FNAL Proton Source High Intensity Operations and Beam Loss Control

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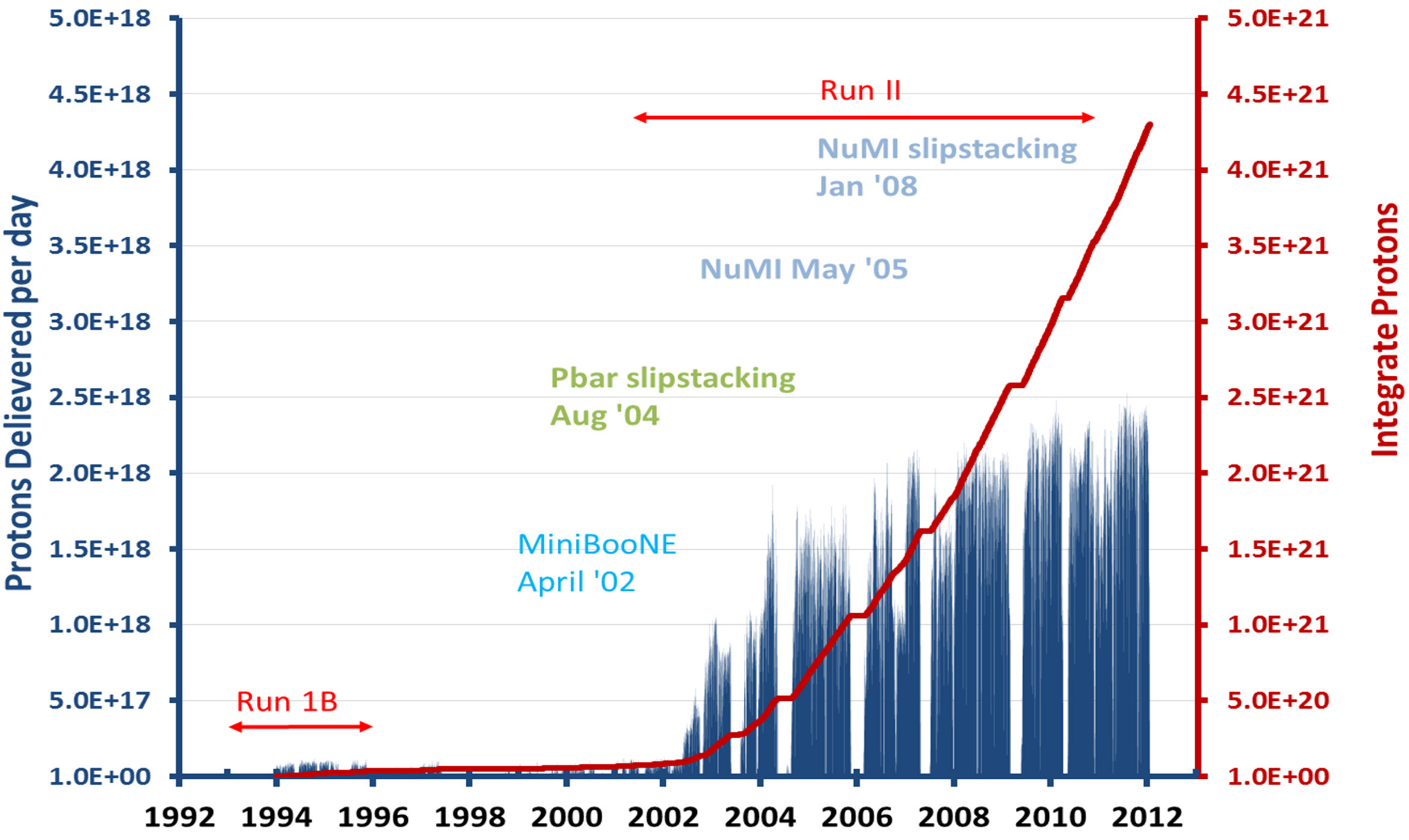
Outline

- History of beam demand at Fermilab
- Current status of the Booster
  - Booster performance
  - Beam loss and mitigation
- Future program to improve Booster proton delivery
  - Proton Improvement Plan
  - Highlights of major tasks underway
- Summary

