Fermilab

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Enhancements of the Fermilab Booster to Reduce Losses and Extend Lifetime: *The Proton Improvement Plan*

Robert Zwaska

11 November 2014

HB2014

PIP Introduction

- PIP is a critical Fermilab "project" to address desired increases in proton production to meet the present and near term experiments
  - PIP's scope is specific to the FNAL Proton Source
    - Proton flux
    - Machine reliability
    - Machine long term viability
  - Official start in FY12
- This talk focuses on a few RF and injection/extraction issues
  - More on beam dynamics issues in K. Seiya's talk this afternoon

- Project Overview
- Notching
  - Kickers
  - Laser Neutralization
- 200 MHz sources
  - Modulator
  - PA (tube or klystron)
- Booster Cavity Refurbishment

Present Proton Production

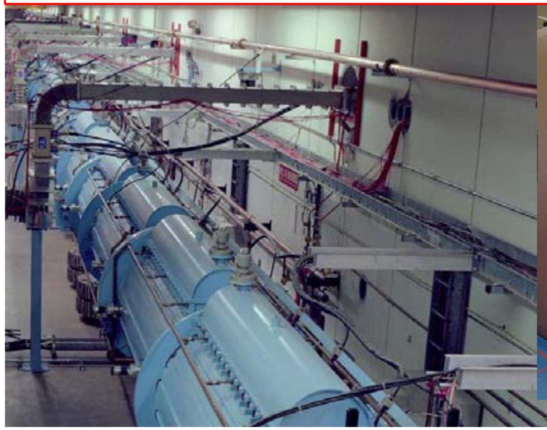
- Linac produces 400 MeV H^-
  - Bunched at 200 MHz
  - 35 mA for up to 40 us at up to 15 Hz

- Booster produces 8 GeV protons (Booster neutrinos, muons, etc.)
  - Bunched at 53 MHz
  - Up to 5e12 (typically 4.3e12) in 1.5 us
  - Ramps at 15 Hz
    - Historically <<= 7 Hz with beam

- Main Injector produces 120 GeV protons (NuMI)
  - Bunched at 53 MHz
  - Up to 5e13 (typically 3.7e13) Operates as quickly as 1.33 s
  - With Recycler integration, designed for 700 kW
    - Has run at 400 kW

Linac Overview

Designed for high intensity single shot proton injection



7835 Socket

7835

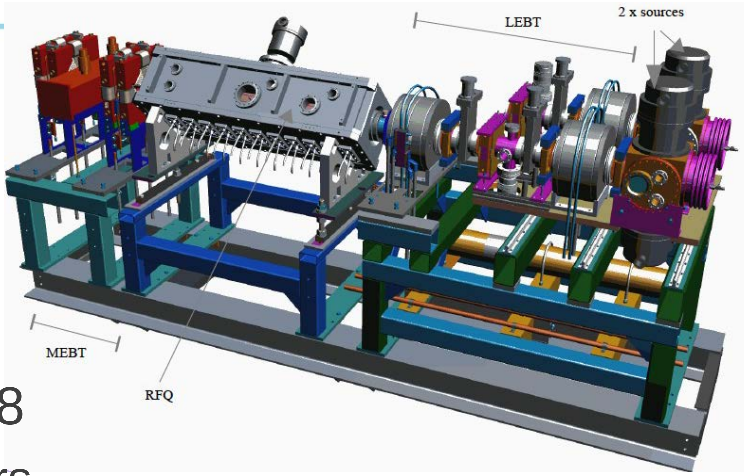
Linac	
Length (m)	200
Pulse Frequency	15 Hz
Kinetic Energy (MeV)	.750 - 4
Frequency (MHz)	201 & 804
Current (operational)	33 ma (Historical low)
Linac Lattice	LE ? HE - Photo
Nº of cavities	5 DTLs, 7 SC, 3 small

LE Linac		
Flat top	350	usec
Raise Fall time	75	usec
Average Axial Field	1.5	MV/m
Rep Rate	15	Hz
RF Peak Power	3.5	MW
Peak Current	35	mA
Beam width	20	usec
Power to the beam	787.50	KW
Average RF Power	19.16	KW
Peak Power	3.50	MW

High Energy Tunnel

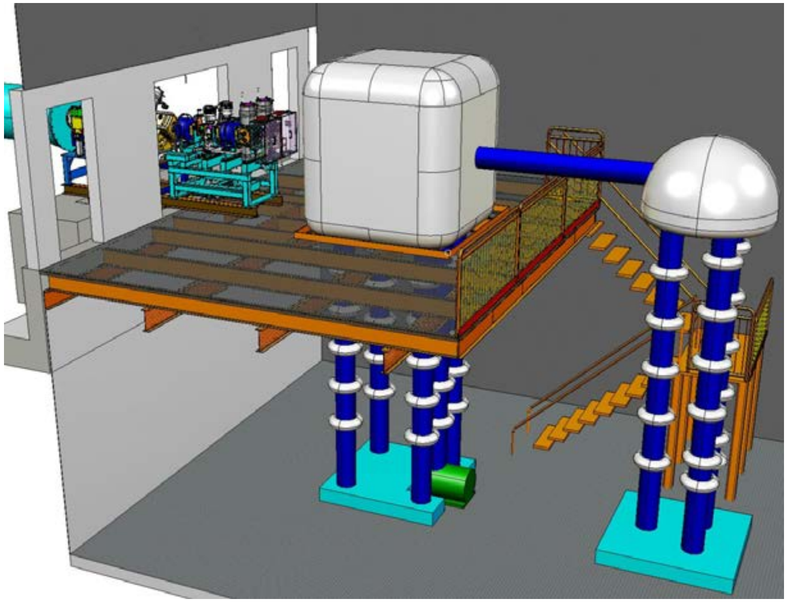
High Energy Linac Gallery

Pre-Injector Upgrade - RFQ



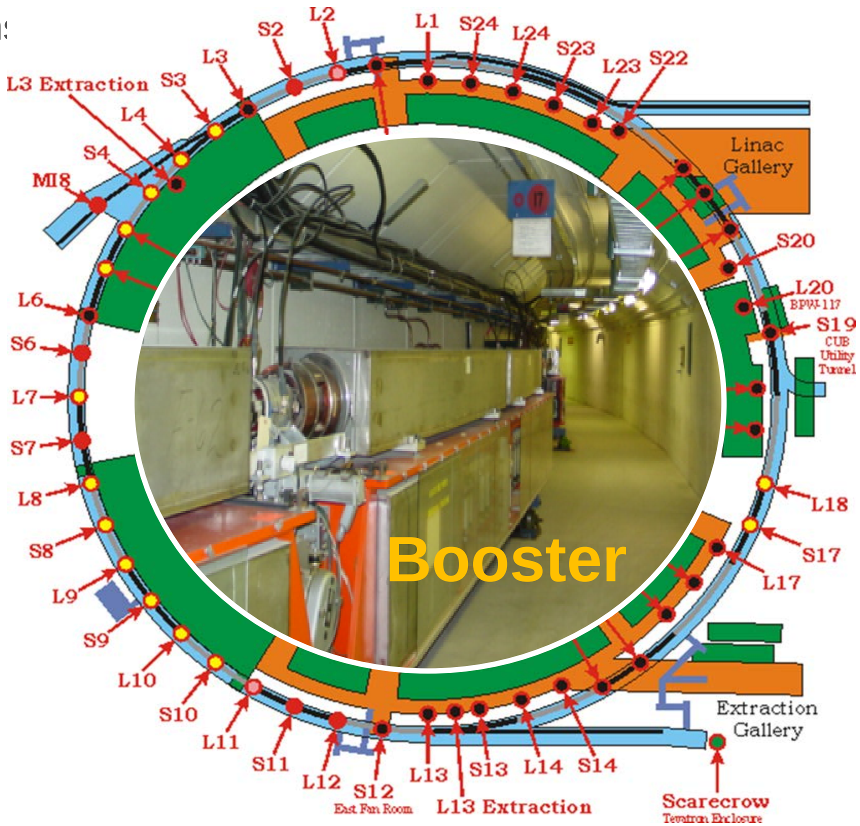
- FNAL considered using RFQ in late 1980's
  - BNL and FNAL worked with LBNL on a RFQ design
  - 200MHz built for BNL but FNAL cancelled order
- FNAL initiated the Pre-injector upgrade in 2008
  - Fermilab retired C-W in August 2012 after 43 years

