Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

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

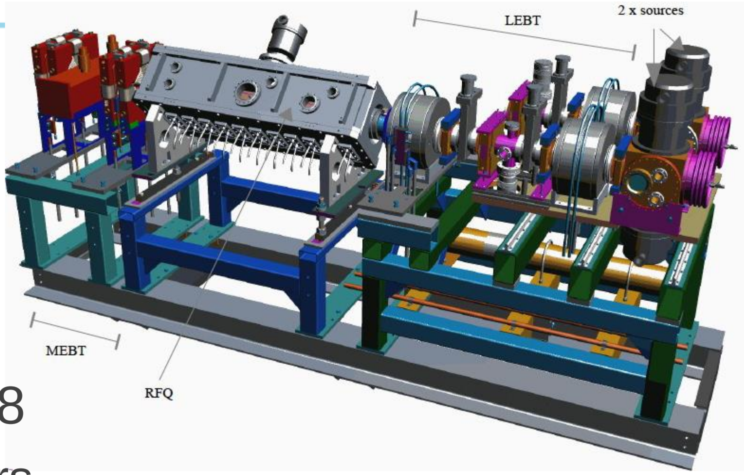
750 keV | 1 | Tank 2 | Tank 3 | Tank 4 | NTF | Tank 5 | 0 | M1 | M2 | M3 | M4 | M5 | M6 | M7 | 400 MeV

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

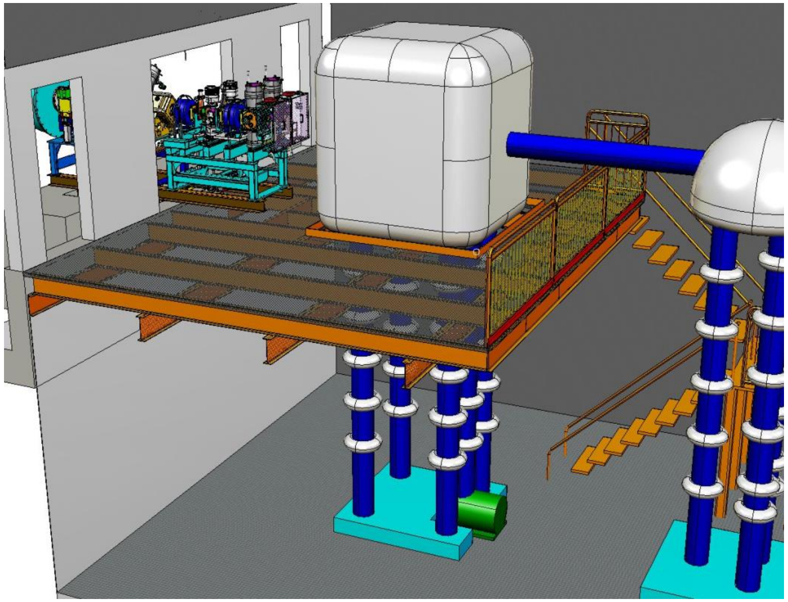
High Energy Linac Gallery

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%

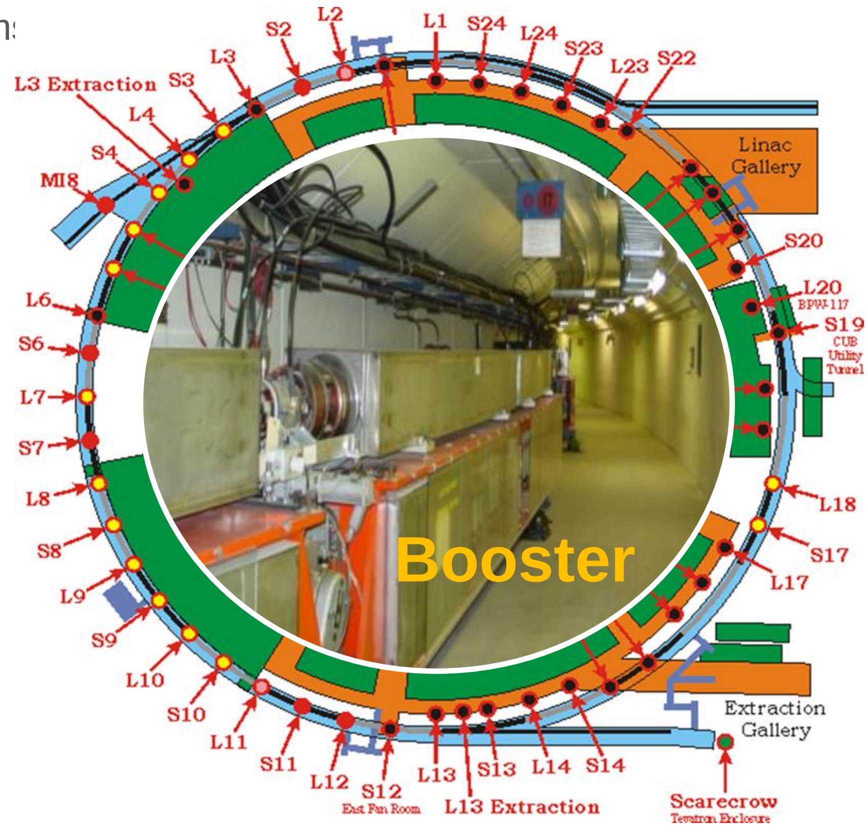


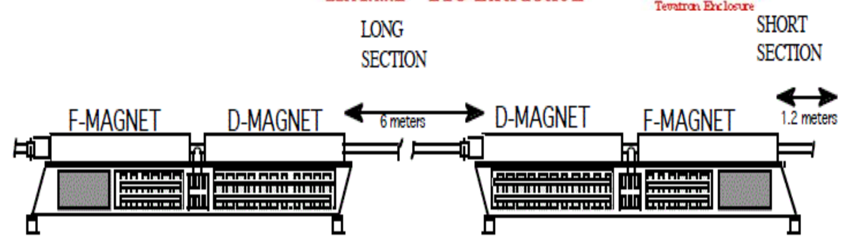
Booster Overview

- 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

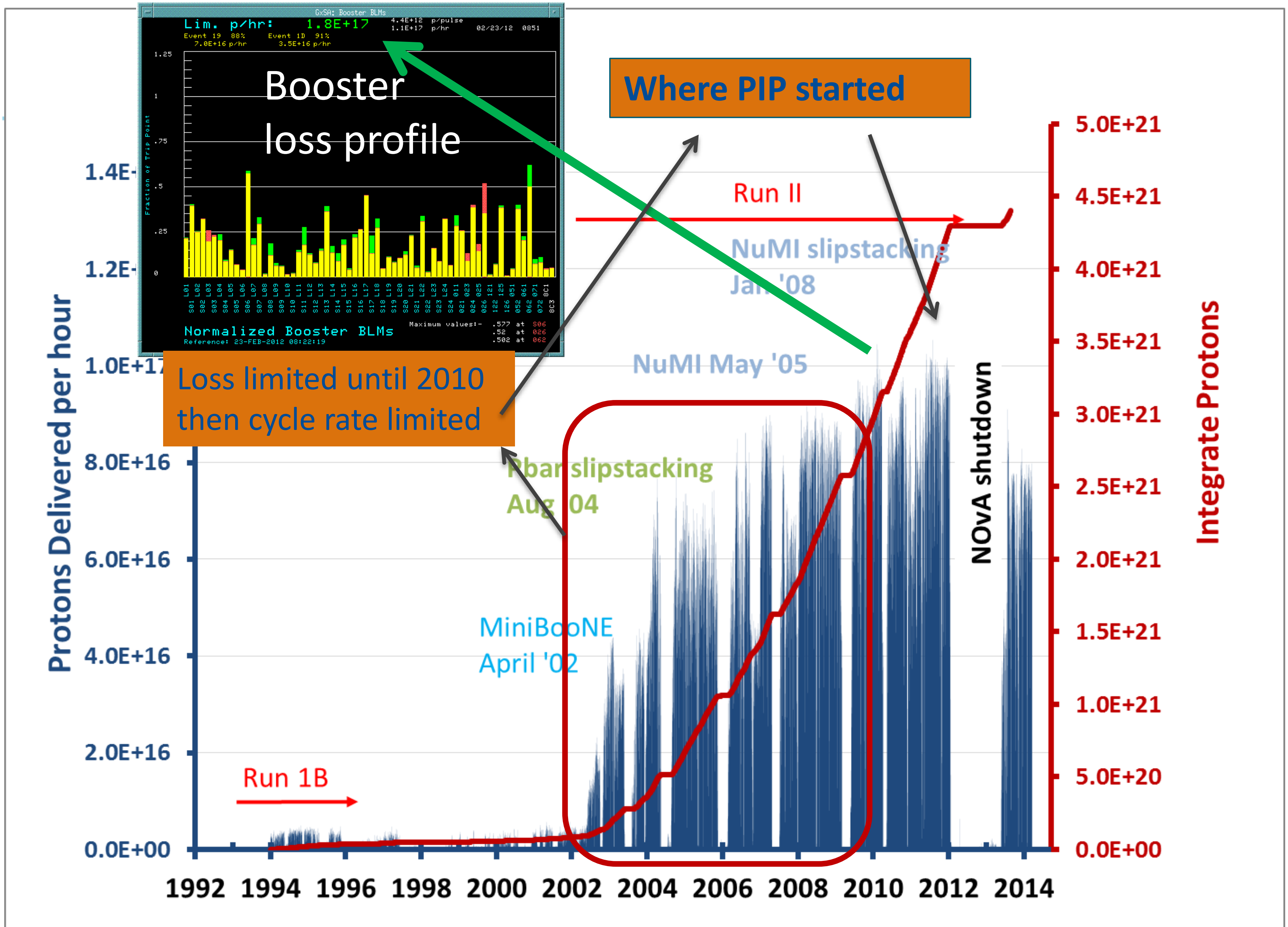
Booster	
Circumference (m)	474
Harmonic Number	84
Kinetic Energy (GeV)	0.4 - 8
Momentum (GeV/c)	0.954 - 8.9
Revolution period (μsec)	$\tau_{(inj)}$ 2.77 – $\tau_{(ext)}$ 1.57
Frequency (MHz)	37.9 - 52.8
Batch size	4.5 E12
Focussing period	FDooDFo (24 total)