Protons Demand up to 2012

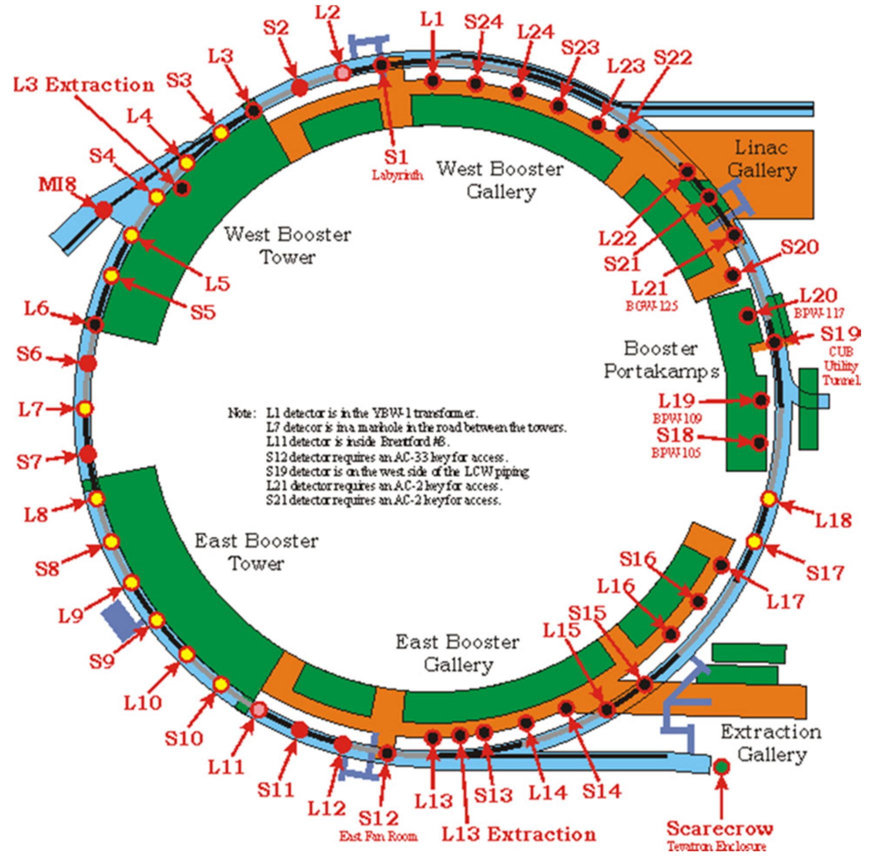
Historical beam throughput in Booster

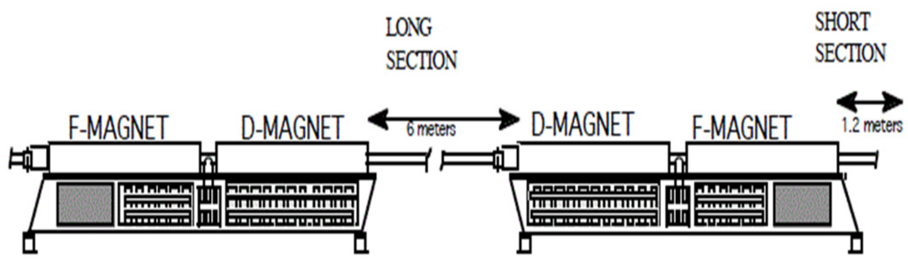


Introduction to FNAL Booster Synchrotron

- 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

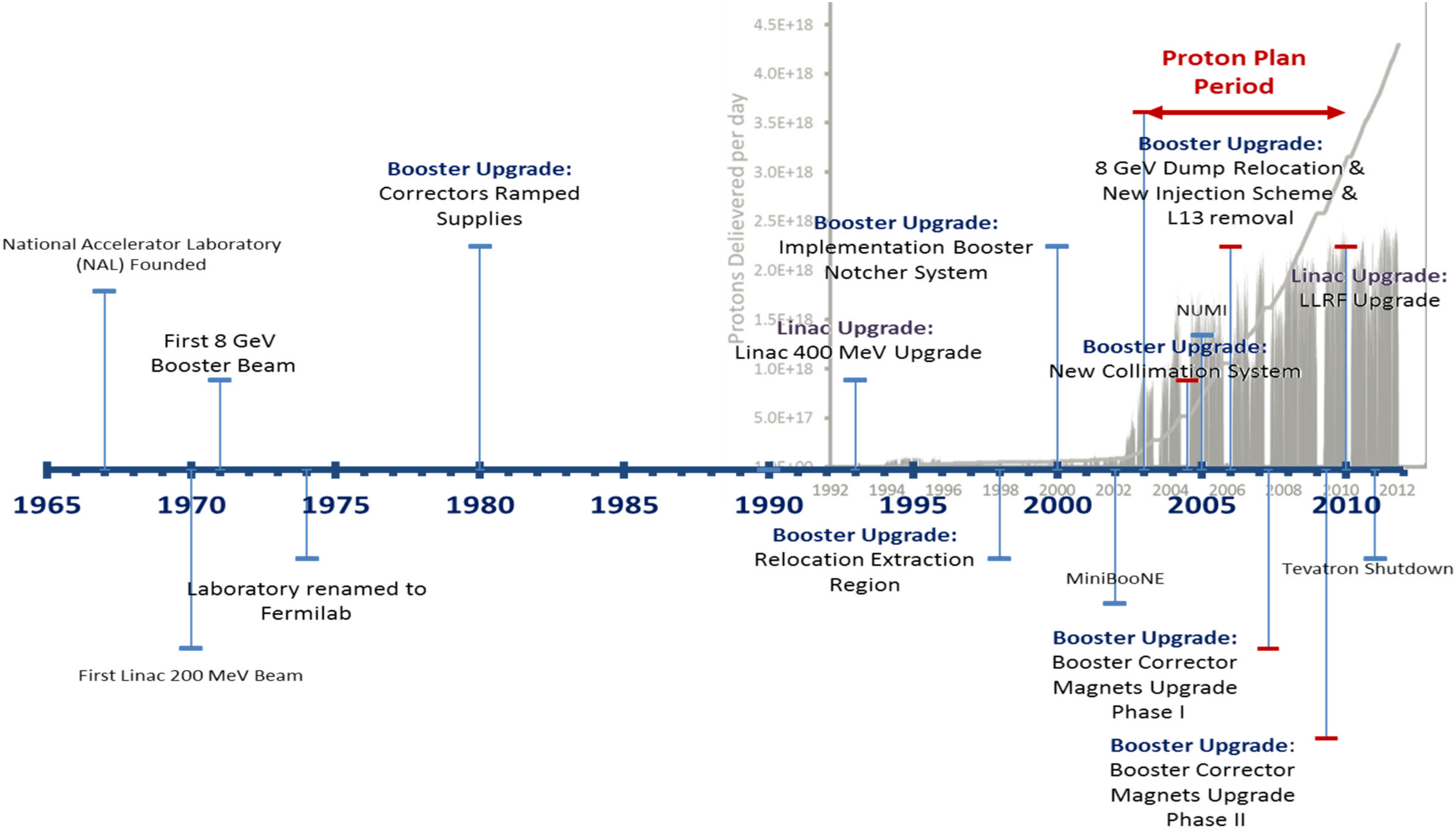
Booster	
Circumference (m)	474
Harmonic Number	84
Kinetic Energy (GeV)	0.4 - 8
Momentum (GeV/c)	0.954 - 8.9
Revolution period (μsec)	$\tau_{(inj)}$ 2.77 – $\tau_{(ext)}$ 1.57
Frequency (MHz)	37.9 - 52.8
Batch size	4.5 E12
Focussing period	FDooDFo
Nº focussing periods	24



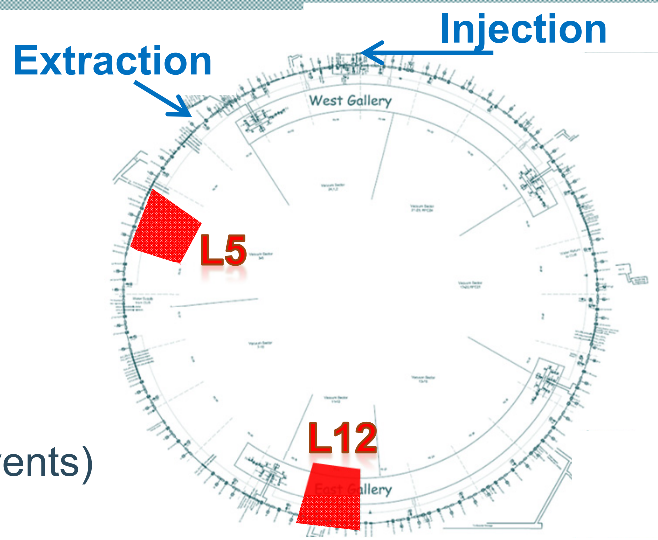


FNAL Proton Source

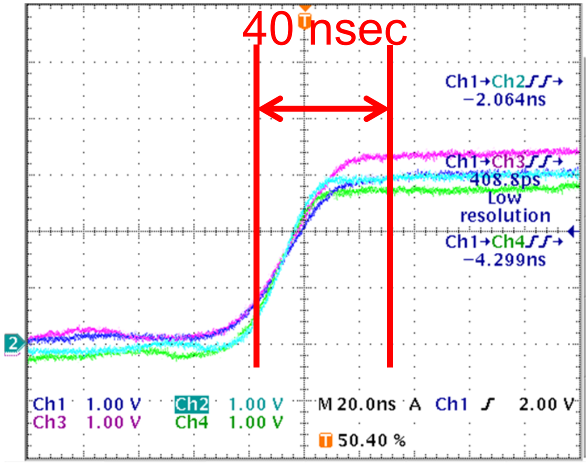
1970 – 2012 Timeline



Present Booster Notch System

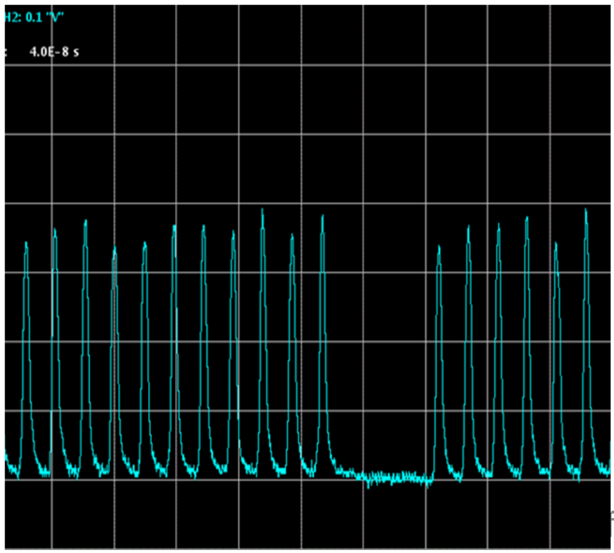


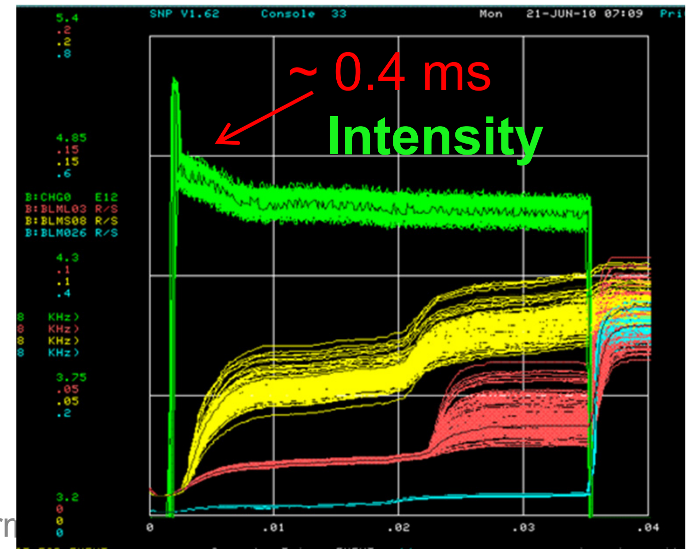
Extraction kicker has rise time of ~ 40 nsec

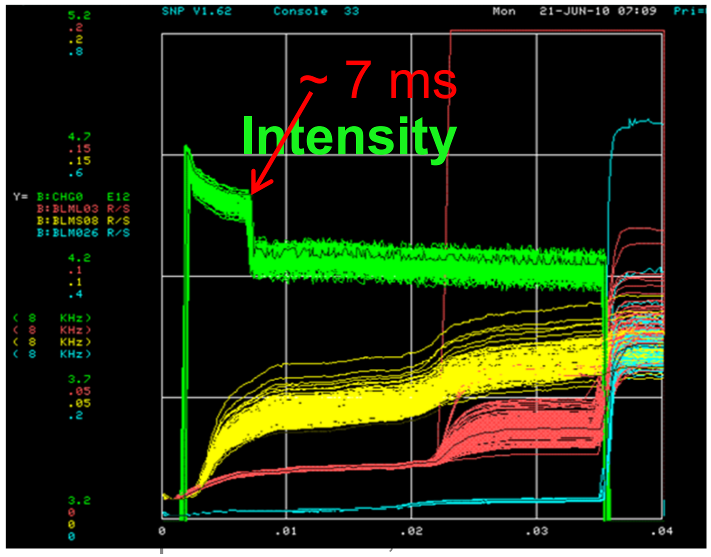


- Beam lost during extraction
  - 3 batches ~ 200 J
- Notch is created by kicking the beam vertically at L5 @ two different cycle times
  - 400 MeV (~0.4 ms) (un-cogged events)
    - Reduce losses down to 5%
  - 700 MeV (~7 ms) (cogged events)
    - Reduce losses down to 9%
- About 87% of beam is removed 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



