Current and Planned High Proton Flux Operations at the FNAL Booster

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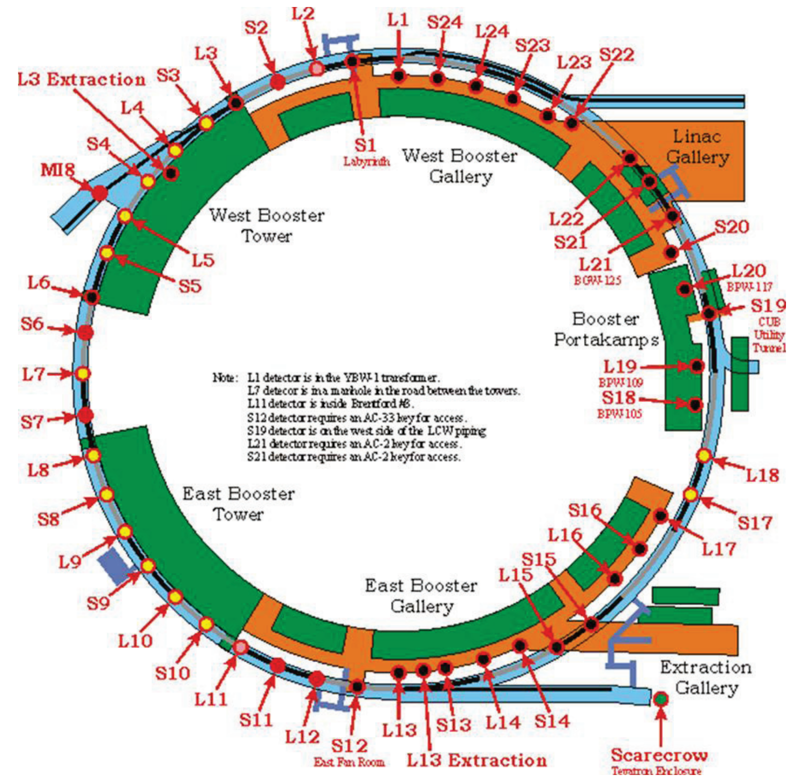
Outline

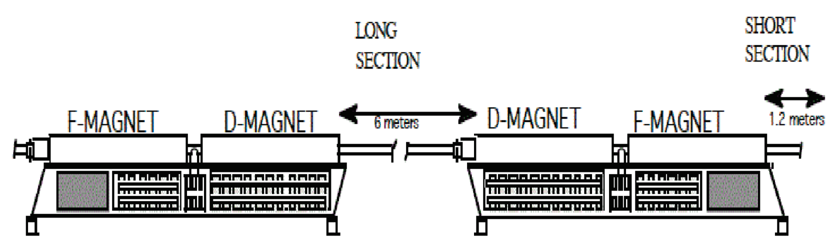
- Overview of Booster performance over the past decade
- Got protons? More, more and more protons…
  - Proton Improvement Plan
    - improvements on
      - beam loss control
      - collimation
      - shielding
- Summary

Introduction to FNAL Booster Synchrotron

- H$^-$ ions are stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 msec
- Fast cycling synchrotron
  - Fast magnet ramping
  - Frequency of 15 Hz
- Single turn extraction

Booster	
Circumference (m)	474
Harmonic Number	84
Kinetic Energy (GeV)	0.4 - 8
Momentum (GeV/c)	0.954 - 8.9
Revolution period (μsec)	$\tau_{(inj)}$ 2.77 – $\tau_{(ext)}$ 1.57
Frequency (MHz)	37.9 - 52.8
Batch size (ppp)	4.5 E12
Focusing period	FDooDFo
Nº focussing periods	24





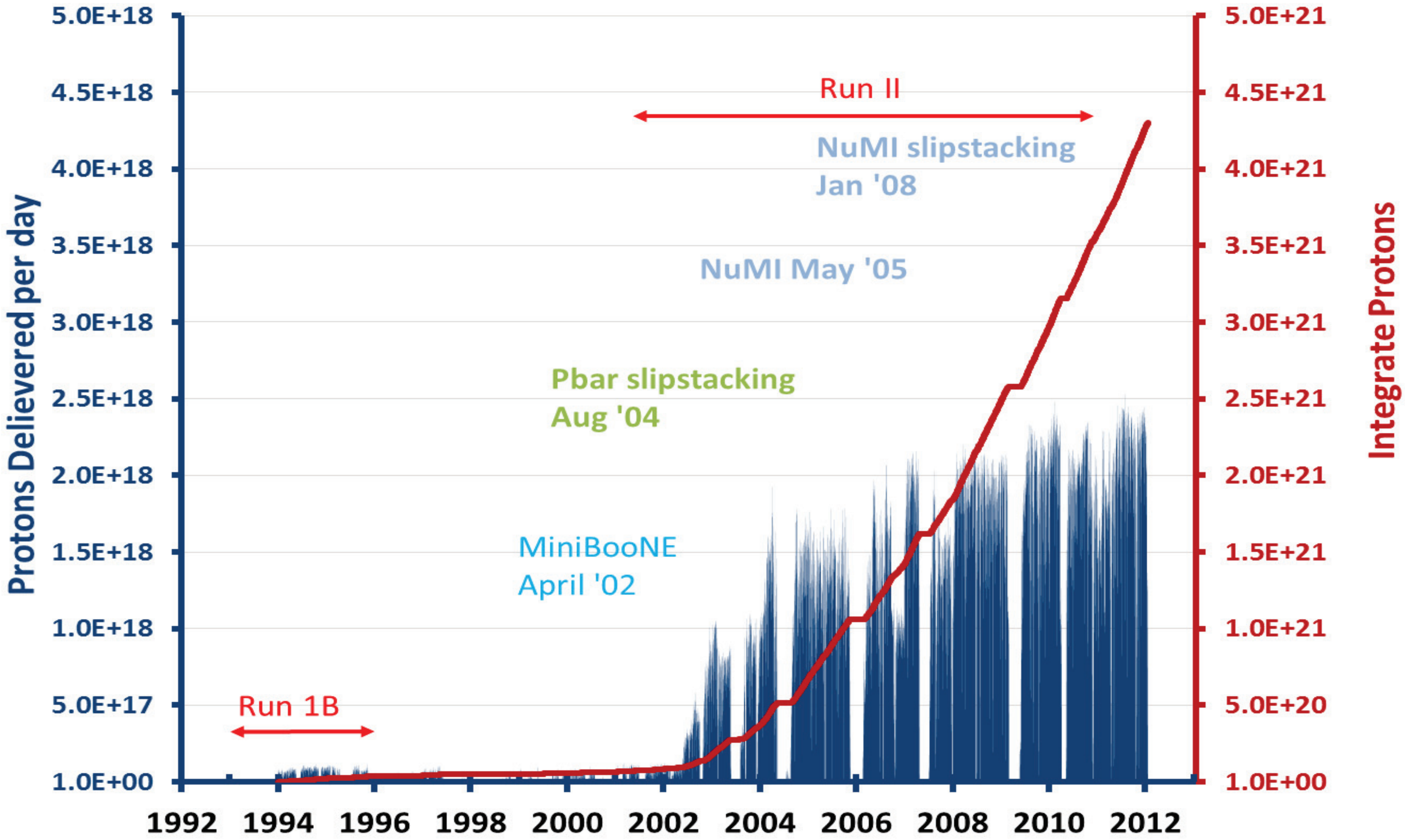
Proton Throughput

- Neutrino program demands lots of protons delivery to target
  - prompted by MiniBooNE and NuMI experiments
  - Booster accelerator performance improved tremendously for the past decade to meet the laboratory programmatic goals