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

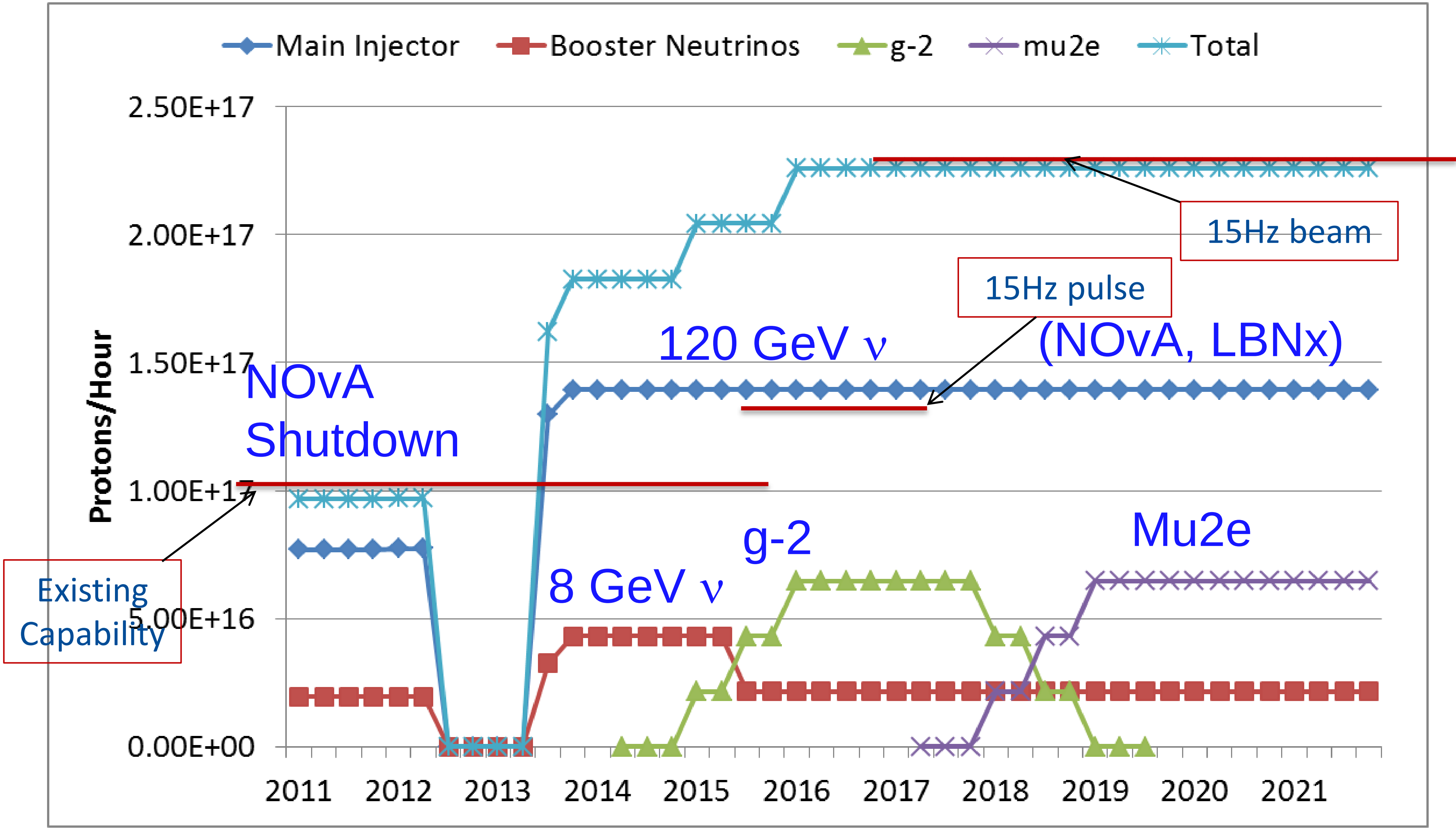




Fermilab


Booster
loss profile
Lim. p/hr: 1.8E+17
Normalized Booster BLMs
Where PIP started
Loss limited until 2010
then cycle rate limited
Run II
NuMI slipstacking
Jan '08
NuMI May '05
Pbar slipstacking
Aug '04
MiniBooNE
April '02
Run 1B
NOvA shutdown
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

Sergei Nagaitsev
Accelerator Division
MS 306

630.840.4397
nsergei@fnal.gov

September 30, 2014

Bill Pellico
Project Manager
Proton Improvement Plan
pellico@fnal.gov

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.