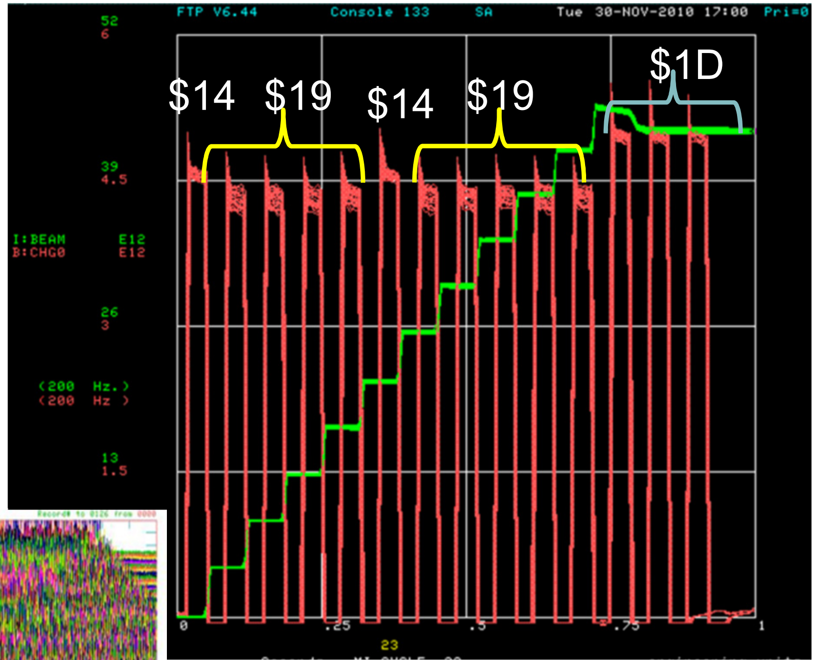


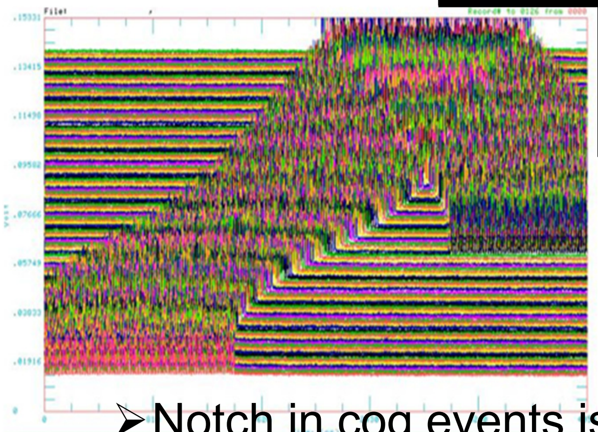


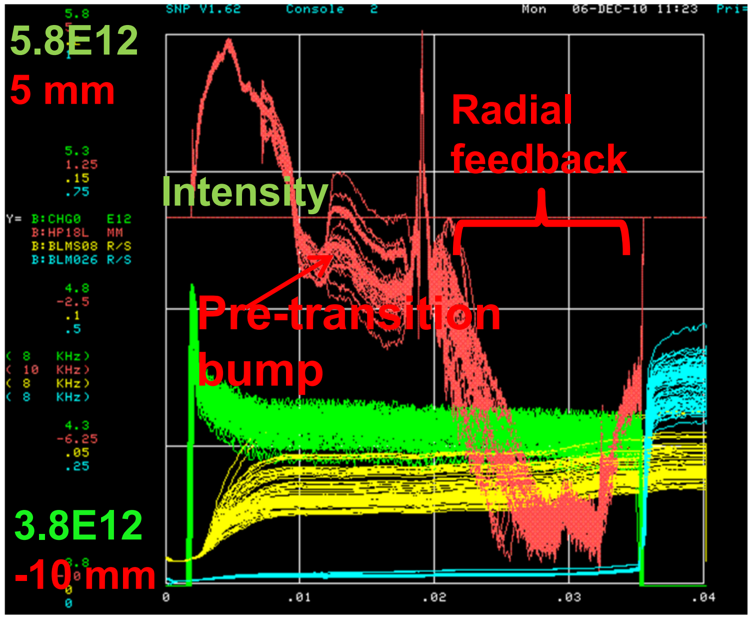
Present Booster Cogging System

- ➢ 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

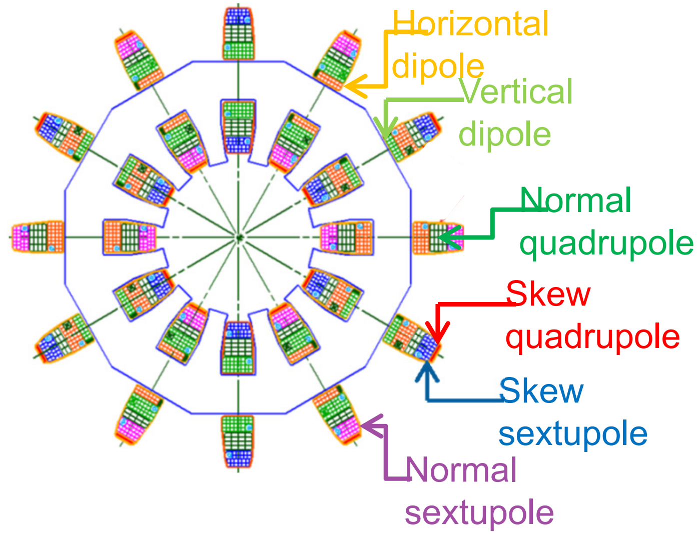






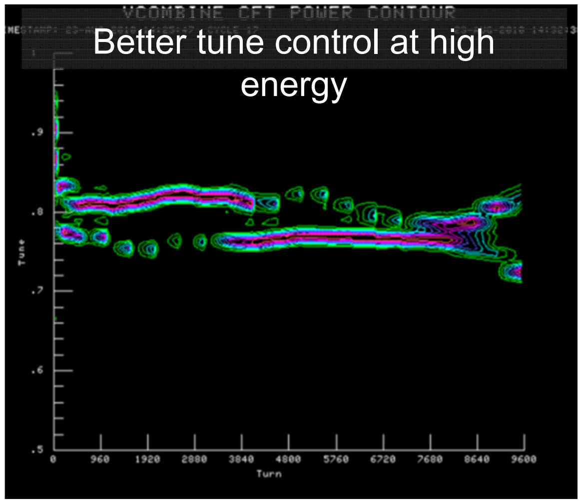
- ➢ Notch in cog events is delayed ~ 7 ms after injection
  - induce higher regular losses (20 J/notch @ 700 MeV)
  - major concern going to higher repetition rates
- ➢ Typical horizontal position vary +/- 6 mm
  - RF frequency cogging complicates the setup of beam collimation scheme due to radial orbit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

Present Booster Orbit Control Corrector System

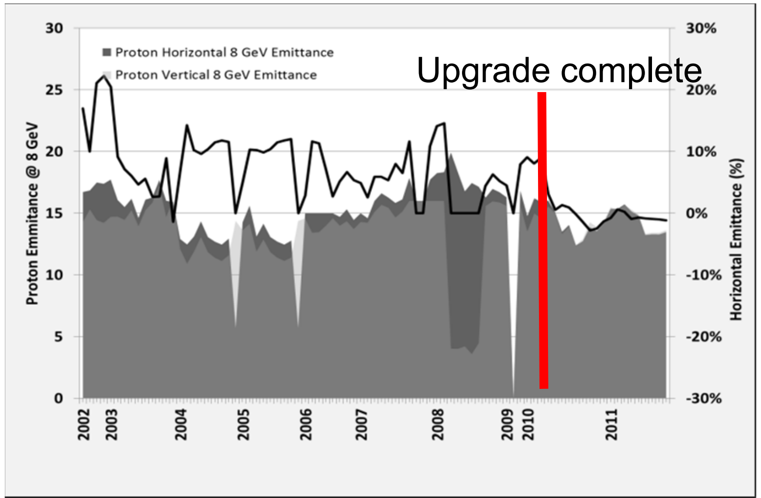


- Old corrector system
  - inability to maintain stability throughout the beam cycle
    - beam position (dipoles); hold constant tune (quadrupoles)
  - provided limited compensation for higher order resonances
- Single corrector multi pole magnet
  - upgraded to current system in 2 phases: '07 and '09
  - long and short location have a ramped corrector
  - contributed to improve the …