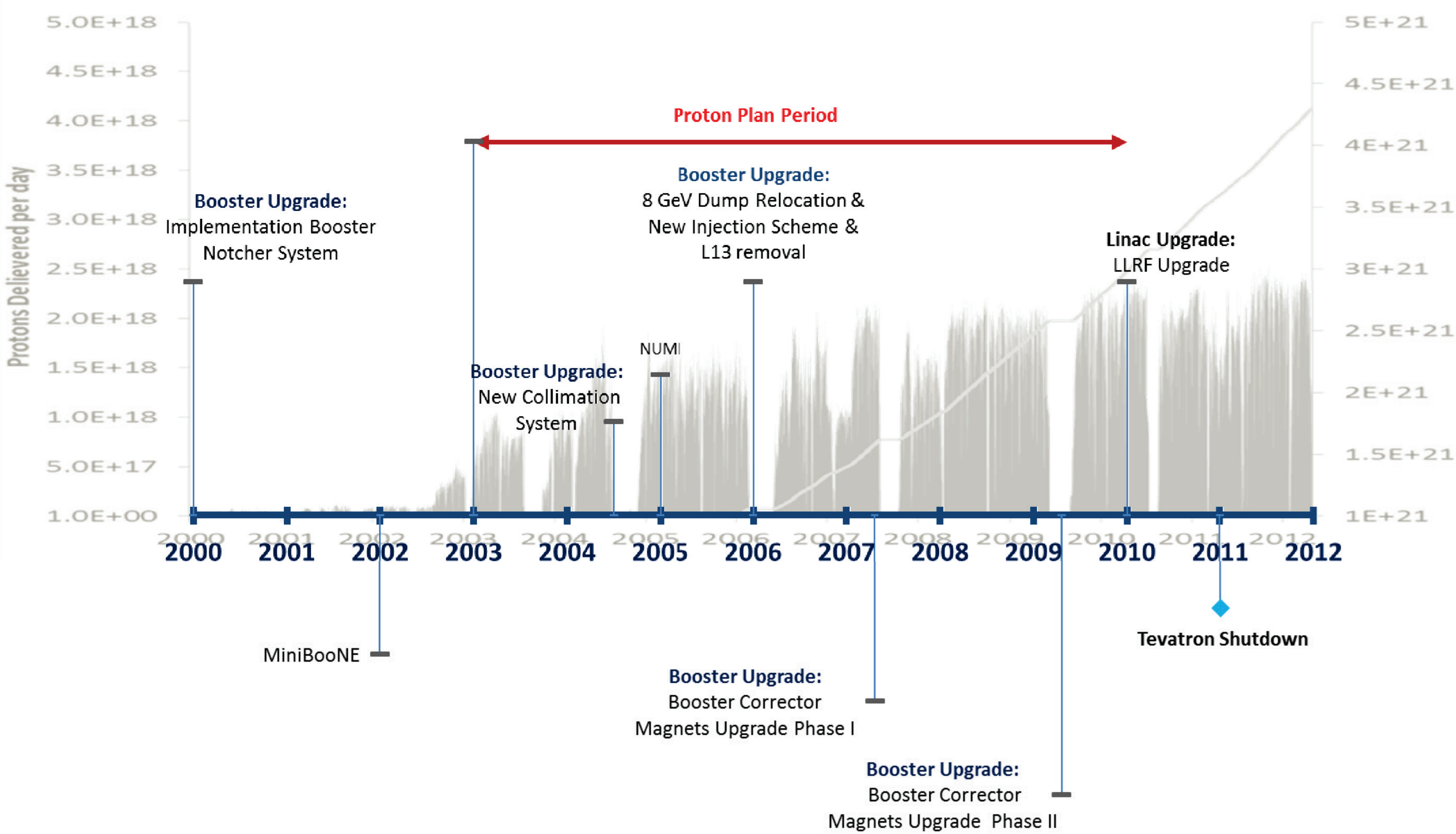
- The future laboratory experiments that are either under construction or in DOE CD-process demands another factor of 2 for the next several years
  - doubling the proton flux by increasing the number of cycles with beam
    - 8 GeV @ ~ 10 kW for Booster Neutrino Beam (BNB) experiments
    - 8 GeV @ ~ 50 kW for 120 GeV Neutrinos at Main Injector (NuMI) experiments
    - 8 GeV @ ~ 20 kW for Muon production (Muon Campus experiments)

- Continue increase demands on the Proton Source threaten reliable operation due to rely on components that are either no longer commercially available or are at risk of being discontinued