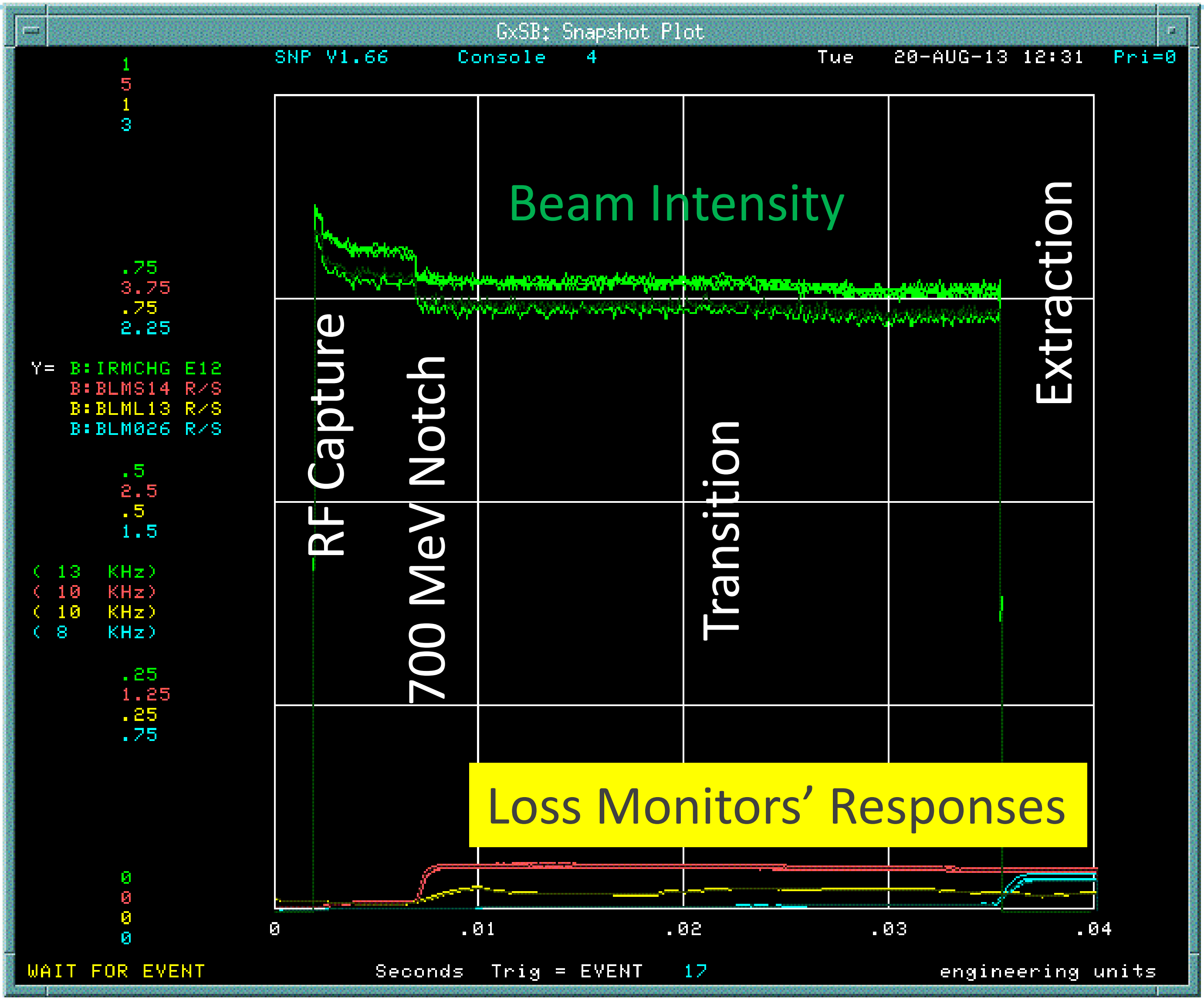
Sincerely,

SNagaitsev 11291

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

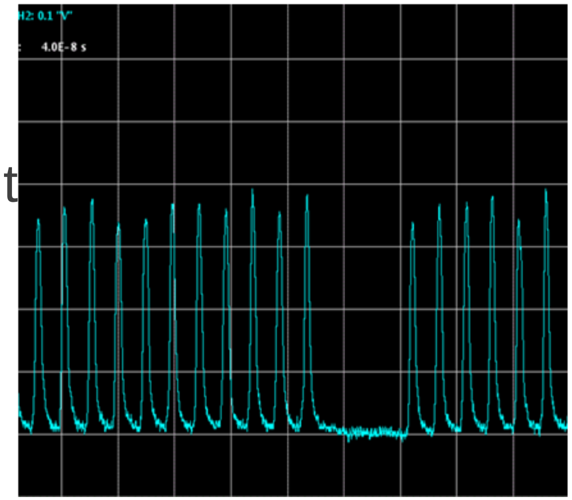
Beam and Losses through Cycle

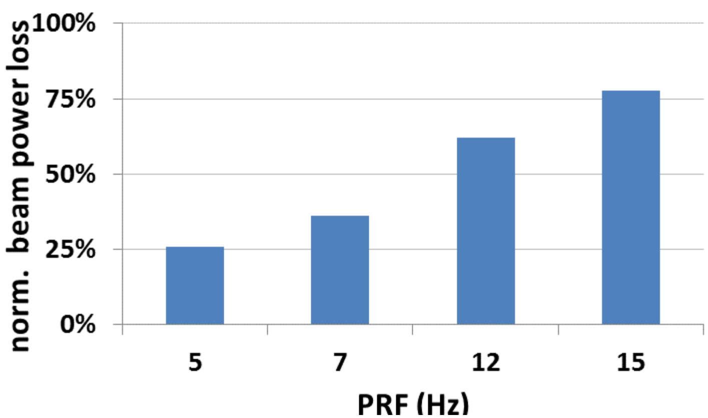


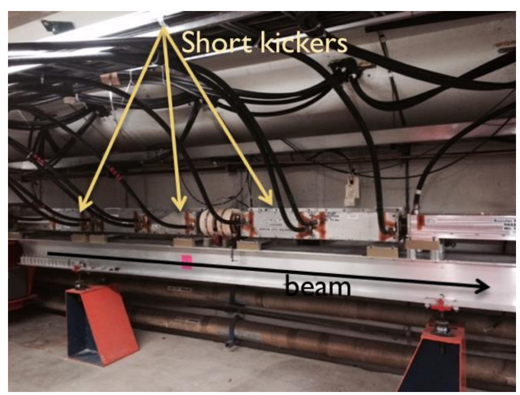
PIP : Notching

- 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

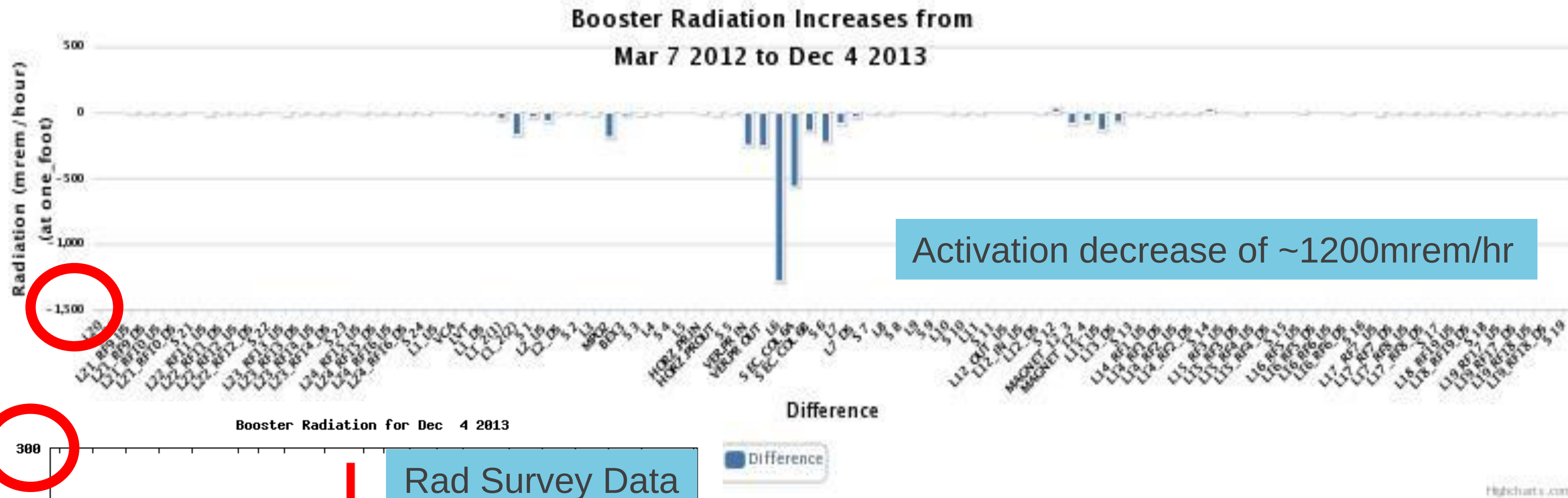


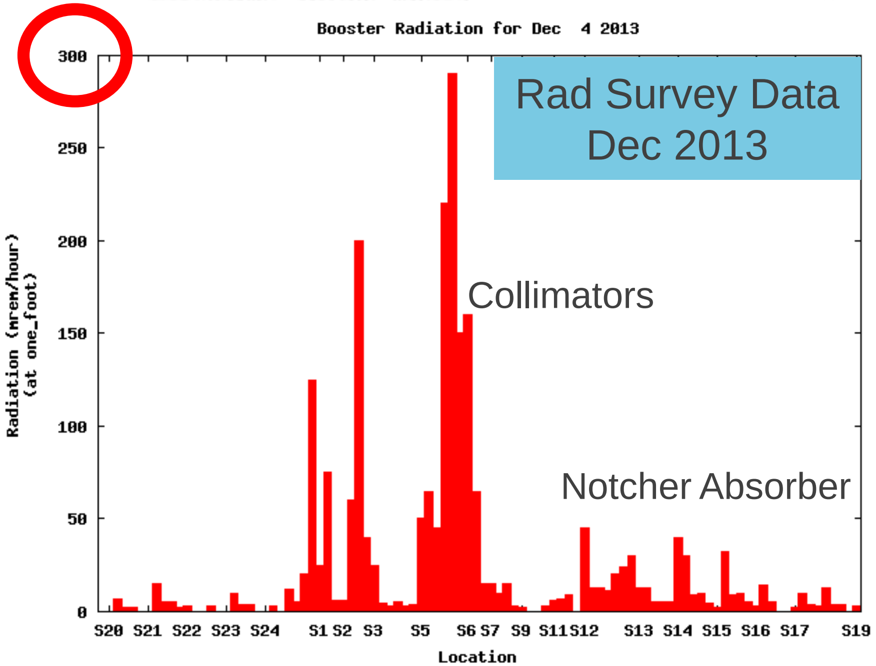




Absorber L13 (2013)

Notcher & Absorber Controlling Beam Losses



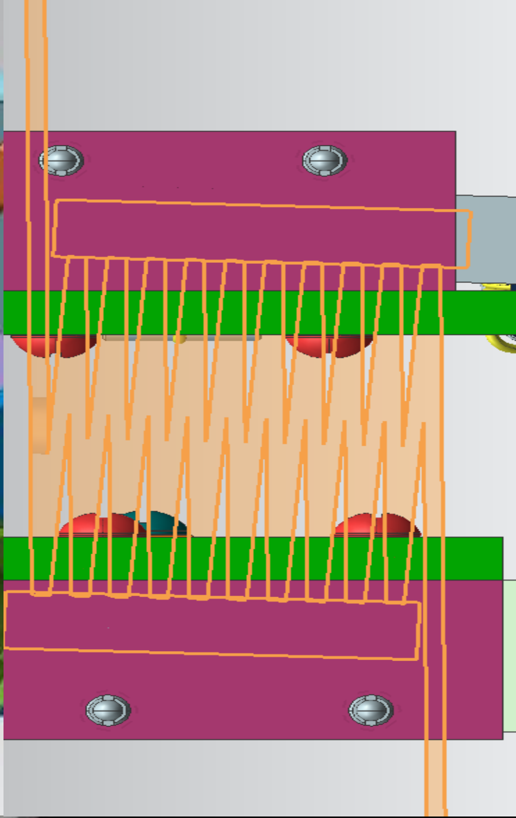


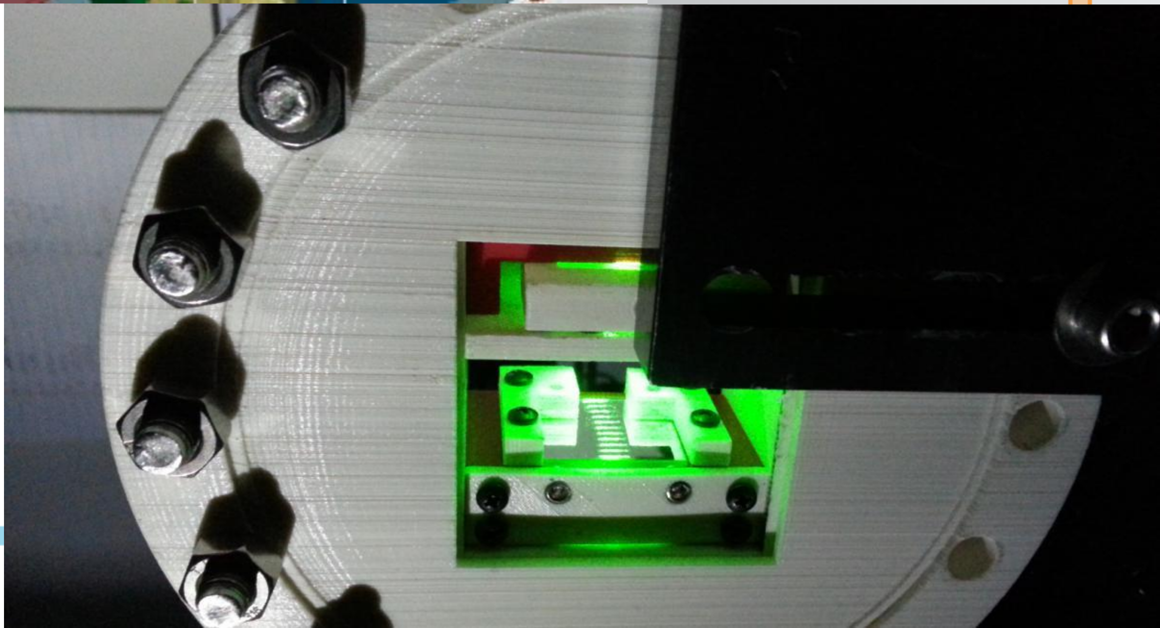
The plot above shows the difference between two radiation activation surveys after running similar flux for a week. The new system has greatly reduced residual activation in several areas of Booster.

