booster:
  - Replace and reconfigure injection bump (ORBUMP) system.
  - Relocate 8 GeV dump from Booster tunnel to MI-8 transfer line
  - Make Booster robust to 9 Hz, and understand requirements to go to 15 Hz
  - Design, build, and install new corrector system
    - Installed separately in long and short straights
- Main Injector:
  - Replace seven quadrupoles with increased aperture versions, to reduce injection and extraction losses.
  - Operationally develop multi-batch and multi-batch slip stacked operation
  - Design and install collimation system, both in the MI-8 line and in the MI ring
  - Modify injection kicker to allow multi-batch slip stacked operation
  - Characterize and improve to RF system, to support high intensity operation.

Red = complete

Organizational Chart by WBS

PROTON PLAN

August 1, 2006



This has now become the ANU part of NoVA

Notes:

1. The individuals shown above with responsibility on subprojects are matrixed to the Proton Plan.
2. Line management for safety is through the subproject departments within AD and TD.
3. Individuals identified at Level 4 are Technical Leads.

Since Last Operational Review

- The last operational review took place near the end of a shutdown in which several critical Proton Plan projects were under way.
  - Booster injection bump (ORBUMP) replacement and 400 MeV injection line reconfiguration.
    - Eliminate rate limitation and improve injection aperture
  - 8 GeV Dump Relocation
    - Move one of the two Booster extraction regions to the MI-8 line to reduce acceleration losses in Booster
  - Install 7 large aperture quads in Main Injector
    - Increase aperture and reduce losses at extraction Lambertsons
  - MI-8 collimation system
    - Reduce first turn losses in Main Injector

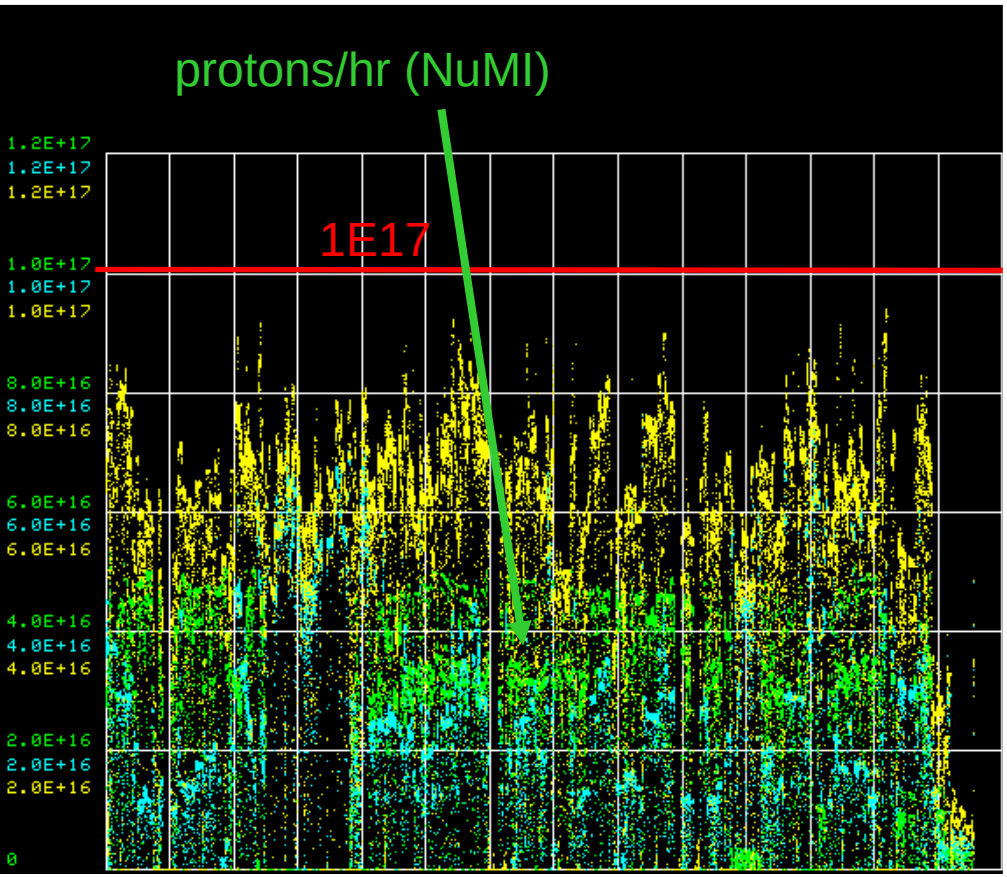
Linac Power Amplifiers

- The Low Energy Linac requires 5 200 MHz power amplifier tubes ("7835's")
- For many years, it was difficult to maintain an adequate supply of these tubes:
  - Often had to resort to borrowing tubes from other labs
  - Consistently identified as a *significant concern for the long term viability of the Linac*
- As part of the Proton Plan (1.1.1), an investigation was launched which considered three options:
  - Work with vendor to increase yield of good tubes
  - Replace 200 MHz RF system
  - Replace entire LEL with 400 MHz, klystron-driven version.
- Recommendation:
  - Work with BNL and vendor to improve QA procedure
  - Place order for two year supply of "strategic spares" (12 tubes), against the possibility that the vendor will stop producing tubes.
  - This is in addition to our normal rebuild and replace cycle which aims to maintain a one year supply of spares (6) at all times.
- Result
  - Now have 17 spares.
  - Plan to keep 12 "sacrosanct" and continue the normal procurement cycle to maintain ~6 additional spares indefinitely.

Benefits of Booster Work

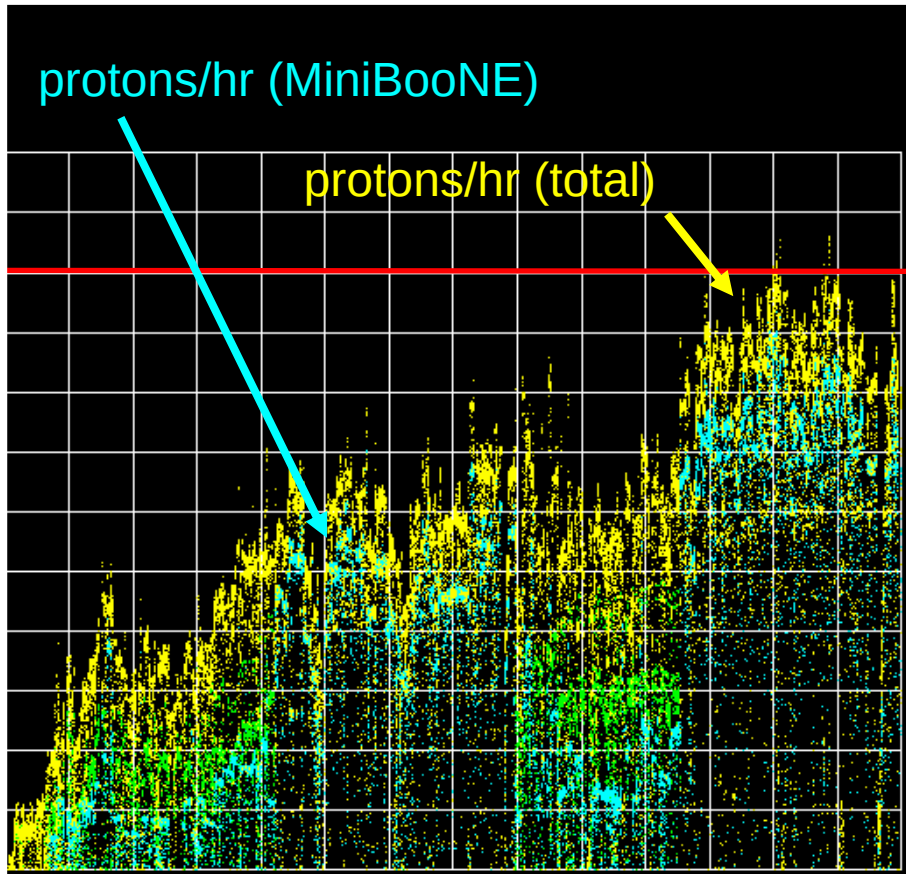
- ORBUMP
  - Maximum repetition rate increased
    - No limit from ORBUMP
    - Overall limit increase from 7->9Hz (from RF system)
      - sufficient for Proton Plan Goals
  - Injection slewing reduced from ~1cm to ~2mm
    - Efficiency increased
    - Injection tuning much less sensitive
  - Greatly improved reliability
- 8 GeV dump relocation
  - Ramp losses reduced
- Result
  - Record intensities
    - 1 hr
      - 9E16 pph MiniBooNE
      - 1E17 pph total
    - 1 week
      - 1.1E19 protons to MiniBooNE
      - 1.2E19 protons total
- Note: NuMI did not *directly* benefit from these total rate increases

