Proton Improvement Plan (PIP)

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Fermilab Science & Technology Review

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U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

PIP S&T Outline

- PIP Summary - Overview
- RFQ Injector
  - Highlights of RFQ Injector Line
- Linac
  - Tasks
  - Technical Work Review
  - Near Term Work Plan
- Booster
  - Tasks
  - Technical Work Review
  - Near Term Work Plan
- Summary

PIP

FNAL Accelerator Associate Director - 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

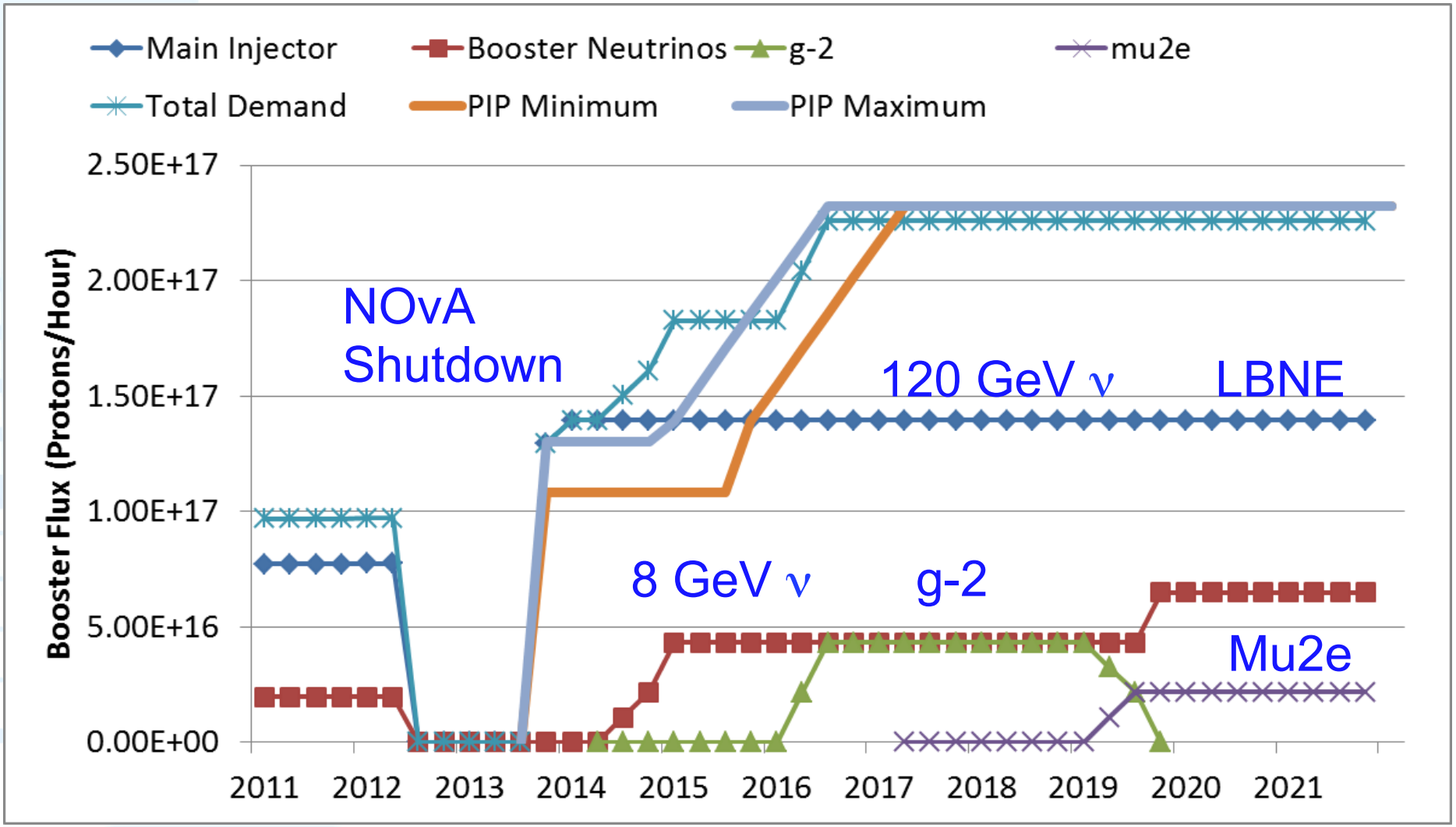
- Linac/Booster availability > 85%, and

- residual activation at acceptable levels

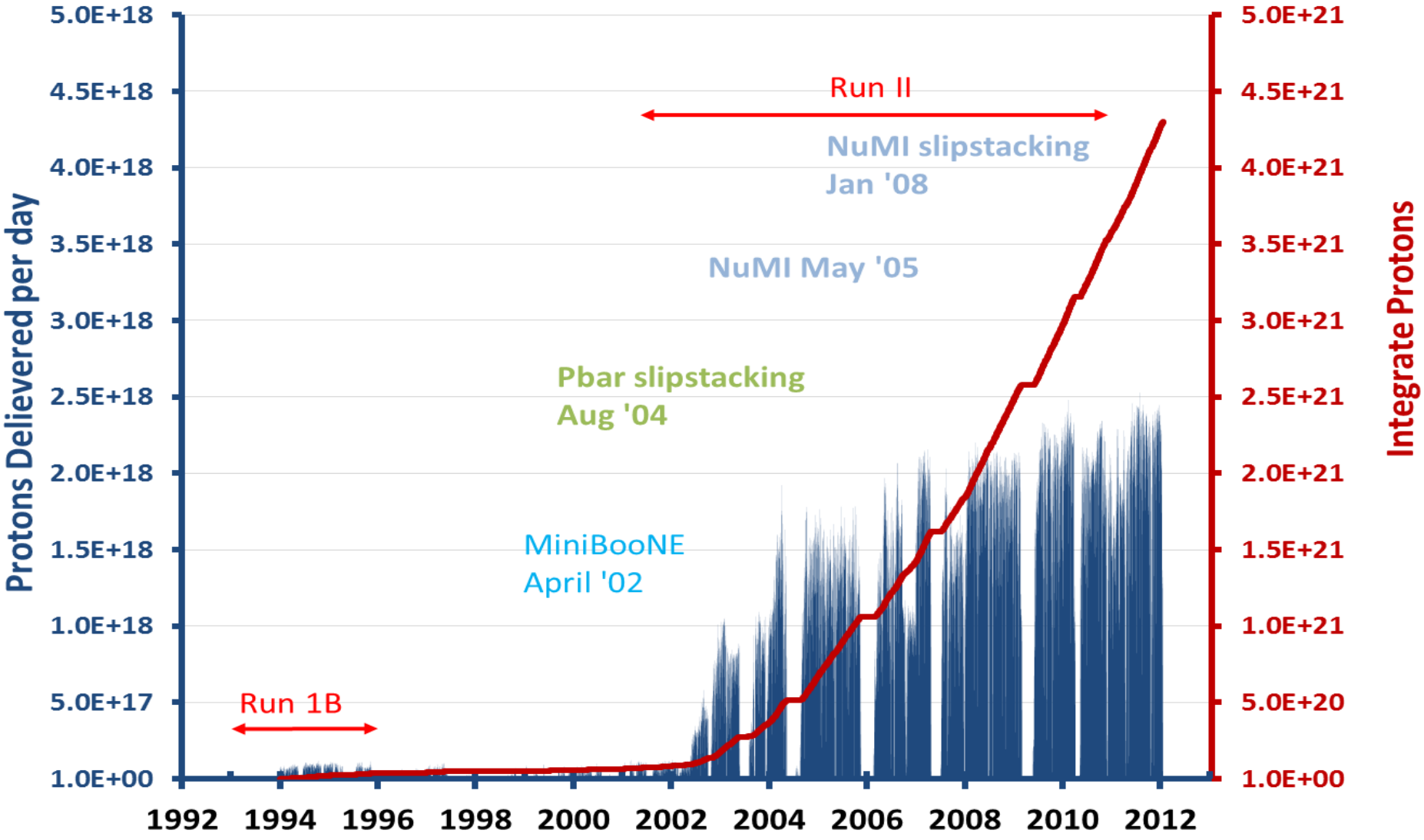
and also ensuring a useful operating life of the proton source through 2025.

- The scope of the ***PIP*** includes
  - increase Booster repetition to 15 Hz rate by upgrading (or replacing) components
  - replacing components that have poor reliability or lifetime issue
  - studying beam dynamics to diagnose performance limitations – necessary to double proton flux while maintaining current levels of activation