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%

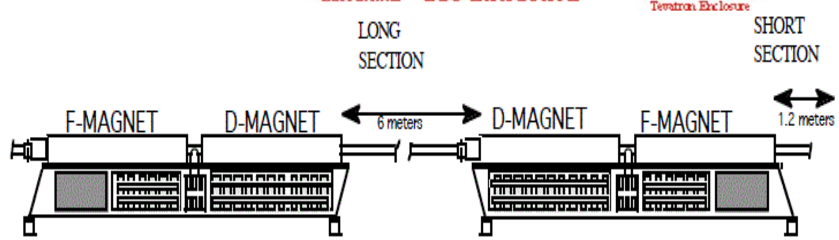


Booster Overview

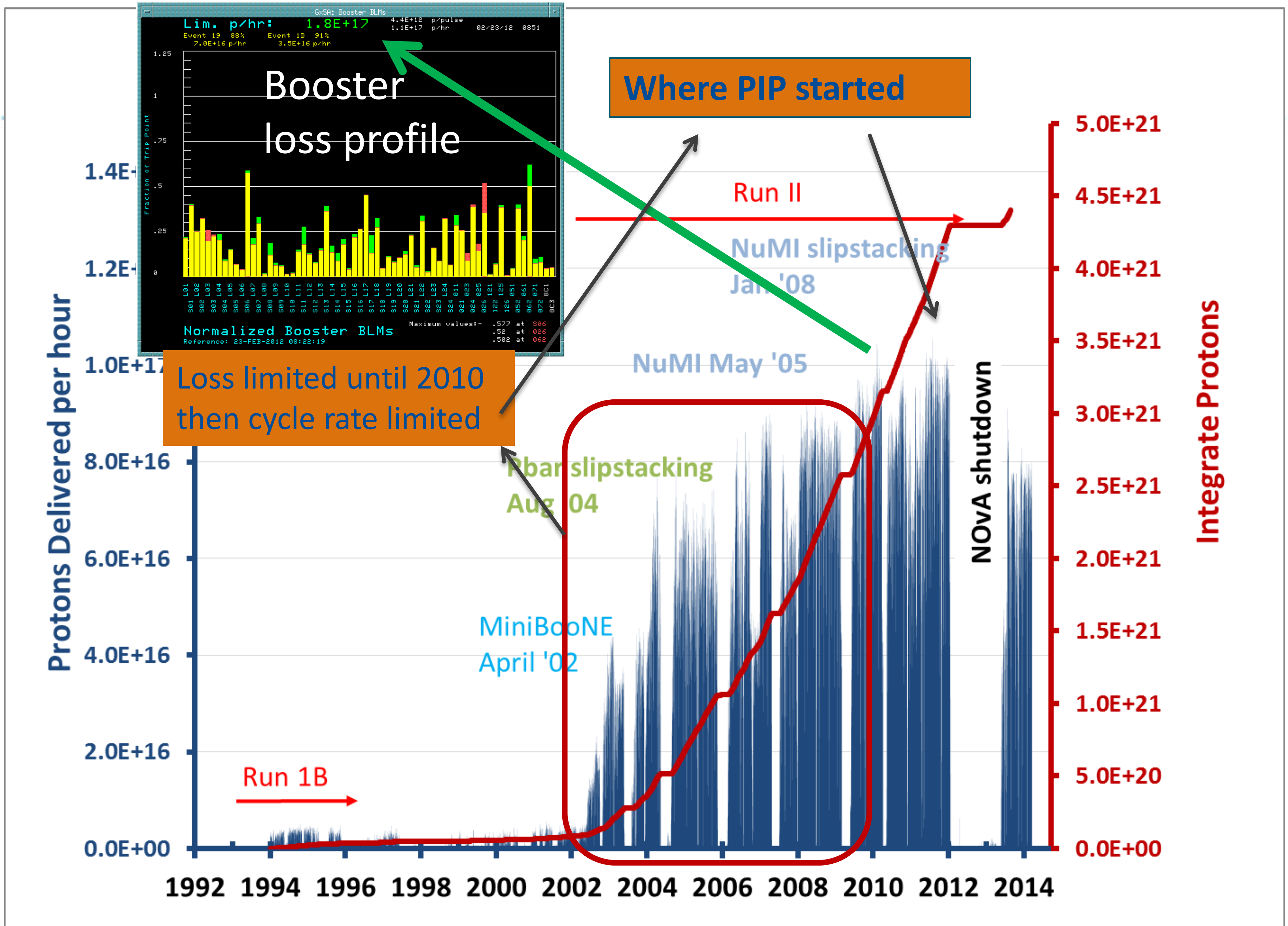
- H^- ions are stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 m
- Fast cycling synchrotron
  - Fast magnet ramping
  - Frequency of 15 Hz
- Single turn extraction



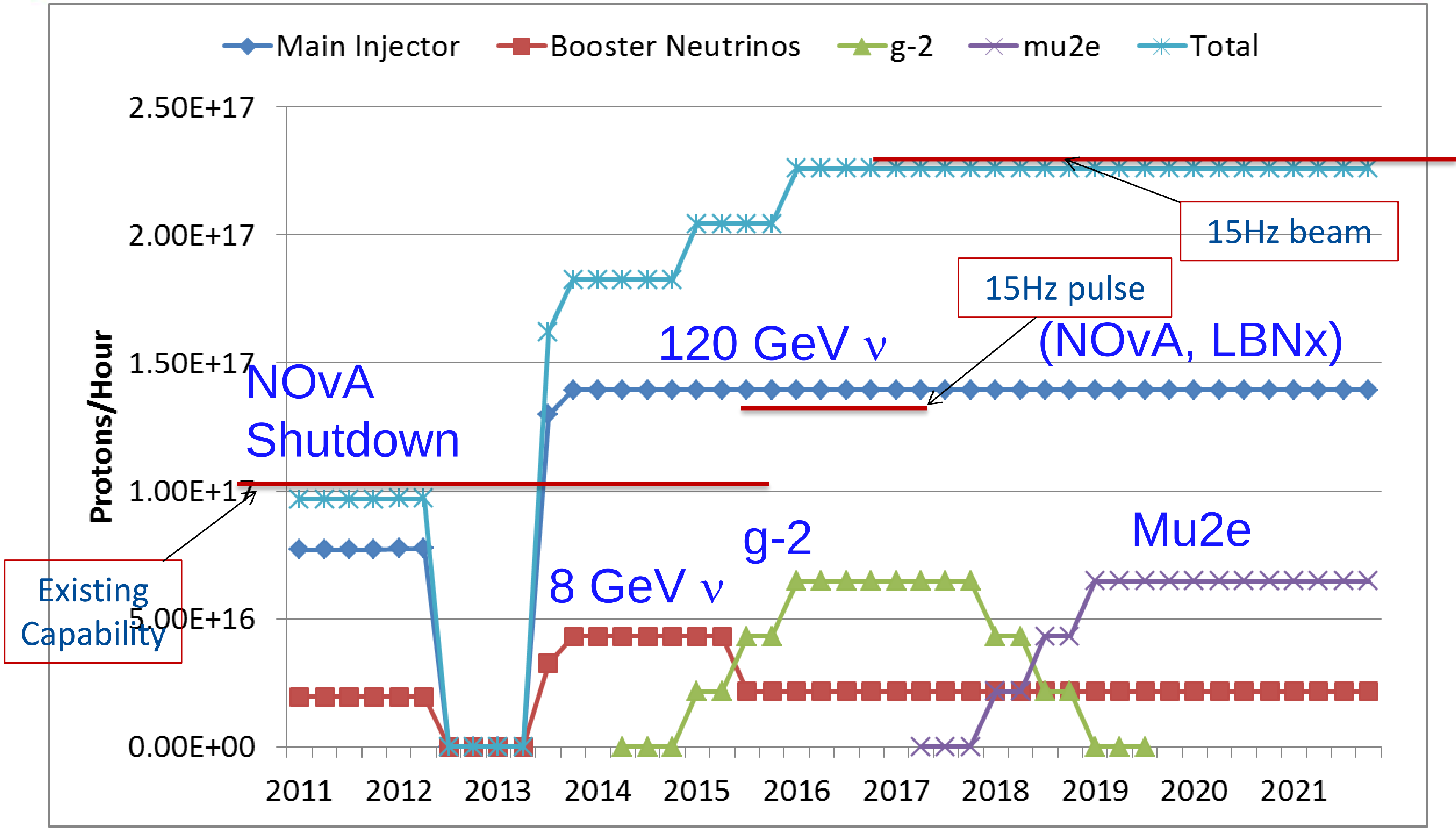
Booster	
Circumference (m)	474
Harmonic Number	84
Kinetic Energy (GeV)	0.4 - 8
Momentum (GeV/c)	0.954 - 8.9
Revolution period (μsec)	$\tau_{(inj)}$ 2.77 – $\tau_{(ext)}$ 1.57
Frequency (MHz)	37.9 - 52.8
Batch size	4.5 E12
Focussing period	FDooDFo (24 total)



Combined Function Magnets
No failures after initial phase…
but 8 spares have been refurbished as part of PIP…


Lim. p/hr: 1.8E+17
Booster
loss profile
Normalized Booster BLMs
Where PIP started
Run II
NuMI slipstacking
Jan '08
NuMI May '05
Loss limited until 2010
then cycle rate limited
Pbar slipstacking
Aug '04
MiniBooNE
April '02
NOvA shutdown
Run 1B
Protons Delivered per hour
Integrate Protons
1.4E+17
1.2E+17
1.0E+17
8.0E+16
6.0E+16
4.0E+16
2.0E+16
0.0E+00
5.0E+21
4.5E+21
4.0E+21
3.5E+21
3.0E+21
2.5E+21
2.0E+21
1.5E+21
1.0E+21
5.0E+20
0.0E+00
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

Requested Proton Flux



Original Goals for the Proton Improvement Plan

- The ***Proton Improvement Plan*** should enable Linac/Booster operation capable of
  - Delivering 2.25E17 protons/hour (at 15 Hz) in 2016

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

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

The scope of the ***Proton Improvement Plan*** includes
- Upgrading (or replacing) components to increase the Booster repetition rate
- Replacing components that have (or will have) poor reliability
- Replacing components that are (or will soon become) obsolete
- Studying beam dynamics to diagnose performance limitations
- Implementing operational changes to reduce beam loss

Scope change to PIP

Modifications to PIP objectives to reflect present laboratory planning.

Extend Booster operations to 2030

Linac operations till 2023

Consider transition to PIP II

Fermilab

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September 30, 2014

Bill Pellico
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Proton Improvement Plan
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Dear Bill,

I would like to update the objectives and goals for the Proton Improvement Plan (PIP) in light of progress to this point and the lab's strategy. Even though PIP is well underway, some adjustments to the project are needed to align with the upcoming PIP-II project. This letter supplants the initial guidance delivered by Stuart Henderson on Dec. 7, 2010, at the Proton Source Workshop and documented in Beams-doc-3739.