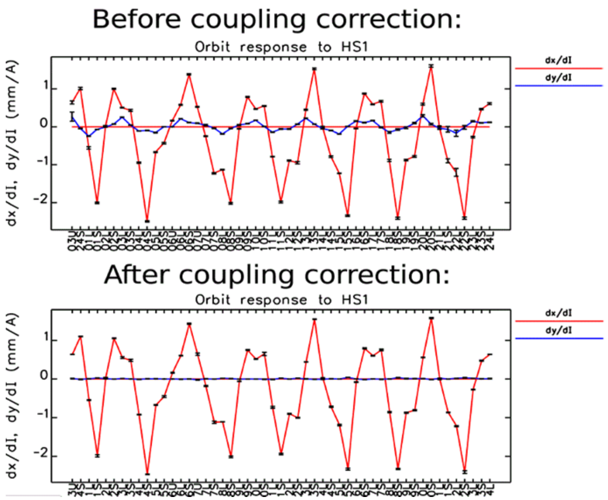
Tunes



Emittance



Orbit control/coupling

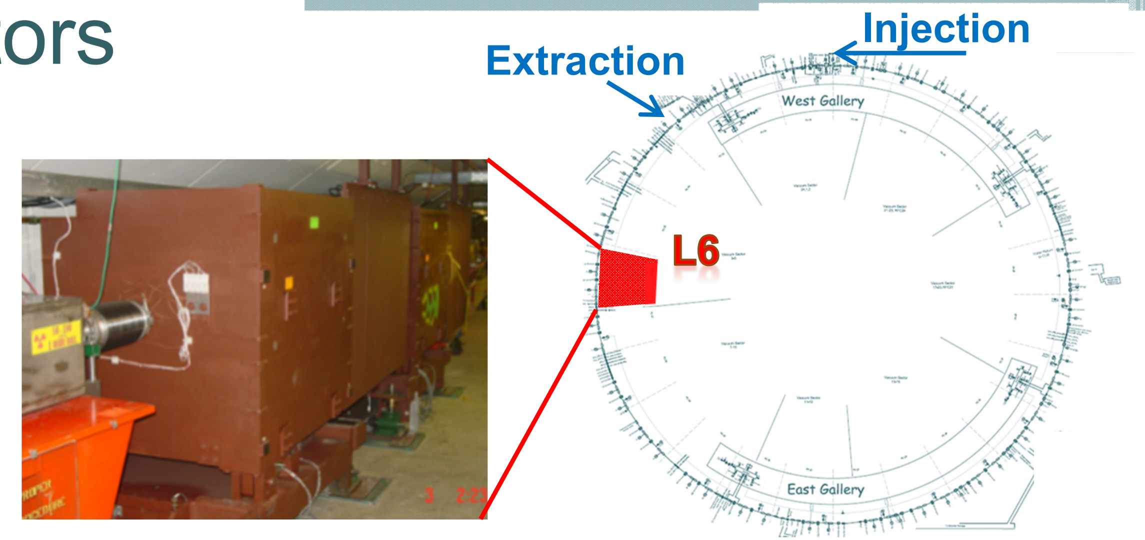


Contribution: A. Petrenko, *et al.*

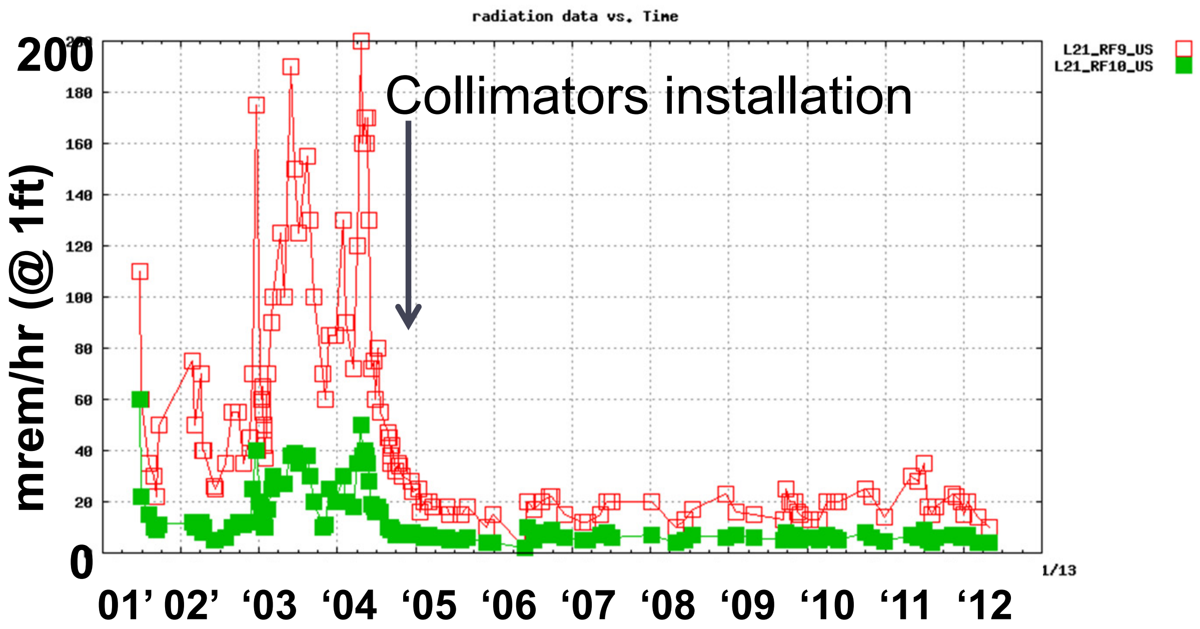
- Work continues in improving beam orbit

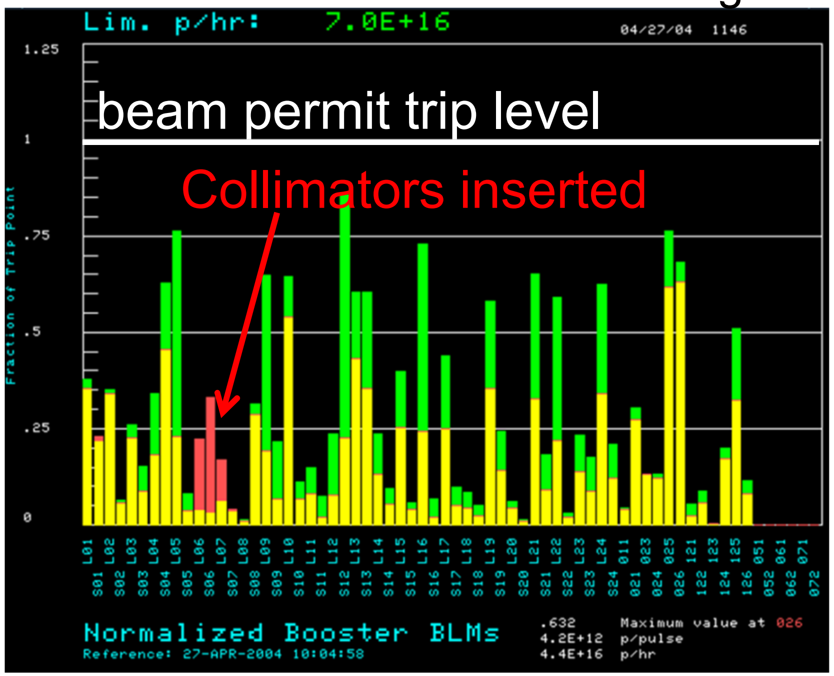
Present Booster Collimators

- Designed to be a 2-stage beam collimation system
  - losses predicted to be as high as tens W/m without collimators
- Collimation system absorbed radiation from uncontrolled beam losses in a location that can be well shielded
  - most likely on the RF cavities and other critical beamline devices



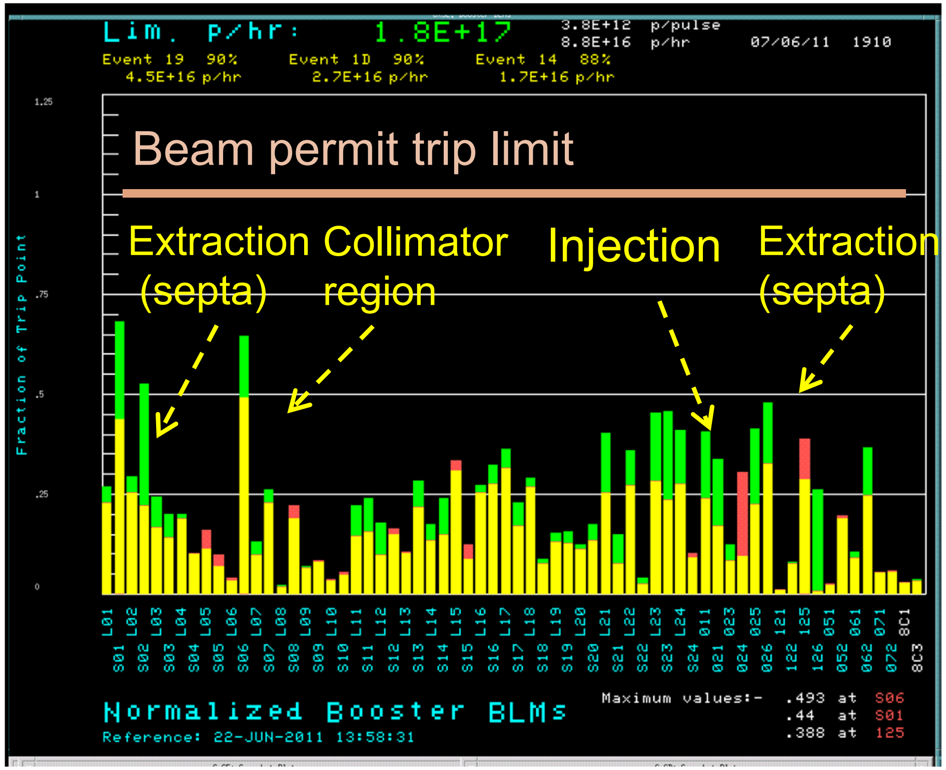
Green: indicates loss is decreasing
Red: indicates loss is increasing