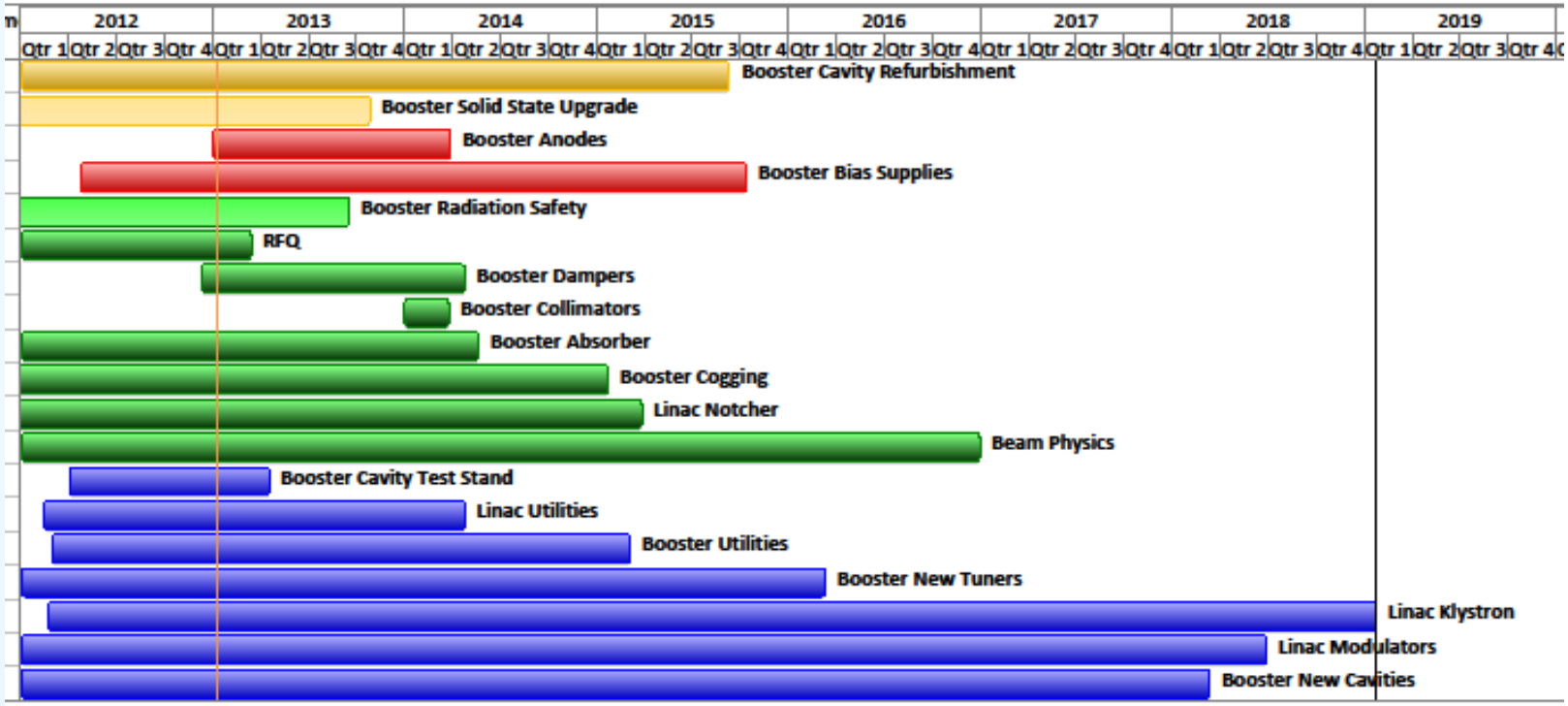
PIP – Program Projection



Historical beam throughput in Proton Source



PIP – Timeline Baselined 2012



~~Required for 12 Hz~~

Required for 15 Hz

Required for Flux

Required for Reliability

End of Proton Plan Effort

Proton Source Task Force 2010

Proton Source Workshop 2010

PIP Begins 2011

PIP Design Handbook & Project Controls 2012

RFQ Injector & Booster RF Solid State Complete 2013

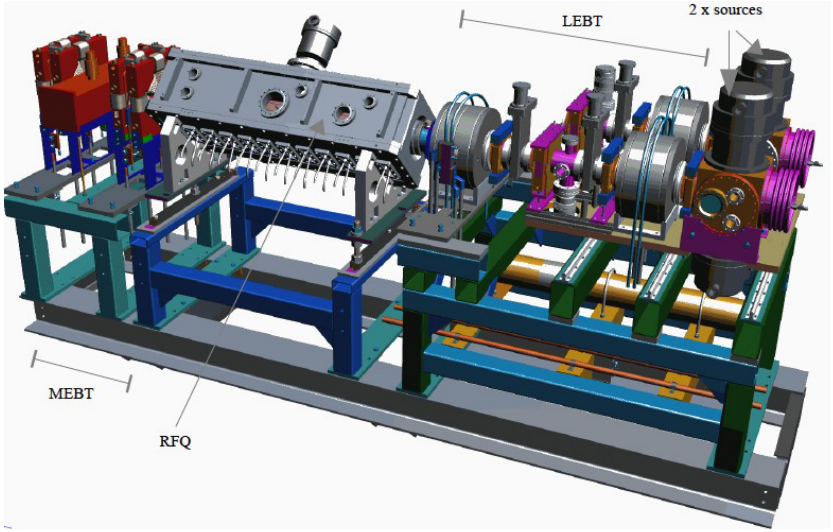
Booster 15 Hz Operation 2015

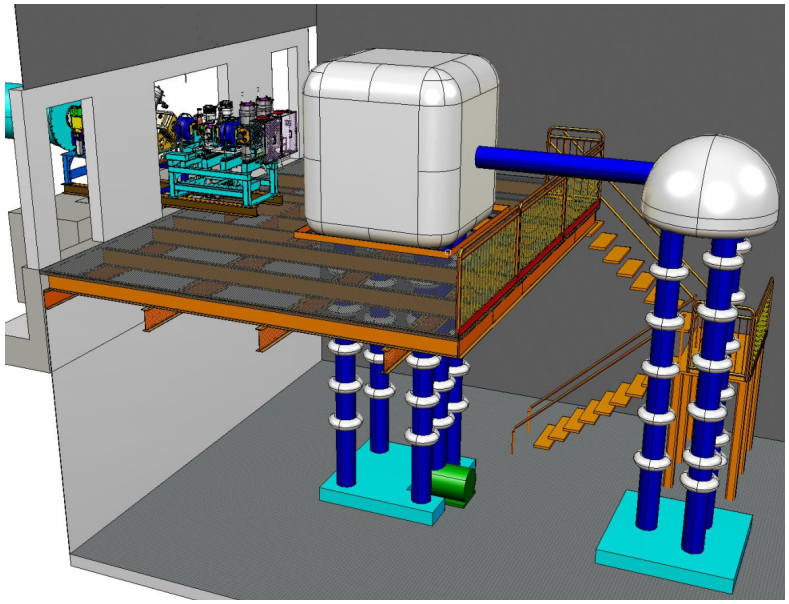
Linac High Power RF System Completed 2019

Project Complete 2019

PIP RFQ Injector

- Started in 2009
- Completed in 2013
  - RFQ Delivered 2011
  - Solenoids 2012
  - Quads/Trims 2012
  - Buncher 2012
- Beam Tests 2012
  - Test Area
    - Full Controls
    - Diagnostics
- Install Fall 2012
  - 1st Beam Nov 2012
  - Fully Commissioned Jan 2013



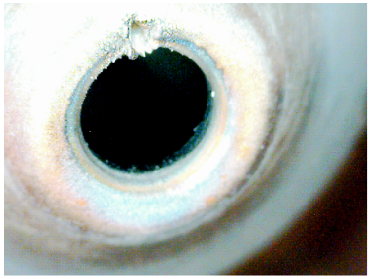


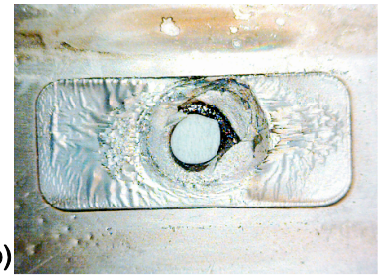
Injector Line

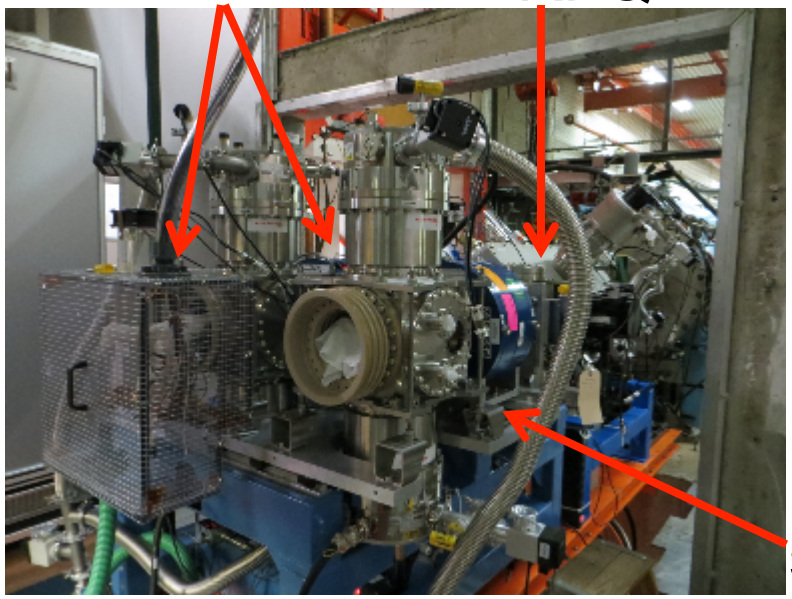
- Source Design (lots of design modifications)
  - Round Dimpled Magnetron Sources
  - Materials, Pressure Control, Magnetic Containment
- Quads / Buncher
  - Based upon BNL design – modified for our needs
- Solenoids/Trims
  - TD design
- RFQ
  - Rod Style – Asymmetric due to support stands
  - Dr. Schempp (University of Frankfurt) design

Parameter	Value
Energy	35 – 750 keV
Frequency	201.25 MHz
Length	120 cm
Design current	60 mA
Peak cavity power	~ 170 kW
Radial aperture	0.3 cm
Duty Factor	0.12%

Changed extractor cone tips from molybdenum to tungsten to prevent damage. Also changed inner anode cover plate from titanium to molybdenum to prevent erosion.

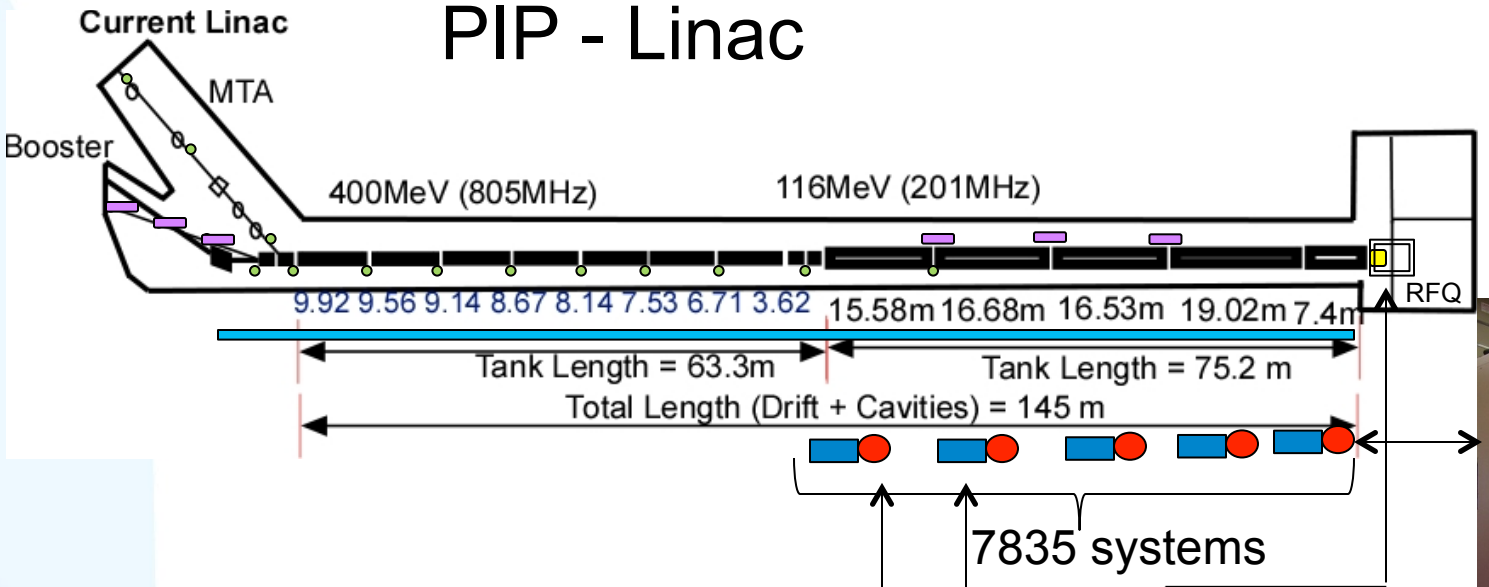
a) 

b) 

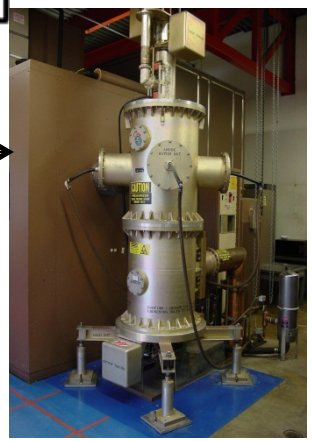


slide

PIP - Linac



Modulator & 7835 Socket



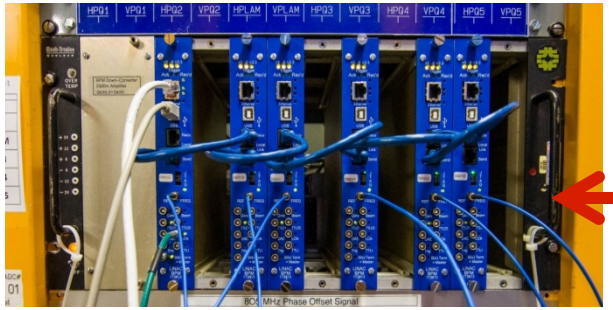
- WBS Linac Tasks
  - 200 MHz PS Prototype
  - 200 MHz PS Modulator
  - 7835 Tube Acquisitions
  - Laser Notching
  - Water Systems
  - Vacuum Systems
  - BPM System
  - Accelerator Physics