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

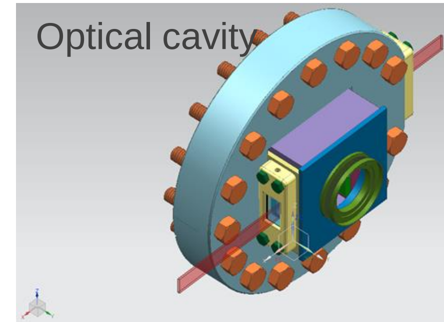
- Neutralize a portion of the Linac beam with a pulsed laser
  - Remove the majority of the loss from the Booster entirely
- Prototype of the laser front-end is operating
  - Atypical laser
    - Multiple timescales
    - High-pulse power
    - Moderate average power (few W)
- Interaction region installed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

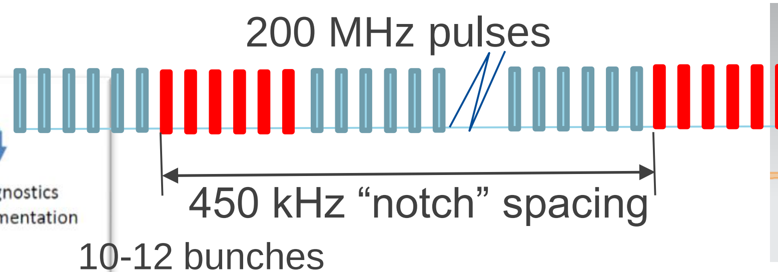


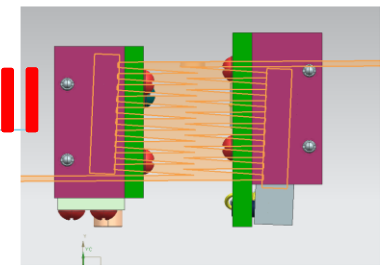


PIP – Accelerator Physics: Linac Laser Notch

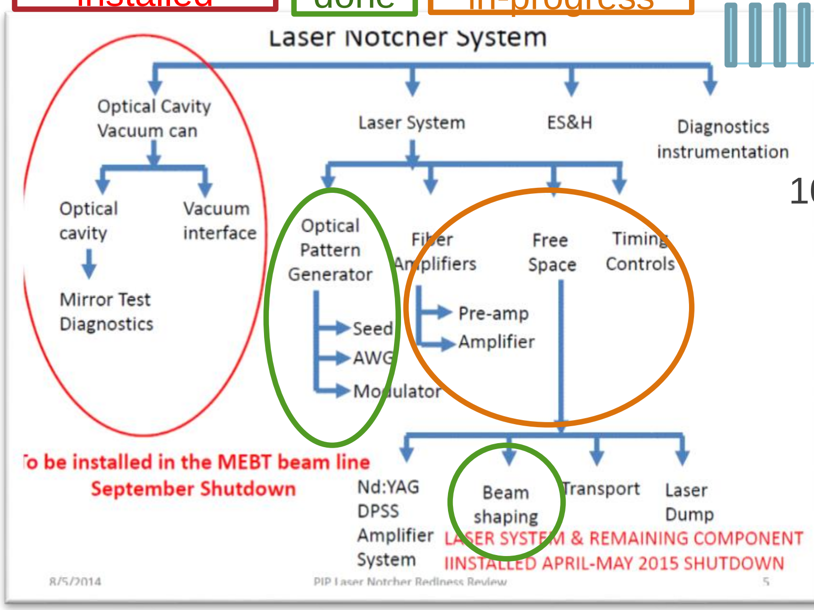
- Neutralize portion of the 750 keV beam using a pulsed laser
  - Create laser pulse pattern for 200 MHz and 450 kHz
  - Amplify pulse using a three-stage fiber amplifier
  - Create spatial uniform photon beam
  - Insert laser into a zig-zag interaction cavity

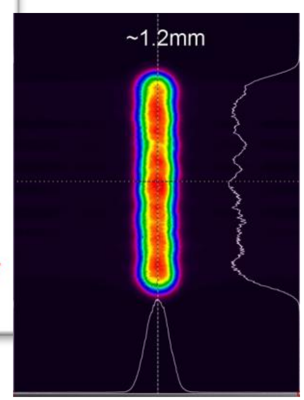


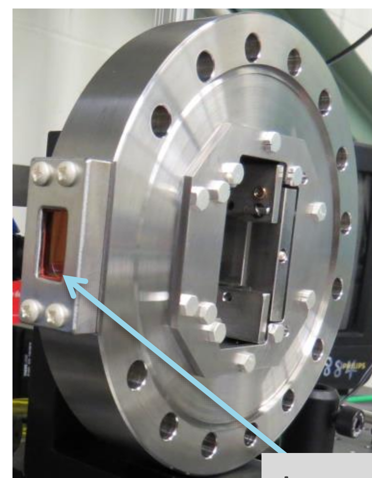


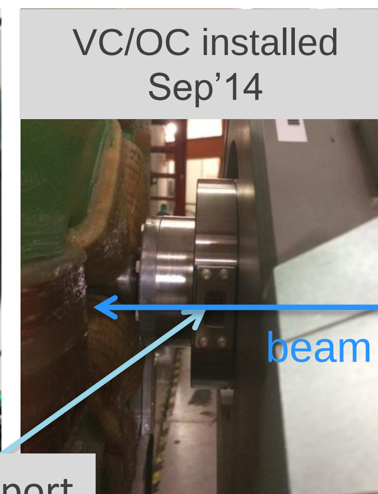


installed | done | in-progress









Laser port

System internal review - Aug'14

APT Seminar – Mar'14

Final installation expected FY15

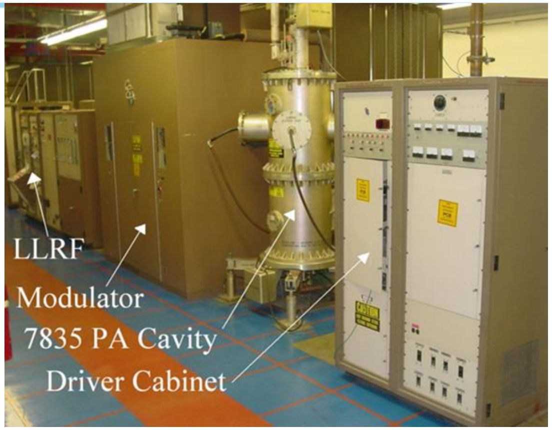
PIP – Linac 200 MHz RF system: issues & risks

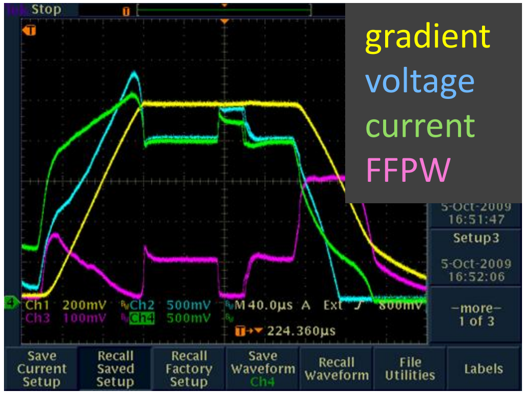
- The 201.25 MHz RF power system has been a big concern for over a decade in regards **long term operational reliability and viability**
- The **issue** of retaining the 201.25 MHz RF system is
  - specialized maintenance required and extensive downtime generated by the tube modulator
    - F1123 discontinued 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)

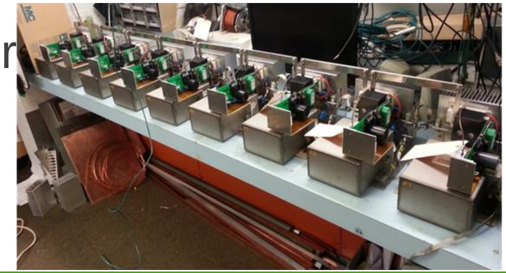




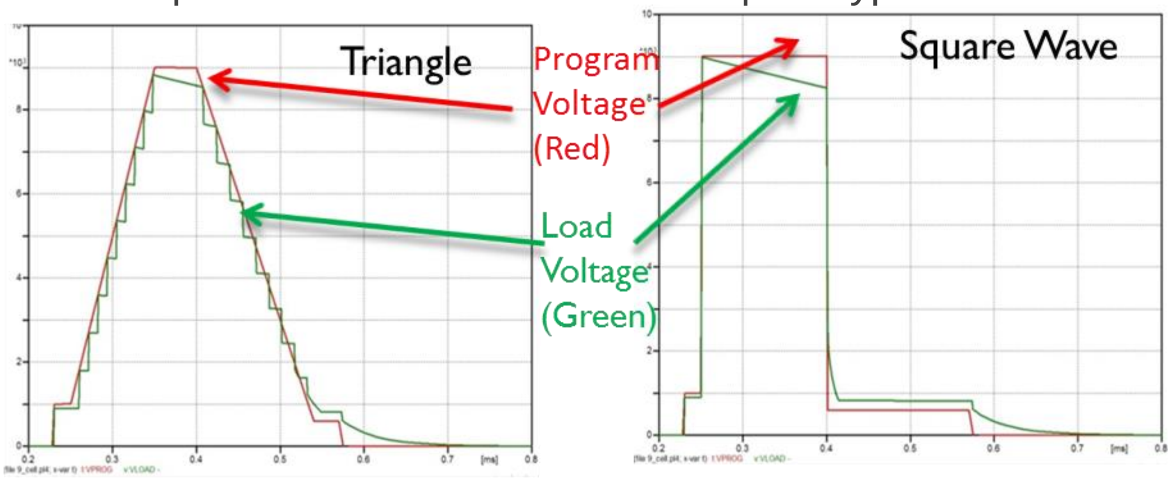
- Modulator contribution to Linac downtime is ~57%
  - Depending on the nature of the fault, each event may bring the system down from a few minutes up to tens of hours
  - MTBF: ~ 10 hrs
    - DC pwr sply – built directly to the frame
    - Switch tubes no longer manufactured
      - Rely on rebuilds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