Effect of Shutdown Work on Booster Rates



11/23/05 6/1/06

Before Shutdown



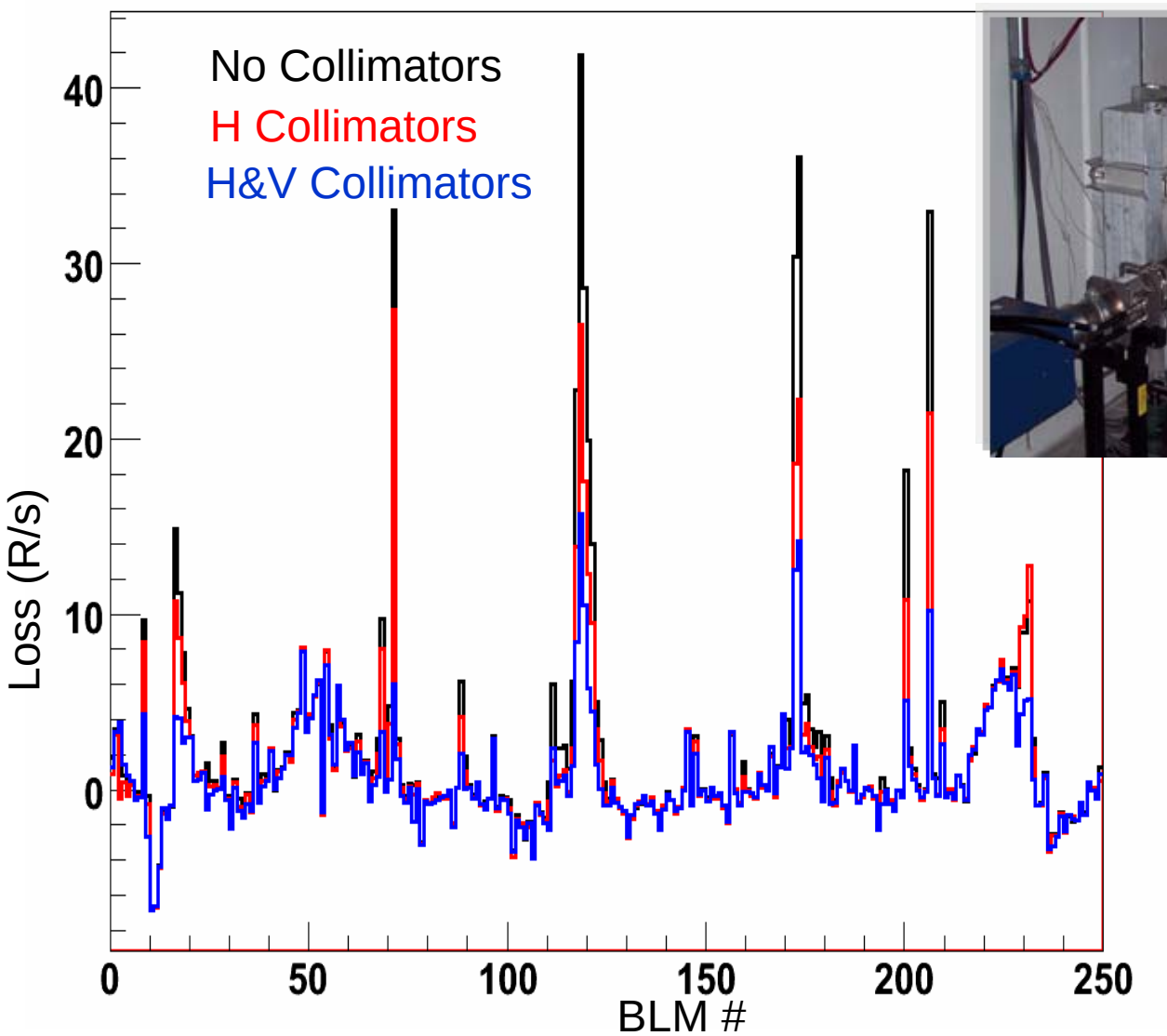
2/29/06 8/28/06

After Shutdown

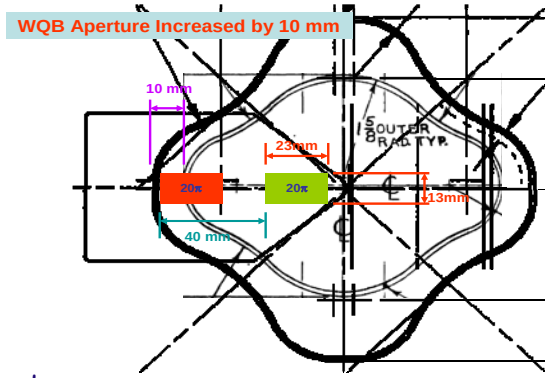
Benefits of MI-8/Main Injector Work

- MI-8 Collimation
  - Reduces first turn losses in Main Injector
  - Now commissioned and used operationally
- Large aperture quads
  - Significant aperture increase at extraction Lambertsons
- Injection kicker modifications
  - All rates necessary to do 2+9 slip stacking

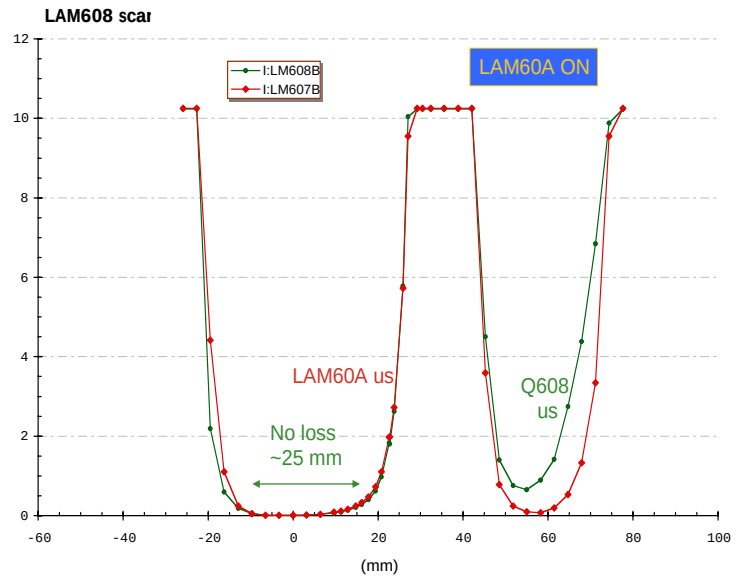
Effect of MI-8 collimation



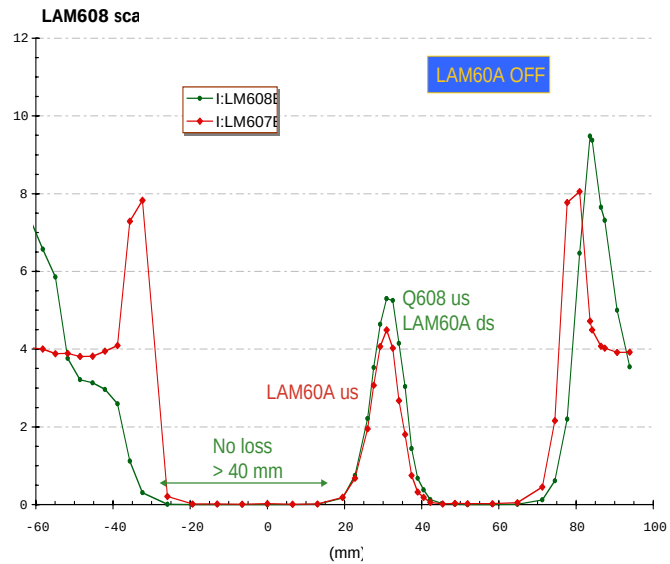
Aperture scans at one of the WQB Locations