Low Energy Linac

Fermilab

PIP – Linac BPM System

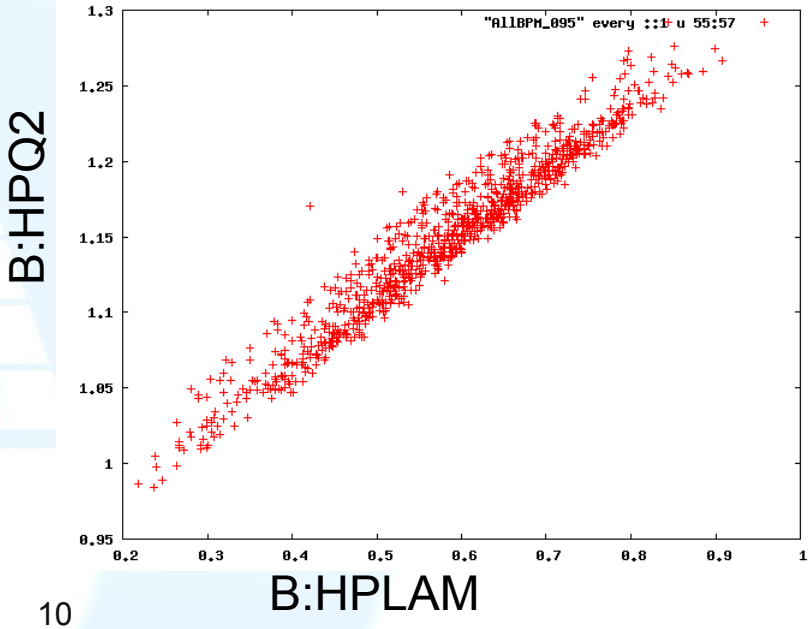
- 67 Dual Plane BPMs
  - Digital System
    - Position
    - Phase
    - Intensity
  - Software



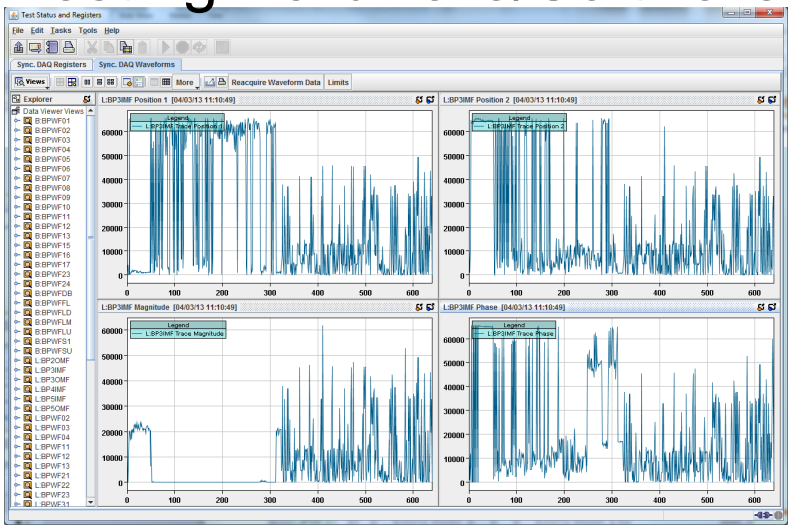
The new custom electronics provide a low cost solution to process the 2nd harmonic of the 805 MHz RF. A single four-channel NIM-bin module is used to readout each four-plate stripline BPM pickup.

BPM ELECTRONICS UPGRADE FOR THE FERMILAB H- LINAC BASED UPON CUSTOM DOWNCONVERTER ELECTRONICS

E. McCrory, N. Eddy, F. G. Garcia, S. Hansen, T. Kiper, M. Slicznia
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA



Testing Hardware/Software



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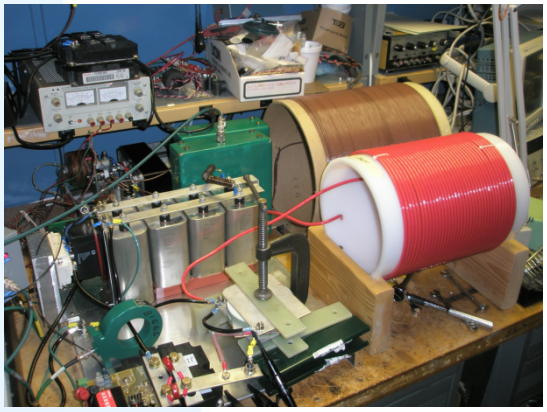
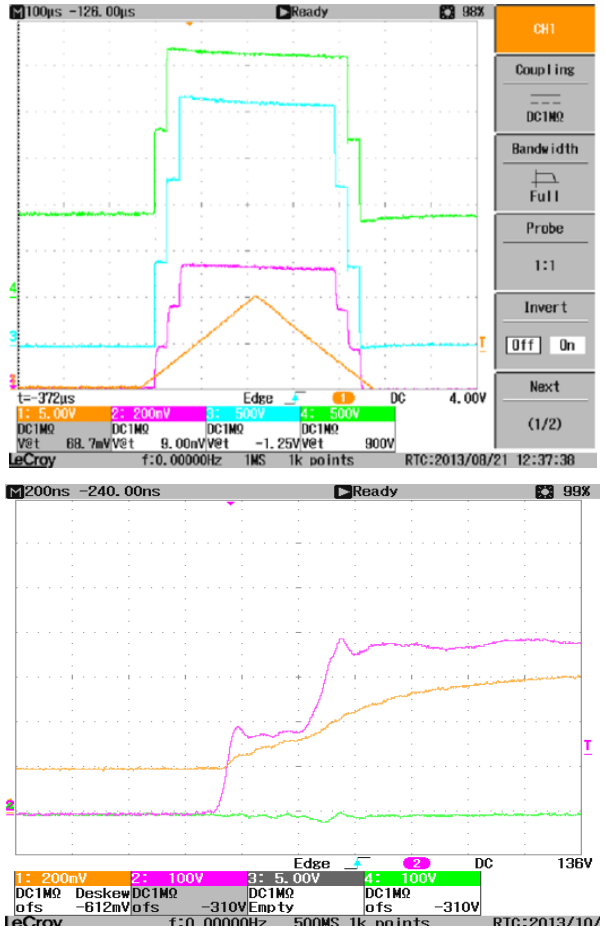
PIP – Linac Modulator

- 7835 Modulator
  - Fermilab EE Support Department
    - Testing the basic elements of the EE-Marx Generator design
    - 3 cells were tested
    - 9 cell prototype being built
  - SLAC
    - Based upon Marx ILC modulator
    - Main and Vernier cell design and testing
    - A learning control System – next step



FNAL - Initial 3 cell IGBT testing

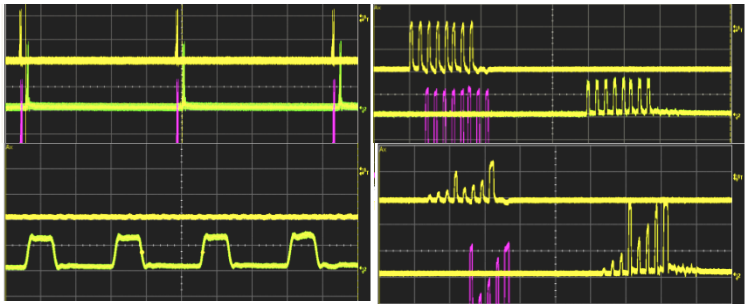


Pink – Voltage Step 200 V
Orange – Load Current 20 A
Green – System Common

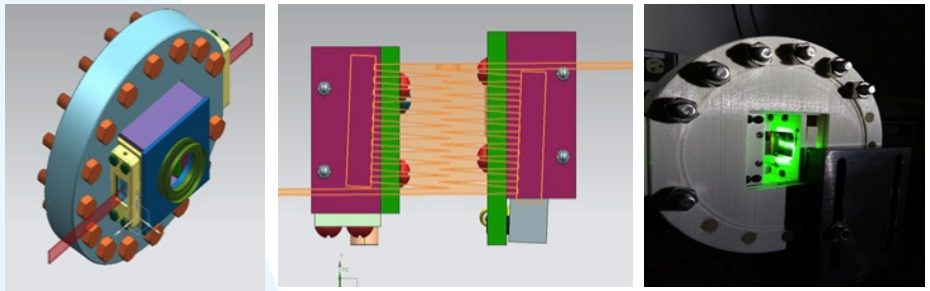
No high frequency ringing

PIP – Laser Notching (750 keV Injector Region)

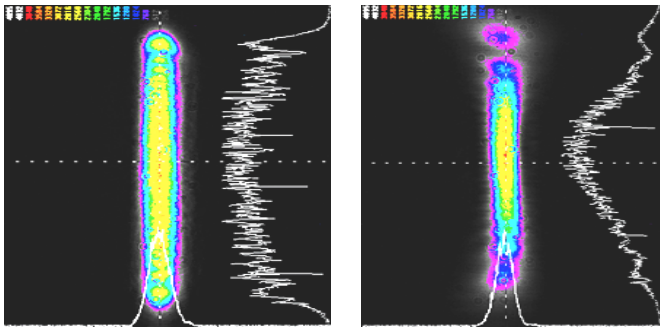
- Laser Beam-Design Parameters
  - Optimize transverse beam shaping
  - Beam line layout
- Hardware Design and Testing
  - Vacuum chamber
  - Amplifiers (fiber & free-space)
    - 1030 nm Cryogenic Yb:YAG technology
  - Waveform generation



Output of AWG (yellow0 and laser pre-amplifier (green) at Booster revolution period (top, left), Linac bunch frequency (top, right), uniform 201.25 MHz laser pulses (bottom, left), and the flexibility to pre-distort the laser pulses at the EOM (bottom, right).



3D model of vacuum chamber and cavity (left), a cut-away of the inside showing the mirrors and laser path (middle), and the 3D printed prototype being tested with green alignment laser (right).



Laser profile of the roof-top beam at 5 cm from the prism (left picture) and 50 cm from the beam (right picture).

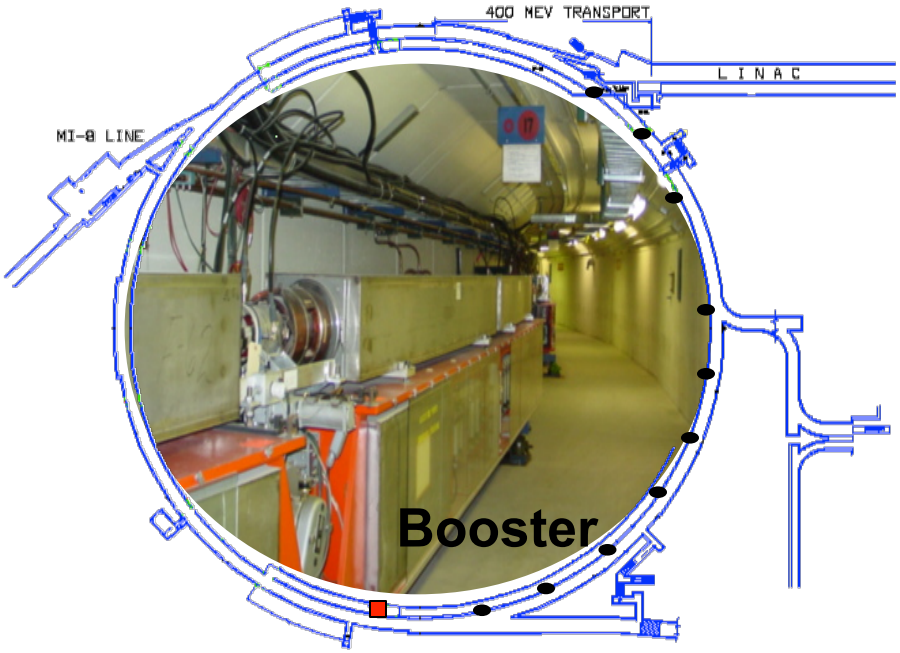
PIP – Linac (Power Amplifier Solutions)

- Building up supply of RF Power Tetrode 7835
  - Single vendor/decreasing lifetime/increasing cost
  - Started with two year inventory
  - PIP plan is to get to 4 year inventory (buffer for termination by vendor)
    - Inventory plan will be adjusted with Klystron effort
- Multi-Beam 201 MHz Klystron (replacement of 7835)
  - Contract negotiations difficult
- Submitted bid for Single Beam Klystron
  - Lower Power
  - Simpler Design
  - Fixed Price Contract
- SLAC personnel working with PIP on vendor/Klystron effort

A critical vulnerability to the Linac operations – will be pursued until certainty of operation or limited liability is reached.