The overarching goal of PIP should now be to develop and implement a plan to meet the targets for Proton Source throughput, while maintaining good availability and acceptable residual activation. Specifically, when executed, PIP should enable Linac/Booster operation capable of delivering 2.3E17 protons per hour at 15 Hz while maintaining Proton Source availability at 85 % and maintaining residual activation at acceptable levels.

These plans should anticipate a useful operating life of the Linac through 2023, and the Booster through 2030. In addition, the plan should anticipate a transition to the new PIP-II linac in 2023, with which the Booster will be expected to deliver 4.7E17 protons per hour at 20 Hz. The remaining deliverables within PIP should be mindful of the PIP-II and possible subsequent upgrades.

Sincerely,

Sergei Nagaitsev
Chief Accelerator Officer
Fermi National Accelerator Laboratory

CC: Nigel Lockyer, Joe Lykken, Tim Meyer, Hasan Padamsee, Greg Bock, Steve Geer, Gina Rameika, Mike Lindren, Rob Roser, Vladimir Shiltsev, Paul Czarapata, Bob Zwaska, Steve Holmes

Beam and Losses through Cycle

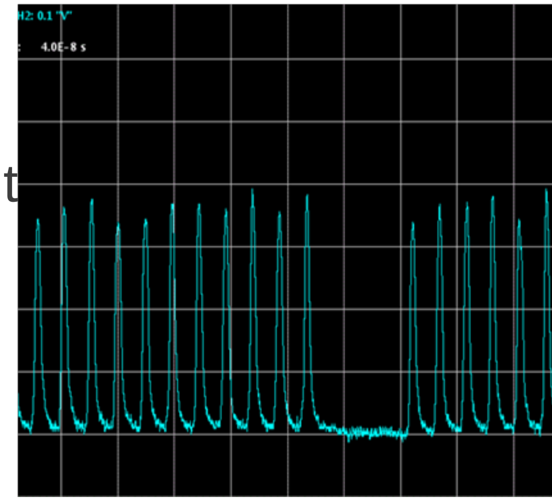
Beam Intensity

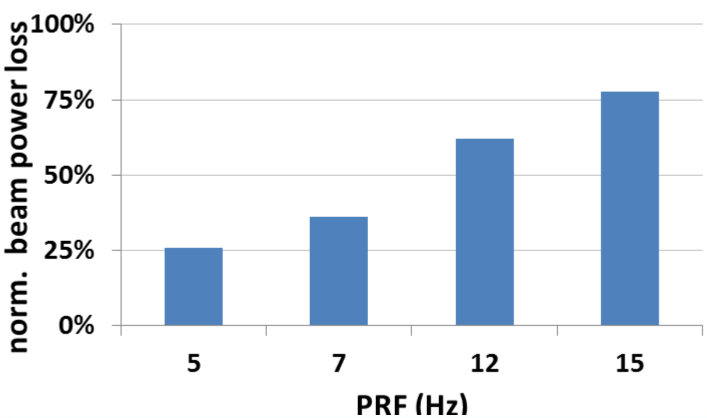
Loss Monitors' Responses

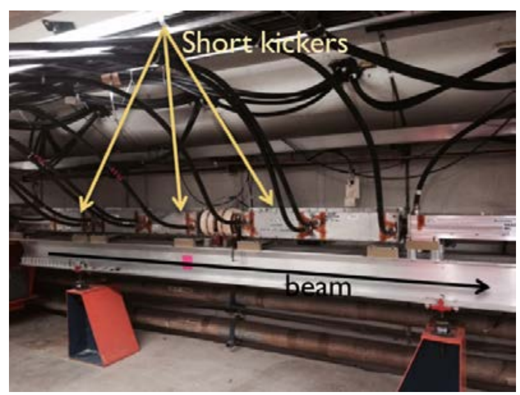
PIP : Notching

- Booster beam requires a notch to allow for the rise time of extraction kicker
  - 40-50 ns notch
- Notch is created by kicking the beam @ 2 different cycle times
  - 400 / 700 MeV ↓ losses down to 5% / 9%
- PIP phase approach
  - Phase I: notch relocation & new absorber
  - Phase II: kicker magnets & power system replacement
  - **Phase III: create notch in Linac**

Bucket spacing at extraction energy ~ 19 nsec

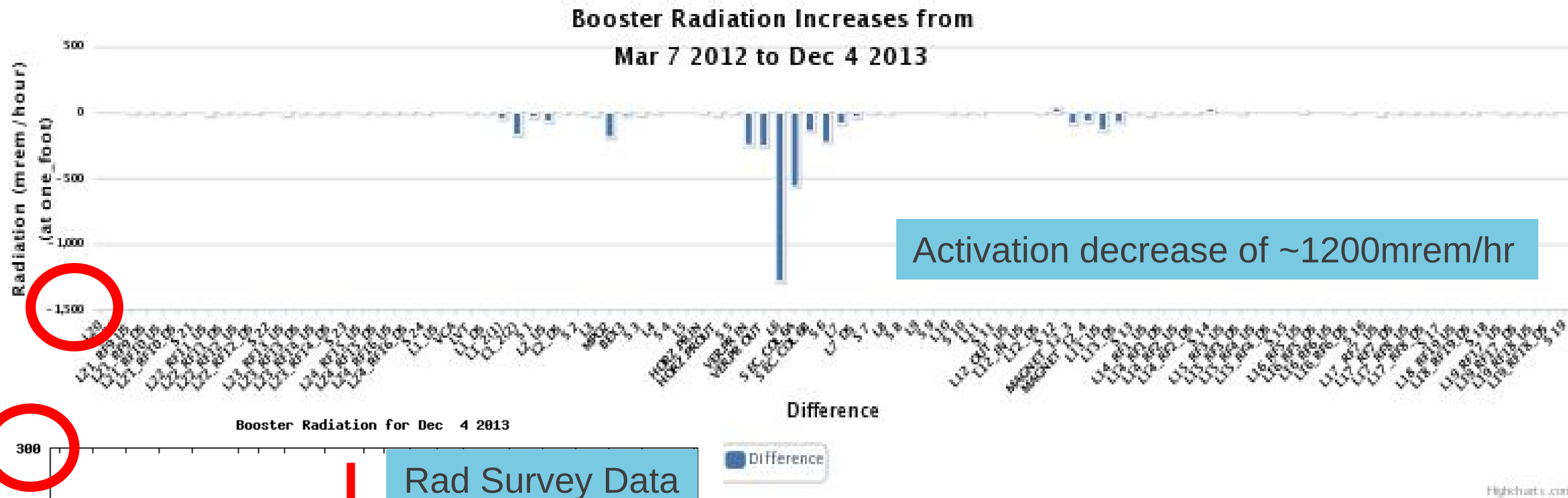


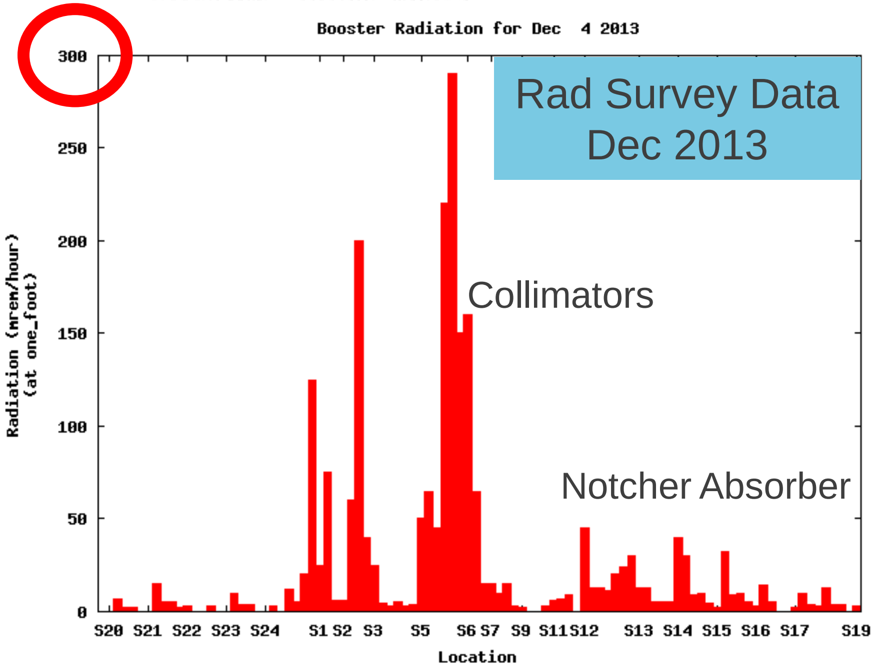





Absorber L13 (2013)