Standard Booster Loss Profile

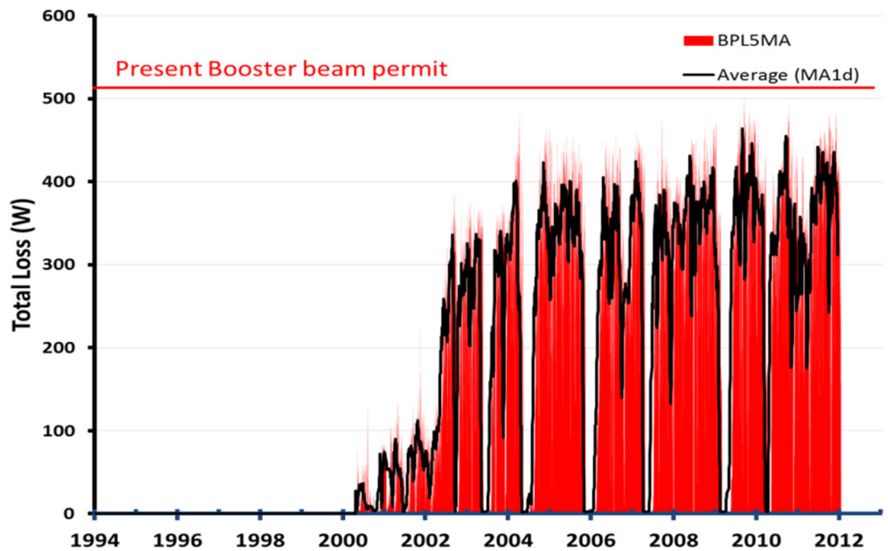
Normalized beam losses

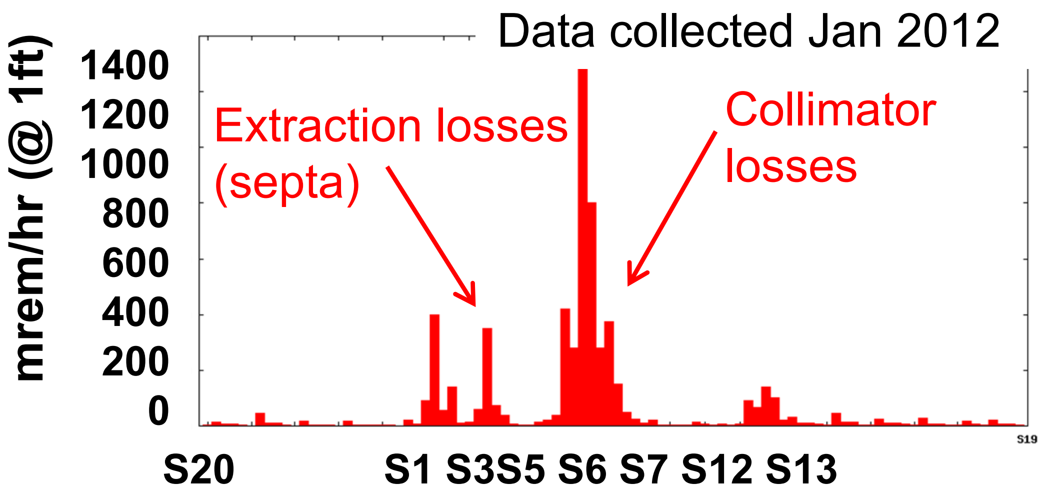


Data show beam losses for three beam cycles

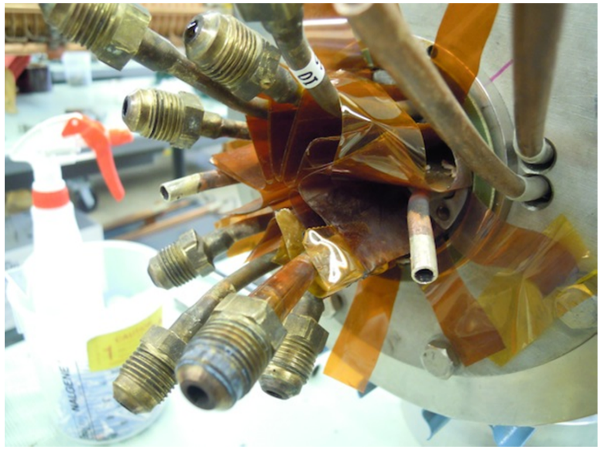
Pbar production	4.5E12 ppp
MiniBooNE	4.5E12 ppp
NUMI	4.1E12 ppp