PIP - Booster

- RF Cavity Refurbishment
- Solid State
- New Tuners (For RF Cavities)
- New Cavities
- Accelerator Physics
  - Alignment
  - Beam Optics
  - Beam Notcher
  - Cogging
- Utilities
  - Vacuum
  - Water



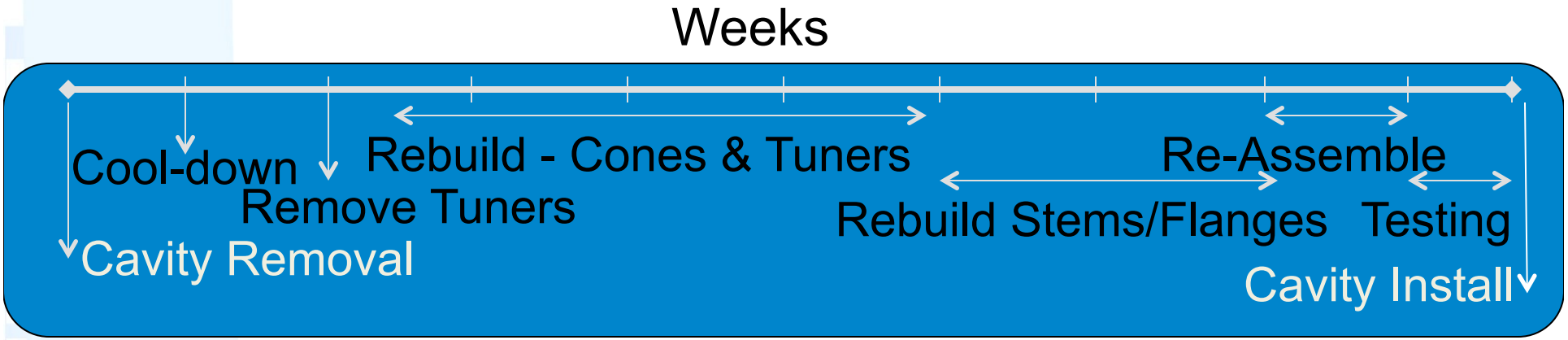
PIP – Booster Cavity Refurbishment (40 year old hardware)

Part of the PIP effort for the Booster Accelerator is to address the increased beam flux that will be demanded by the Fermilab program. The increased flux will be achieved by providing beam on more of the Booster cycles. RF system equipment will increase from an average 7.5 Hz to 15 Hz.

Currently there are 19 RF stations in the Booster. All cavities are required to be certified before running reliably above present beam cycle rate.

In addition to refurbishment, effort is underway to replace RF anode supplies and upgrade bias supplies. Both are necessary for 15 Hz beam operation.

PIP – Booster Cavity Refurbishment Timeline

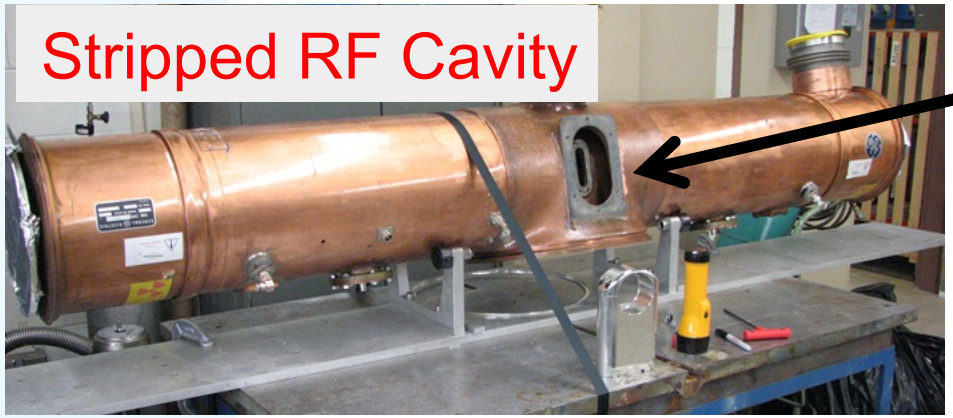


Highlights/Issues

- Cones rework (part of tuner that sits inside of ferrites of tuner) is a labor intensive process that we are working to find an alternate solution
- Worker dose accumulation a big concern
- Limited testing times (minimum 3 days)
- Skilled technicians – training takes months and requires long term commitment
- Limited number of replaceable ferrites (recent success in qualifying vendor)
- Original cavities were built with unacceptable tolerances for 15 Hz
- Rebuilding of tuners has been a re-learning experience and is labor intensive

PIP – Booster RF Refurbishment

Flange Repair Example

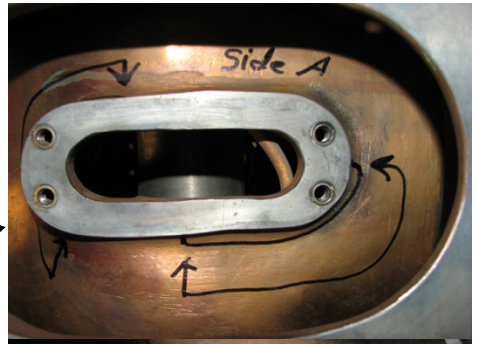


The repair of the flange interface is a critical step in the rebuild process. This connection has been shown to be one of the limiting factors in reaching 15 Hz operation.

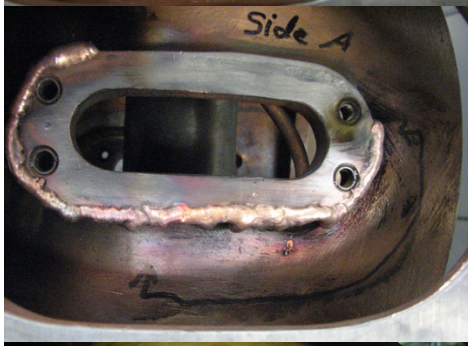
The original design was insufficient for high rep rate operation and has several design flaws.

Recent addition of a milling machine will help.

Check of tuner connection gap size (typically uneven/gaps)

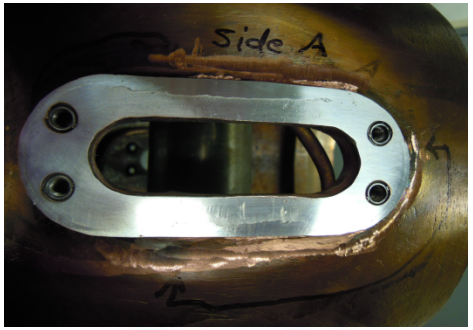


Welding on filling



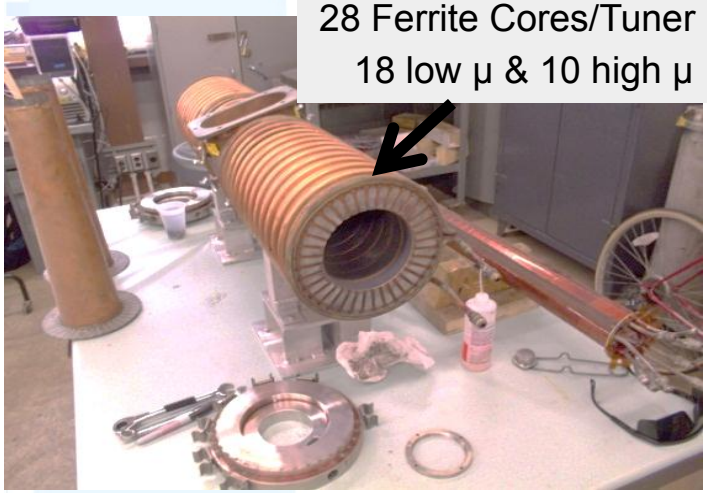
After grinding down welding fill - sanding