Historical beam throughput in Booster

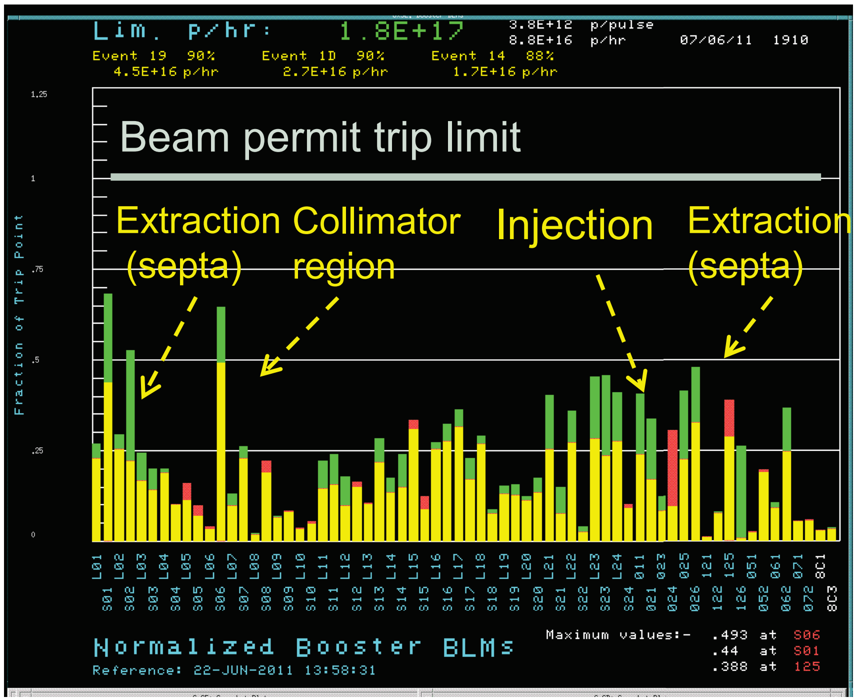


FNAL Proton Source
2000 – 2012 Timeline



Standard Booster Loss Profile

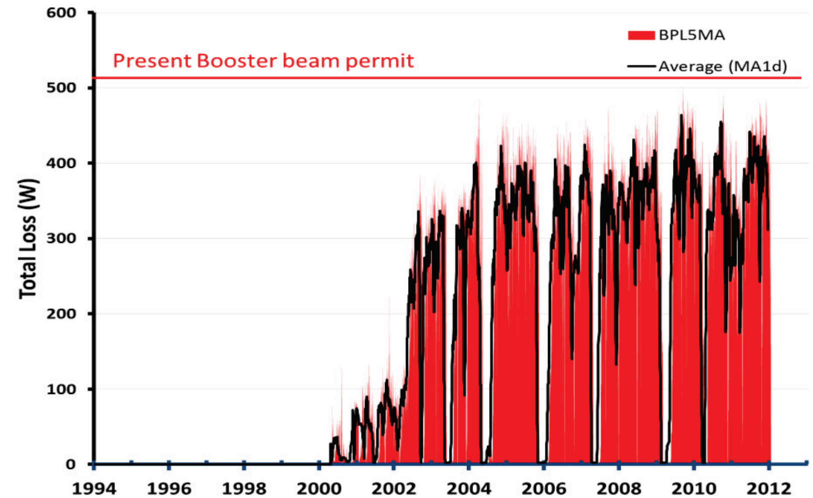
Normalized beam losses

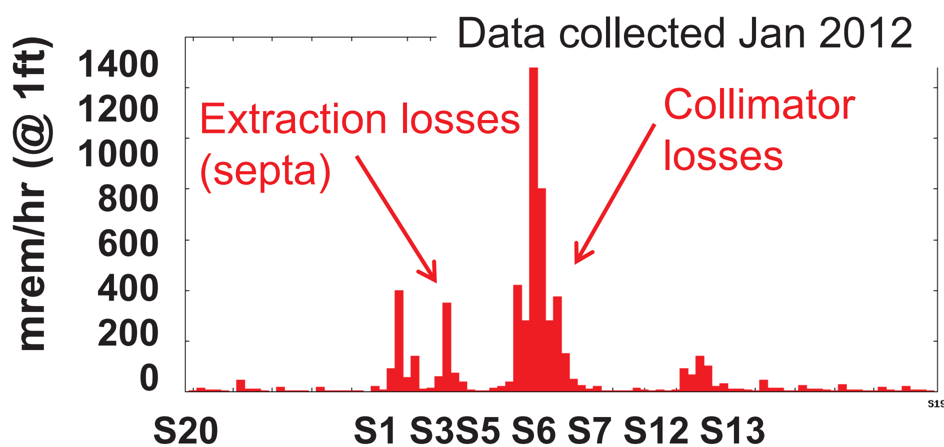


Data show beam losses for three beam cycles

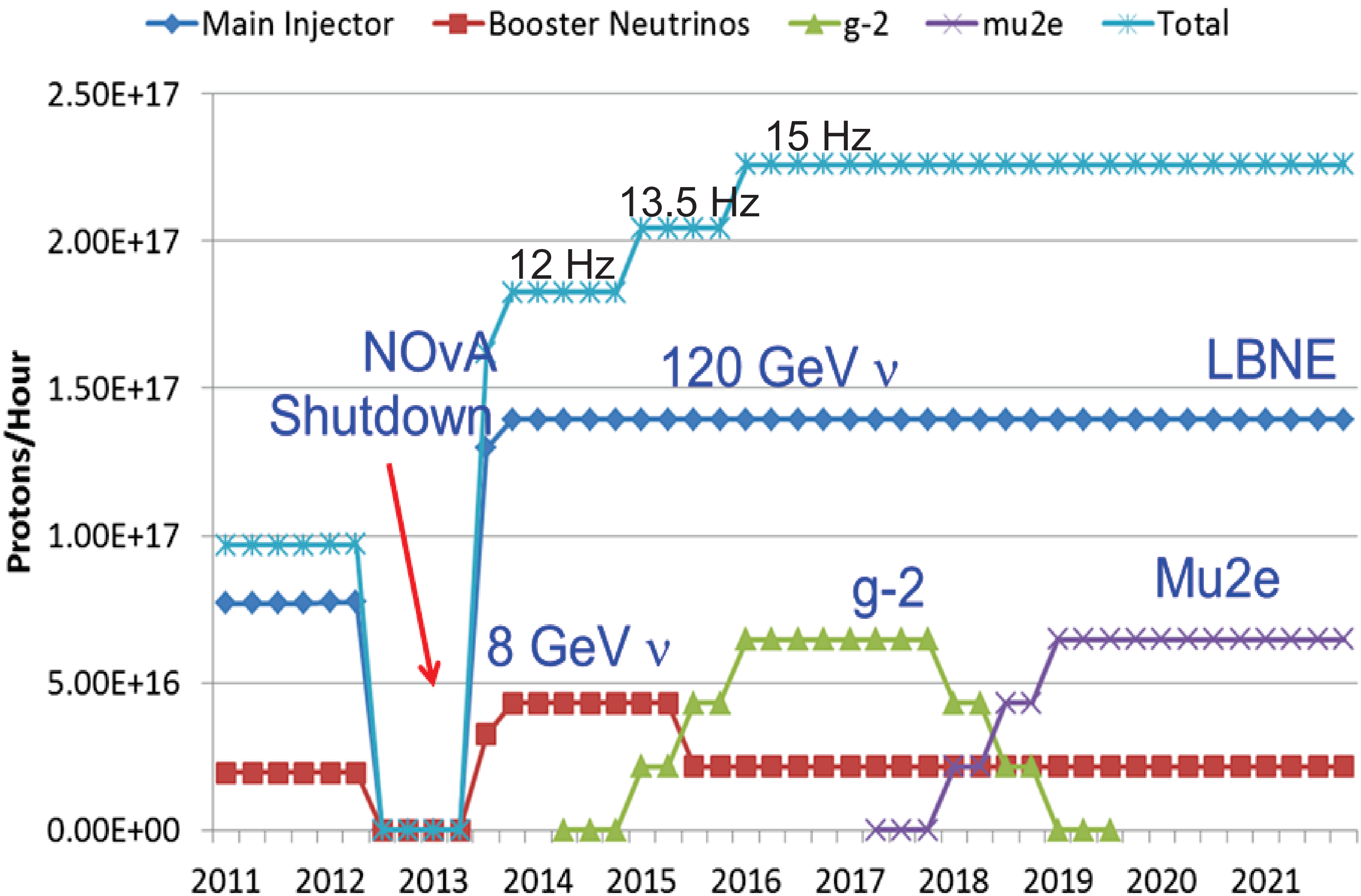
Pbar production	4.5E12 ppp
MiniBooNE	4.5E12 ppp
NUMI	4.1E12 ppp

Power loss & radiation survey

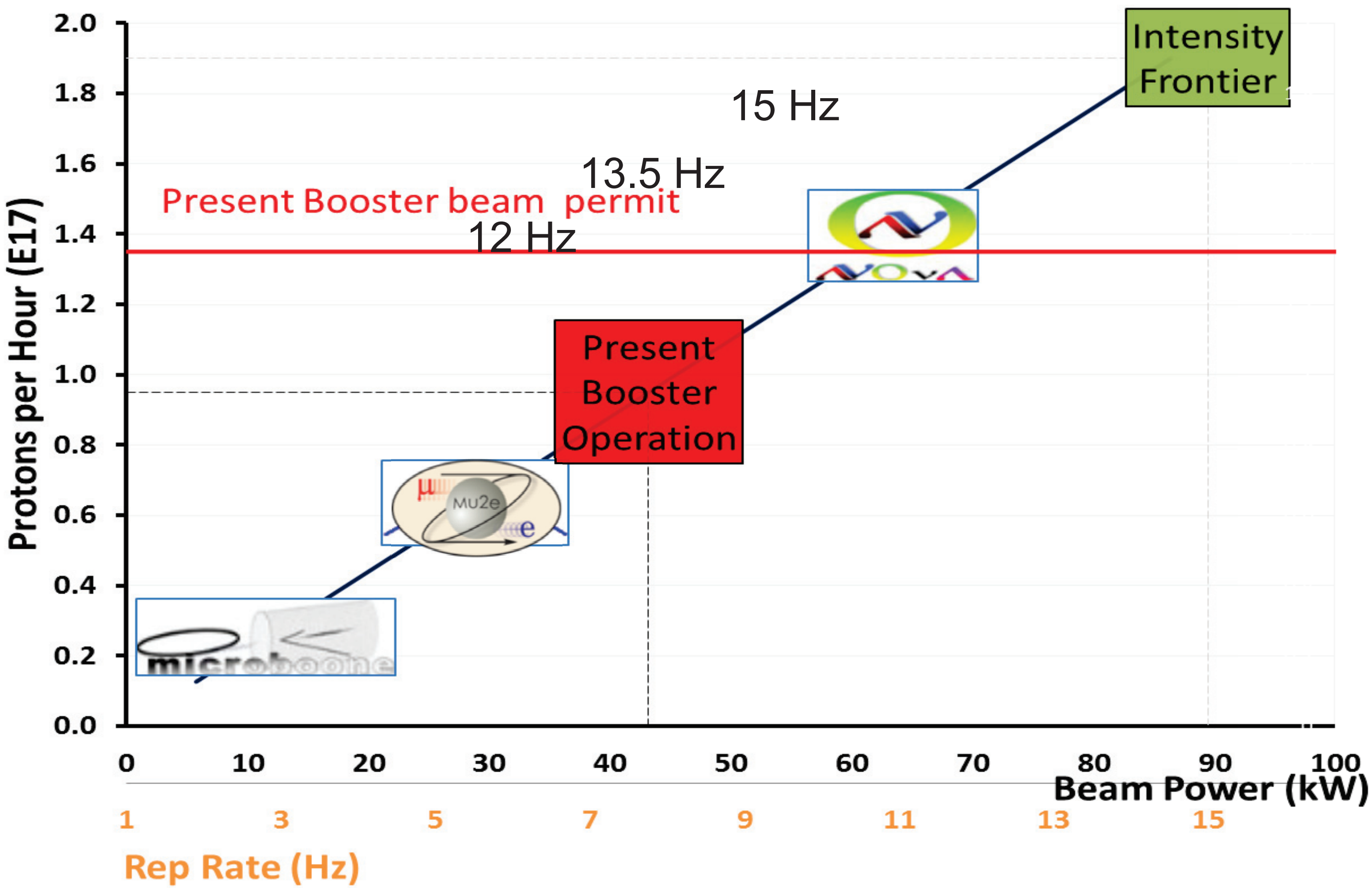




Booster in the Intensity Frontier Era



Booster in the Intensity Frontier Era



Proton Improvement Plan - PIP

FNAL Accelerator Associate Director set the direction in Dec'10:

*The **Proton Improvement Plan** should enable Linac/Booster operation capable of*

- *deliver 2.2E17 protons per hour (at 15 Hz) in 2016*

while maintaining

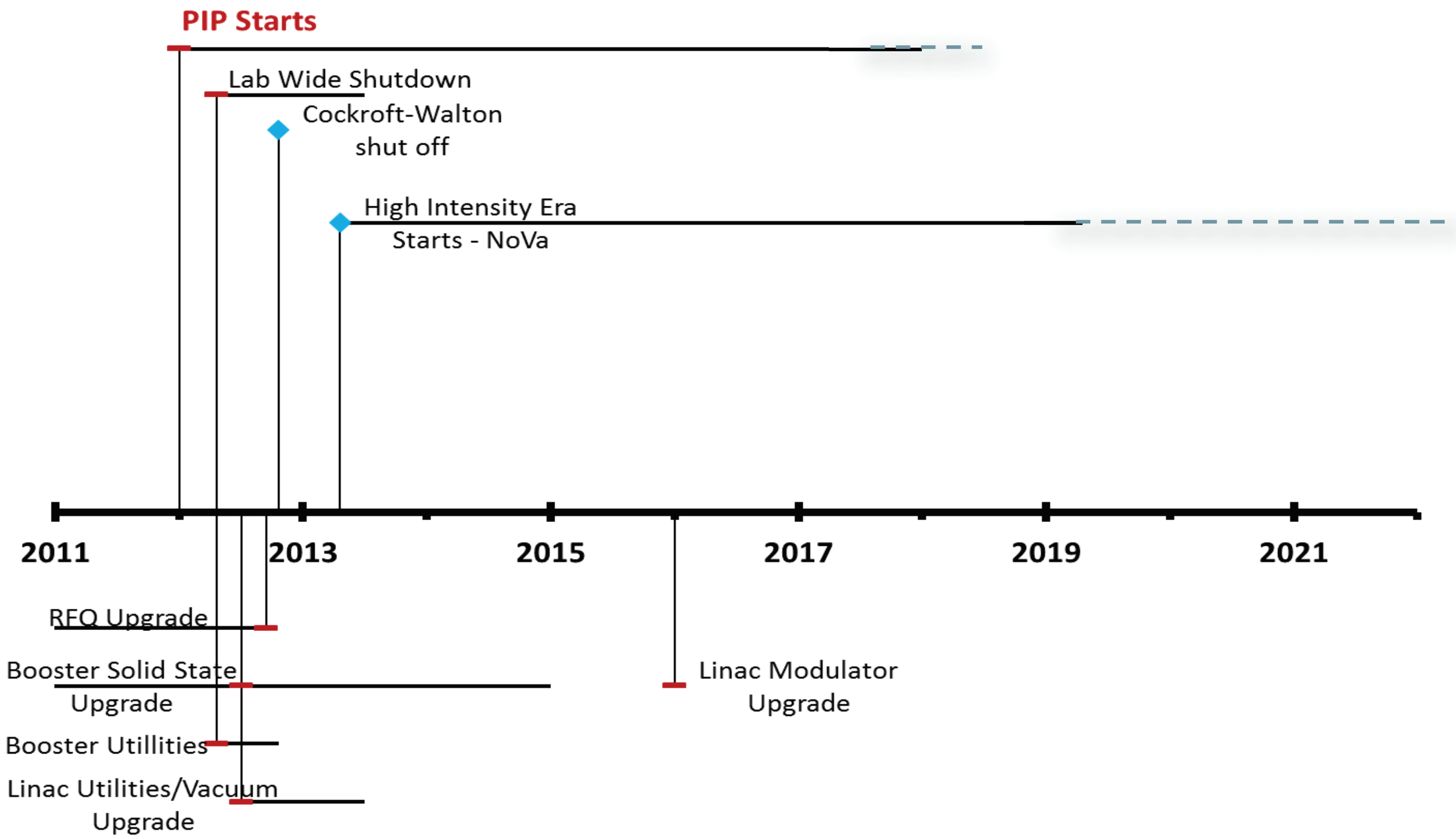
- *Linac/Booster availability > 85%, and*
- *residual activation at acceptable levels*

and also ensuring a useful operating life of the proton source through 2025.

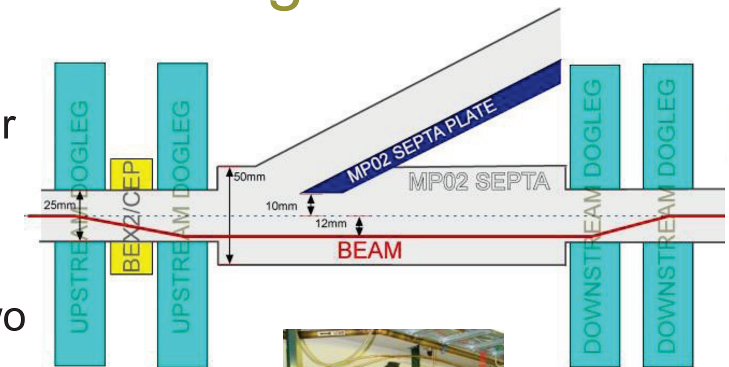
S. Henderson

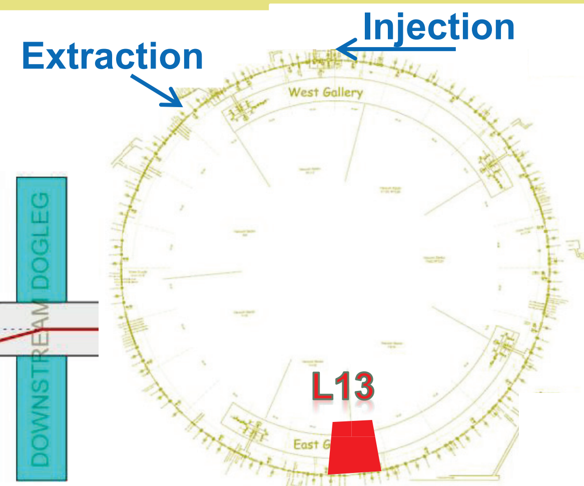
- The scope of the ***PIP*** includes
  - increase Booster repetition rate by upgrading (or replacing) components
  - replacing components that have poor reliability
  - studying beam dynamics to diagnose performance limitations

FNAL Proton Source
Looking into the Future
2013 and beyond

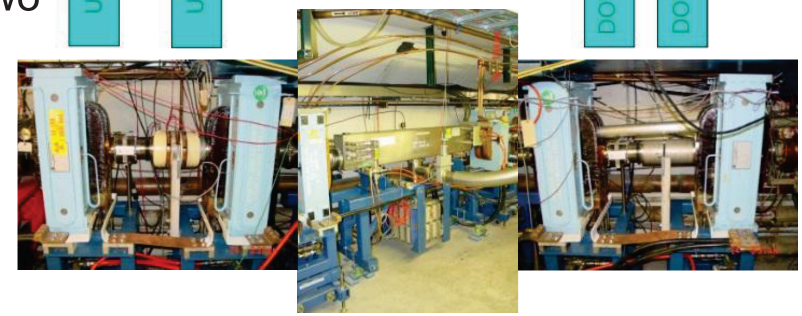


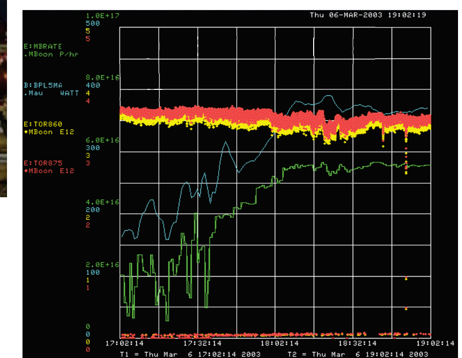
Aperture Improvement : Removal of L13 Extraction Region