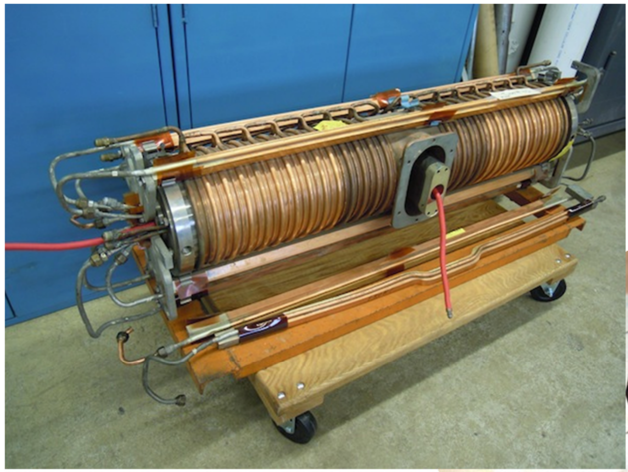
Power loss & radiation survey

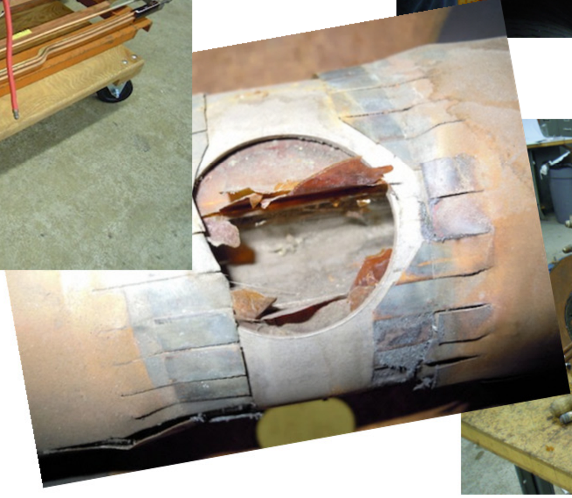


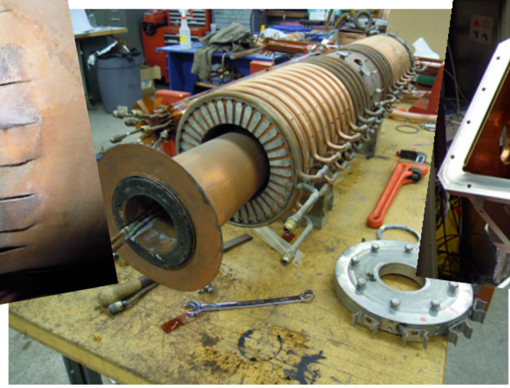


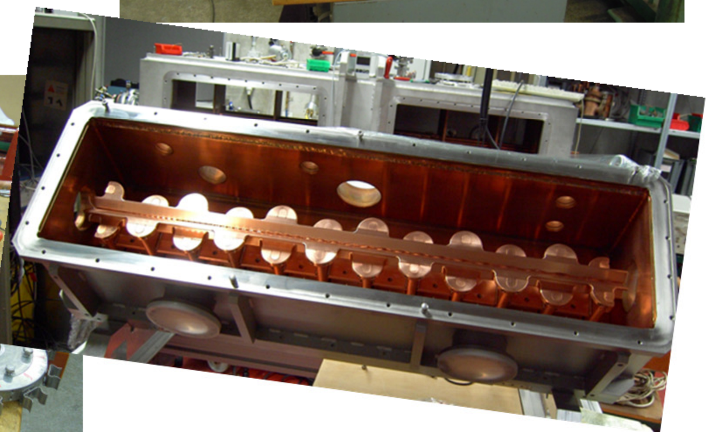
Current at the FNAL shutdown 2012











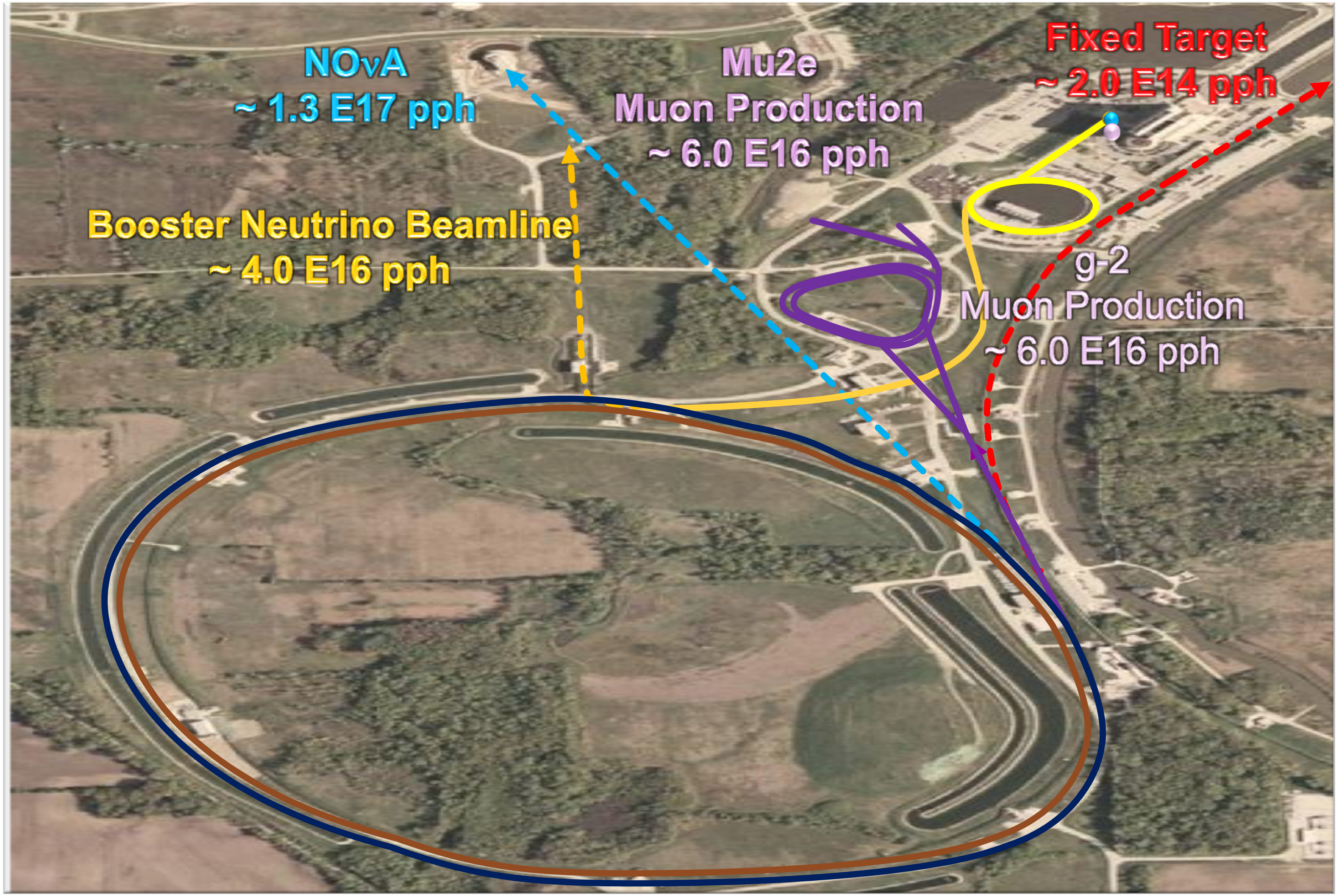
Proton Throughput

- 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

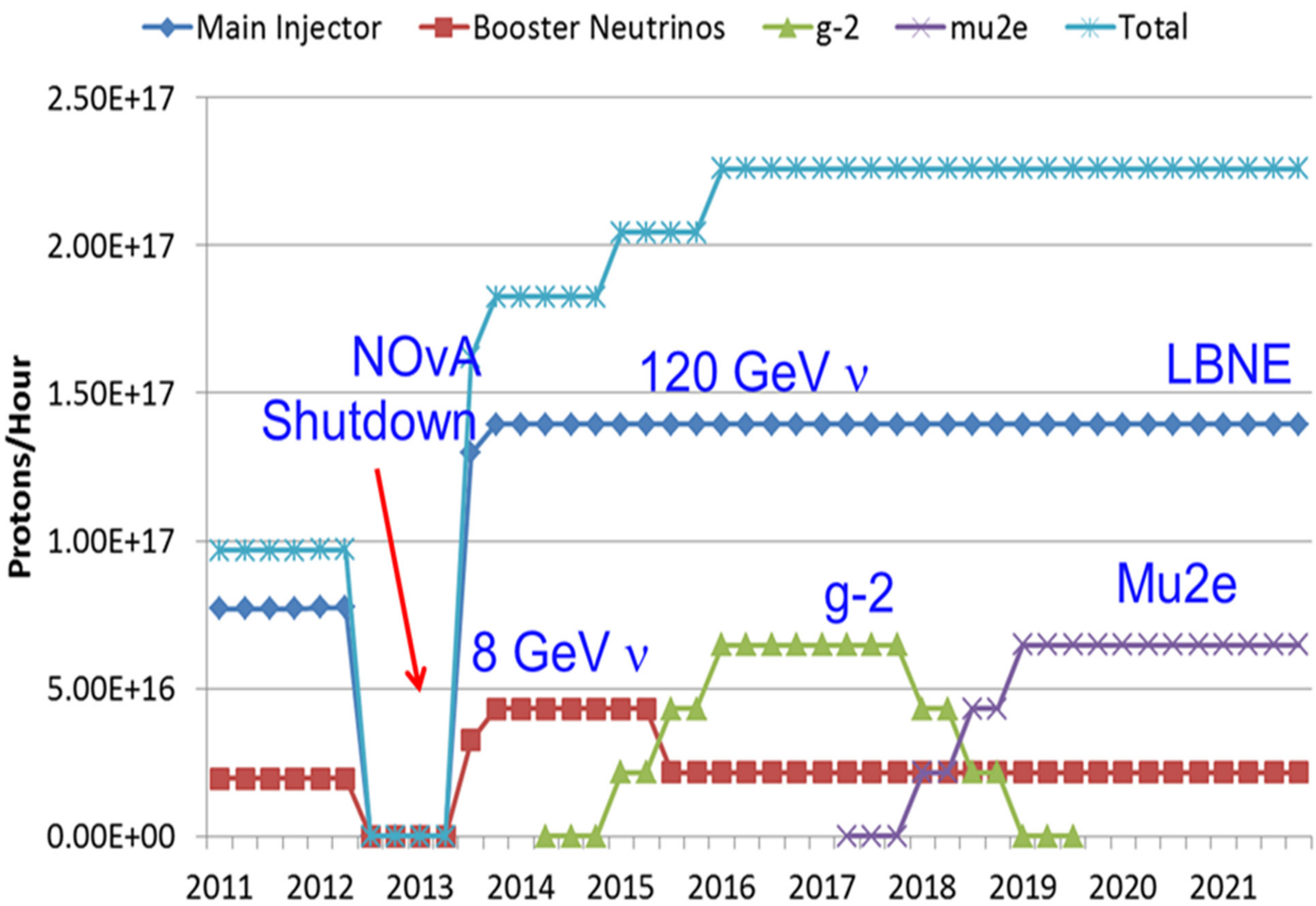
- The future laboratory experiments that are either under construction or in DOE CD-process demands another factor of 2 for the next several years
  - doubling the proton flux by increasing the number of cycles with beam
    - 8 GeV @ ~ 10 kW for Booster Neutrino Beam (BNB) experiments
    - 8 GeV @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

Protons Demand after 2013



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*

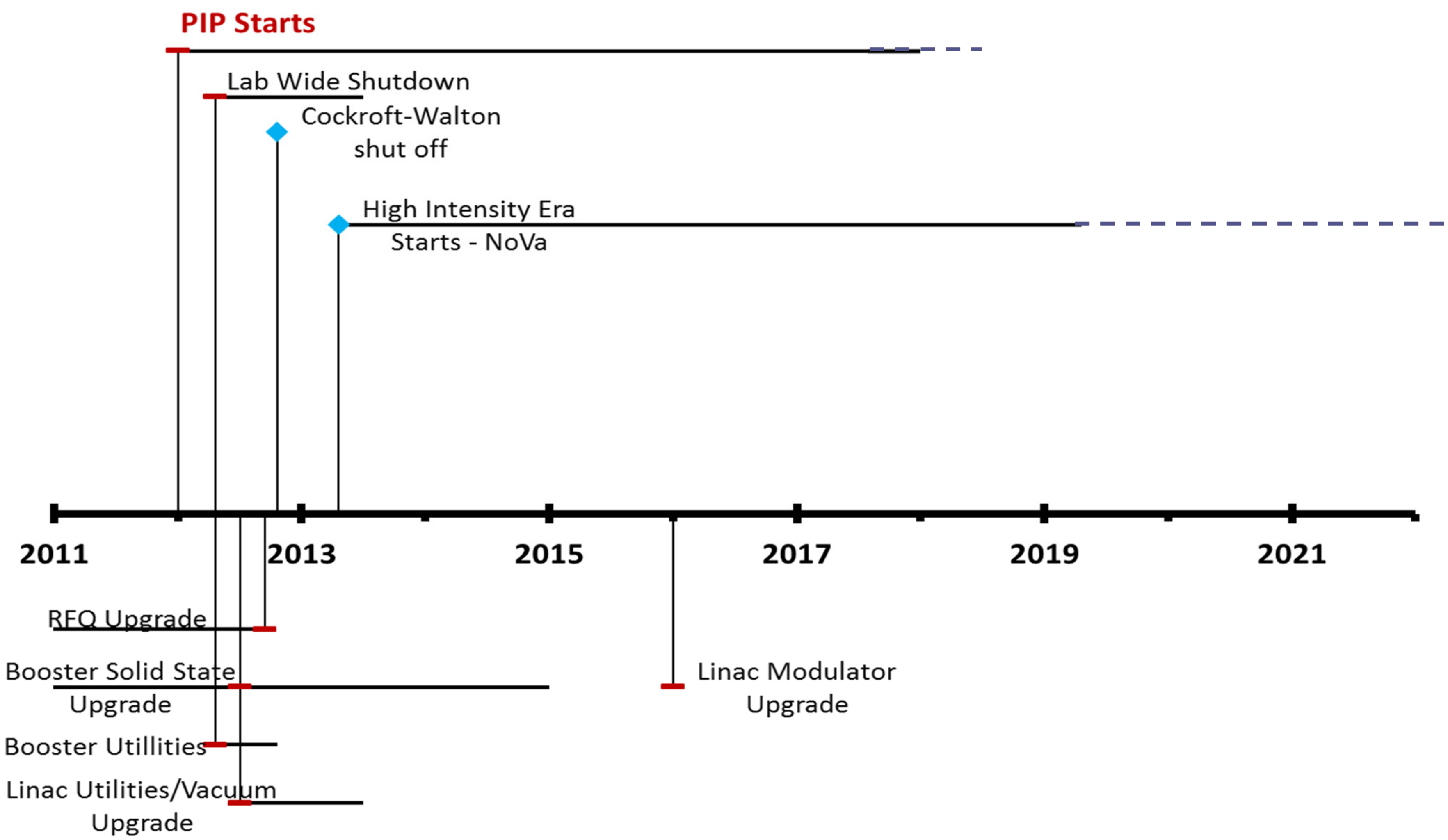
and also ensuring a useful operating life of the proton source through 2025.