MI608 aperture scan, before shut-down



MI608 location aperture scan, now



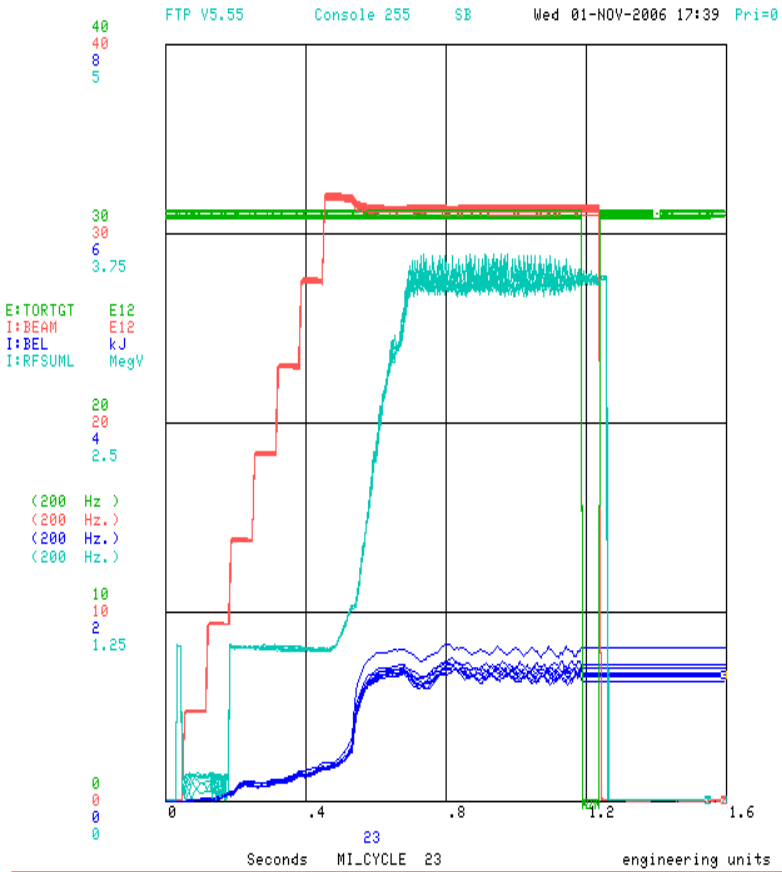
50% aperture increase at the Lambertsons

Slip Stacking Progress

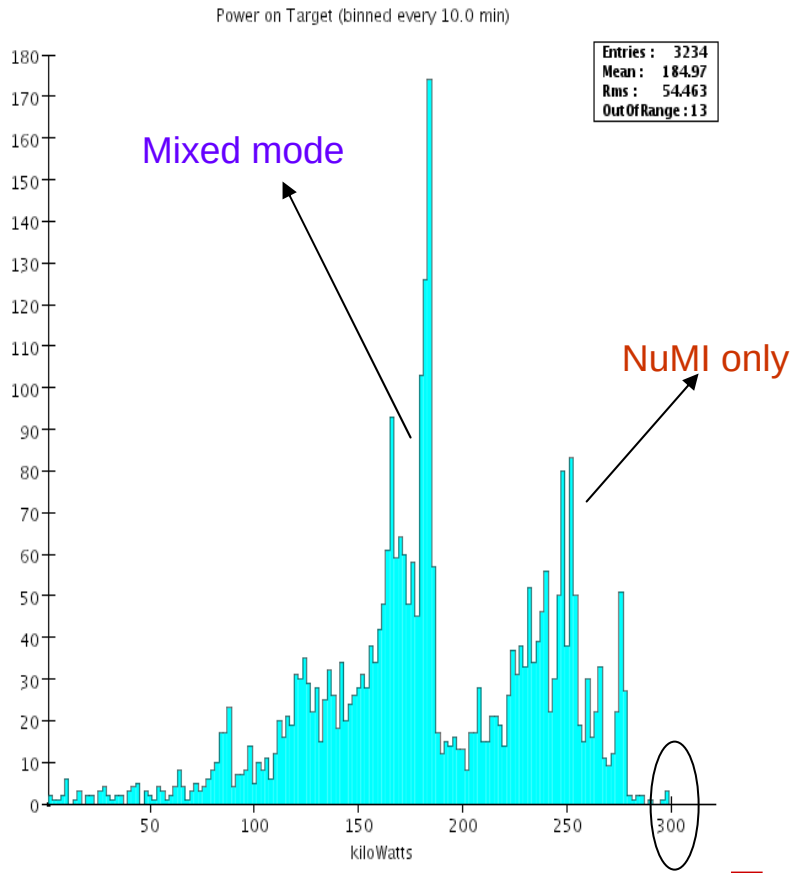
- When the Proton Plan was first formalized, it was believed that we could begin ramping up to NuMI slip stacking following the 2006 shutdown.
- As we began to understand the process, we realized that there were limitation in the Main Injector which would prevent operational 2+9 operation:
  - RF limited by series tube power dissipation RF stability
  - 95% capture efficiency means 5% beam loss at 8GeV in Main Injector
    - Unacceptable
    - Ring collimation required
- These improvements will be implemented during the next shutdown.
- It's vital that we do sufficient studies this year, such that we may quickly ramp up to full slip stacked operation after next shutdown.
  - Current projections assume 3 month ramp up.

Beam Intensity and Power to NuMI target for 2+5 operation

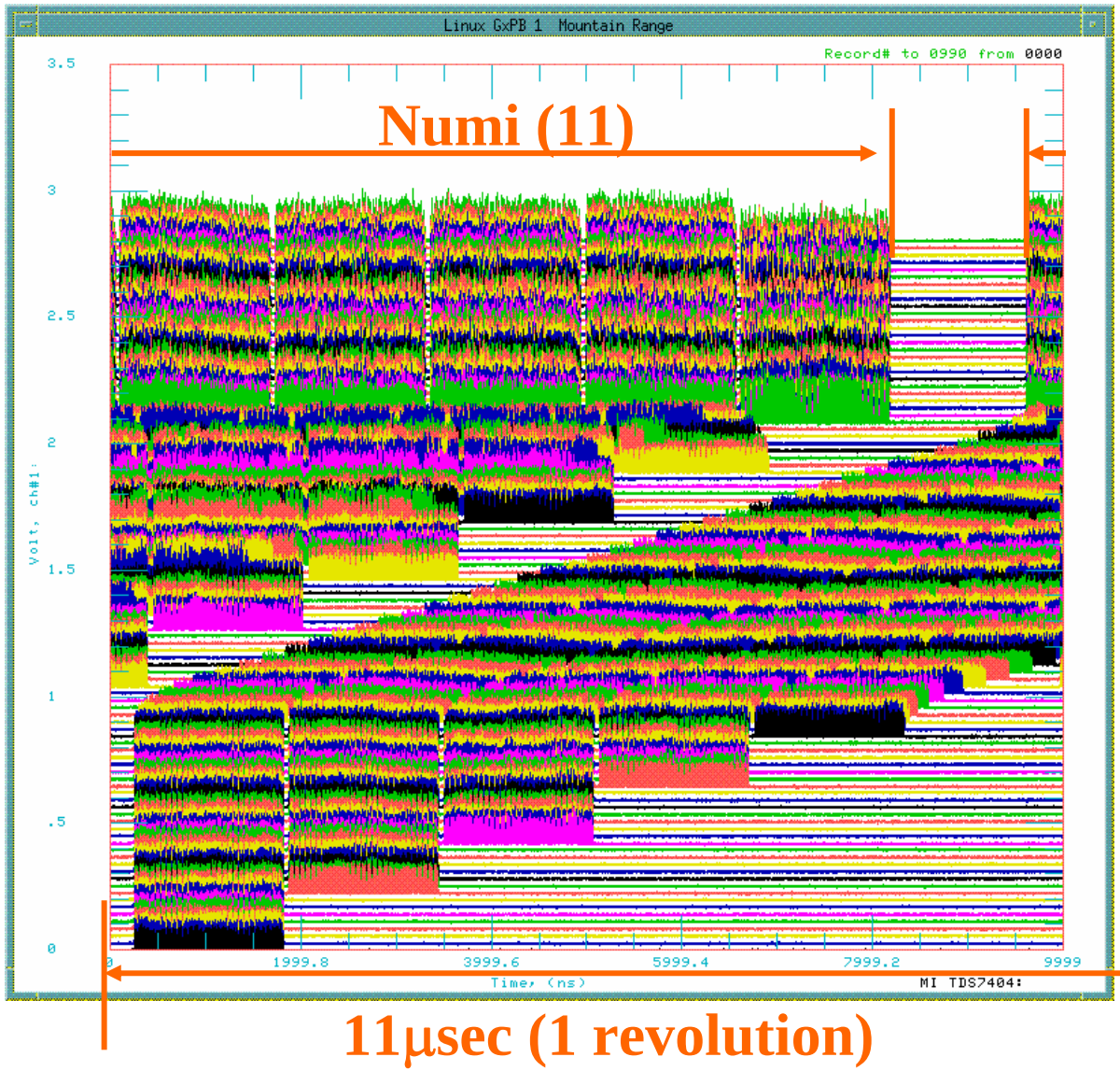
Beam Intensity, rf voltage and losses for a NuMI only cycle (2+5 batches).