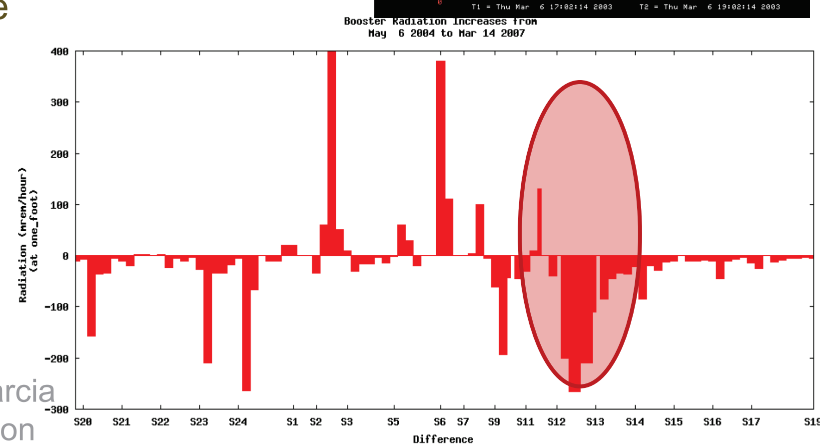


- Beam is extracted from Booster in a dogleg configuration
  - DC vertical dipoles work with 3-bump (BEXBUMP)
- In the old days, Booster had two extraction regions
  - L13: old extraction region to Main Ring
  - L3: present extraction region to Main Injector (MI)





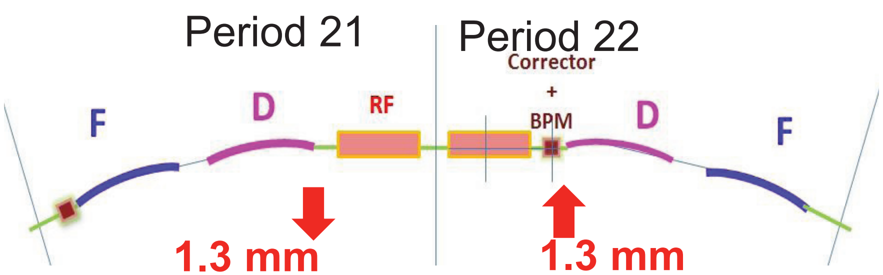
- L13 septa remained in place for operation with MI
  - septa obstructed top part of the aperture
  - vertical acceptance at 400MeV was ½ of otherwise available
  - increased complexity on tuning to extract at L3
  - increased downtime due to components failure with the increase in radiation
- Overall gains
  - beam throughput in the range of 15-18%
  - reduce an important localized high loss

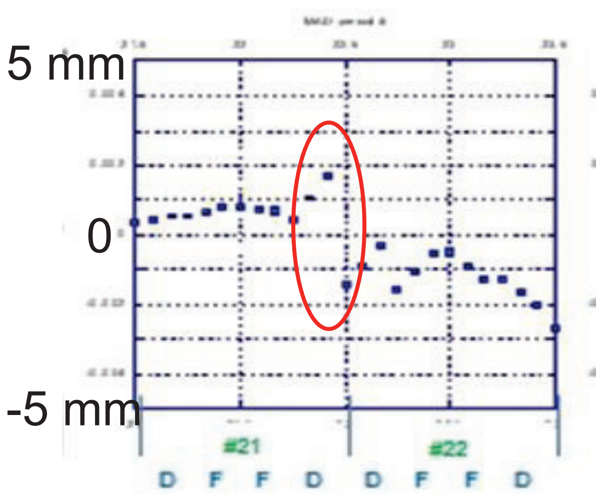


Booster Orbit Control Improvements
Magnet Move

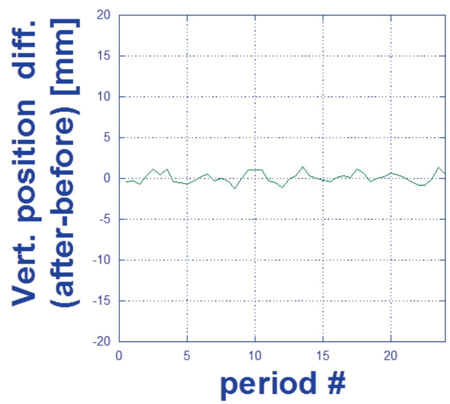
Contribution by K. Seiya

- Improve acceptance with goal of reducing beam loss
- Two magnets were realigned prior to 2012 shutdown as a bench test to verify procedure



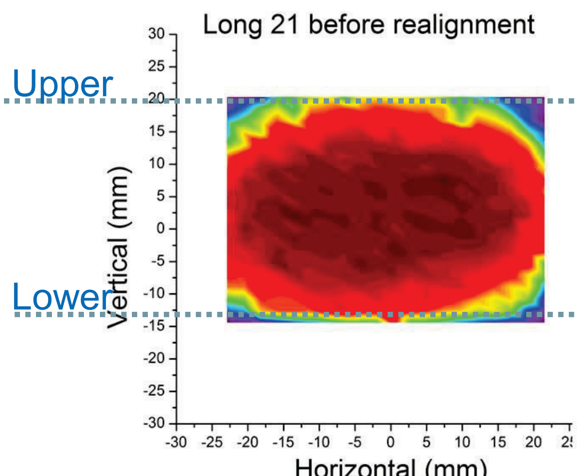


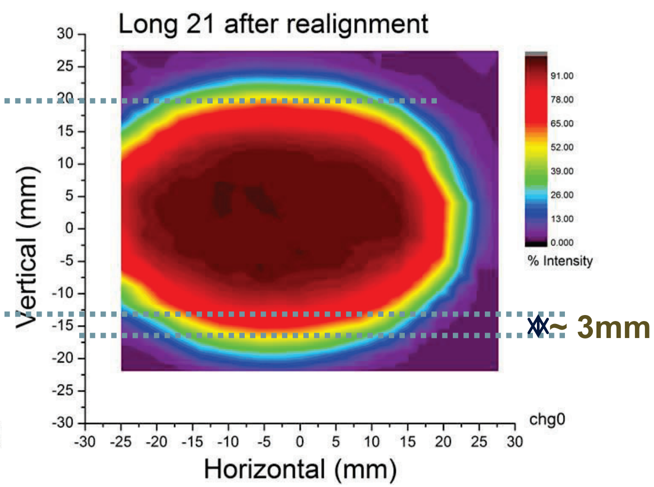
After alignment…



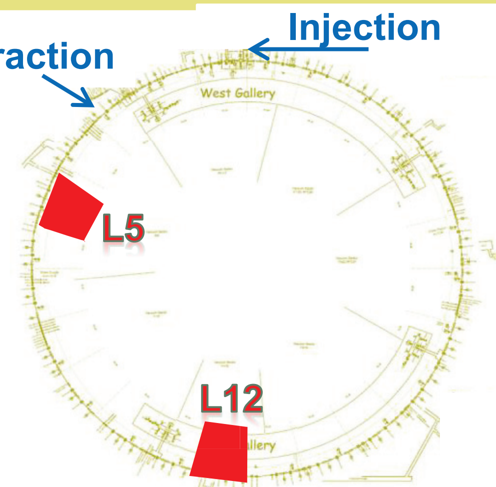
Difference of the measured orbit between before and after magnet move is ~ +/- 2 mm.

Measured aperture before (left) and after (right) the magnet realignment.