S. Henderson

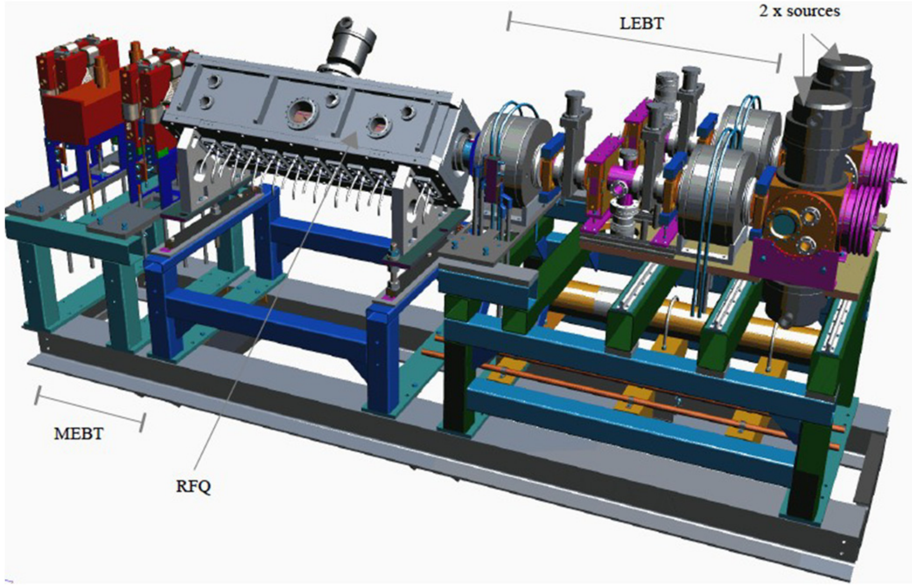
- The scope of the ***PIP*** includes
  - increase Booster repetition rate by upgrading (or replacing) components
  - replacing components that have poor reliability
  - studying beam dynamics to diagnose performance limitations

FNAL Proton Source Looking into the Future

2013 and beyond

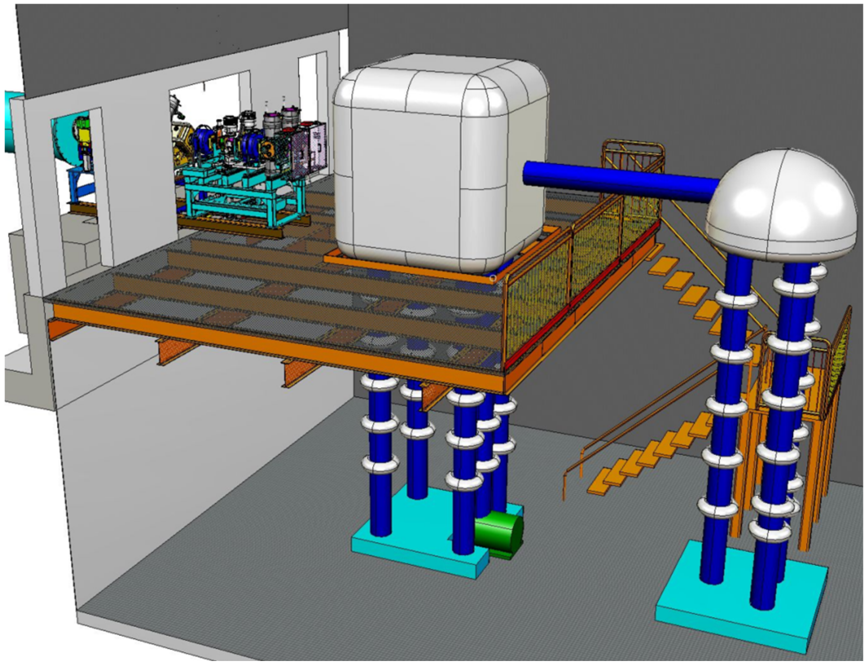


Pre-Injector Upgrade - RFQ



- FNAL has considered using RFQ in late 1980's
  - BNL and FNAL worked with LBNL on a RFQ design
  - 200MHz built for BNL but FNAL cancelled order
- FNAL initiated the Pre-injector upgrade in 2008
  - Fermilab retired C-W in August 2012 after 43 years of operation

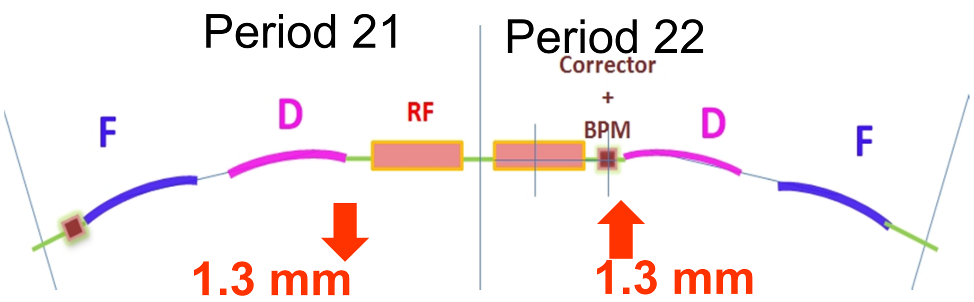
Parameter	Value (units)
Energy	35 – 750 (keV)
Frequency	201.25 (MHz)
Length	120 (cm)
Design current	60 (mA)
Peak cavity power	~ 140 (kW)
Radial aperture	0.3 (cm)
Duty Factor	0.12%

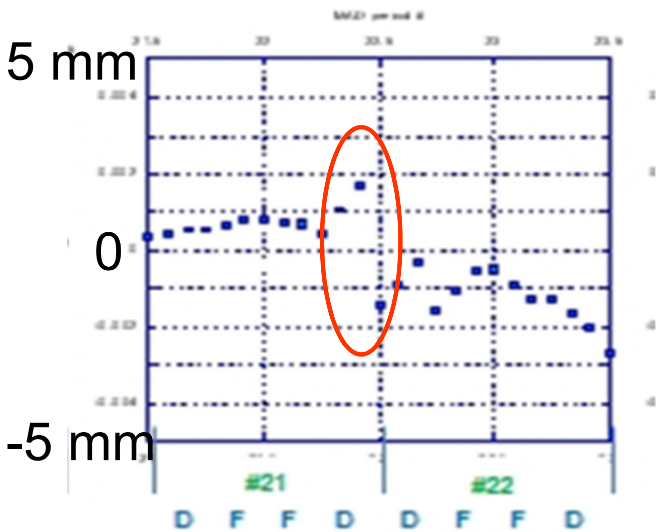


Booster Orbit Control Improvements
Magnet Move

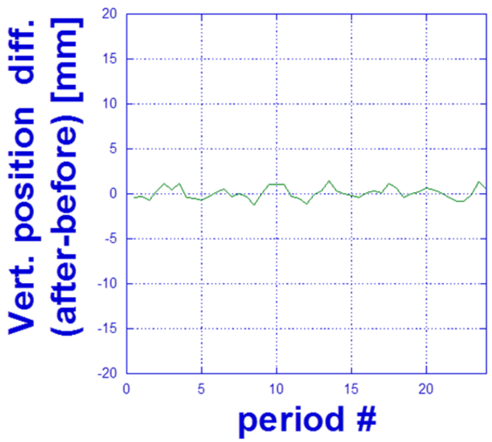
Contribution by K. Seiya

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



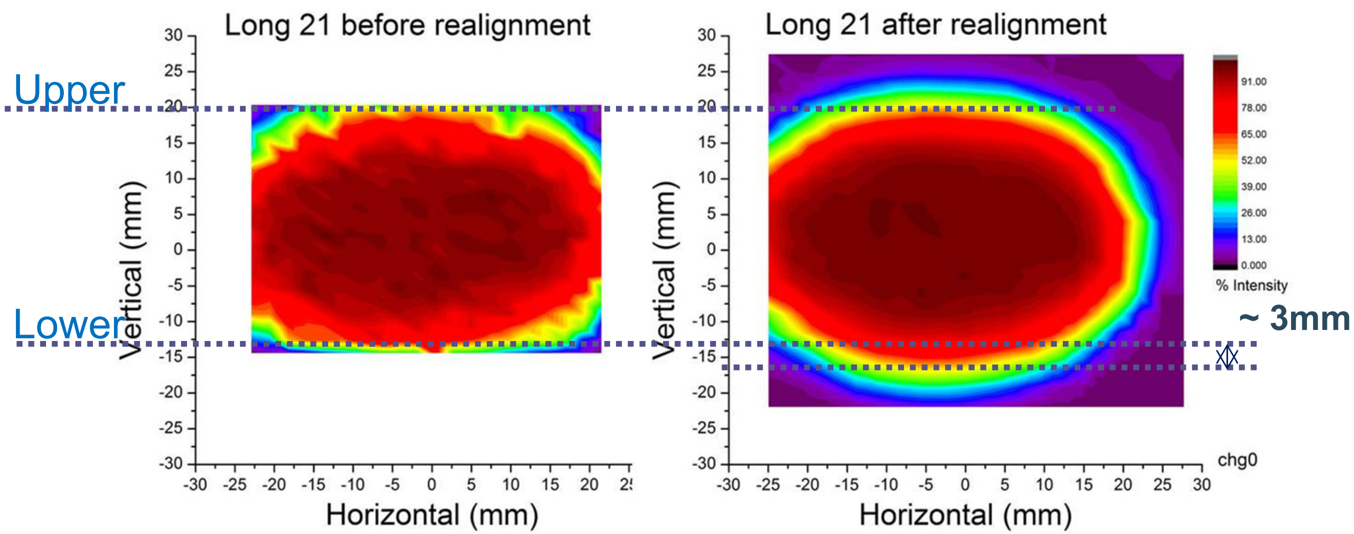


After alignment…

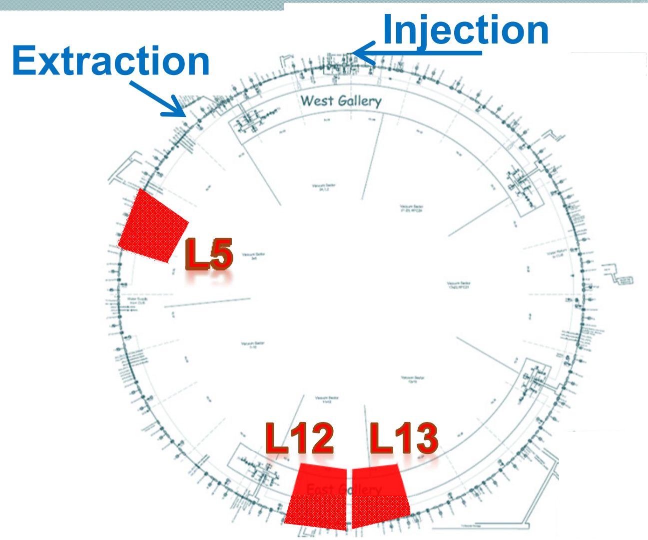


Difference of the measured orbit between before and after magnet move is ~ +/- 2 mm.