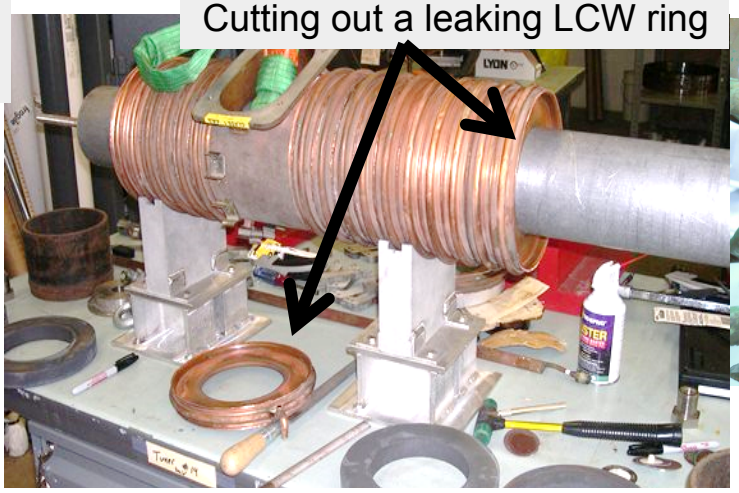
After Tin electroplating



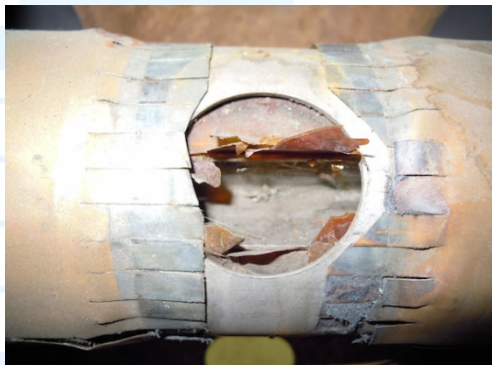
PIP – Booster RF Refurbishment

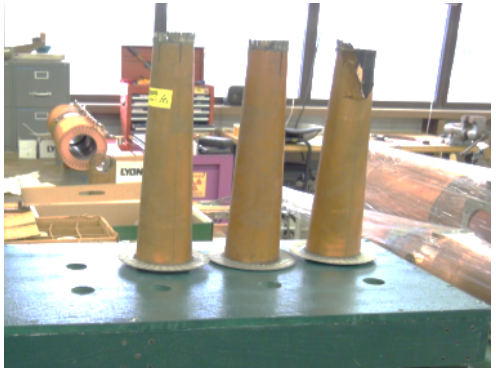
Tuner Repair/Rebuild

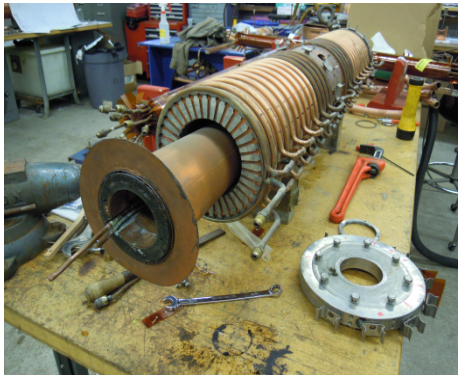




Tuner with LCW leak being reworked





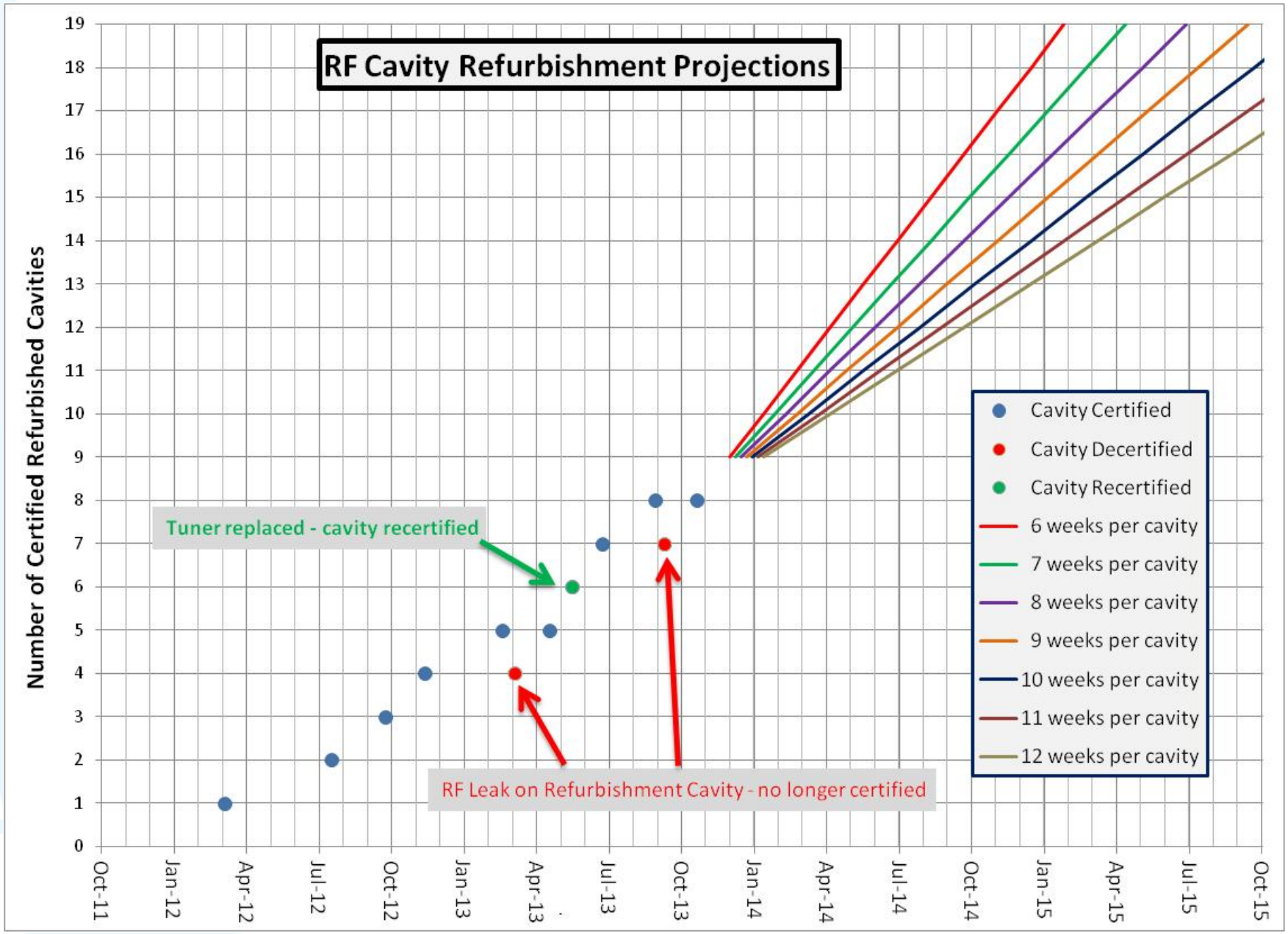


Damaged RF tuner fingers – new cones being assembled – tuner being assembled

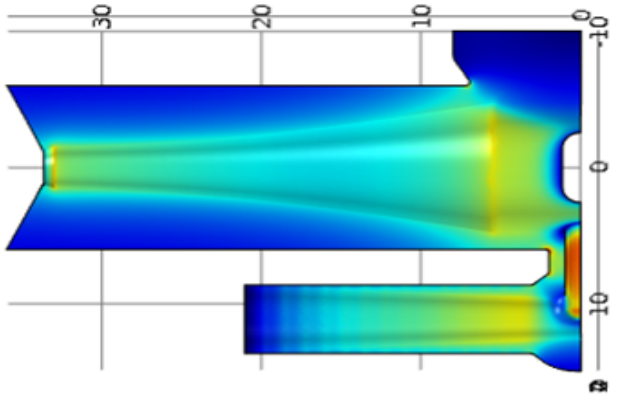
- The tuner repair is a labor intensive job.
- The rework of the tuners varies cavity to cavity but requires new cones, reworking of LCW and finger stock repairs.
- Ferrites are usually reused but have new copper casing.

PIP – Ferrite Cores

- Want additional ferrite cores (μ = 12 & μ = 20)
  - Replace damaged cores during refurbishment
  - Build new tuners (Technical Division team)
    - Possibly speed up refurbishment
    - Possibly use with new cavity
- Vendor is re-inventing process for high bias-current ferrites
  - Problems achieving correct permeability
  - Problems with large bias current destroying permeability
- 2012-2013 working with the vendor
  - Sent low power testing device to vendor to be used in QA
  - PIP does high-power testing on delivered cores
  - Iterative process which has taken 2-3 months per round
  - Have delivered 150 low μ cores recently (PIP has accepted)
  - Hopefully, one last iteration on high μ cores


RF Cavity Refurbishment Projections
Number of Certified Refurbished Cavities
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Oct-11
Jan-12
Apr-12
Jul-12
Oct-12
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Apr-14
Jul-14
Oct-14
Jan-15
Apr-15
Jul-15
Oct-15
Tuner replaced - cavity recertified
RF Leak on Refurbishment Cavity - no longer certified
Cavity Certified
Cavity Decertified
Cavity Recertified
6 weeks per cavity
7 weeks per cavity
8 weeks per cavity
9 weeks per cavity
10 weeks per cavity
11 weeks per cavity
12 weeks per cavity

PIP – Booster New Cavity



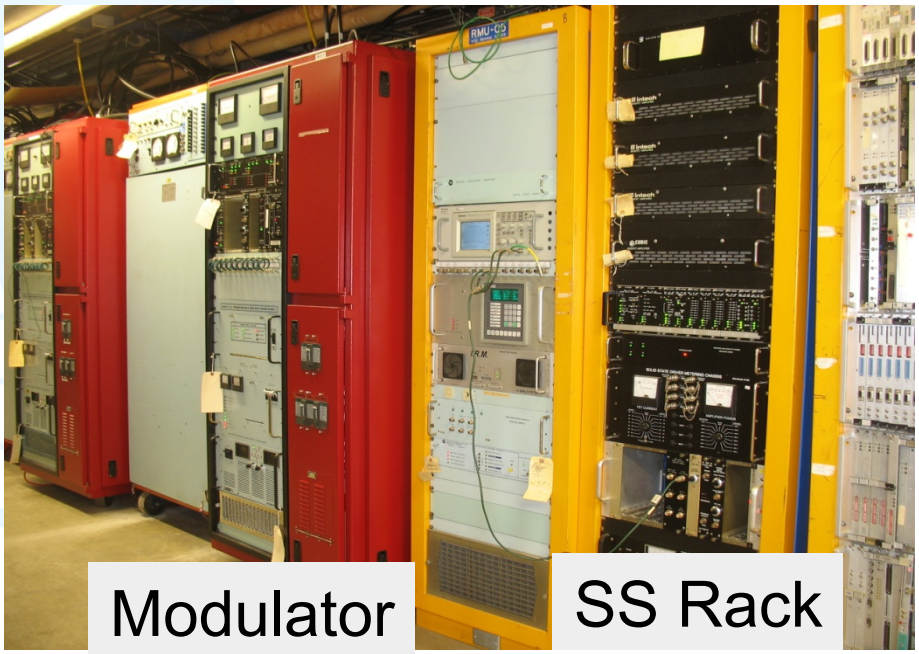
- Building new accelerating cavities
- Increase number of stations 19 → 22
- Design under study
  - Optimize for today
  - Compatibility
  - Reliability
- Build three in near-term
  - Prototypes
- Prepared to build more

	Current	Modified
Frequency Range	37.80-52.82 MHz	Same
V_{acc}	55 kV	60 kV +
R/Q	~50	~50
Duty Cycle	Effectively 25%	50%
Repetition Rate	Effectively 7 Hz	15 Hz
Cavity Tuning	Horizontal Bias	Same
Beam Pipe Diameter	2.25”	>3”
Higher Order Mode Impedance	<1000 Ohm	<1000 Ohm
Cooling	LCW at 95 F, Water flow up to 21 gpm	Same

PIP – Booster Solid State Upgrade Completed

With the completion of the SS upgrade, the Booster RF power system can now cycle at 15 Hz. Other expected benefits include higher uptime, lower exposure, ability to do beam loading compensation and lower operating cost by ~1M$/year

- New technology
- Simpler design, more modular and NO component point to point wiring
- Easier to fix and maintain
- Can run at higher voltage



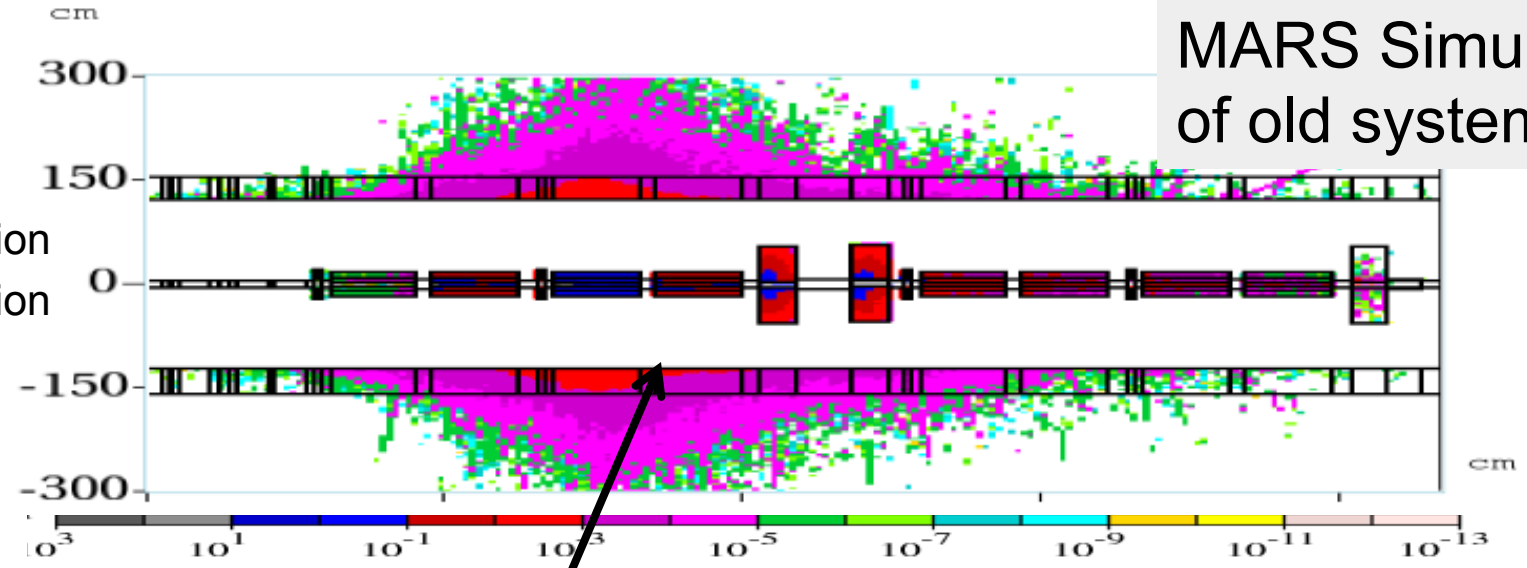
- New technology
- No more tubes (20 tetrodes/cavity) in tunnel/radiation
- Reduced worker exposure – most work done upstairs
- Longer operating lifetime – cost savings