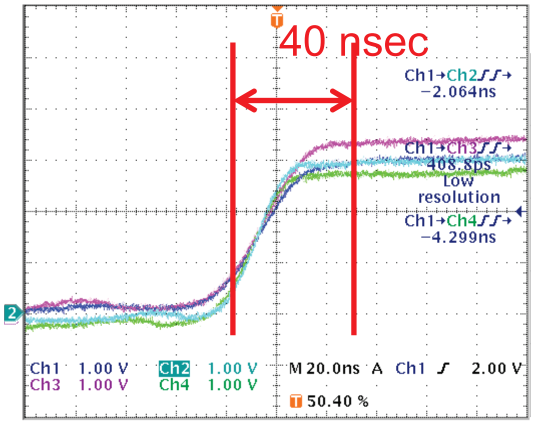




Present Booster Notch System

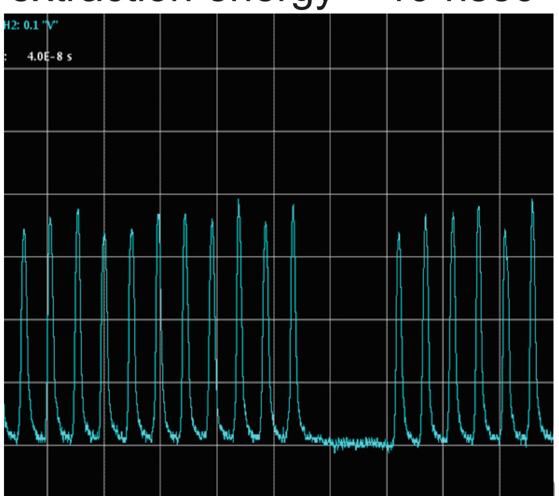


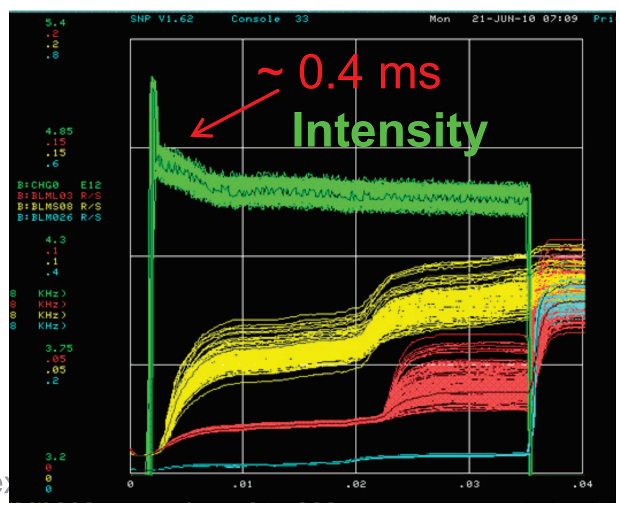
Extraction kicker has rise time of ~ 40 nsec

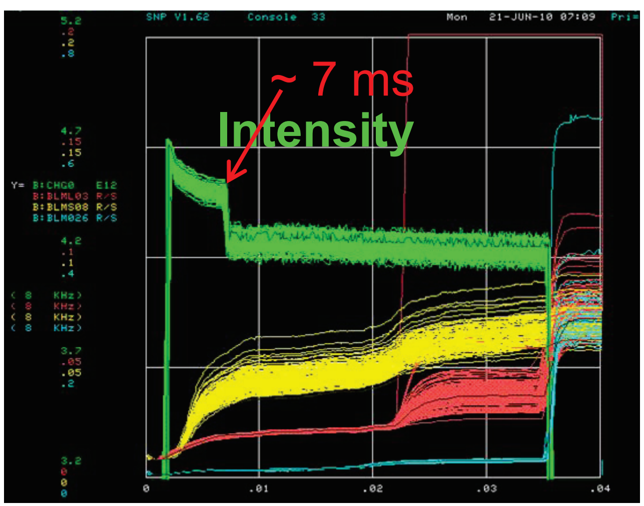


- Beam lost during extraction
  - 3 batches ~ 200 J
- Notch is created by kicking the beam vertically at L5 @ 2 different cycle times
  - 400 MeV (~0.4 ms) (un-cog events)
    Reduce losses down to 5%
  - 700 MeV (~7 ms) (cog events)
    Reduce losses down to 9%
- About 87% of beam is removed from the bucket
  - most of particles are intercepted by magnet pole tips. Major concern!
  - remaining beam is "nocked" at L12 into L13 absorbers
- Booster has never lost a magnet, but radiation is noticeable

Bucket spacing at extraction energy ~ 19 nsec

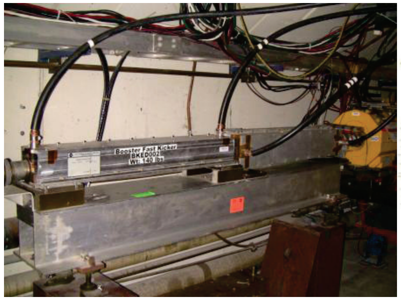


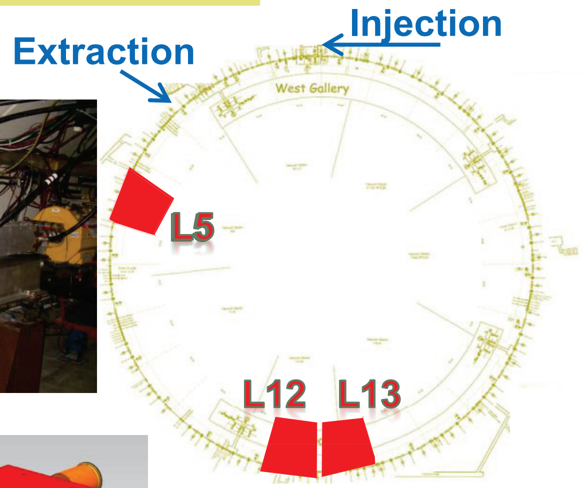


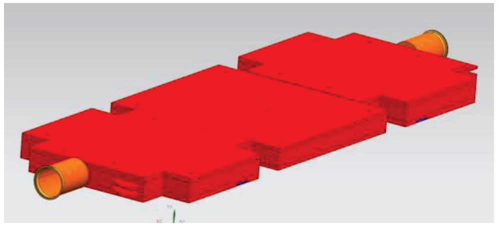


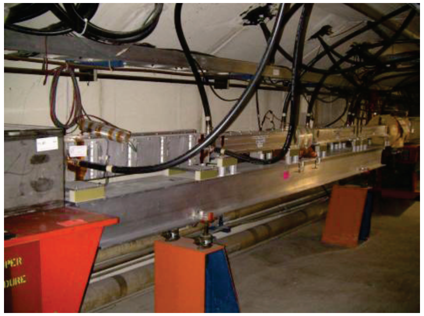
Future Booster L13 Notching & Absorber

- PHASE I: Notcher Relocation
  - Abort gap is created using 3 long kickers located at Long 12
  - Beam is kicked **horizontally** into new absorber at Long 13
    - Notching efficiency increased by ~ 10%
  - Notching cycle time will remain unchanged
- Beam will be deposited at a new absorber

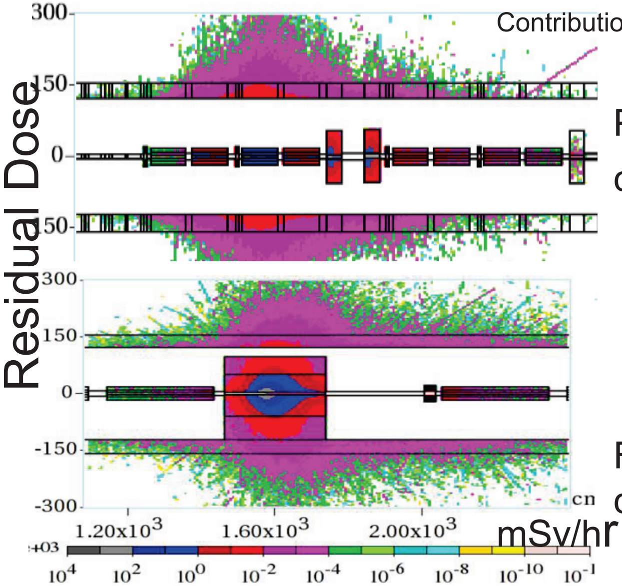








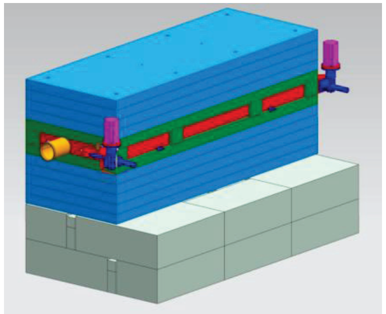
Contribution by I. Tropin



Present configuration

Future configuration

- Absorber elements
  - stainless steel vacuum liner
  - steel absorber blocks
  - concrete blocks
  - not shown
    - polyethylene masks
    - marble to further shield the personnel corridor aisle
- Radiation concerns
  - ALARA for personnel
  - sump water
  - beam-on radiation in the gallery