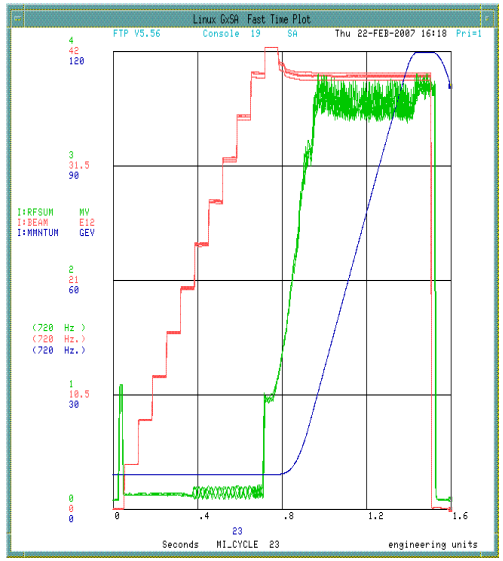


Histogram of beam power to NuMI during Oct. 06



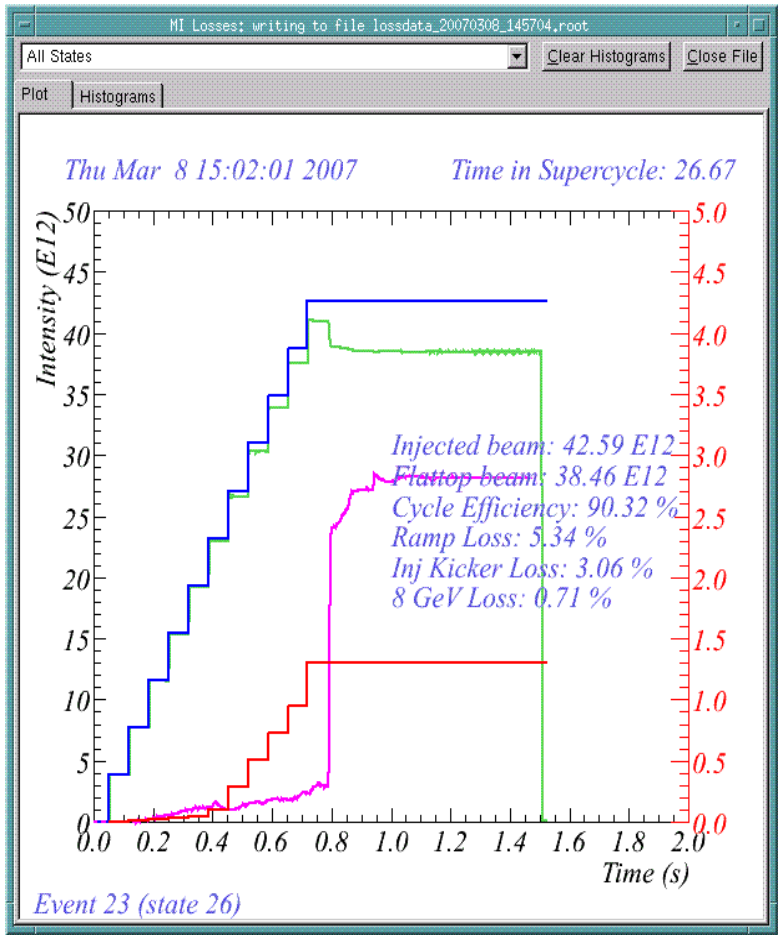
Multi-batch slip stacking status



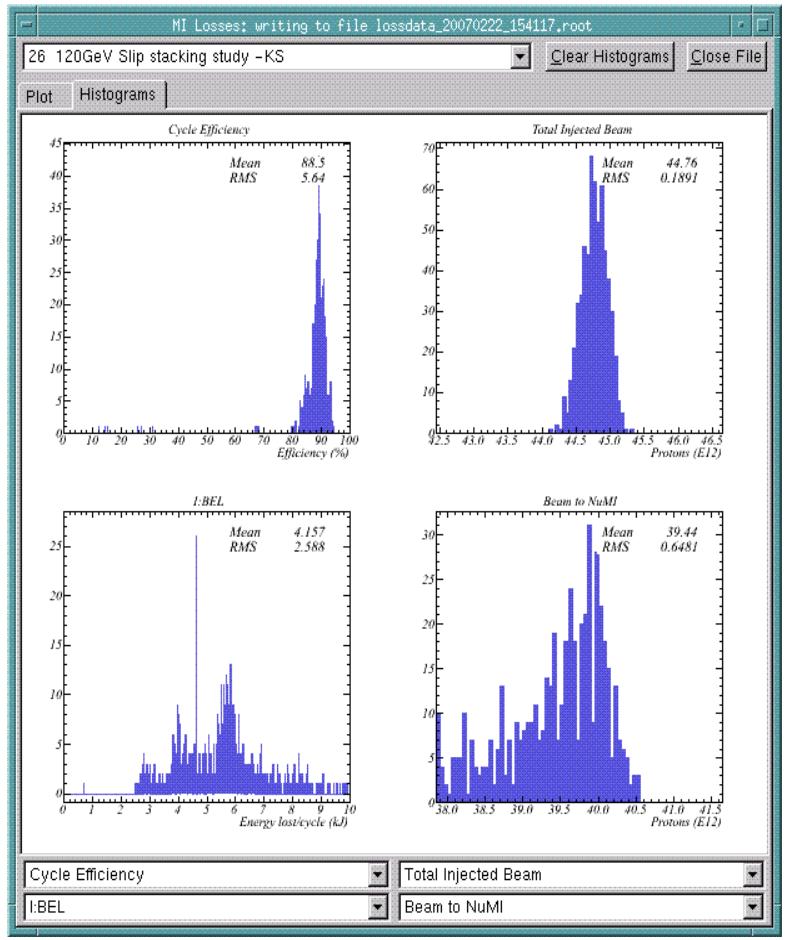


- Record:
  - 4.05E13 protons to NuMI (NuMI only)
  - 90% efficiency
- Goal:
  - 4.4E13 protons to 120 GeV (NuMI + pBar)
  - 95% efficiency

Multi-batch slip stacking status (2)



Different losses during multi-batch slip stacking



Histograms of intensities and efficiencies during a multi-batch slip stacking study.