PIP – Booster Notcher & Absorber

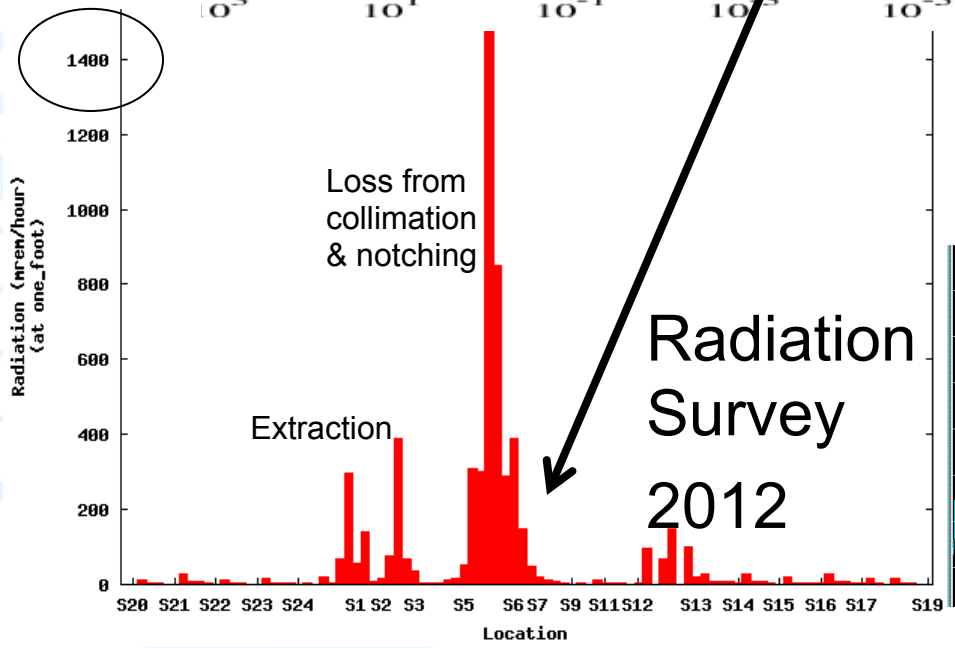
To operate the Booster at 15 Hz with beam required a new notching system

MARS Simulations of old system

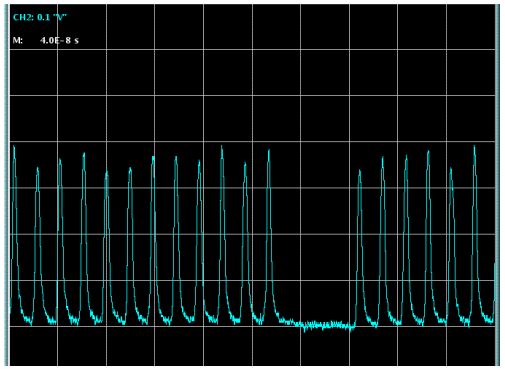
Collimation Region



Residual dose (mSv/hr).



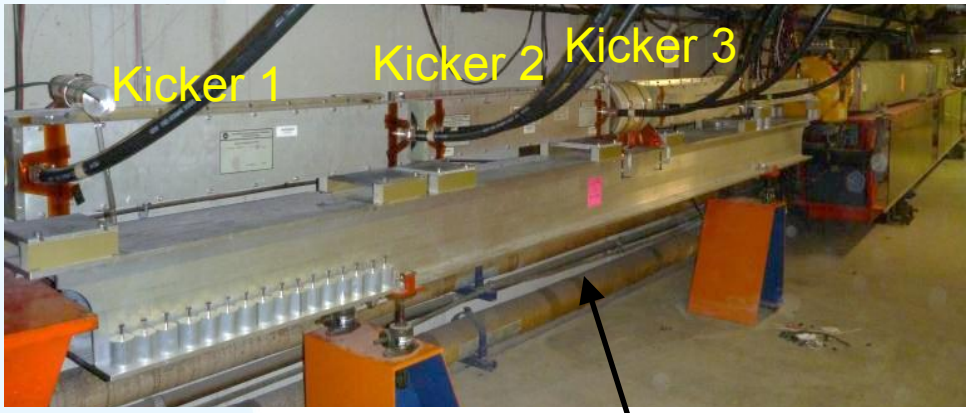
Radiation Survey 2012

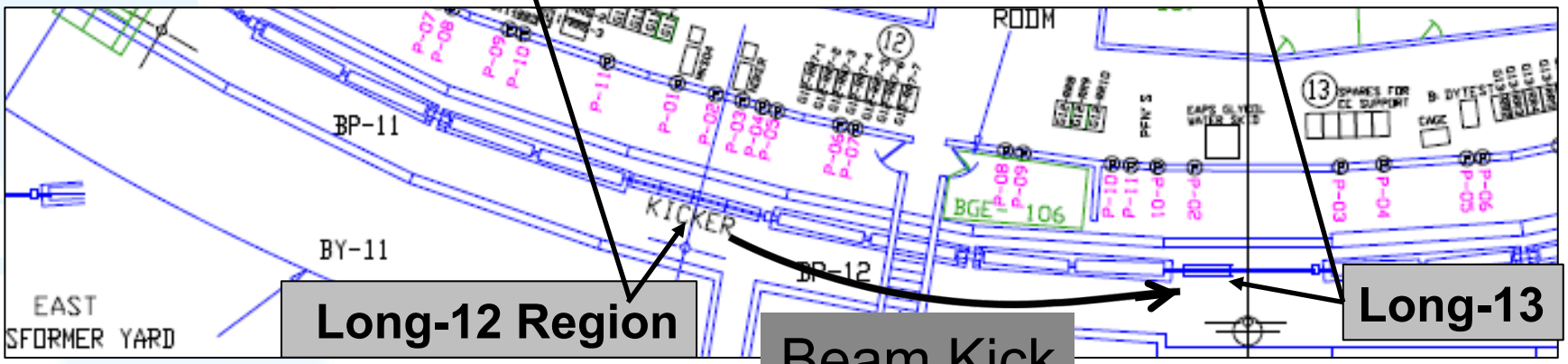


Scope plot of notched beam

PIP – Booster Notcher & Absorber

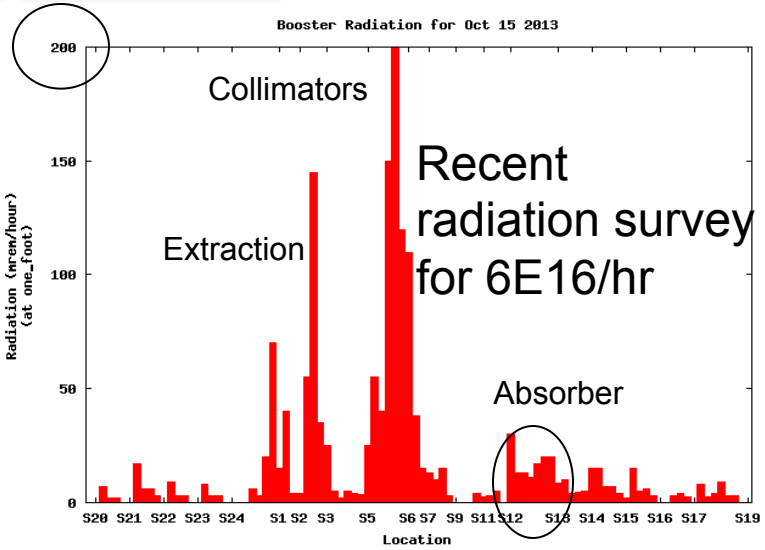
The new beam notch absorber system was required to maintain acceptable dose rates while operating Booster at the higher flux rates of the PIP.

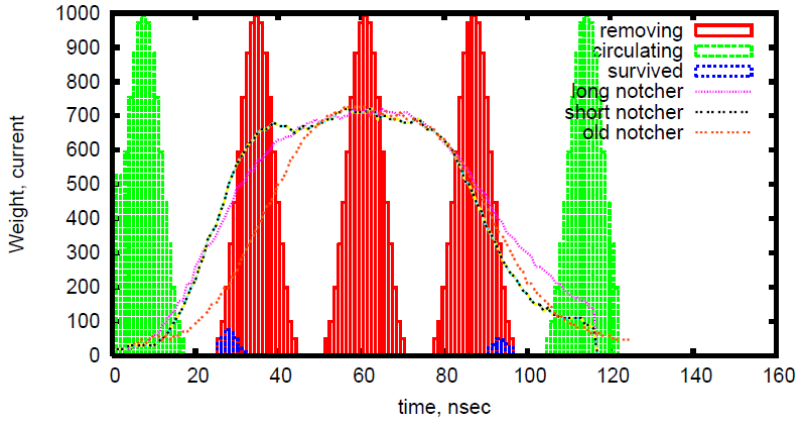




PIP – Booster Notcher & Absorber

The new absorber system is working well. Building new PS and short kickers.





The above plot shows current notch simulation with 3 long kickers.

Shorter kickers will have faster rise times, cleaner notch and reduced kick on circulating beam.

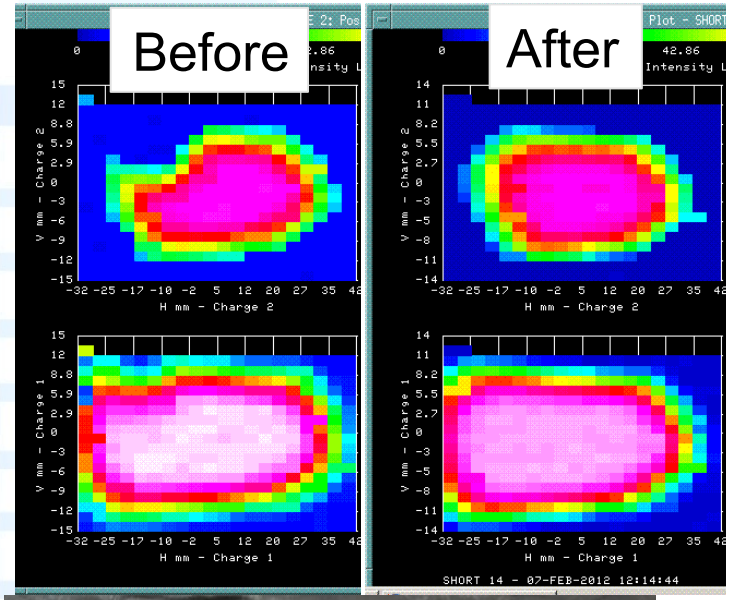
Testing of first two short kickers underway.