Notcher & Absorber Controlling Beam Losses



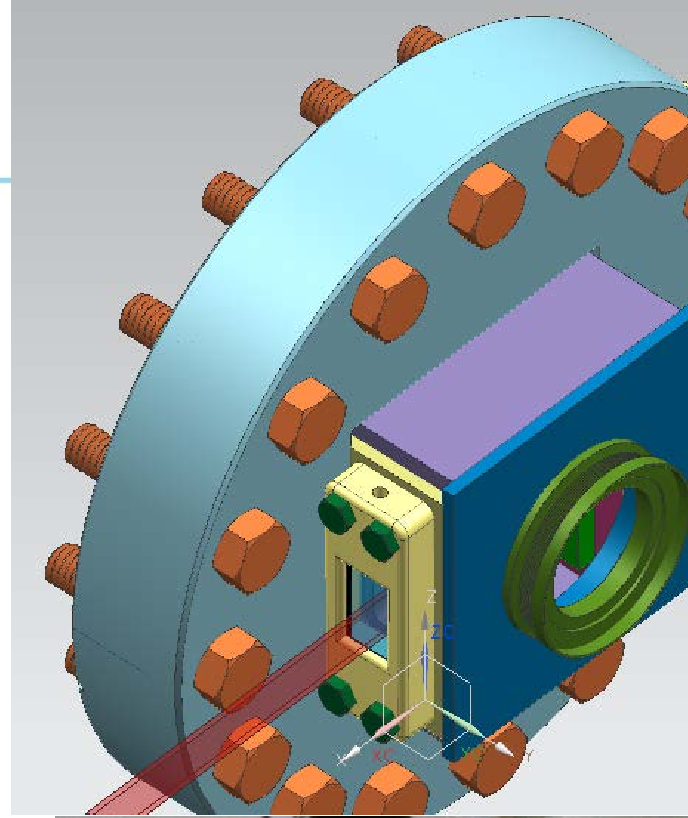


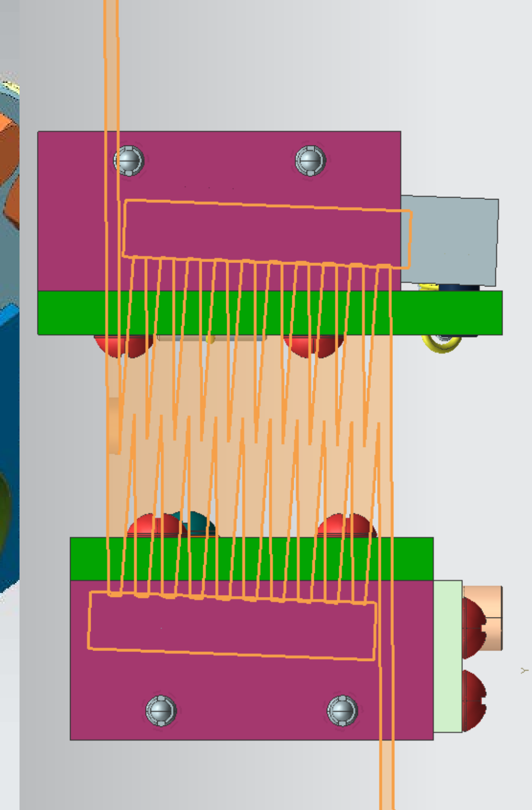
The plot above shows the difference between two radiation activation surveys after running similar flux for a week. The new system has greatly reduced residual activation in several areas of Booster.

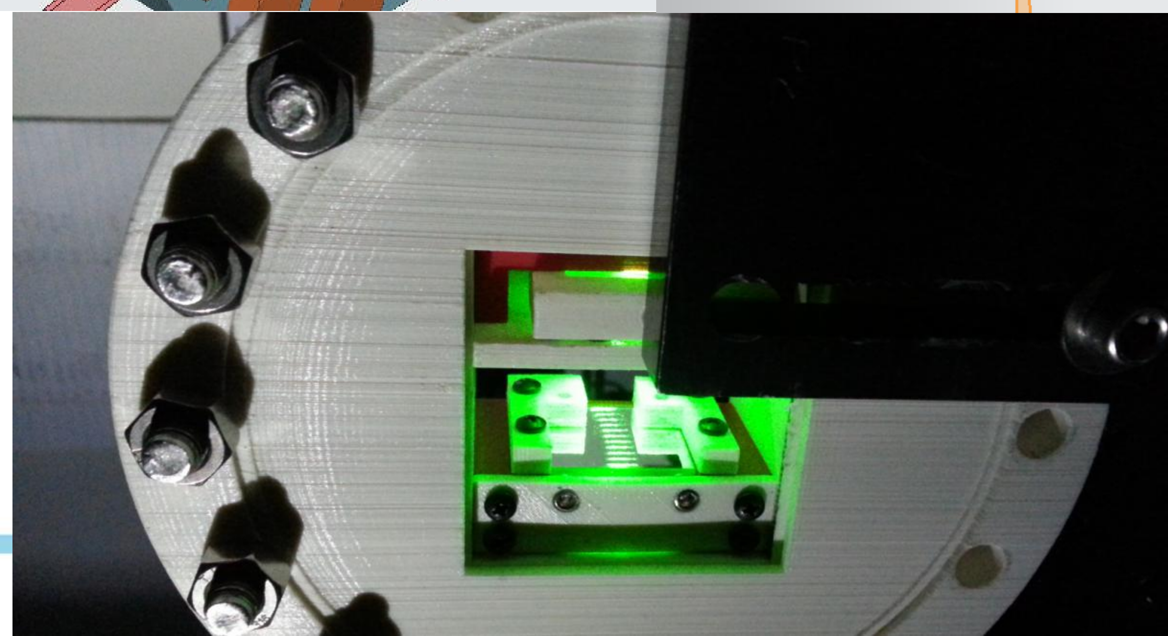
The new notcher system directs the beam to an absorber – old system was not designed for high flux and the kicked 'notched' beam into collimators -- uncontrolled

Laser Notcher

- Neutralize a portion of the Linac beam with a pulsed laser
  - Remove the majority of the loss from the Booster entirely
- Prototype of the laser front-end is operating
  - Atypical laser
    - Multiple timescales
    - High-pulse power
    - Moderate average power (few W)
- Interaction region installed in Linac

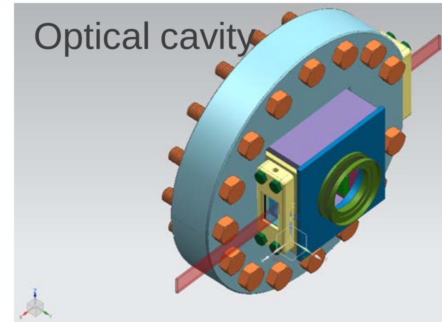


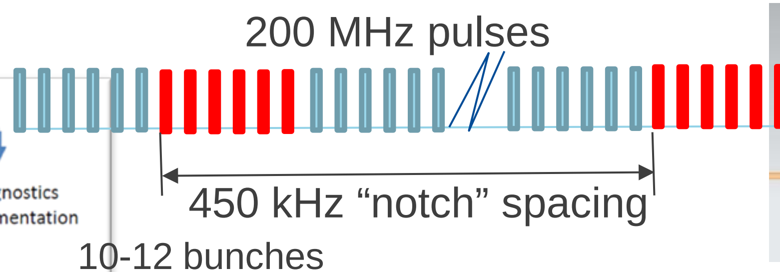


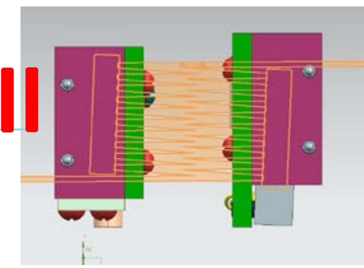


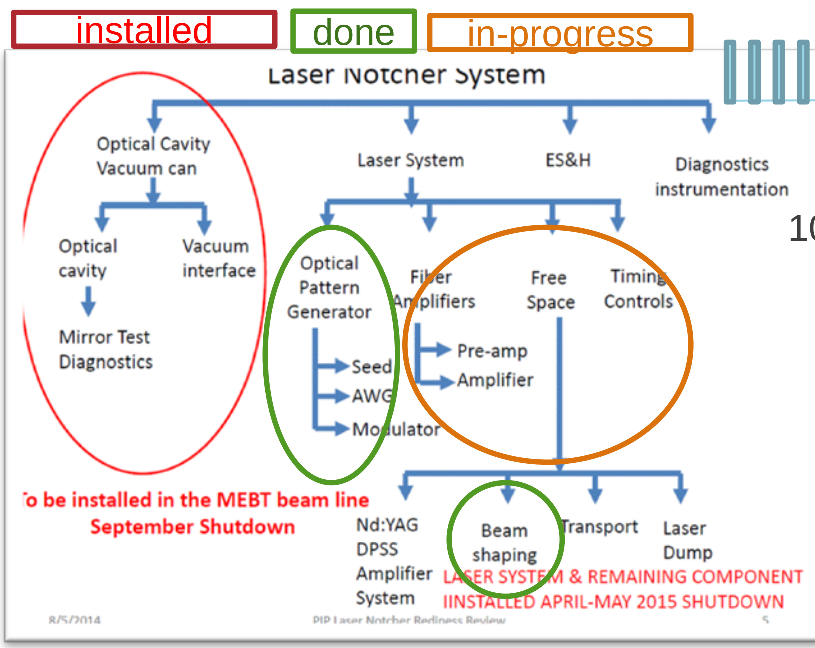
PIP – Accelerator Physics: Linac Laser Notch

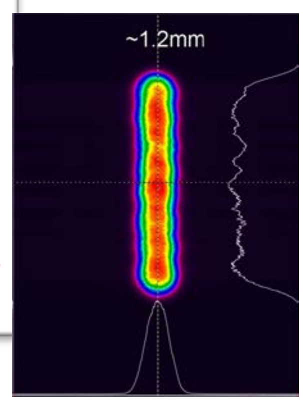
- Neutralize portion of the 750 keV beam using a pulsed laser
  - Create laser pulse pattern for 200 MHz and 450 kHz
  - Amplify pulse using a three-stage fiber amplifier
  - Create spatial uniform photon beam
  - Insert laser into a zig-zag interaction cavity