Response to 2006 Recommendation

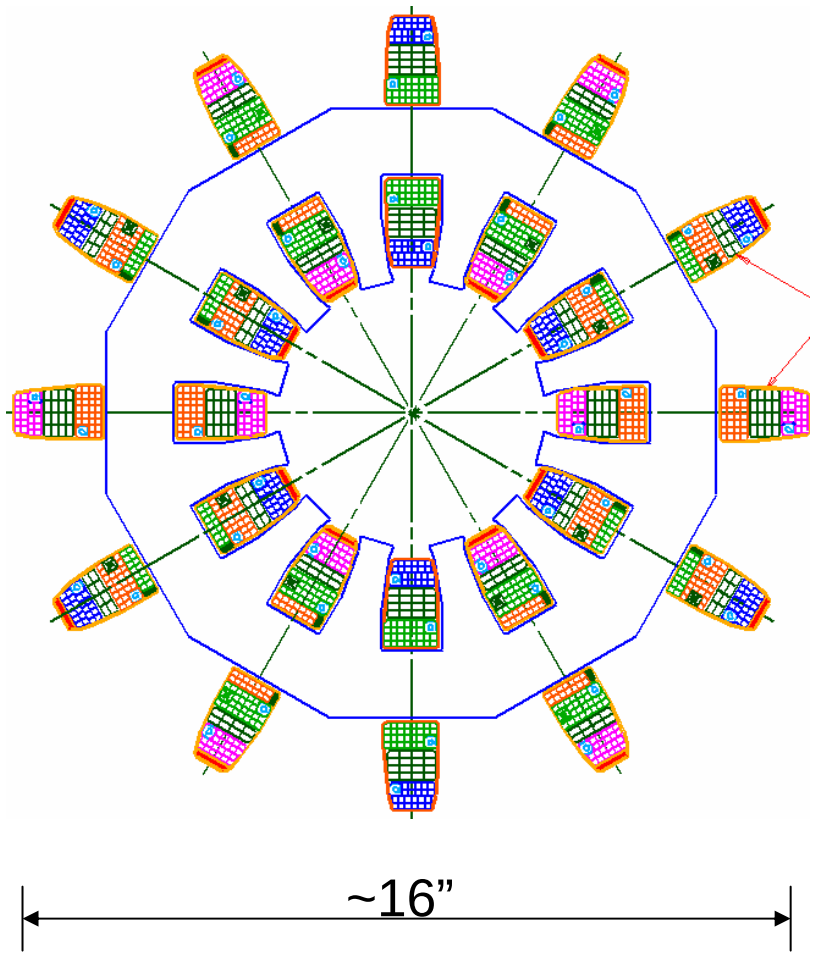
2006 Tev Operations Review - 3. Accelerator Operations & Integration		
No.	**Recommendations**	**Status**
3.2.1	Evaluate the high intensity limitations of the proton plan.	Complete. We have achieved MI intensities up to 4.1E13 protons (90% of the Proton Plan design intensity) without any problems with instabilities. The growth rates of the transverse coupled bunch modes have been measured and compared with predictions. Based on those measurements we expect our transverse bunch by bunch damper system to be adequate. Ref: X. Huang, P. Adamson et al Beams-doc-2059 and Beams-doc-2120, B. Zwaska, Beams-doc-2166. Due to the large longitudinal emittance of the slipped stacked bunches we do not expect to have problems with the longitudinal coupled bunch modes. Ref: V. Wu, Beams-doc-2275. We have started simulations and measurements of the e-cloud effect in MI. So far we do not anticipate e-cloud to be a problem at the Proton Plan intensities. Ref: M. A. Furman, K. Sonnad, and J.-L. Vay, LBNL-61921/CBP-761. B. Zwaska, “Electron Cloud measurements in MI” Beams-doc-2278

Significant Projects for 2007 Shutdown

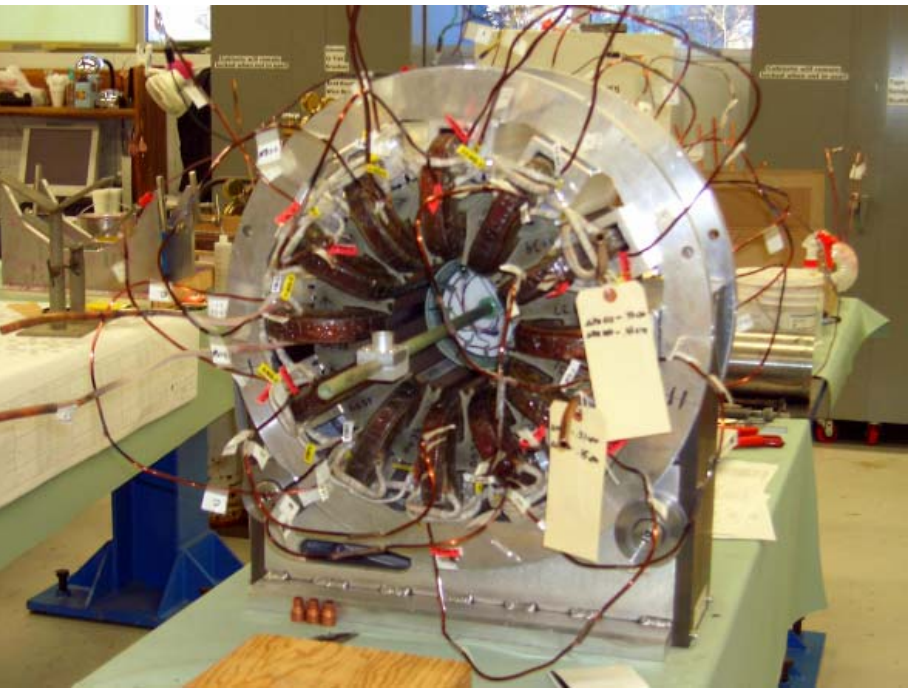
- Linac
  - We will implement an improved low level RF system for the low energy Linac
    - The goal is to improve energy and phase stability, resulting in more consistent Booster operation.
- Booster
  - The largest single project in the Proton Plan is the replacement of the Booster corrector system with a vastly improved version
    - Half of these will go in in this shutdown
- Main Injector
  - A two stage collimation system will be implemented, to handle the 5% beam loss anticipated for 2+9 slip stacked operation.
  - The RF system will be upgraded to reduce series tube power dissipation and insure stability

Booster Corrector System

- Replace all 48 (original) Booster corrector packages.
  - Unique new design
- Six independent multipoles
  - Stronger H and V dipoles
    - ±1cm beam motion throughout cycle
  - Stronger quad
    - Arbitrary tune working point throughout cycle
  - Skew quad
    - Coupling, same strength as before.
  - Sextupole and skew sextupole at every period.
    - Less emittance blowup
    - More control of harmonic resonances.
- Integrated BPM
  - Saves space



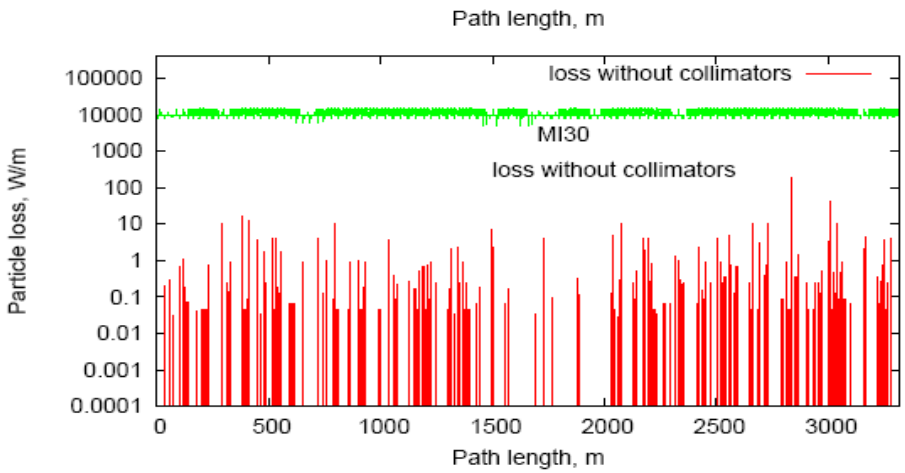
Correctors: Status



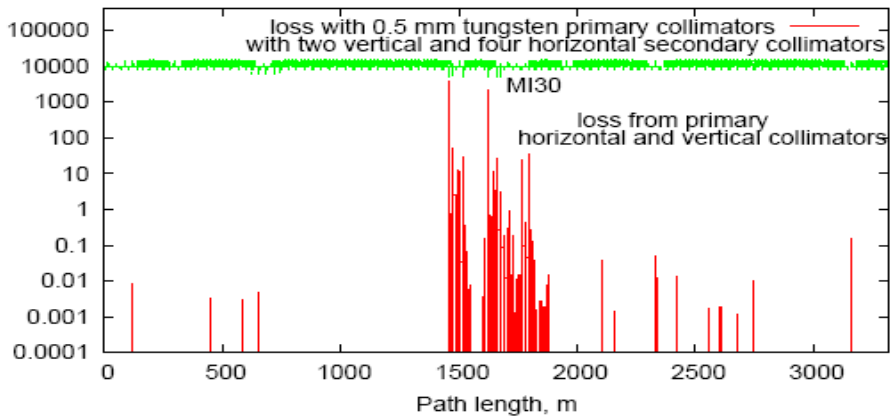
- Two prototypes built
  - Tests look good
- Coils and cores arriving from vendors
- Assembly fixtures being completed at Technical Division
- Power supplies in procurement
- Half of correctors will installed in 2007 shutdown.
- Second half in 2008 shutdown.