New pulser

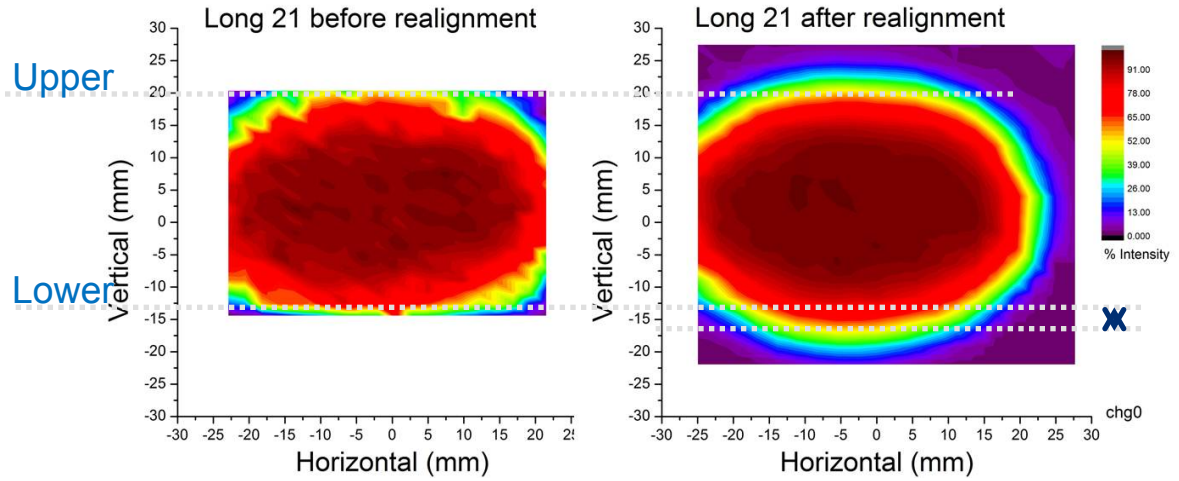
NOvA style

Booster Short Kickers – drop in replacements

PIP – Booster Physics: Alignment/Aperture Scans



- The aperture scans have successfully increased the acceptance
  - Found Restrictions
  - Corrected Misalignments.
- More moves are planned but smaller
- New software is fast and easy to use
  - Used after all tunnel work
  - Used by operators as part of normal startup after beam line work



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PIP – Booster Physics: Higher Order Corrections

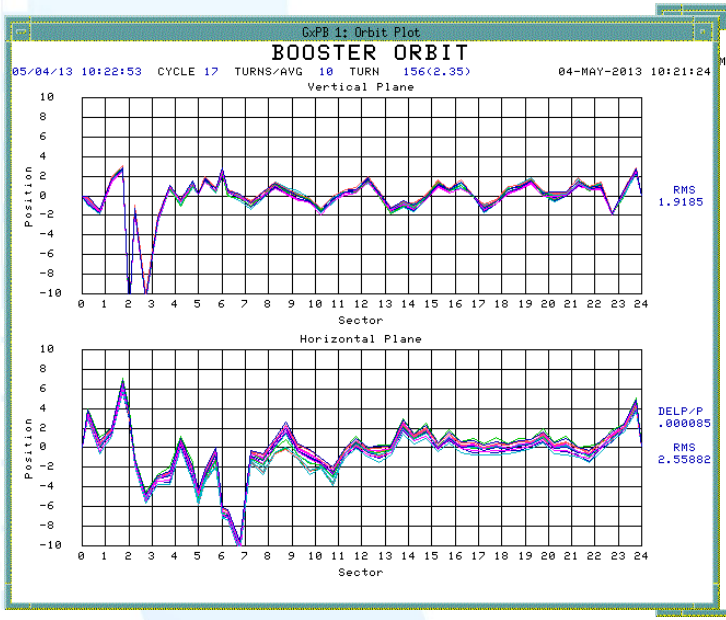
Correcting Booster orbit, coupling, tunes and chromaticity

- Beta errors – Beta beating
  - Individual setting of trim quadrupoles
- Tunes set through cycle
- Coupling reduced
- Chromaticity set to desired values
- Orbits smoothed
- Lots of new software
  - Working to speed up process of measurements and corrections

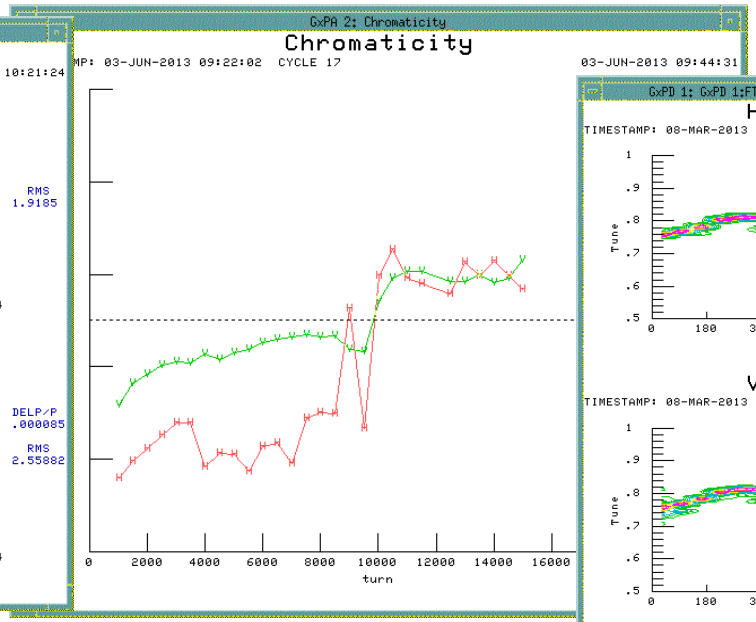
PIP – Booster Physics: Higher Order Corrections

The measuring of Booster optics has gone from expert driven to operator

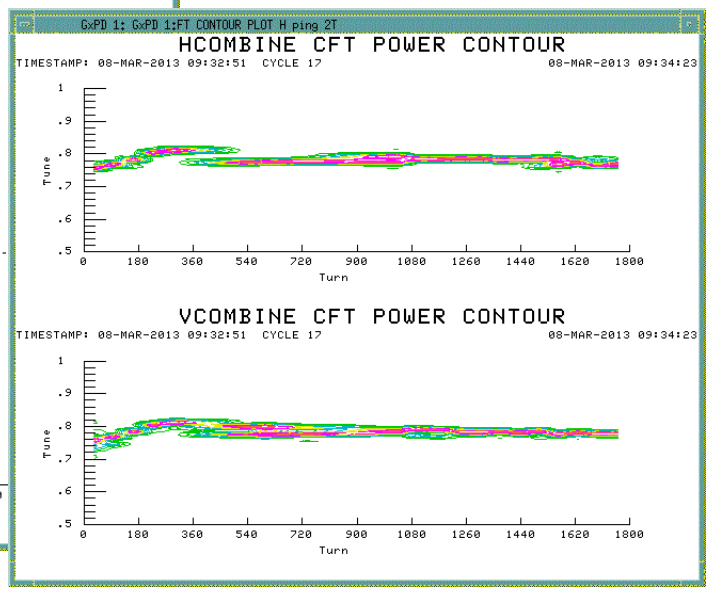
- Tunes (pinging of beam and use of BPM accusations/analysis software)
- Chromaticity (tunes measured with radial position)
- Orbit smoothing (added breakpoints – increased orbit and harmonic control)



Orbit



Chromaticity



Tunes

PIP – Booster Physics: Higher Order Corrections

Software effort to reduce complexity and increase speed.

- Complete measurement and correction of Booster lattice was completed in March 2013.
- Booster lattice description has been completely moved from Elegant to MADX
  - Latest Booster lattice is now in a RedMine repository.
- Booster LOCO has been ported to the control system
  - All dependencies on Mathematica, Octave, TCL, Elegant have been removed.

PIP - Summary

- PIP has been very successful since it started in FY12
  - RFQ Injector finished to the week on time
  - Solid State finished on time and under budget (just a little!)
  - Shutdown work was completed on time and beam delivered on schedule
    - Absorber
    - Linac BPMs
    - Transformers
    - LCW upgrade

PIP work is critical to Fermilab and has been supported by laboratory and HEP community. PIP goals are difficult but recent success has put the plan on a path to success and continued support will result in PIP reaching stated directives.

PIP - Additional

PIP – Funding Profile

	PIP Design * Handbook	Revision Oct 2013
FY12	$ 17,346,668	$ 13,956,000
FY13	$ 14,779,844	$ 8,612,000
FY14	$ 19,437,625	$ 11,000,000
FY15	$ 19,873,626	$ 15,000,000
FY16	$ 14,188,092	$ 16,000,000
FY17	$ 1,113,348	$ 16,000,000
FY18	$ -	$ 9,000,000
Total	**$ 86,739,204**	**$ 89,568,000**

* 2012 Baseline

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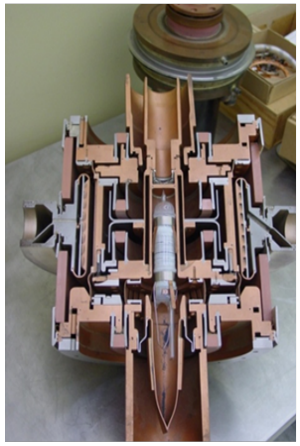
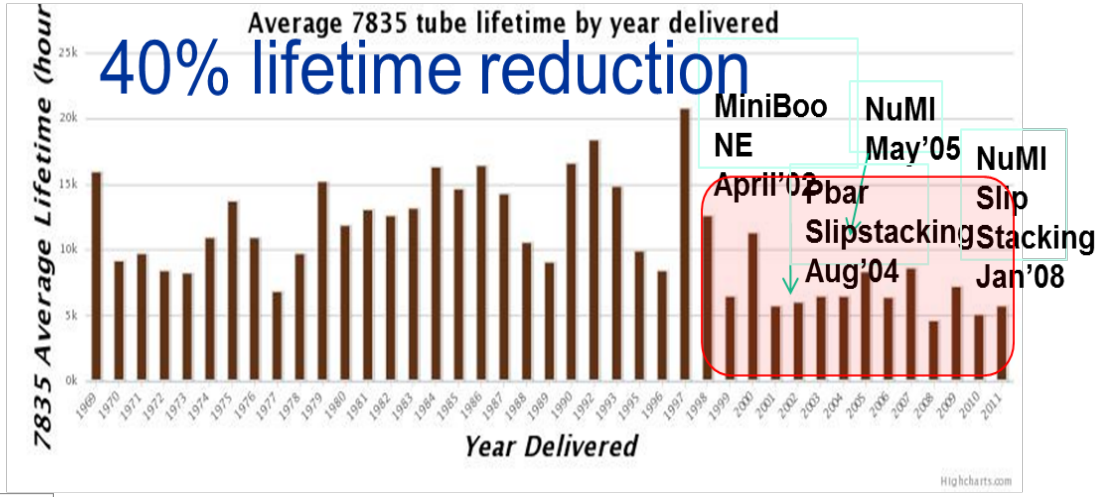
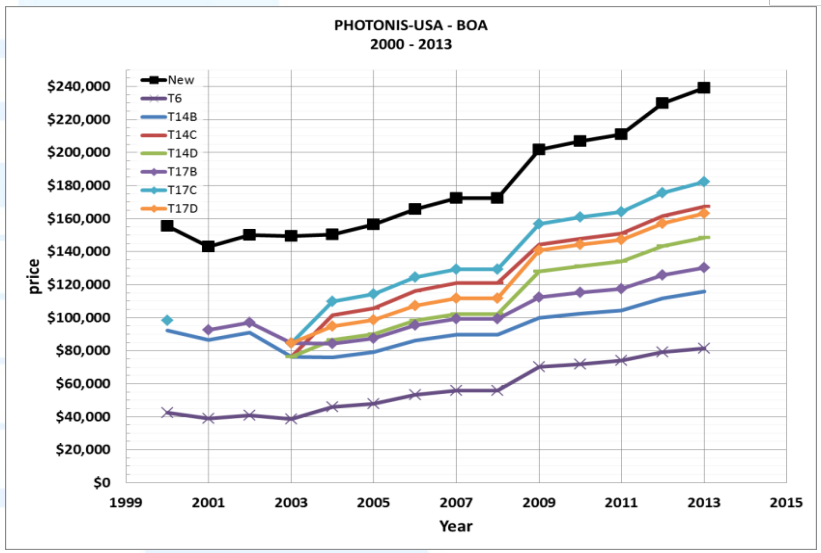
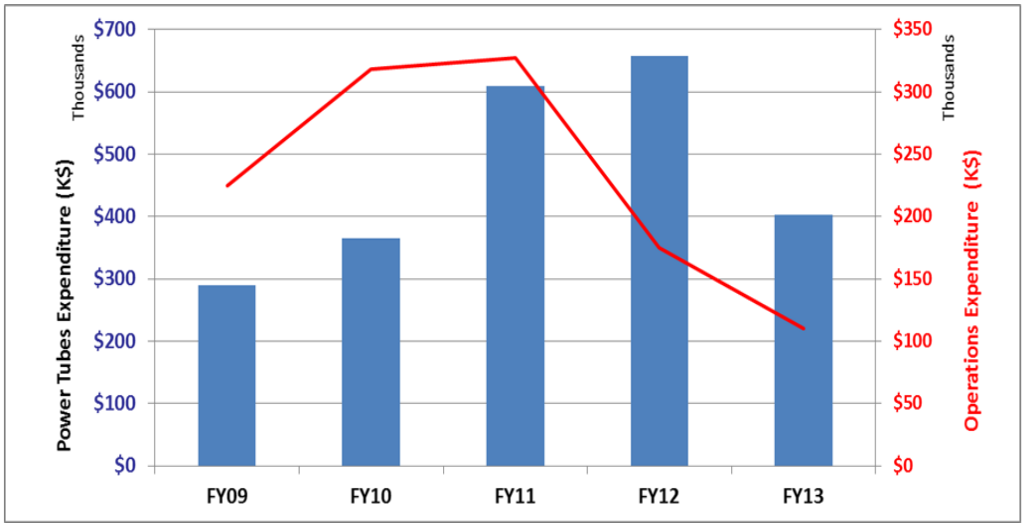
Triode Primary Amplifier PHOTONIS