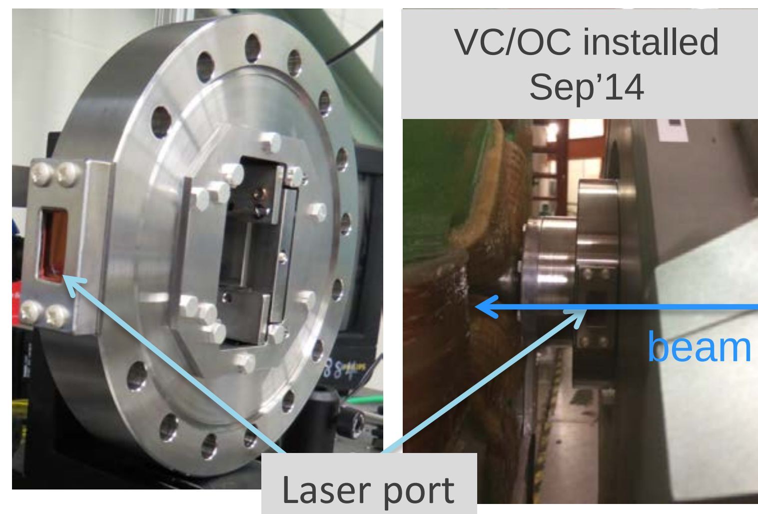












System internal review - Aug’14

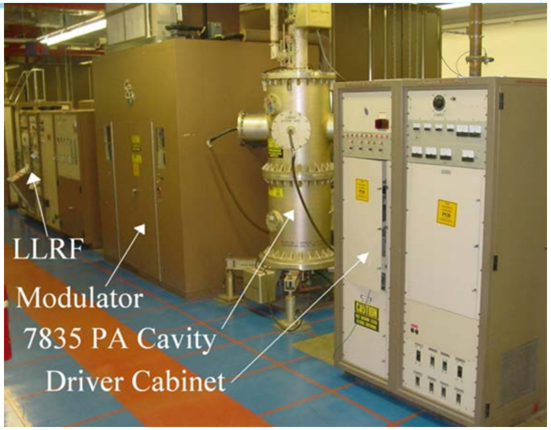
APT Seminar – Mar’14

Final installation expected FY15

PIP – Linac 200 MHz RF system: issues & risks

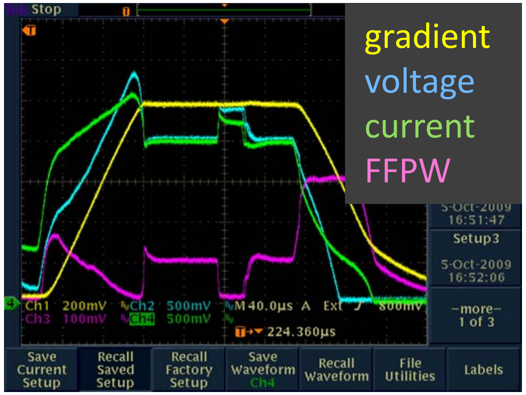
- The 201.25 MHz RF power system has been a big concern for over a decade in regards **long term operational reliability and viability**
- The **issue** of retaining the 201.25 MHz RF system is
  - specialized maintenance required and extensive downtime generated by the tube modulator
    - F1123 discontinued production for over 10 years
  - short lifetime, high-cost & limited market of the final power amplifier
- The **risk** of retaining the 201.25 MHz RF system is that
  - power tubes could become unobtainable to support operations until 2025
  - additional vacuum tubes could become obsolete in the modulator &
    - F1123 no longer be rebuilt -> years of operation ~ **6 years**
- **PIP plan** to address these issues is
  - build-up 4 year in-house inventory of the 7835
  - develop a workable plan to replace the final amplifier in case tube line production is discontinued
  - replace the high voltage modulator with present day technology

PIP – Linac 200 MHz RF system: Modulator



- Modulator provide pulsed power to the plate of the 7835 triode
  - Plate modulation to provide tank field control

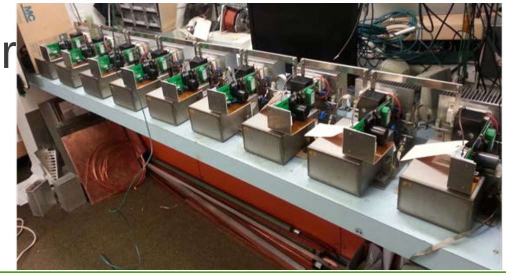
60kV 35 amp DC PS → (30kV 350 A) → Modulator F1123 3 triodes → (10-35kV 100-350 A) → FPA 7835 plate → (0.6MW 3.5MW)



- Modulator contribution to Linac downtime is ~57%
  - Depending on the nature of the fault, each event may bring the system down from a few minutes up to tens of hours
  - MTBF: ~ 10 hrs
    - DC pwr sply – built directly to the frame
    - Switch tubes no longer manufactured
      - Rely on rebuilds to operate
    - Outdated relays & interlocks
    - Minimal diagnostic capability

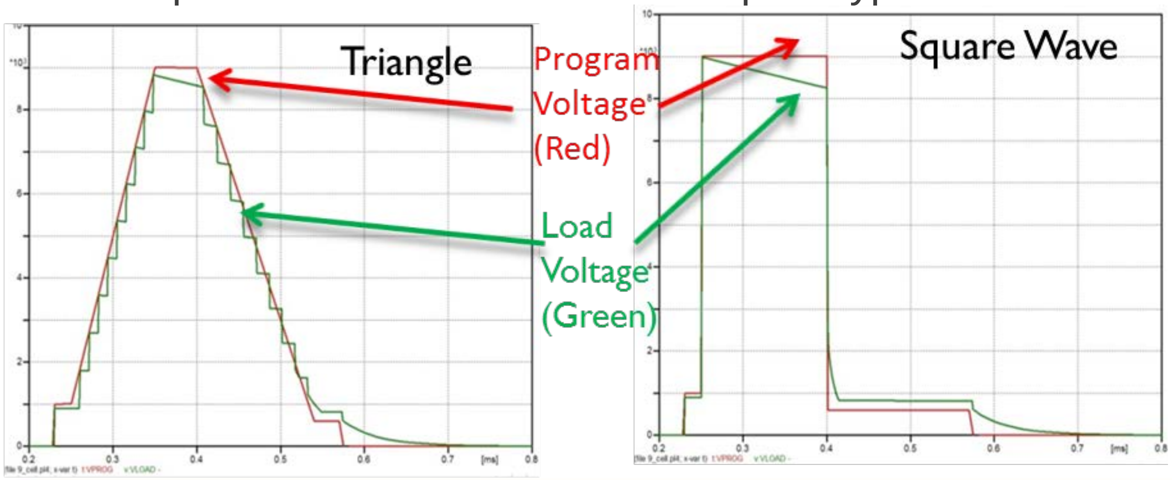
PIP – Linac 200 MHz RF system: Modulator

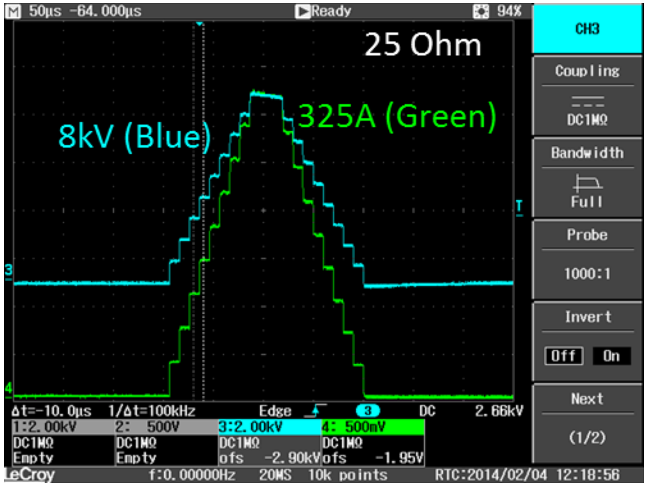
- **Modulator upgrade – 35 kV, Marx-topology modulator to drive triode**
  - Could even drive klystron with proper pulse transformer
- **SLAC** "ILC-like" modulator (uses 3 kV cells)
  - ILC Mark modulator (-120 kV/140Amp w/ ***32 cells***)
  - modified ILC (35kV/350 Amp w/ ***15 cells***)
- **AD/EE** designed using modulator specification
  - designed with 1 kV cells, requiring ***53 cells*** total
  - built 9 cell modulator for testing (see pictures)
  - building 25 cell modulator for further testing
  - plan to build full 53 modulator prototype in FY15



AD/EE design

- best meets original specifications
- lower cost than SLAC
- in-house expertise

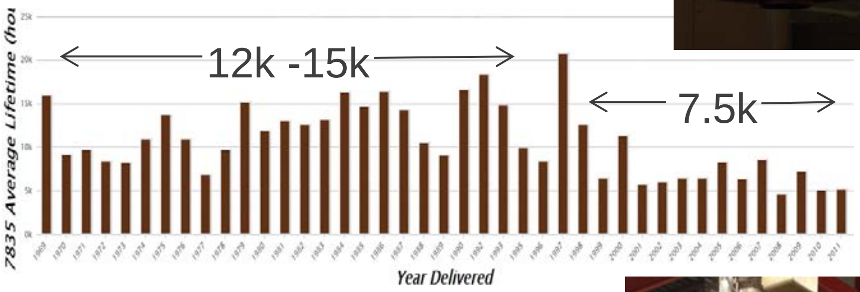


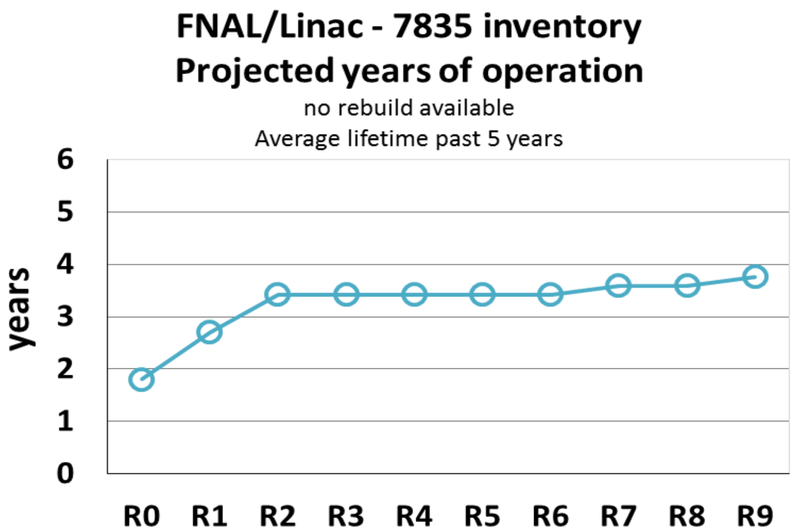


PIP – Linac 200 MHz RF system: PA

- 201.25 MHz final power amplifier
  - Single vendor: Photonis USA (former Burle)
  - National laboratories are the only users (FNAL,BNL,LANL*)
  - Typical delivery time: 200 days
  - Operation needs: 5 tubes
  - Lifetime: ~ 8-10 months