Main Injector Collimation

- Collimation system designed to handle loss from multi-batch slip stacked cycles
- Similar to Booster collimation system
  - .5 mm thin tungsten primary (scattering) collimators
  - Four secondary collimators
- On track for installation in 2007 shutdown



w/o collimation

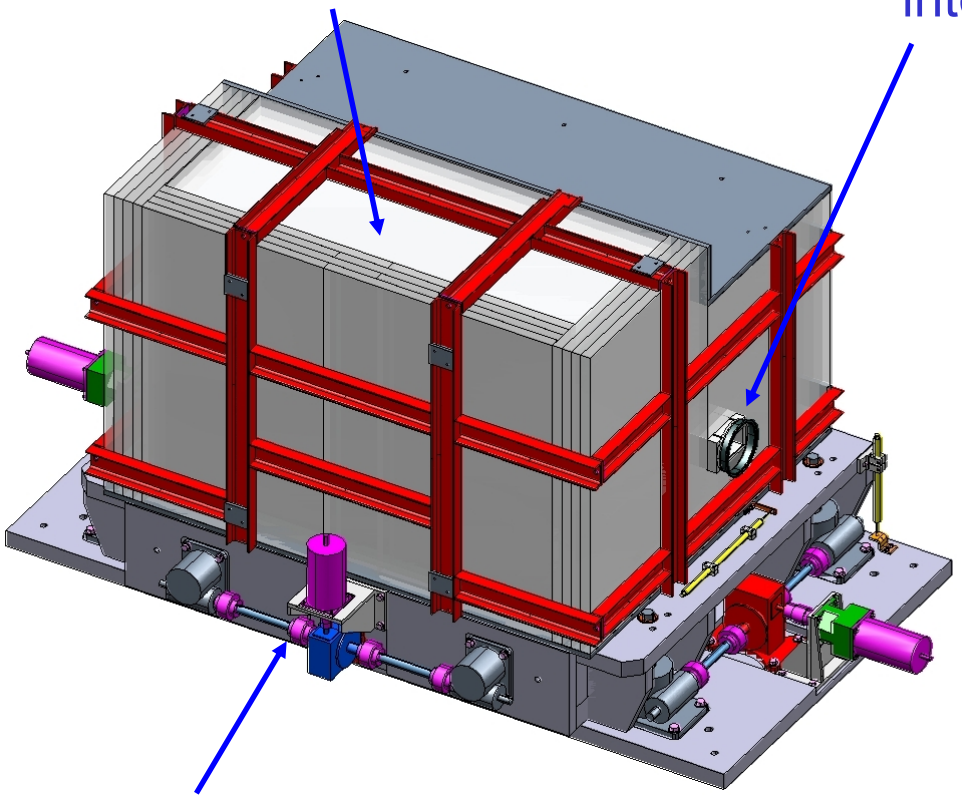


with collimation

Collimator Design and Installation

Marble cladding to reduce residual surface activation

"Booster style" fixed aperture with integrated shielding



Horizontal and vertical motion

Installation will require re-routing of water and power.

Main Injector RF Upgrade

- Upgrade the Anode Power Supplies transformers in order to address power dissipation and reliability issues.
  - Replace center transformer with on-site spare similar to North
  - Procure 2 additional rectifier transformers

- Upgrade the DC supplies from the solid state drivers to the 15KW version

- Develop double peaked comb filter with one turn delay in order to further stabilize the coupled bunch modes.

After the 2007 Shutdown

- After the 2007 shutdown, the remaining Proton Plan Projects will he
  - Second half of the Booster correctors
    - In the 24 short straight sections.
  - Upgraded gamma-t jump system in Booster
    - Capable of running at required repetition rate
    - Must be installed along with correctors
  - Booster chopper notcher
    - Reduce losses when creating extraction gap
- These are all currently scheduled for the 2008 shutdown
- We allow a year after this to achieve the ultimate benefits
  - Proton plan will officially end in mid to late 2009
- It is likely that the plan will absorb some scope to enable full 15 Hz operation.
  - Refurbish RF anode supply
  - Retrofit half the RF bias supplies
  - Recommission RF cavity tuner cooling
  - Not necessary for NuMI

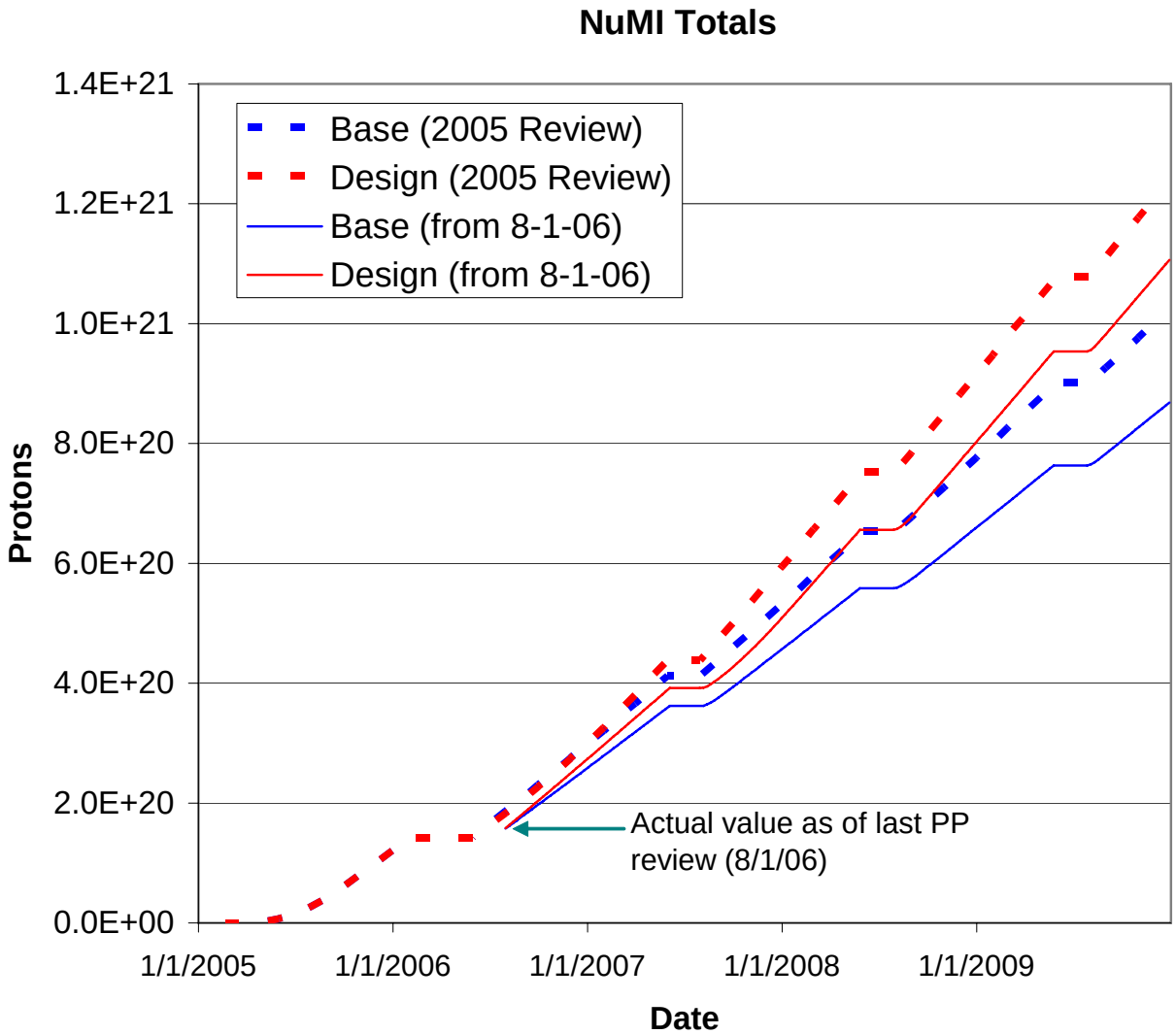
Proton Plan Projections

- Proton Plan represents the first ever attempt to accurately predict total proton output from Booster.
- Determining Booster output capacity is challenging. Our procedure is to:
  - Evaluate the potential of particular improvements based on effective aperture increase or uncontrolled beam loss reduction:
    - For example, if something reduces uncontrolled loss by 10%, it has the potential to allow us to send 10% more beam.
  - Consider the following scenarios:
    - "Design": After *one year* of tuning, we realize *half* of the potential benefit.
    - "Fallback": After *one year* of tuning, we realize *one quarter* of the potential benefit.