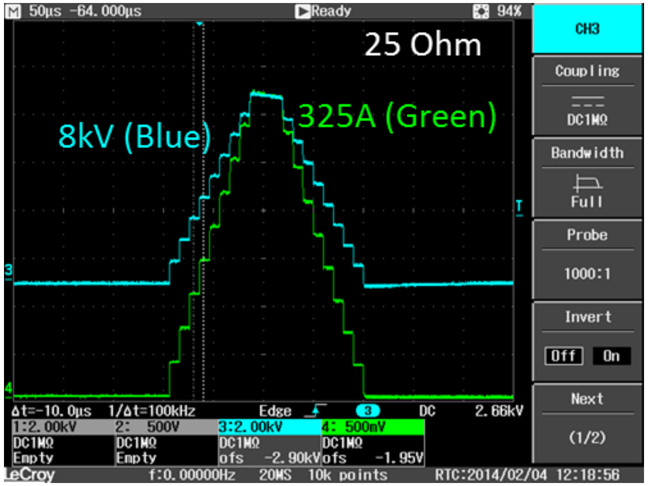
PIP – Linac 200 MHz RF system: Modulator

- **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

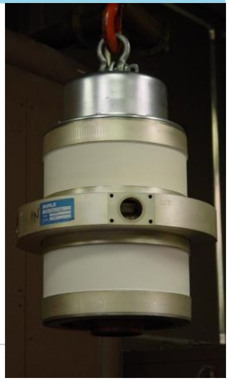


AD/EE design
- best meets original specifications
- lower cost than SLAC
- in-house expertise



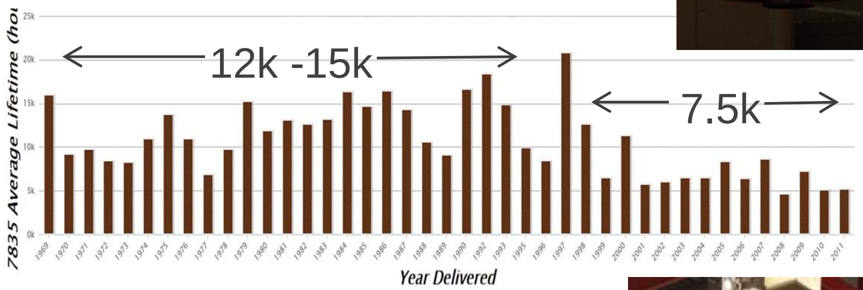


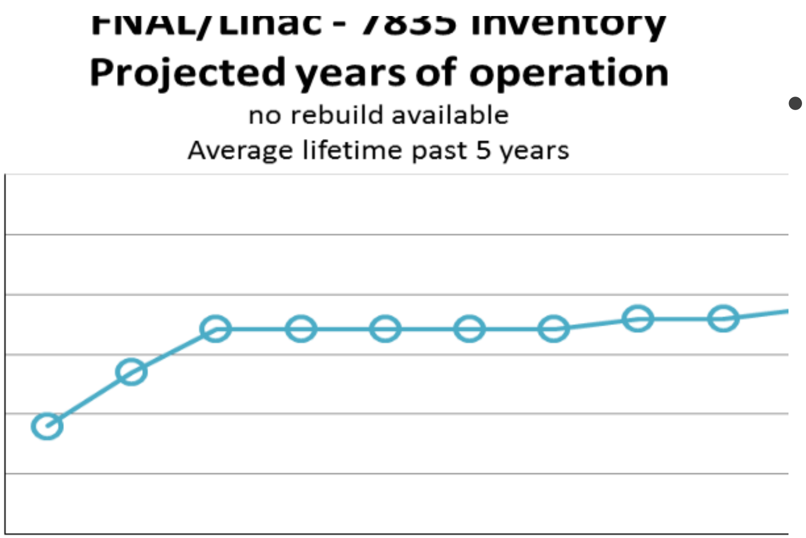
PIP – Linac 200 MHz RF system: PA



- 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





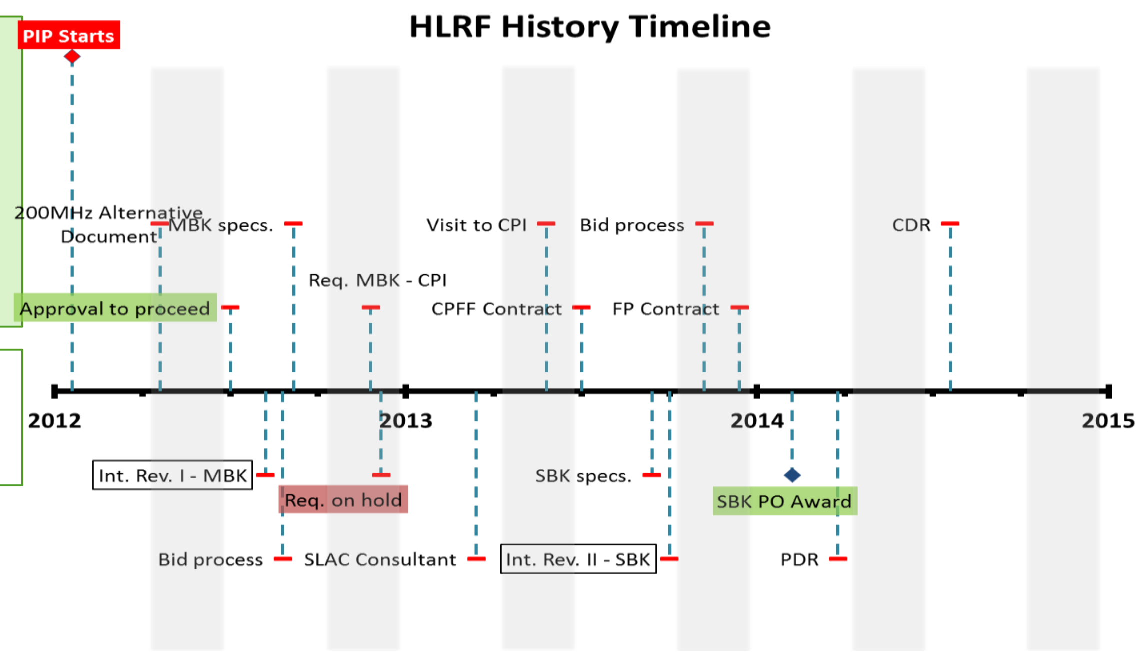
- There is no RF conditioning at the vendor site
  - Typical 15 days/tube for 2 techs
  - 6 tubes conditioned annually
  - Time consuming effort (4-5 months)

PIP – Linac 200 MHz RF system: HLRF

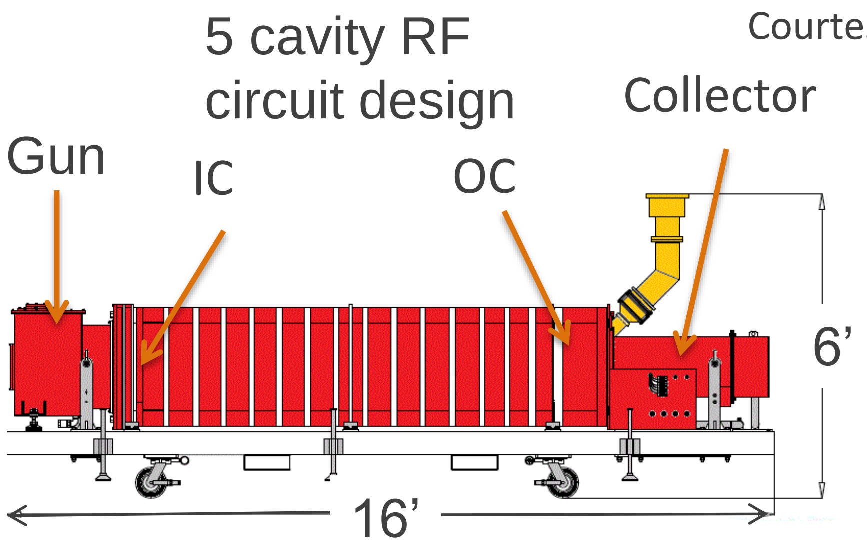
- Study conducted in 2012 discussed alternatives to the triodes
  - Tetrodes (LANL design)
  - Klystron-based 200 MHz RF
  - “SNS-like” 400 MHz Linac
  - Cost took in consideration series of criteria evaluated against over the expected lifetime of the Linac
    - Criteria: supply chain, technical risk,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

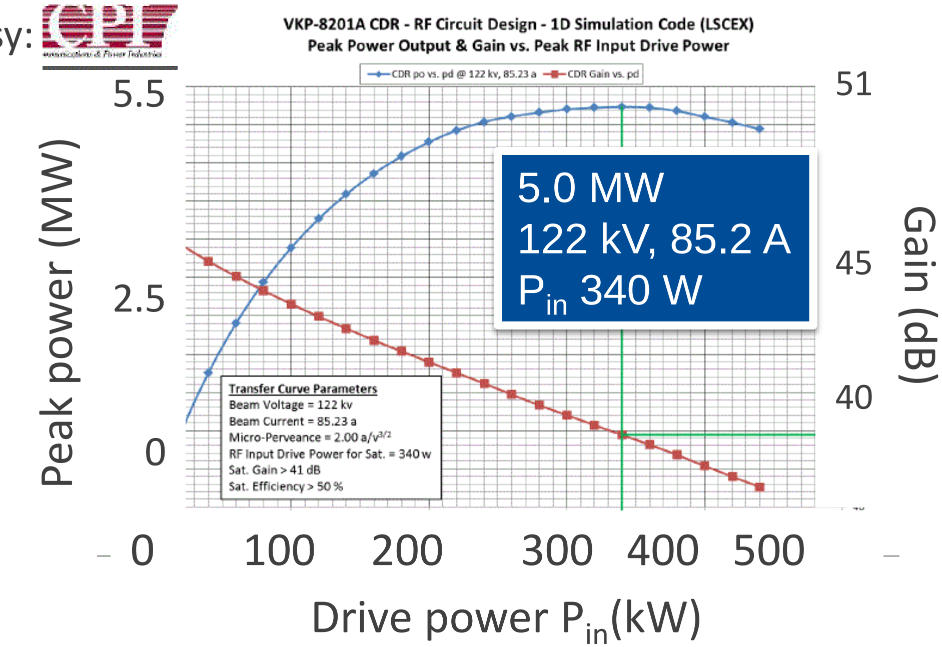
After careful consideration, the **201.25MHz klystron-based** RF power system was chosen as a plausible replacement for the 7835 triode