*LANL upgraded one tank to diacrode Jul/2014





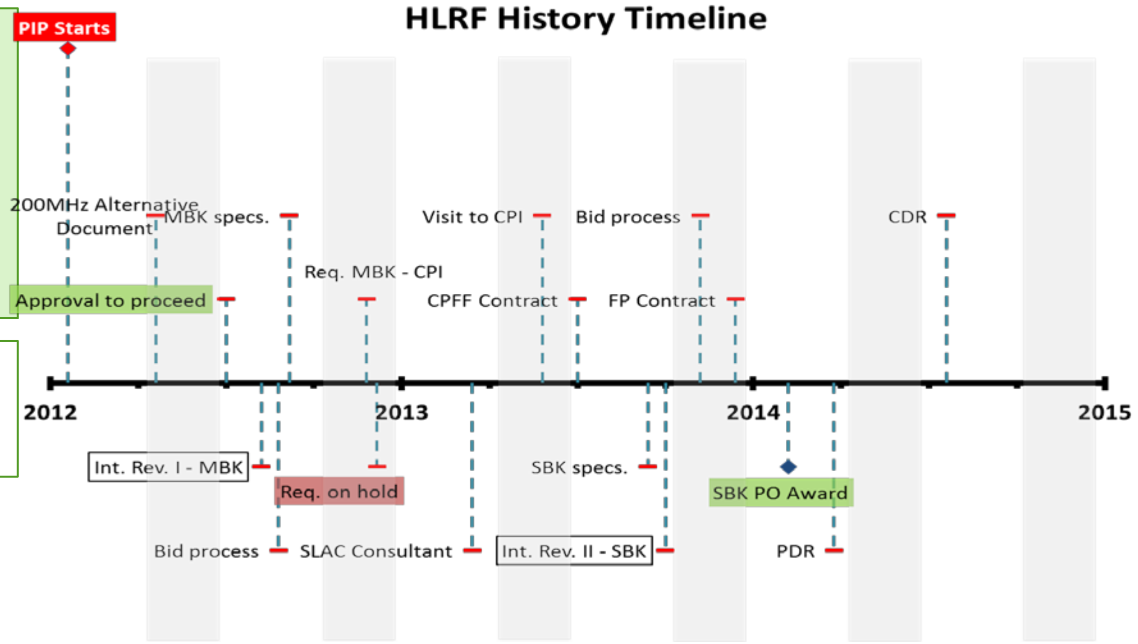
- There is no RF conditioning at the vendor site
  - Typical 15 days/tube for 2 techs
  - 6 tubes conditioned annually
  - Time consuming effort (4-5 months)

PIP – Linac 200 MHz RF system: HLRF

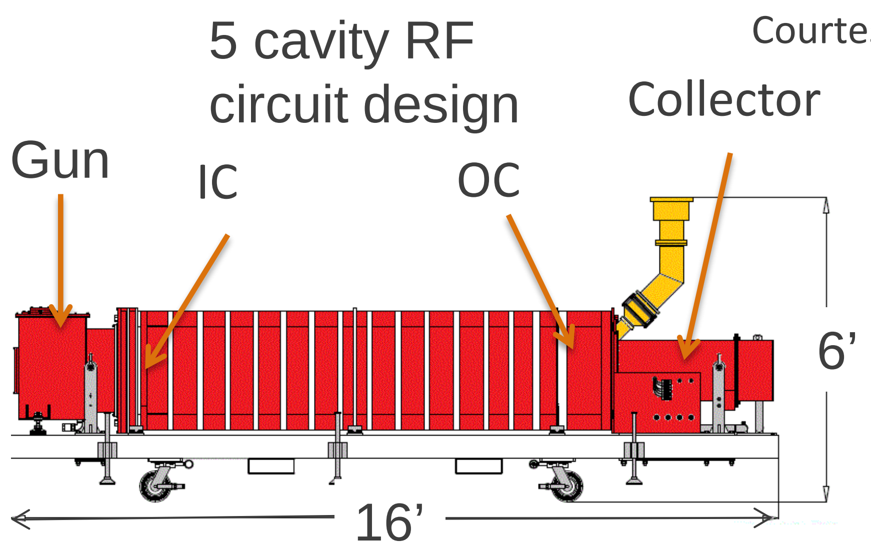
- Study conducted in 2012 discussed alternatives to the triodes
  - Tetrodes (LANL design)
  - Klystron-based 200 MHz RF
  - “SNS-like” 400 MHz Linac
  - Cost took in consideration series of criteria evaluated against over the expected lifetime of the Linac
    - Criteria: supply chain, technical risk, M&S/labor construction, upgrade time, maintenance cost and program interruption time

After careful consideration, the **201.25MHz klystron-based** RF power system was chosen as a plausible replacement for the 7835 triode

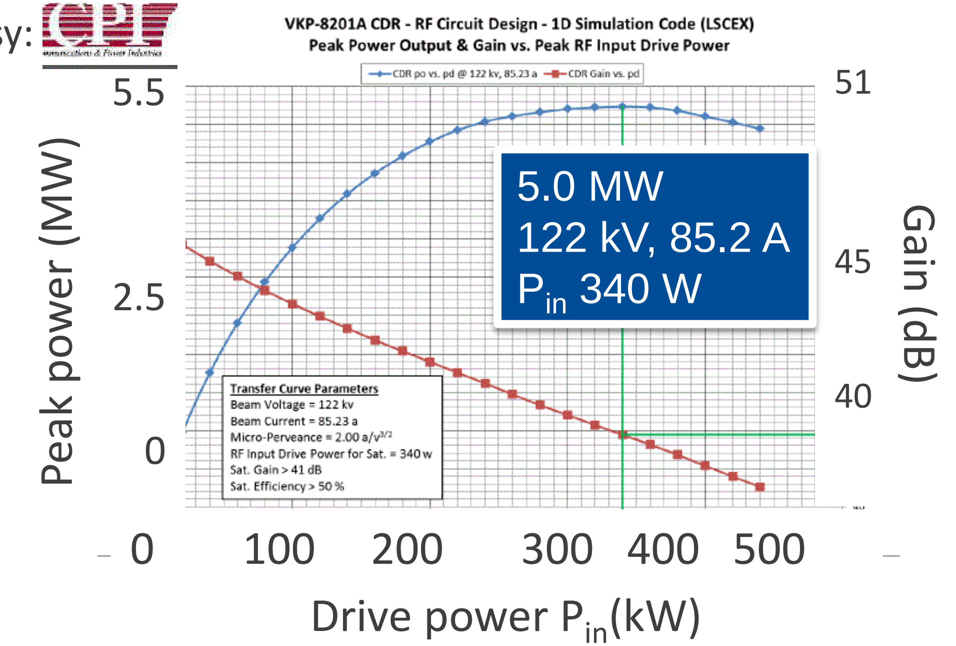
A prototype is being designed and built at CPI