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



Future Booster L13 Notching & Absorber

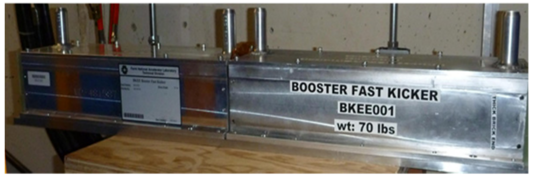


- PHASE I: Notcher relocation
  - abort gap is created using 3 long kickers located at Long 12
  - beam is kicked **horizontally** into new absorber at Long 13
    - notching efficiency expected to increase by ~ 10%
    - reduce activation of components in the tunnel
  - notching cycle time will remain unchanged

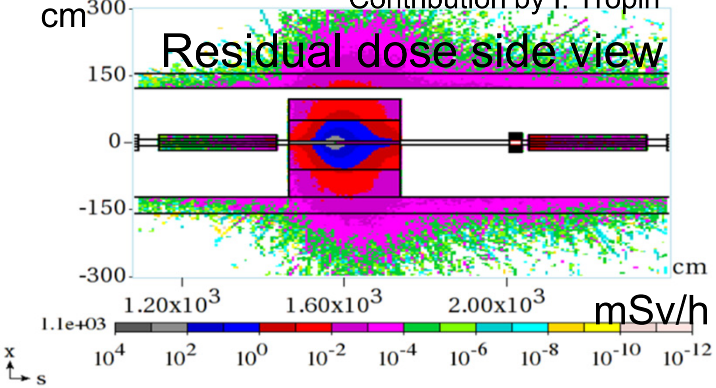
Contribution by . Sidorov

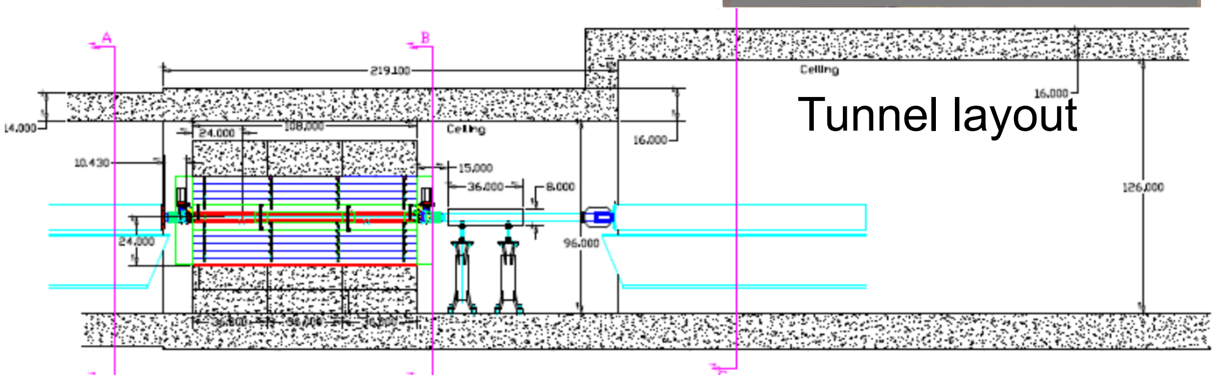

New notch beam absorber

- PHASE II: kicker magnets replacement
  - convert 3 long kickers to 6 short kickers
    - allow cleaner notch
    - reduce operational losses even further

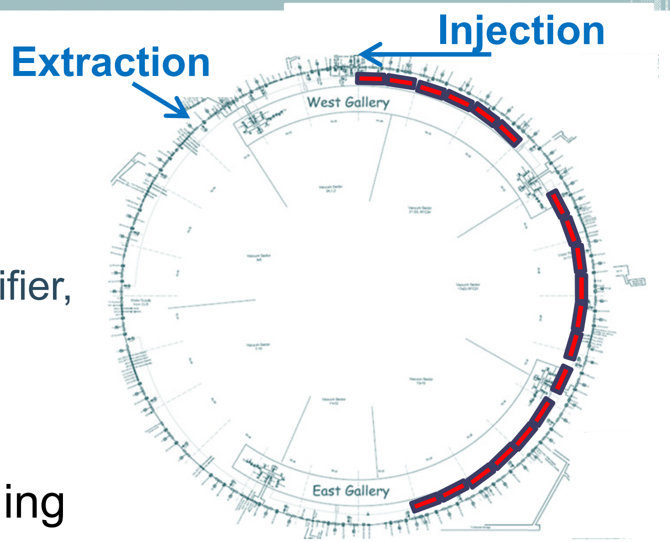


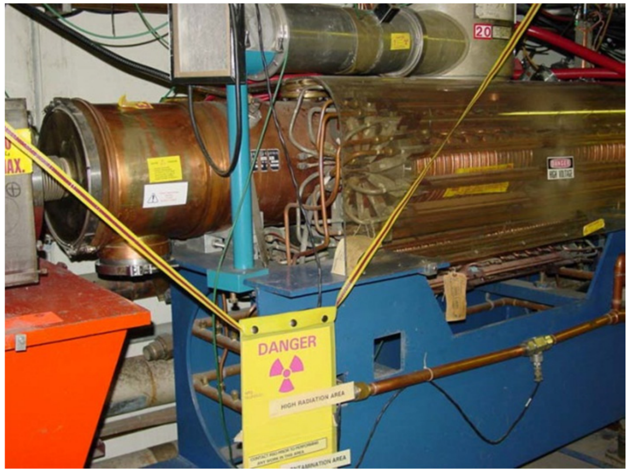
Contribution by I. Tropin





Future Booster Solid State RF Cavity Refurbishment & Tuner Re-work





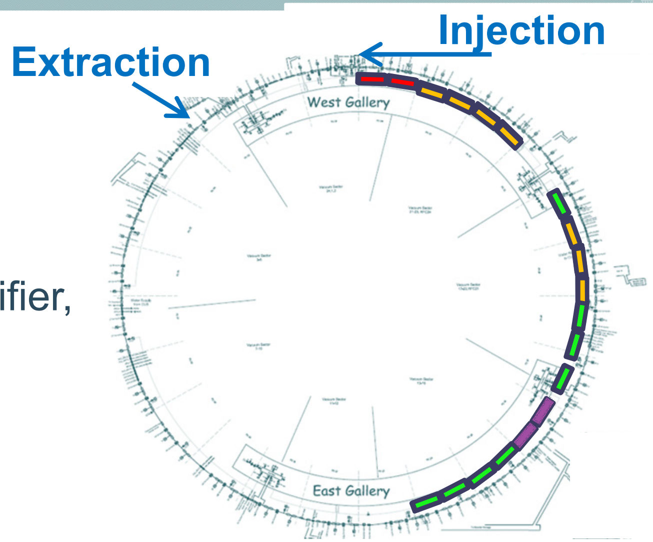
- 19 RF stations in total
  - each station includes 1 power amplifier, 1 cavity & 3 ferrite bias tuners
  - RF components require the most maintenance
- Cavities and 3 tuners require cooling re-work to support higher repetition rates
  - each station needs to be removed from the tunnel, tuners removed, inspected, cleaned, re-worked, reassembled, vacuum certified & tested at 15 Hz

- Tuner cones rebuild process
  - require clean room and special PPE
  - extensive methodical work

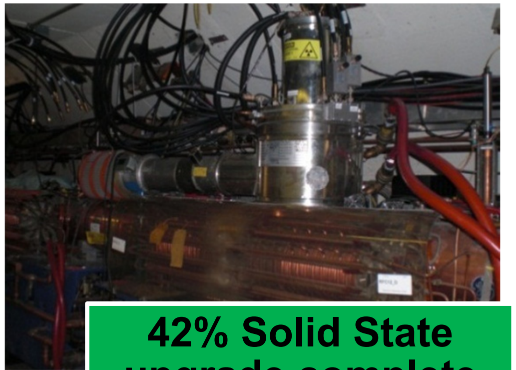
- Currently 2 cavities have been completely refurbished
  - essential to achieve 15 Hz operations
  - estimate: Jun 2015

Future Booster Solid State RF
Solid State Power Amplifier Upgrade

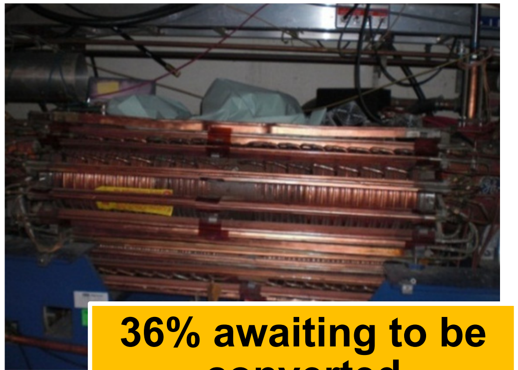
- 19 RF stations in total
  - each station includes 1 power amplifier, 1 cavity & 3 ferrite bias tuners
  - RF components require the most maintenance



Current Status



42% Solid State upgrade complete



36% awaiting to be converted

2 cavities being refurbished

2 cavities not yet worked on

Summary

- Fermilab Proton Source machines have been operating for the past 42 years
  - Cockcroft-Walton pre-injector decommissioned Aug'12
- The US High Energy Physics program for the next 15 years relies on the viability and vitality of the Fermilab Proton Source
- To continue support Fermilab program operation through 2025 Proton Source do 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 is estimated to be completed in 2018