Factors Considered in Projections

- Linear ramp-up to see benefit of improvements
- Slip stacking efficiency
- Different Booster efficiency for cogged (pBar+NuMI) cycles and uncogged (BNB) cycles.
  - Added in for 2006 review
- Annual shutdowns (assume 2 mo/yr)
  - Overall asymptotic ramp-up after shutdown (improved for FY06)
- Uptimes: based on MiniBooNE 2004 and NuMI 2005
  - Modified for 2006
- Peak to average corrections
  - Accounts for non-optimal running

Long Term Projections

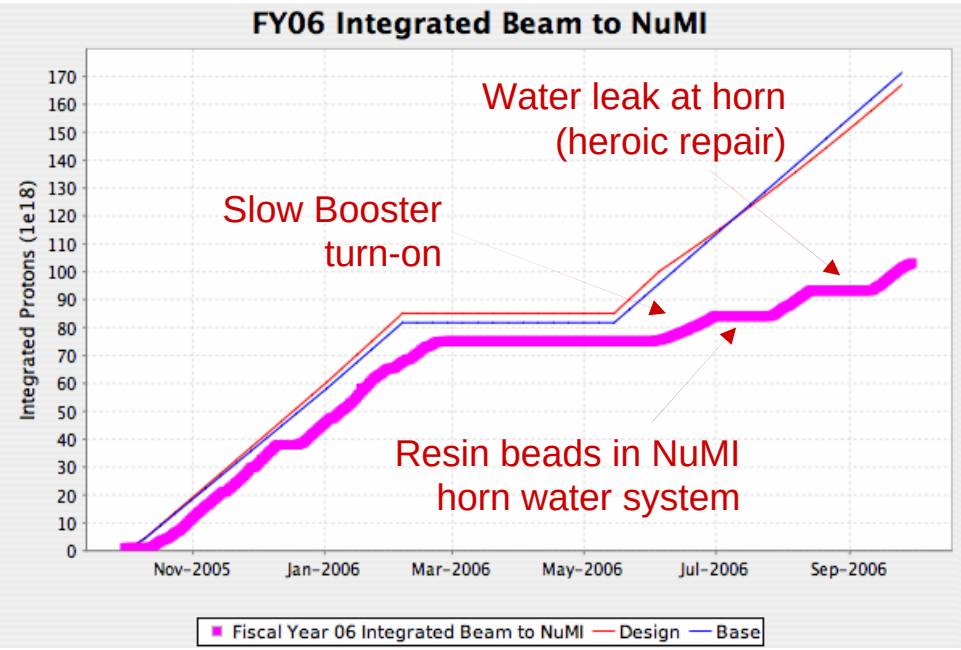


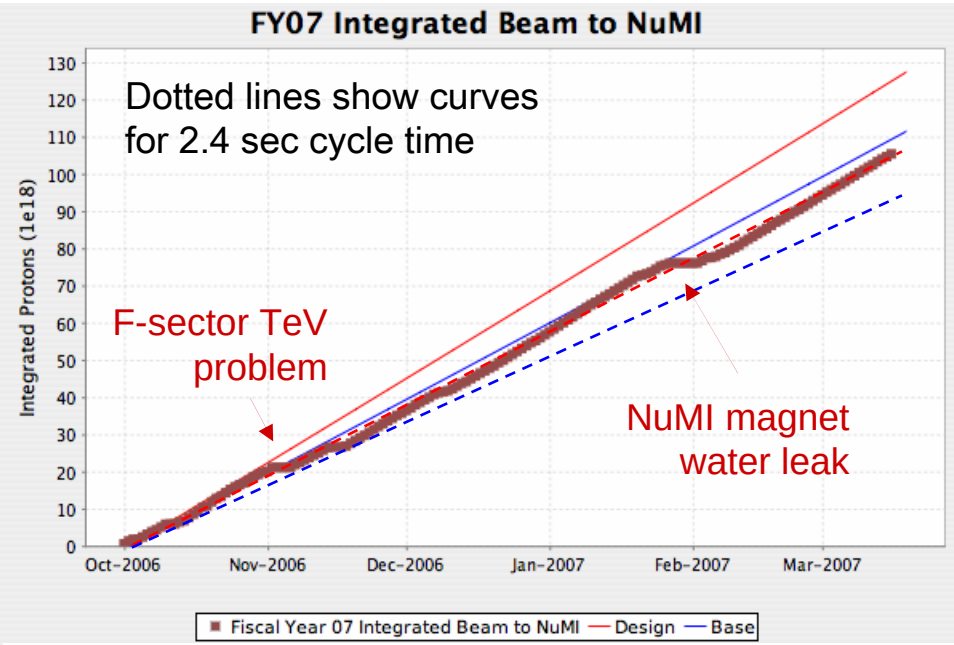
- The 2006 revision was the basis for the FY07 projections

NuMI Cycle Time Issues

- Because pBar and NuMI batches are accelerated together, the NuMI cycle time is locked to the pBar production cycle time.
- Original assumption:
  - NuMI and pBar would run at 2 second cycle times during 2+5 operation (limited by minimum pBar rep. rate)
  - Cycle time would change to 2.2 seconds for 2+9 operation (limited by MI loading time)
- In fact:
  - pBar has problems running below 2.4 seconds, significantly reducing beam to NuMI
  - The effect was originally largely cancelled by NuMI only cycles (during shot setup and "interleaved" mode when the accumulator had large stacks)
  - Now with fast transfers to Recycler, there are very limited NuMI-only cycles
- Present status:
  - Working to optimize pBar for 2.2 cycle time
  - Will lock complex to that time through end of collider program
  - Not yet accounted for in this year's projections

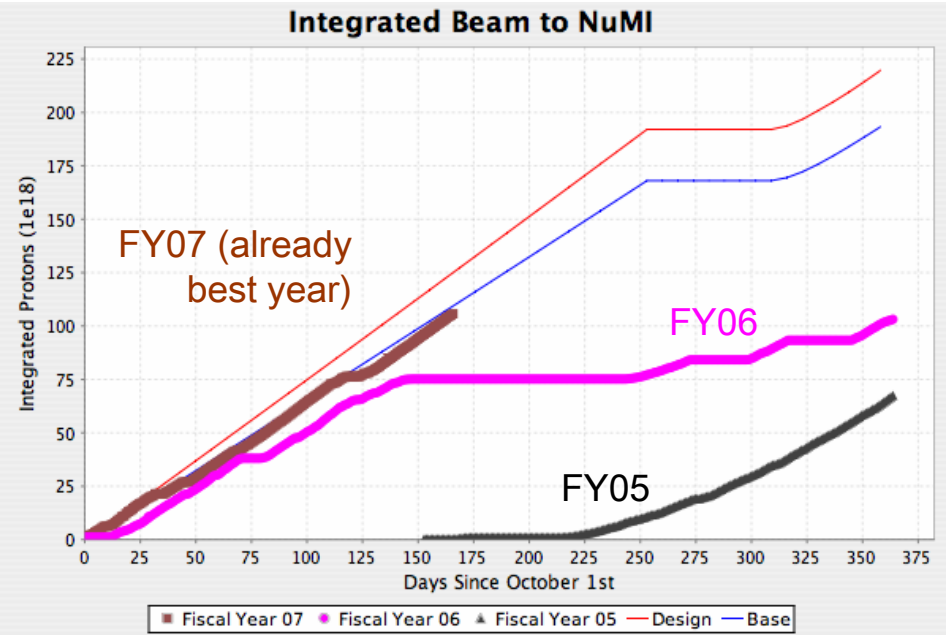
NuMI Beam Delivery (since last ops review)