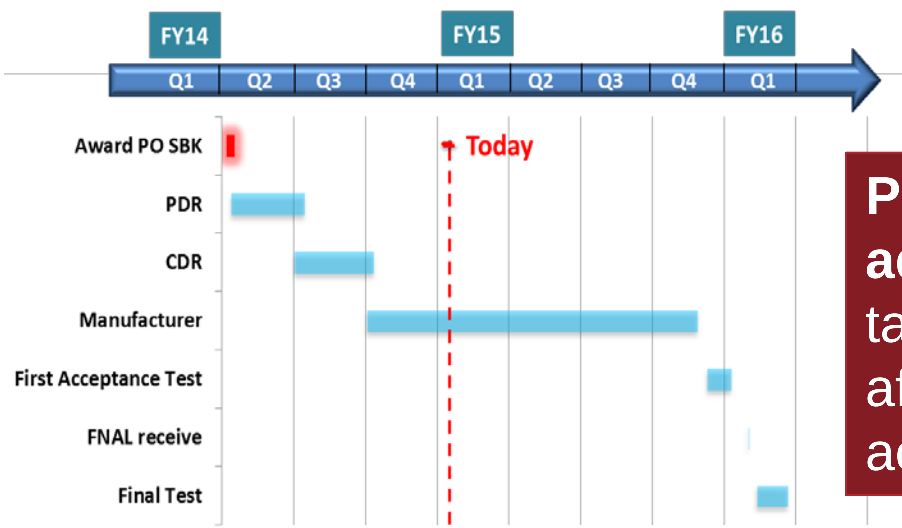


PIP – Linac 200 MHz RF system: HLRF



Courtesy: CPI

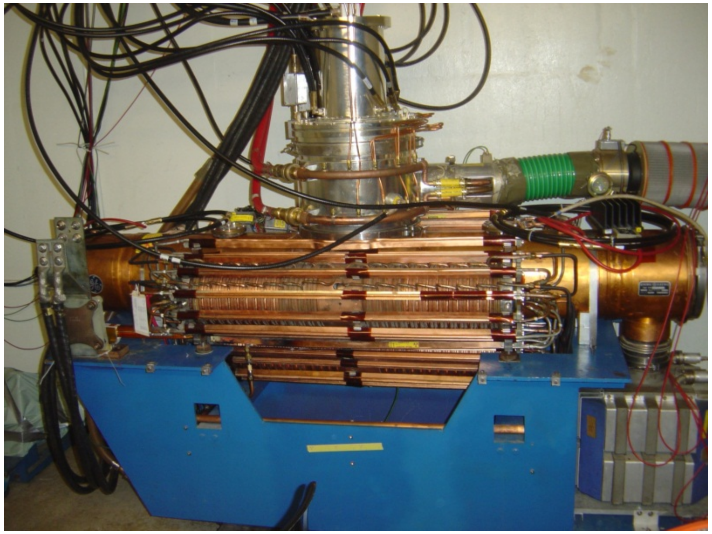


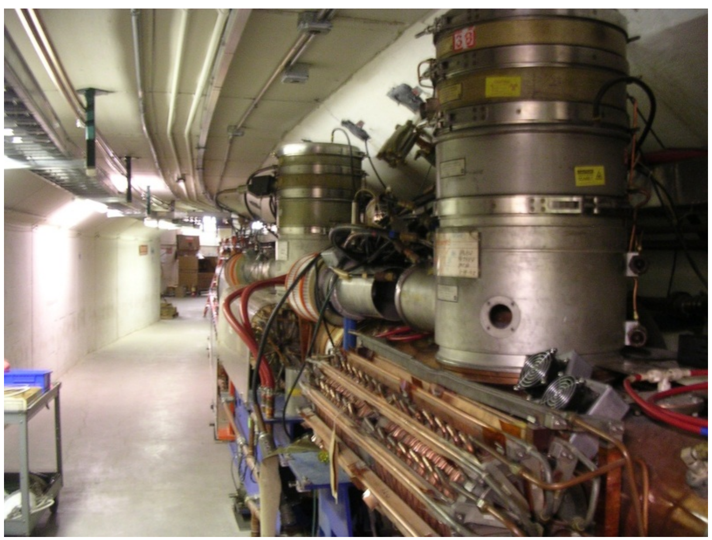


PIP to PIP-II adjustment:
task completes after successful acceptance-test

DTL
f_0: 201.25 MHz
Saturated efficiency: > 48%
Perveance: 2.0 mA/V$^{1.5}$
PRF: 15 Hz
Pulse length: 450 msec
J_{cath} : 1 A/cm^2
Expected lifetime: > 200 hrs

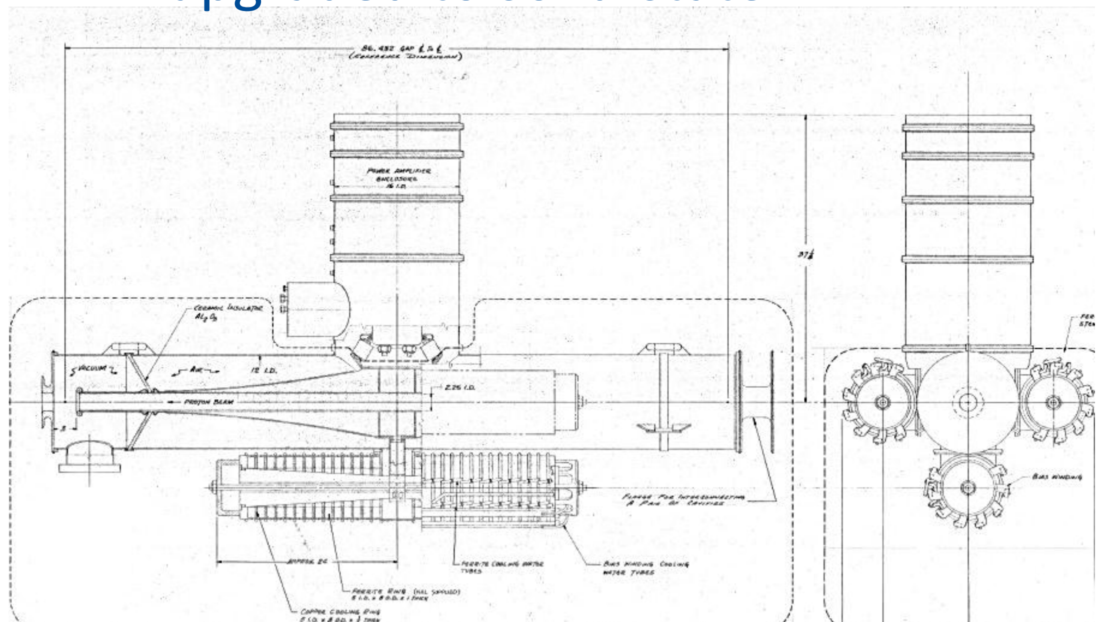
Booster RF cavity





Designed in 1969 – several small modifications but largely original cavity

- 19 stations
- 2 gaps @ ~ 24 kV
- Tunable 24 – 53 MHz
- Power amplifier system already upgraded to solid-state in PIP



Booster PIP - Refurbishment of 40 year old cavities

(Weeks)