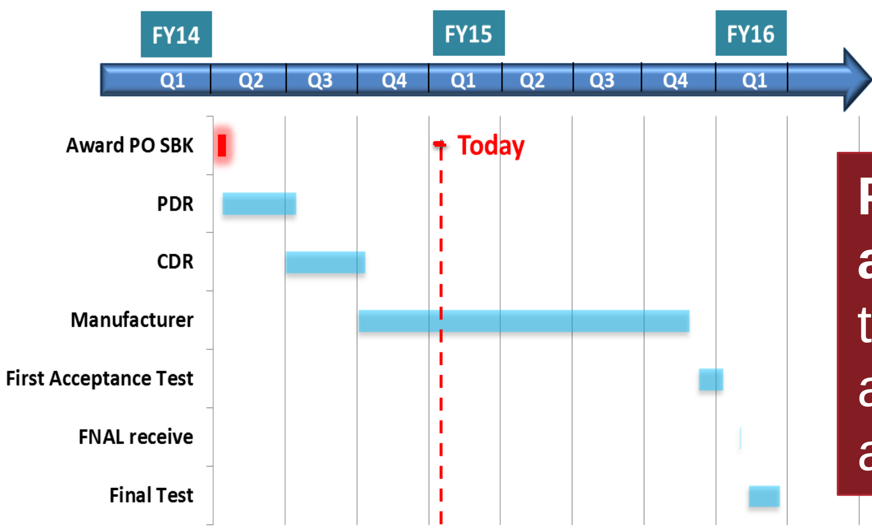
A prototype is being designed and built at CPI