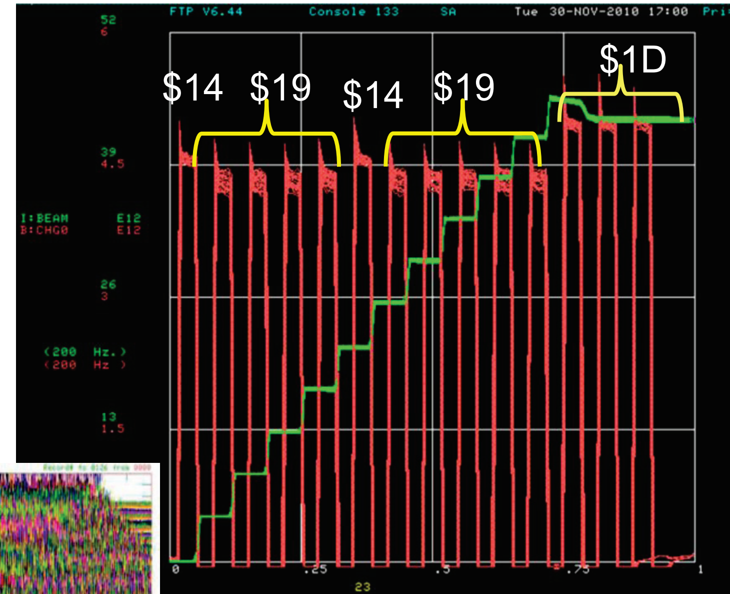


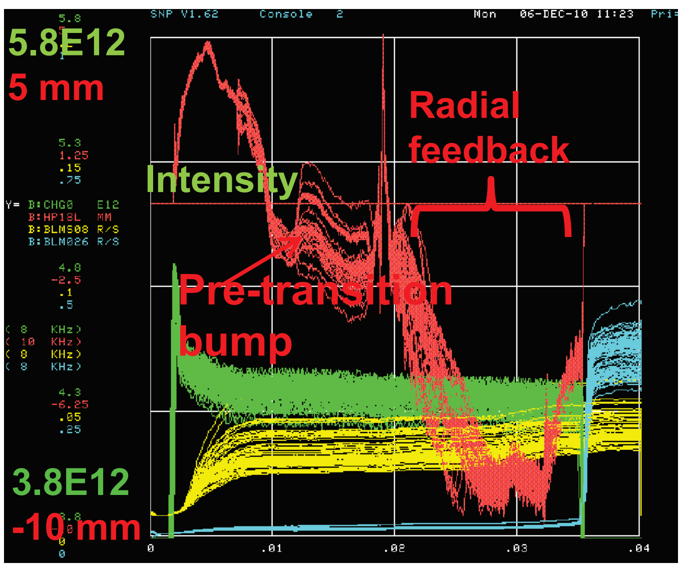
Courtesy: V. Sidorov

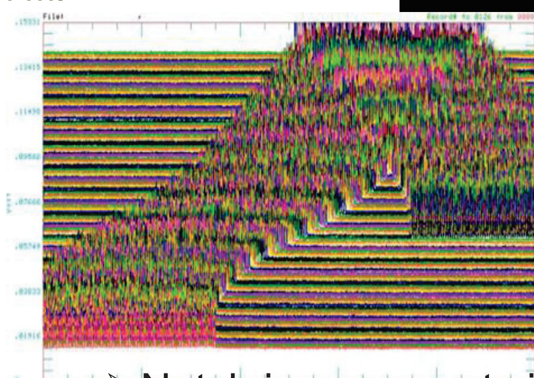
Present Booster Cogging System

- Booster beam has a notch
- Extraction is timed to coincide with the notch
  - synchronized to the beam already in the Main Injector
- Synchronization obtained by manipulating the radial position
  - change beam's velocity and beam path
- Required for multiple batch operation in MI
  - pbar production for Run II and NuMI
  - essential for slip-stacking operation in MI

Multi-batch “2+9” Operation Scheme



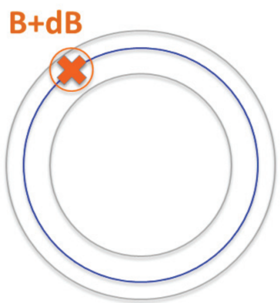




- Notch in cog events is delayed ~ 7 ms after injection
  - induce higher regular losses (20 J/notch @ 700 MeV)
  - major concern going to higher repetition rates
- Typical horizontal position vary +/- 6 mm
  - RF frequency cogging complicates the setup of beam collimation scheme due to radial orbit changing

Future Booster Cogging System

- Extract 12 pulses every 15Hz for the NOvA operation
- New Booster correctors allow for magnetic cogging
  - Dipoles are much stronger than previous corrector package



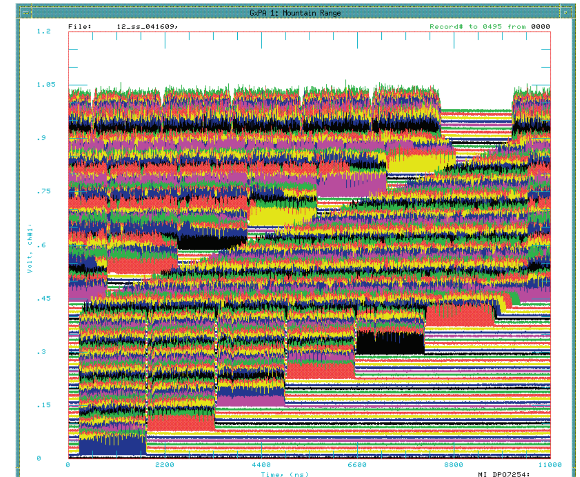
$$\frac{\Delta f_{rev}}{f_{rev}} = \frac{1}{\gamma^2}\frac{\Delta P}{P} - \frac{\Delta L}{L}$$

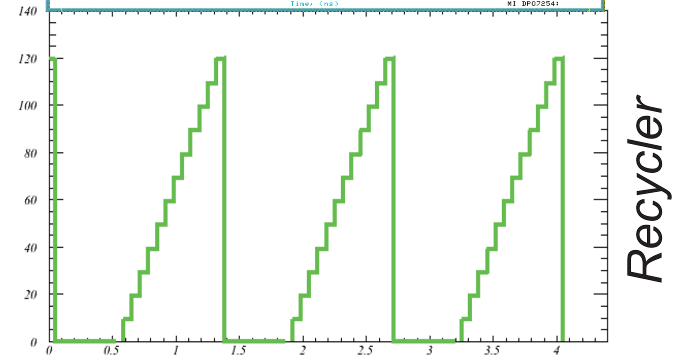
Fixed with RPOS feedback

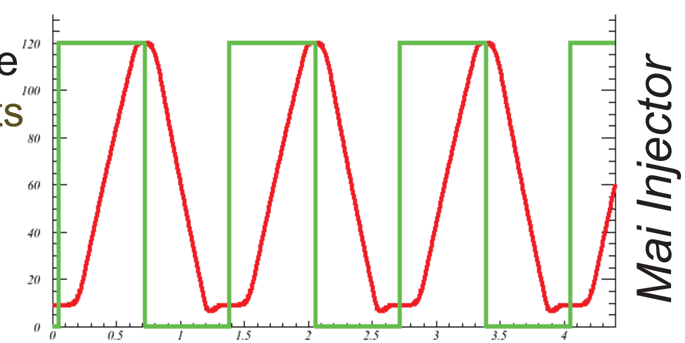
$$= \frac{1}{\gamma^2}\frac{\Delta B}{B}$$