Cool-down

Remove Tuners

Cavity Removal

Rebuild - Cones & Tuners

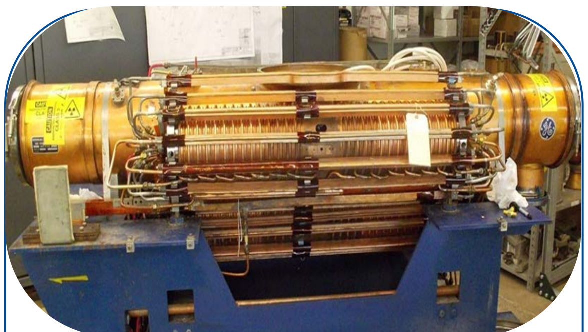
Rebuild Stems/Flanges

Re-Assemble

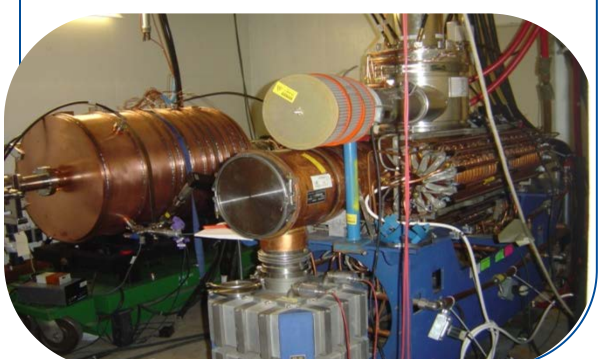
Testing

Cavity Removal - Stripping

Tuners Rebuild



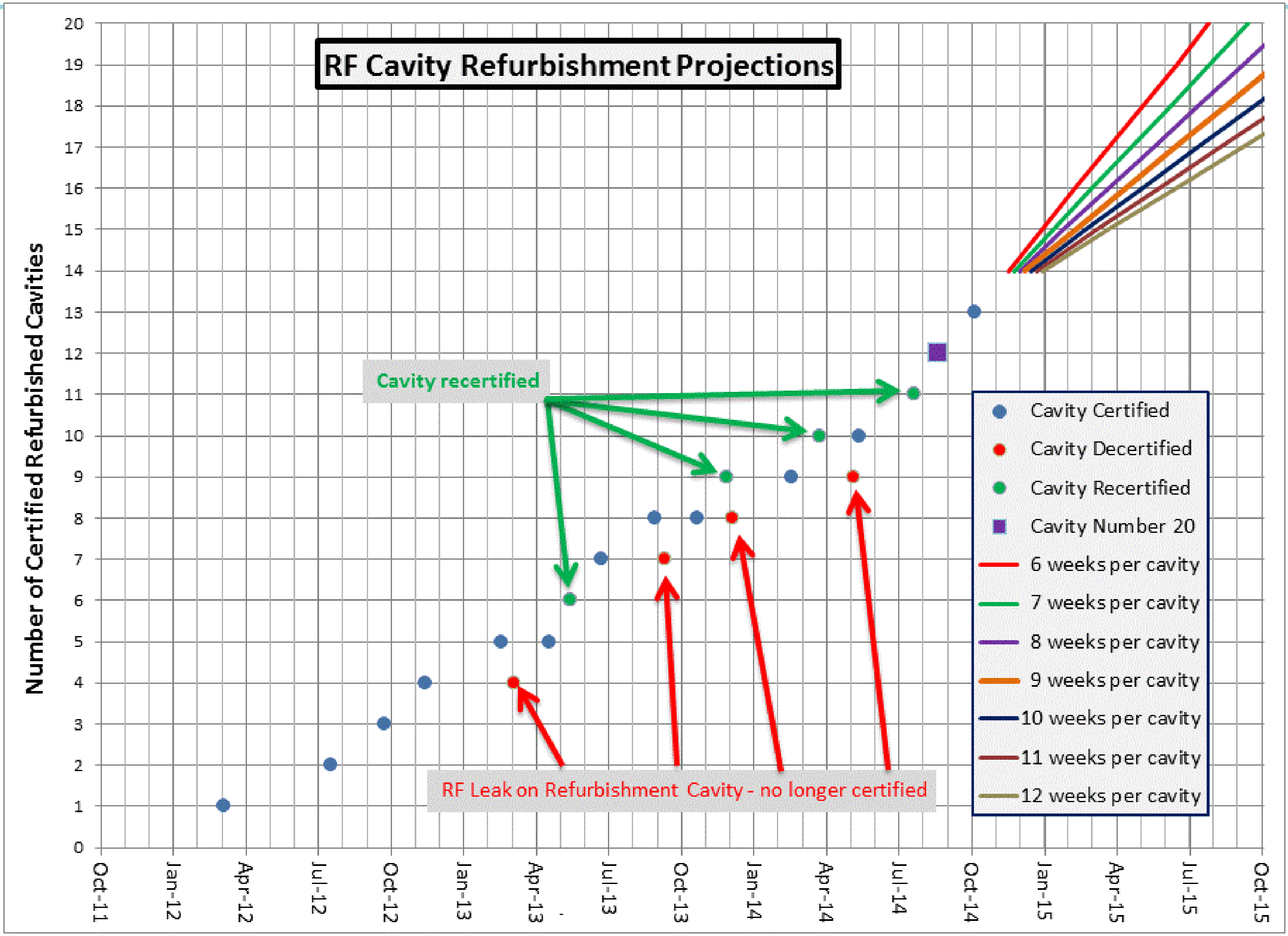
Rebuild and Test



Booster refurbishment

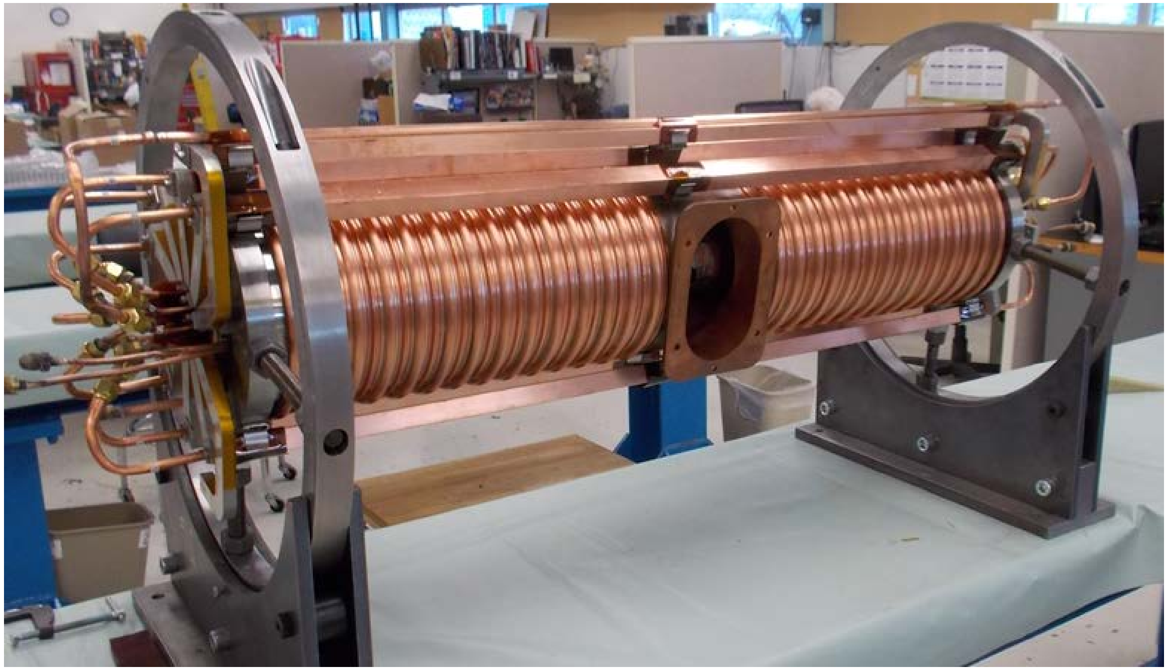
- Goals: Completion of Refurbishment in FY15
  - (19+1) cavities after refurbishment is complete
    - (+1) comes from an originally rejected cavity
  - 22 cavities will be the final number
    - 2 cavities will come from the Proton Driver project after modifications to their aperture
  - Reliable 15 Hz operations will require overhead
    - Uncertain failure rate at 15 Hz operations
    - At least 17 cavities for 4.5e12 protons per pulse
      - longitudinal beam quality is decreased, higher losses through transition.
  - Make 20 spare tuners (3 tuners per cavity)
    - New tuners will be made by TD for refurbishment as well as for long term operations.
      - Reduced repair time
      - Lower worker exposure rate

Booster RF cavity refurbishment status



New tuners

- Build new tuners to replace complete failures, accelerate refurbishment process, and reduce worker dose
- New tuner has been in service for 10 weeks of running
- Placed requisition for ferrites (enough for 20 tuners)
  - worked with vendor (National) for 2+ years to get recipe for ferrites correct
  - Delivery before end of year – ready to build immediately

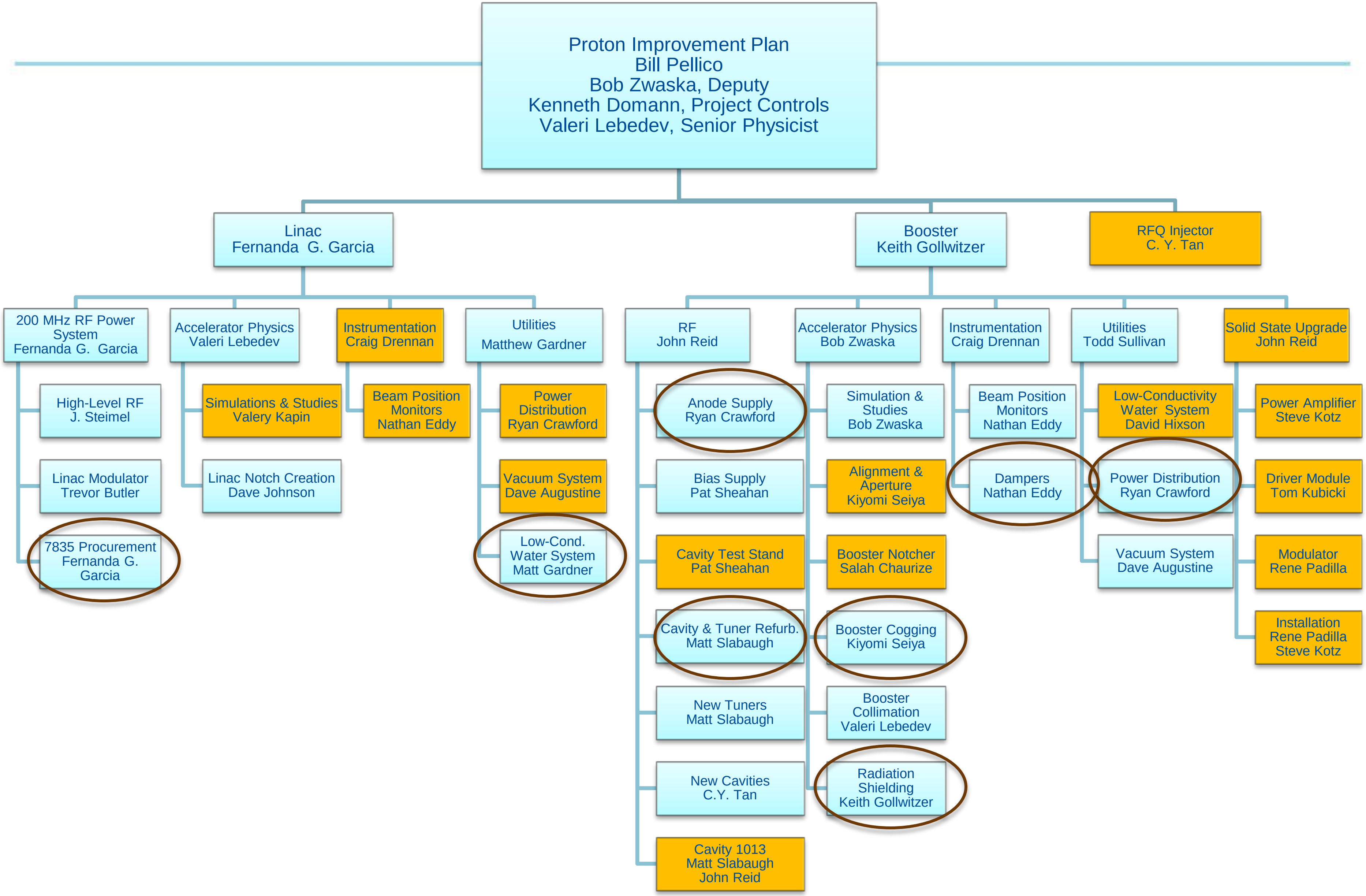


Booster RF station (Solid State upgrade completed in FY13)

Ferrite Bias Supply · Modulator · Control Rack · SSD · Controls · Ferrite Bias Supply · Modulator

Original Booster RF Station

Upgraded RF Station with SSD + New Modulator


Proton Improvement Plan
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Driver Module
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Modulator
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Installation
Rene Padilla
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Conclusion

- PIP has been working for three years
  - Many infrastructure upgrades already performed
  - Notching improvements are straightforward path to higher throughput
    - Control loss with improved notching in Booster
    - Eliminate loss with laser notching in MEBT
  - 200 MHz RF: replace modulators, reduce risk on power amplifiers
  - Booster cavities: refurbish all, gain overhead, replace many parts

- Transition time coming for PIP:
  - Increased proton demand to be realized with Recycler commissioning, new experiments
  - Scope adjustments to anticipate a PIP-II Linac replacement

Fermilab

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Enhancements of the Fermilab Booster to Reduce Losses and Extend Lifetime:
The Proton Improvement Plan

Robert Zwaska

11 November 2014

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