PIP – Linac 200 MHz RF system: HLRF



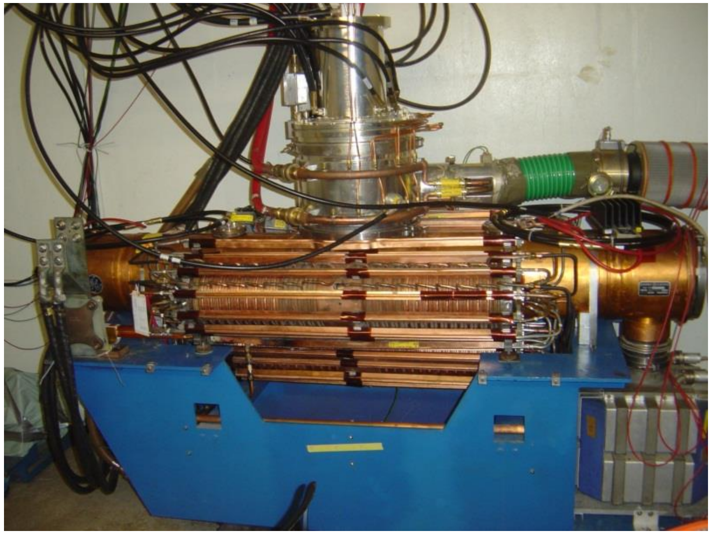


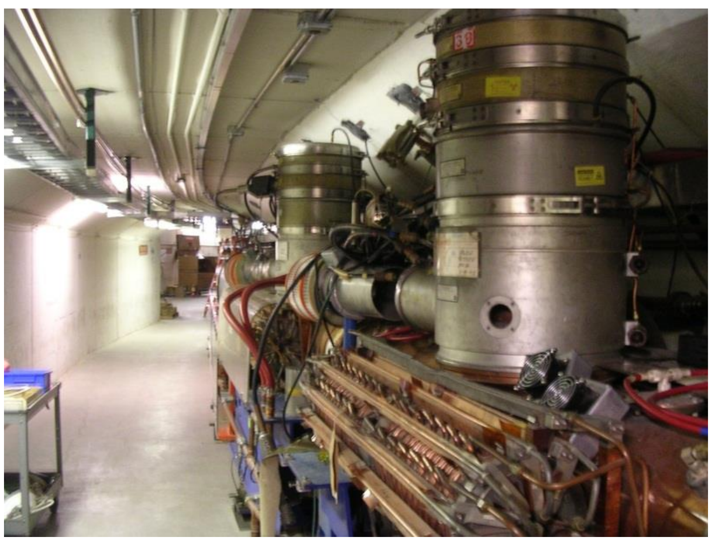


PIP to PIP-II adjustment:
task completes after successful acceptance-test

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

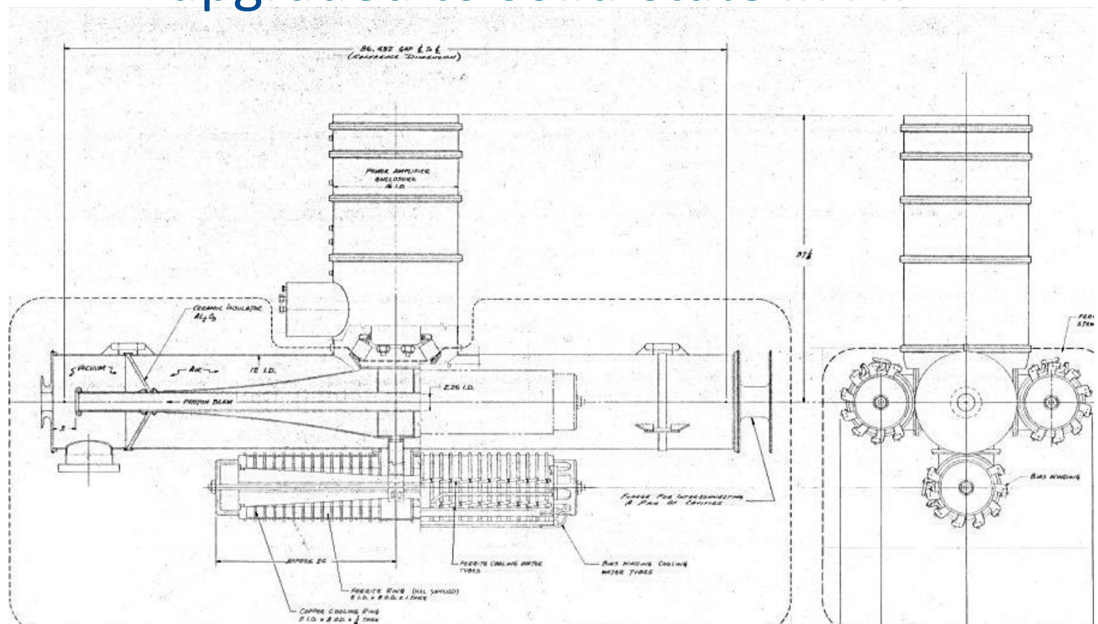
Booster RF cavity





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

Cavity Removal

Remove Tuners

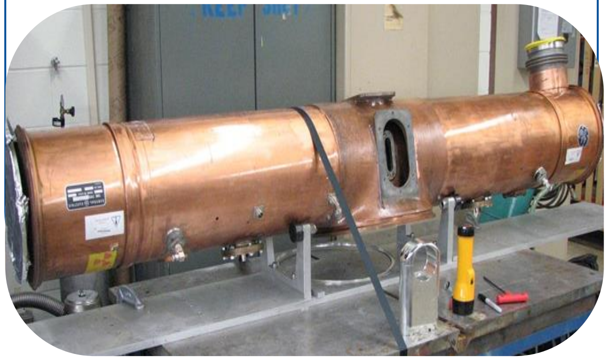
Rebuild - Cones & Tuners

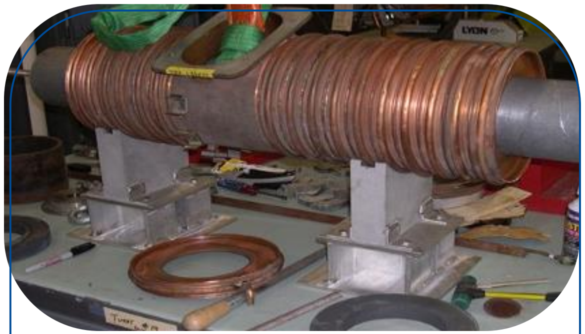
Rebuild Stems/Flanges

Re-Assemble

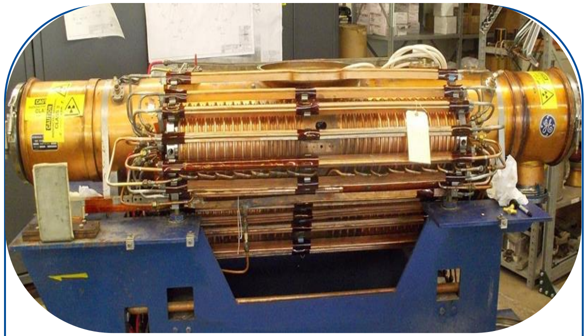
Testing

Cavity Removal - Stripping

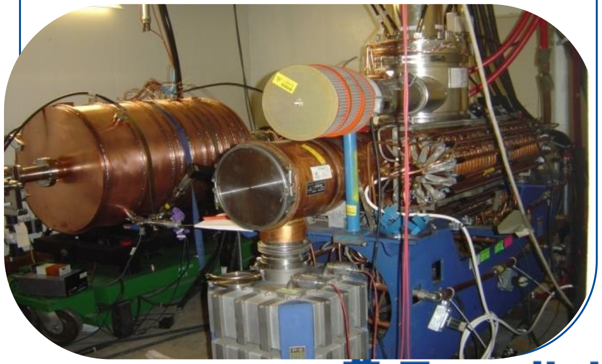




Tuners Rebuild



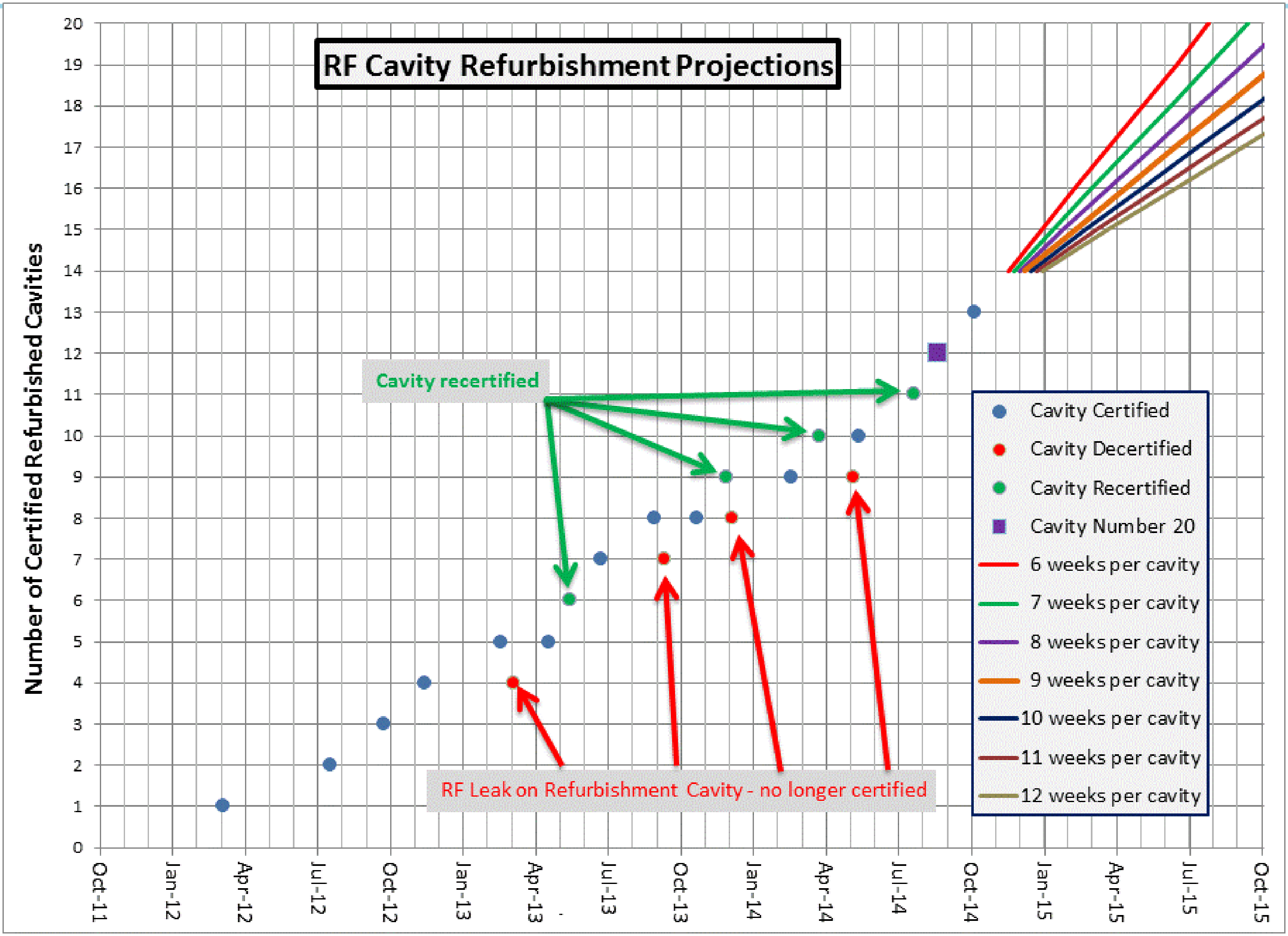
Rebuild and Test



Booster refurbishment

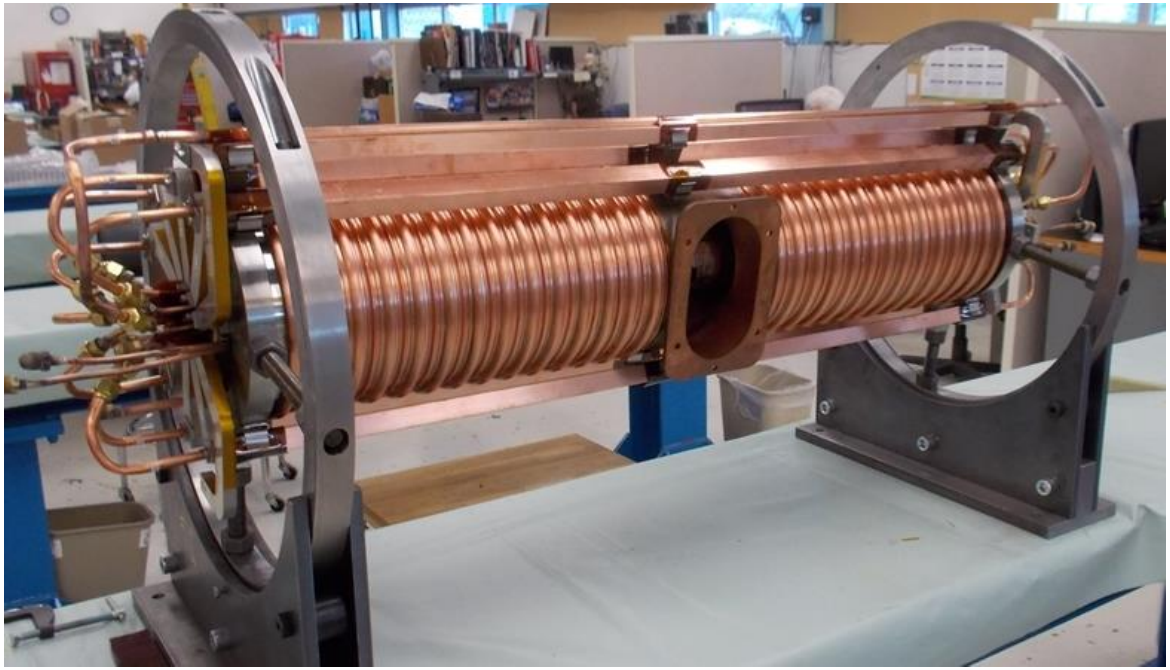
- Goals: Completion of Refurbishment in FY15
  - (19+1) cavities after refurbishment is complete
    - (+1) comes from an originally rejected cavity
  - 22 cavities will be the final number
    - 2 cavities will come from the Proton Driver project after modifications to their aperture
  - Reliable 15 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



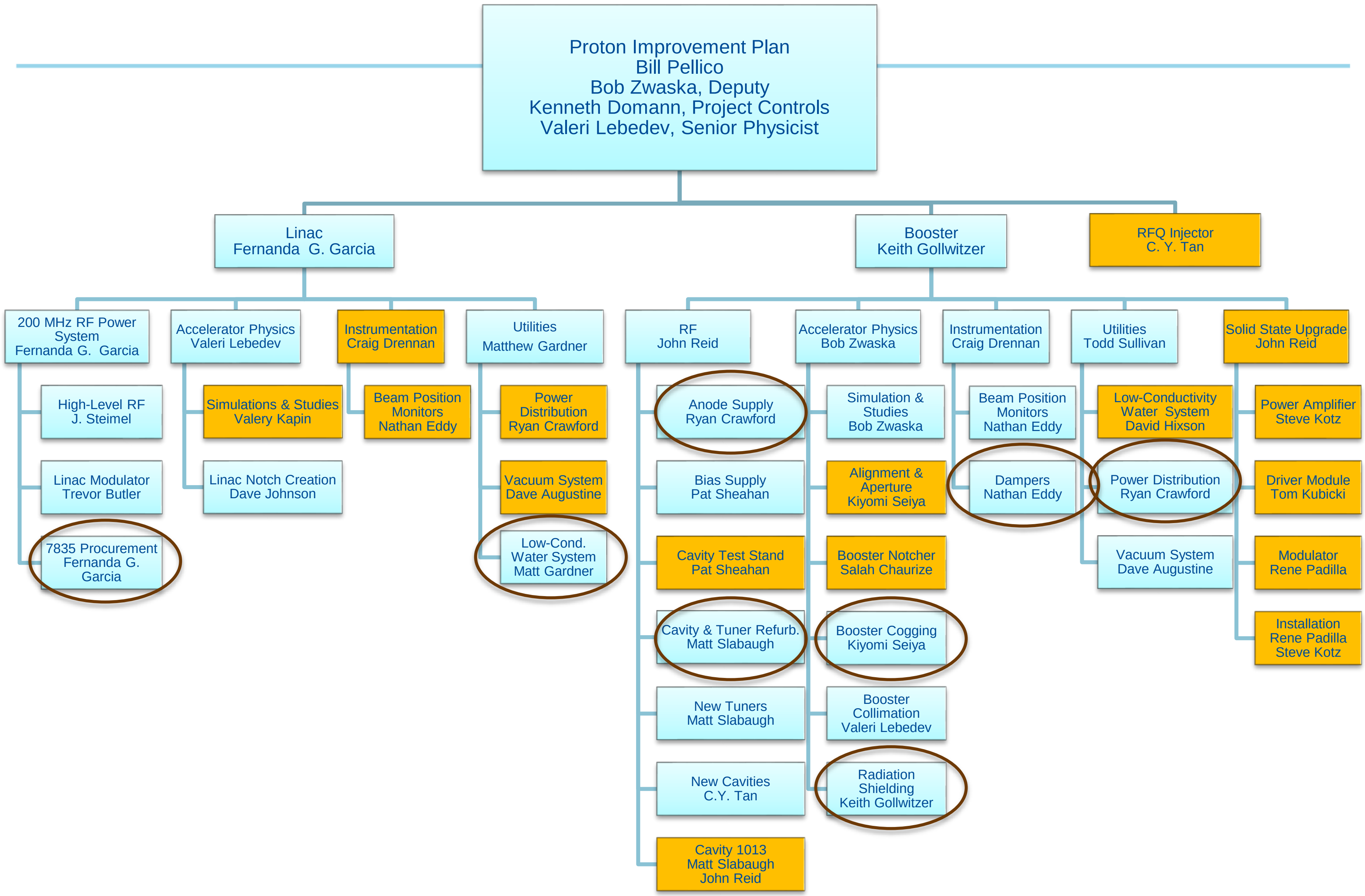
Booster RF station (Solid State upgrade completed in FY13)