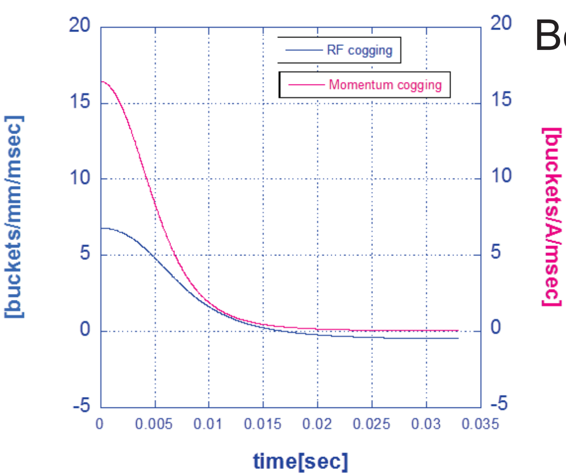
Changed by dipole corrector

Contribution: K. Seiya







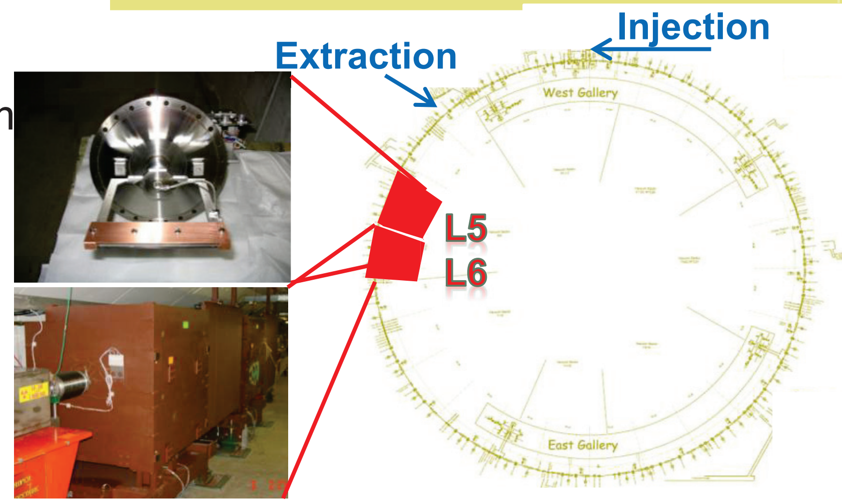


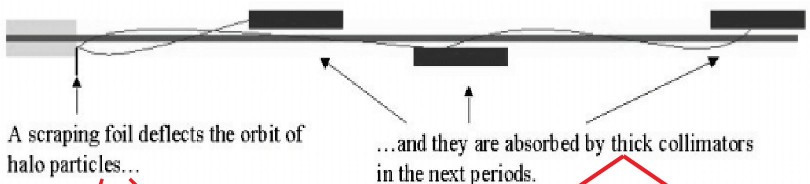
Benefits

- Keeps the orbit centered
  - saves aperture
- Stronger at the start of the cycle
  - allows notch in cogging events to happen earlier in the cycle
  - reduces beam power loss
  - makes notch outside Booster possible

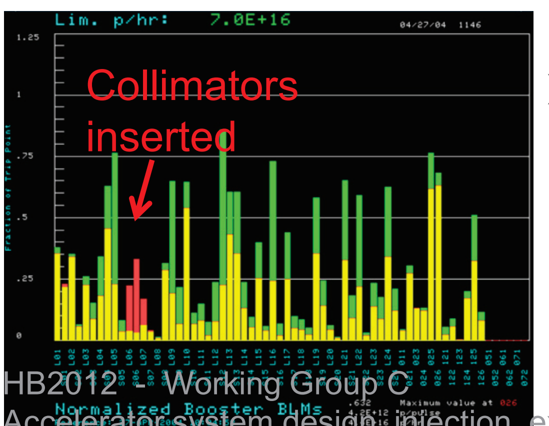
Present Booster Collimators

- Designed to be a 2-stage beam collimation system
  - enforce strict aperture in a location
  - high amplitude particles are intercepted by a thin primary foil
  - subsequently absorbed by thick stainless steel secondary collimators



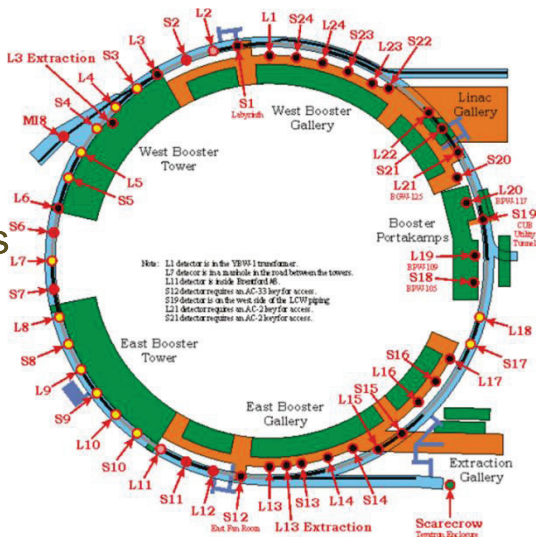


- Collimation system absorbed radiation from uncontrolled beam losses in a location that can be well shielded



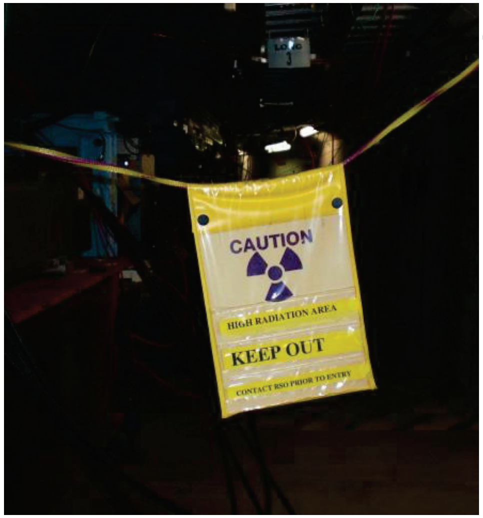
- Collimation system has not been operated as designed
  - the primary collimator is retracted
  - secondary collimator positions (H&V) are optimized to cope with radial orbit variation inherited in the RF cogging system

Present Booster Radiation Protection Scheme



Above ground radiation protection scheme

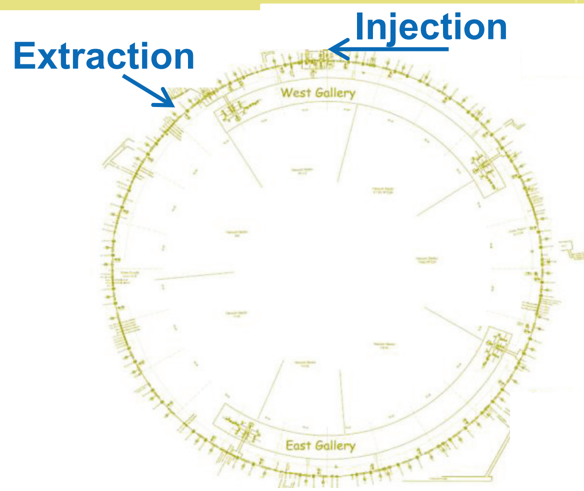
- Additional steel installed above the L3 extraction region
- Notch beam was established
- Concrete shelf installed inside both East and West Booster towers
- Collimation system absorbed radiation from uncontrolled beam losses in a location that can be well shielded
- Array of 50 interlock radiation detectors covered all loss points around the ring
    - trip set point based on the occupancy of the area it is protecting



Tunnel activation protection scheme

- Beam losses cause activation of accelerator components
    - potential to lead to equipment failure
    - long down times due to the need to restrict doses to personnel
- Operational efficiency demands that high maintenance components (e.g. RF cavities) have stricter limits
- Array of 60 beam loss monitors (BLMs) control losses locally
    - each BLM has a device which measures the total loss sum over the past 100 sec

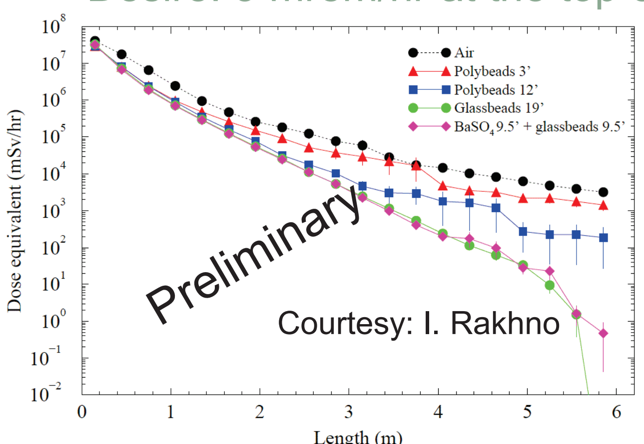
Future Booster Radiation Protection Scheme



Booster shielding was assessed in 1998

Accelerator Shielding Envelope	1.8E17 p/hr
Operational limit	1.22 E17 p/hr
Warning Limit	1.09 E17 p/hr

- The main concern is improving shielding in the 182 single-leg penetrations
  - currently filled with 12 feet of polyethylene beads
  - Desire: 5 mrem/hr at the top of penetrations



1 mSv/hr=100 mrem/hr

- The most penetrating radiation component is neutrons.
  - Detailed description of neutron interactions with matter was used in these simulations by means of MCNP mode in MARS code
- Work continues to identify the best solution

Summary

- ➤ To continue to support Fermilab program operation through 2025 Proton Source will need additional improvements
  - *Proton Improvement Plan flux goal will double present running conditions*
    - ➤ ensure continuity of operations in the face of potential delays for Project X
    - ➤ The PIP is currently underway and will be completed in 2018