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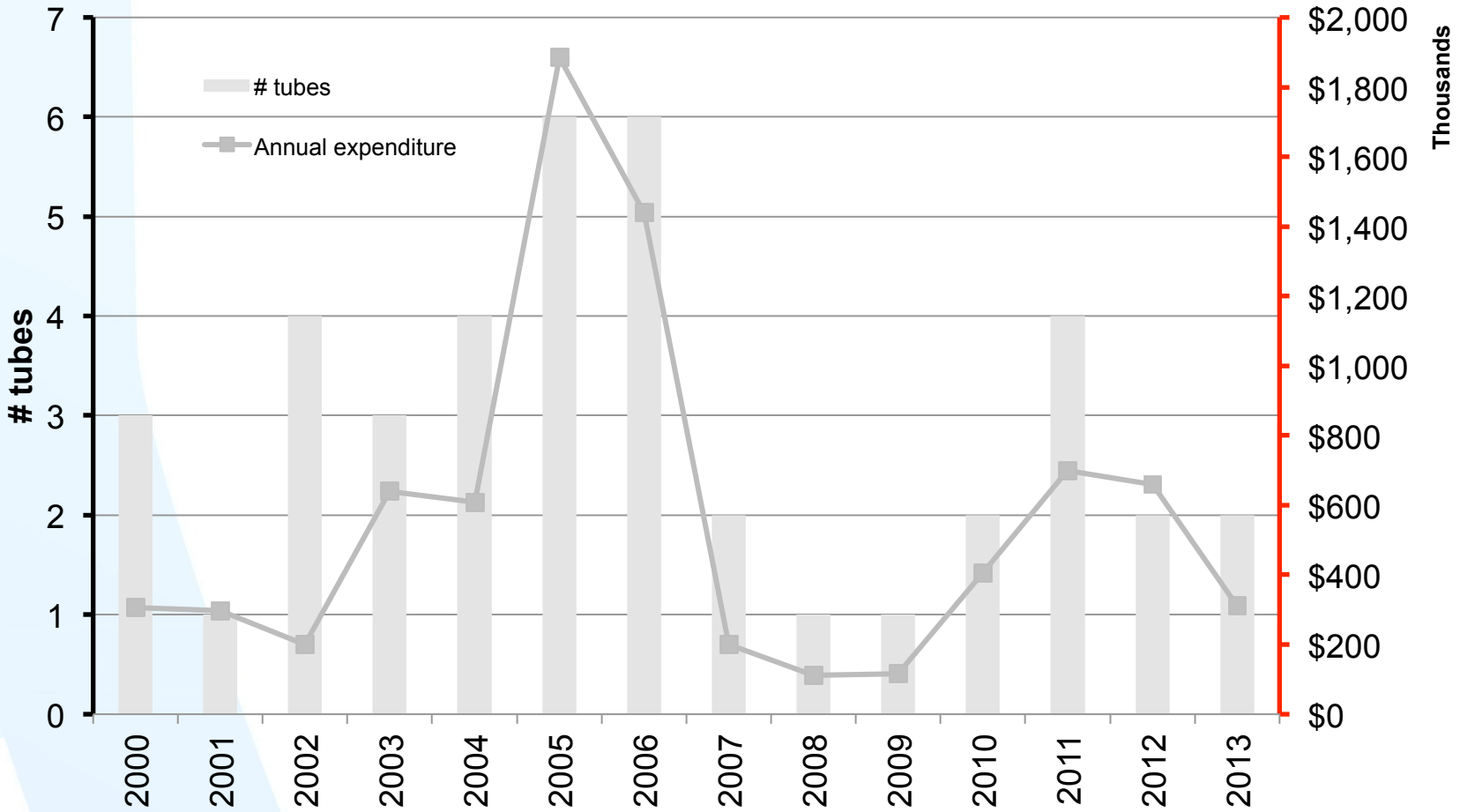

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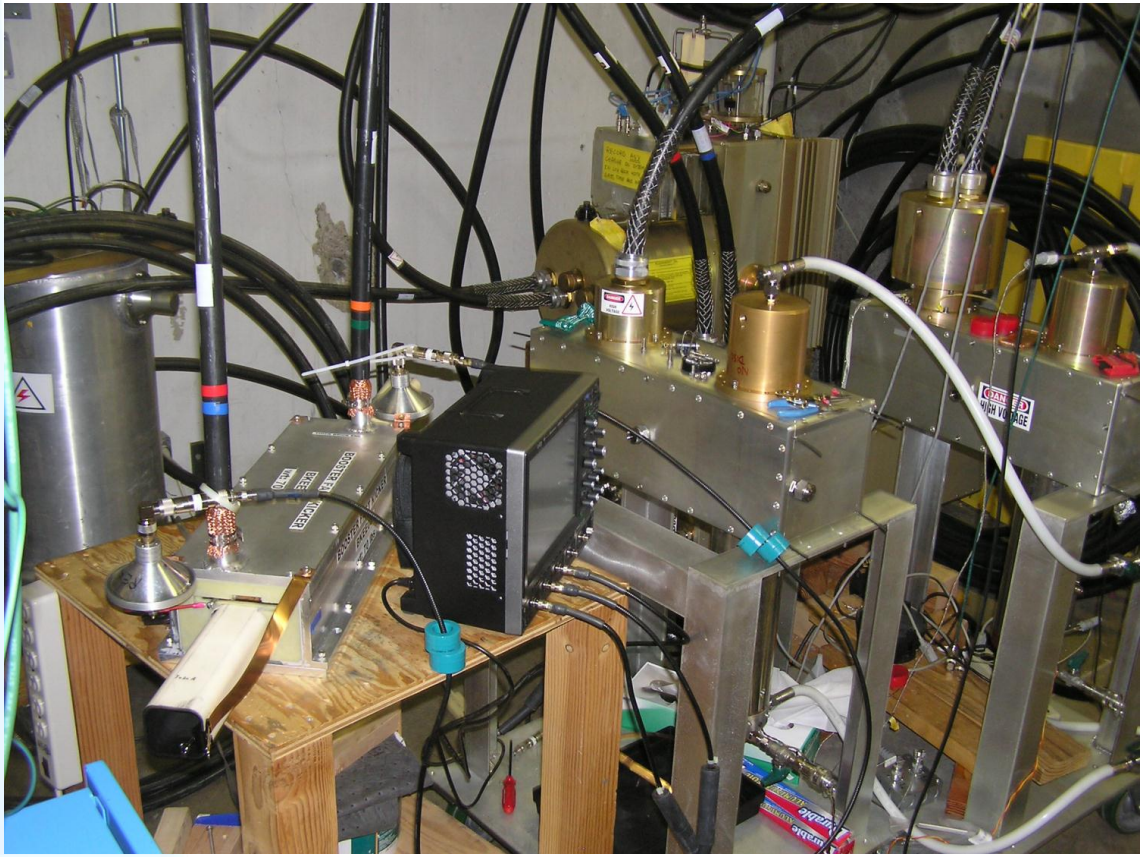
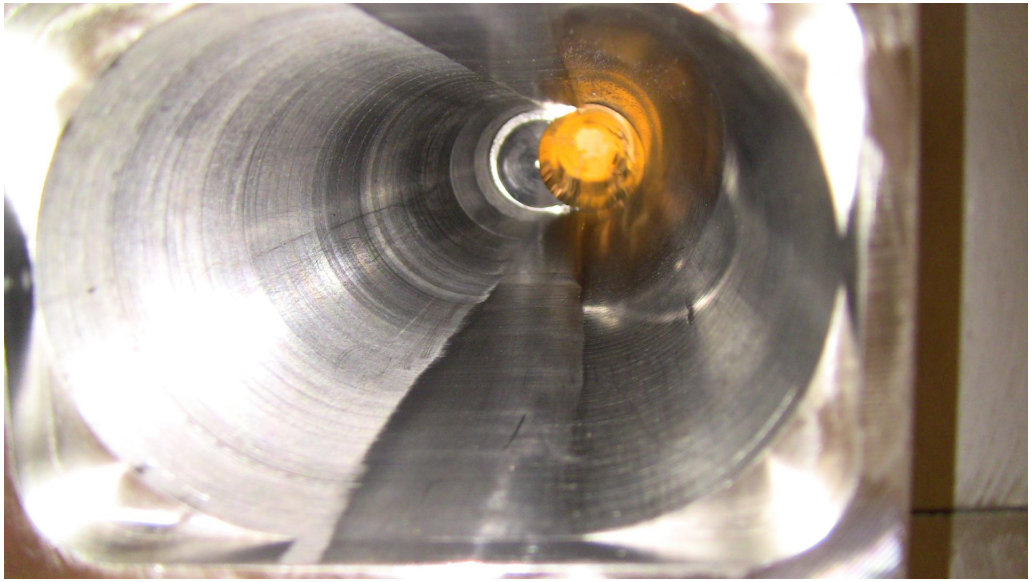
PIP – Short Kicker Testing



Absorber