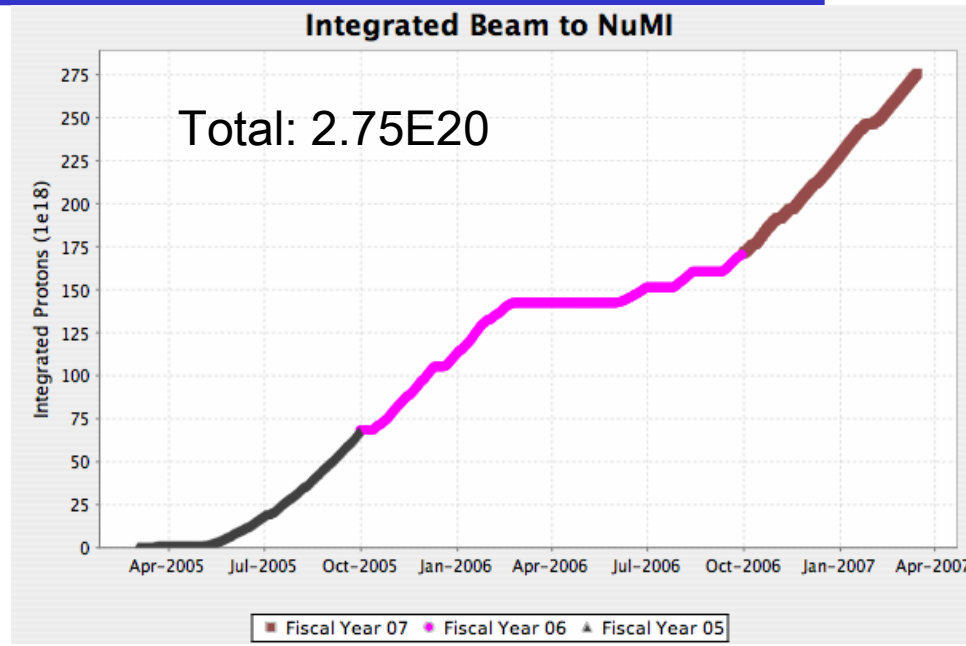




- In spite of the unrealistic timeline assumptions, we are currently delivering beam at roughly the advertised design rate.
- This is due primarily to increased up time and high intensity NuMI only cycles, when possible.

Total NuMI Beam

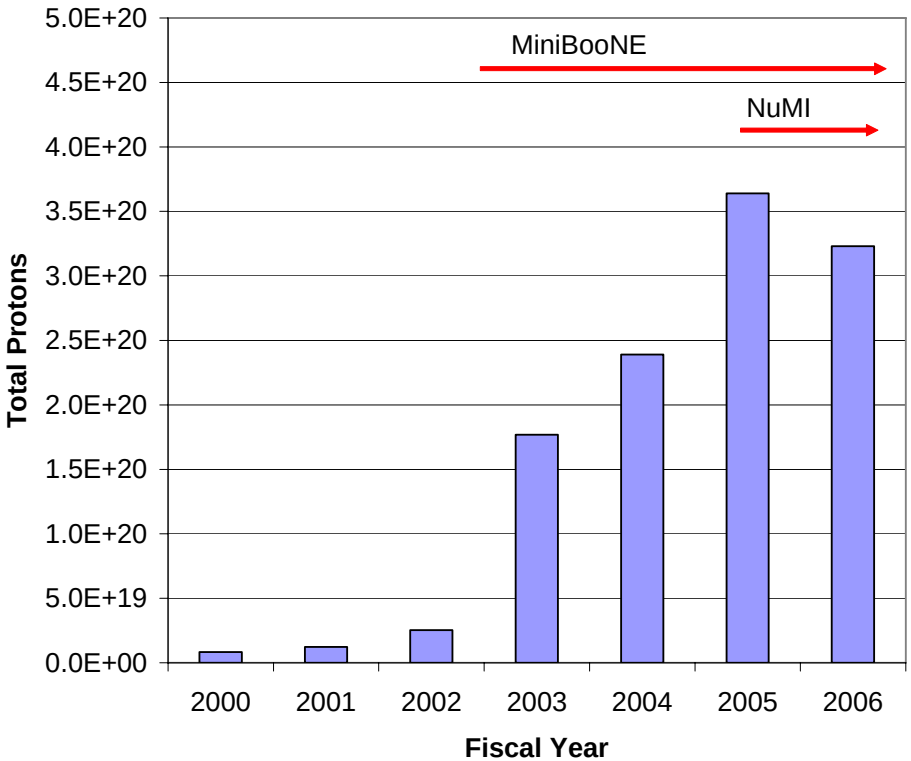




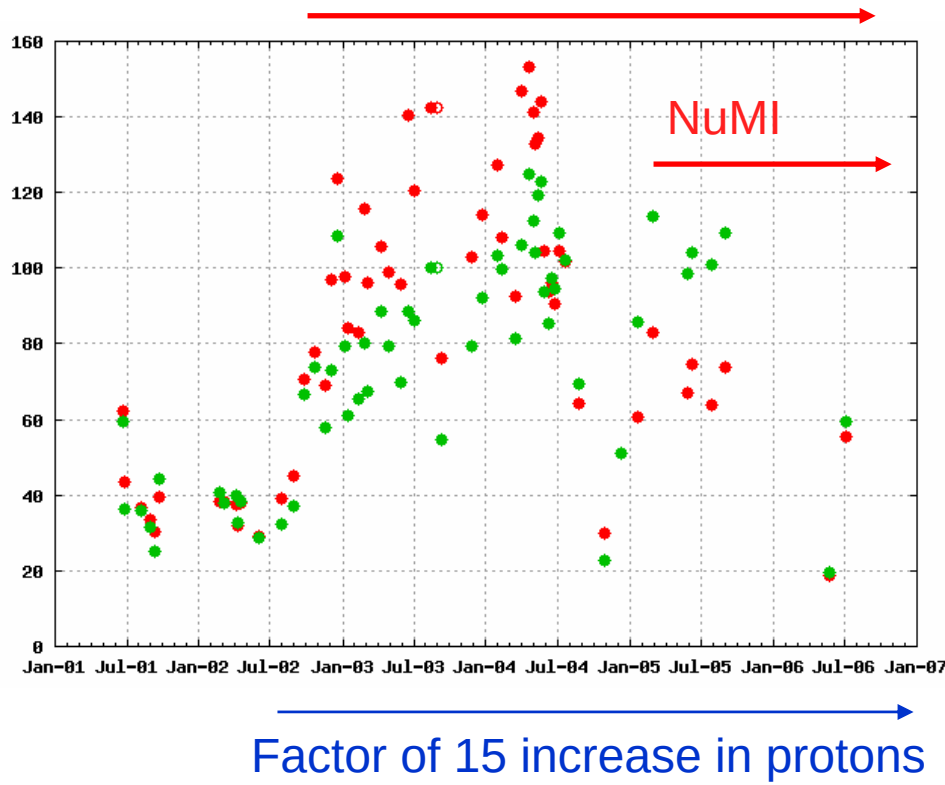
- Not yet corrected for actual shutdown date, which will certainly be a bit later
- Expect at least 2E20 for the fiscal year, bringing the total close to 4E20.

Success of Plan

Total Protons Delivered



Average Booster Activation



Factor of 15 increase in protons

Conclusions

- The Proton Plan has enabled us to manage a large number of diverse activities necessary to deliver the unprecedented proton intensities required by the neutrino program.
- The major projects in the Booster and Main Injector that were under way at the time of the last Operations Review have been commissioned and have allowed us to reach record proton intensities.
- We are in good shape for implementing the remaining Proton Plan improvements on schedule.
- We have done a good job of estimating the proton delivery to the experimental program.