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
Bill Pellico
Bob Zwaska, Deputy
Kenneth Domann, Project Controls
Valeri Lebedev, Senior Physicist
Linac
Fernanda G. Garcia
Booster
Keith Gollwitzer
RFQ Injector
C. Y. Tan
200 MHz RF Power System
Fernanda G. Garcia
Accelerator Physics
Valeri Lebedev
Instrumentation
Craig Drennan
Utilities
Matthew Gardner
RF
John Reid
Accelerator Physics
Bob Zwaska
Instrumentation
Craig Drennan
Utilities
Todd Sullivan
Solid State Upgrade
John Reid
High-Level RF
J. Steimel
Linac Modulator
Trevor Butler
7835 Procurement
Fernanda G. Garcia
Simulations & Studies
Valery Kapin
Linac Notch Creation
Dave Johnson
Beam Position Monitors
Nathan Eddy
Power Distribution
Ryan Crawford
Vacuum System
Dave Augustine
Low-Cond. Water System
Matt Gardner
Anode Supply
Ryan Crawford
Bias Supply
Pat Sheahan
Cavity Test Stand
Pat Sheahan
Cavity & Tuner Refurb.
Matt Slabaugh
New Tuners
Matt Slabaugh
New Cavities
C.Y. Tan
Cavity 1013
Matt Slabaugh
John Reid
Simulation & Studies
Bob Zwaska
Alignment & Aperture
Kiyomi Seiya
Booster Notcher
Salah Chaurize
Booster Cogging
Kiyomi Seiya
Booster Collimation
Valeri Lebedev
Radiation Shielding
Keith Gollwitzer
Beam Position Monitors
Nathan Eddy
Dampers
Nathan Eddy
Low-Conductivity Water System
David Hixson
Power Distribution
Ryan Crawford
Vacuum System
Dave Augustine
Power Amplifier
Steve Kotz
Driver Module
Tom Kubicki
Modulator
Rene Padilla
Installation
Rene Padilla
Steve Kotz

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

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

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

Robert Zwaska

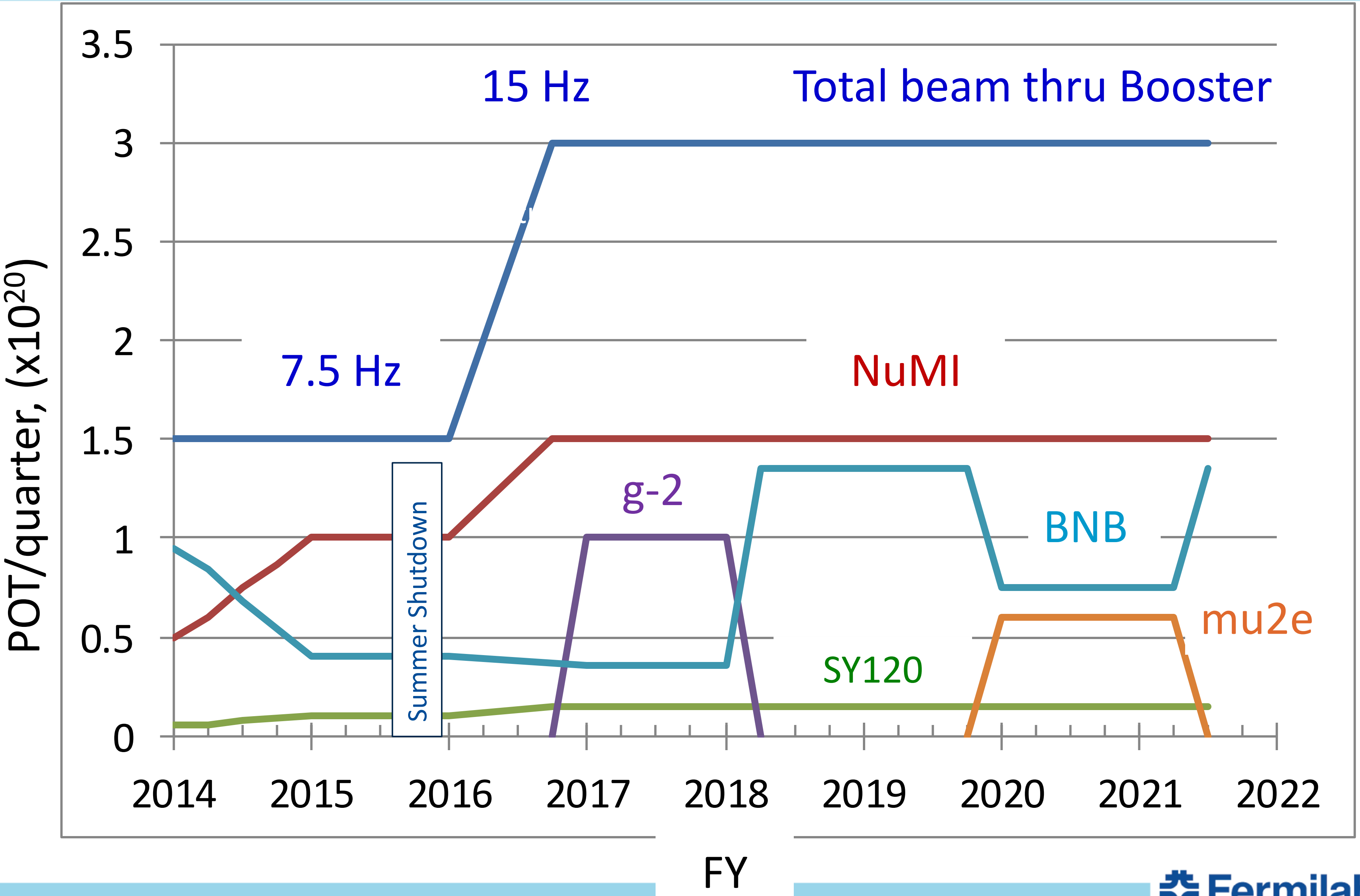
11 November 2014

HB2014

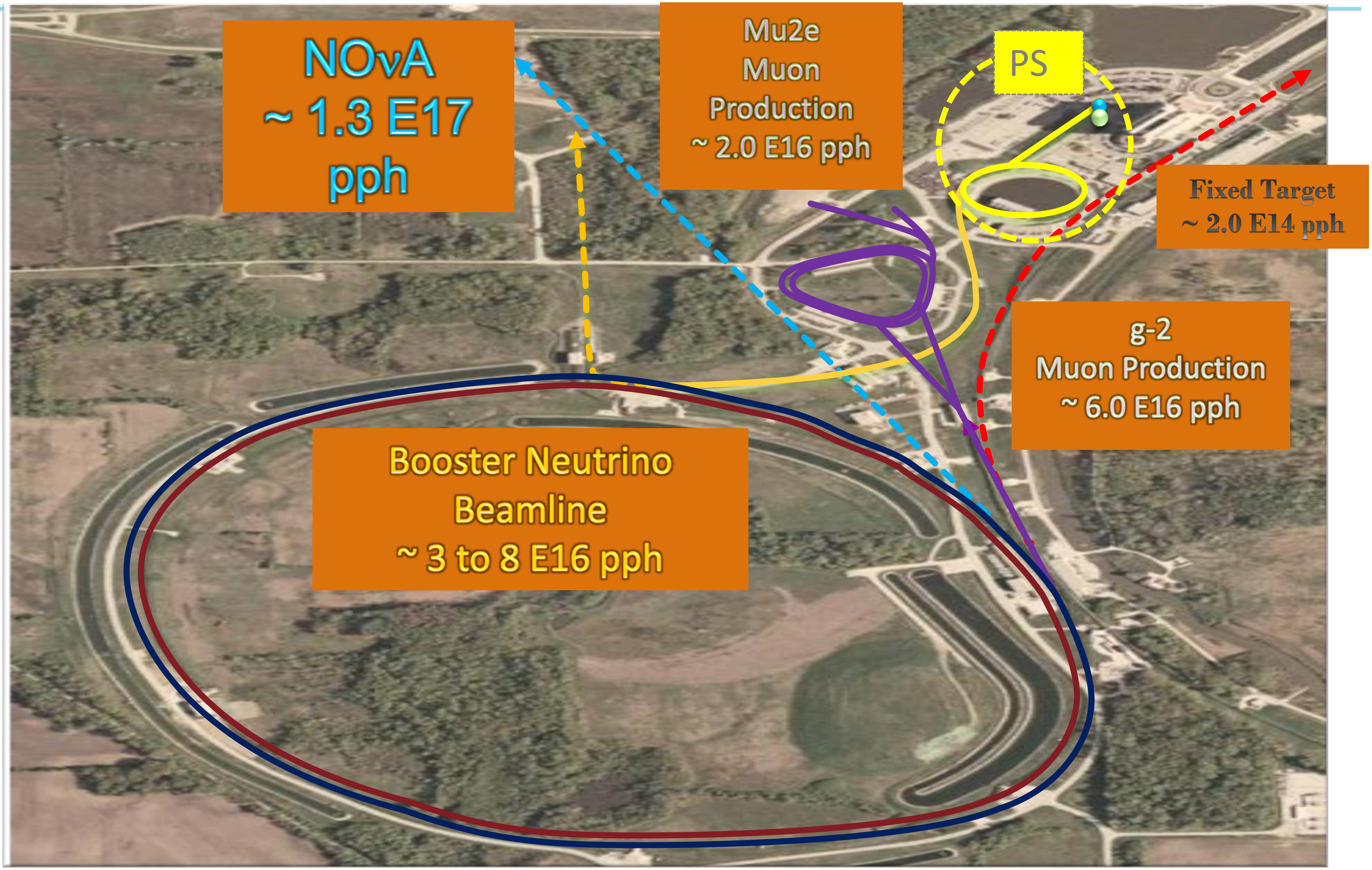
PIP Booster Beam Parameters (At Completion

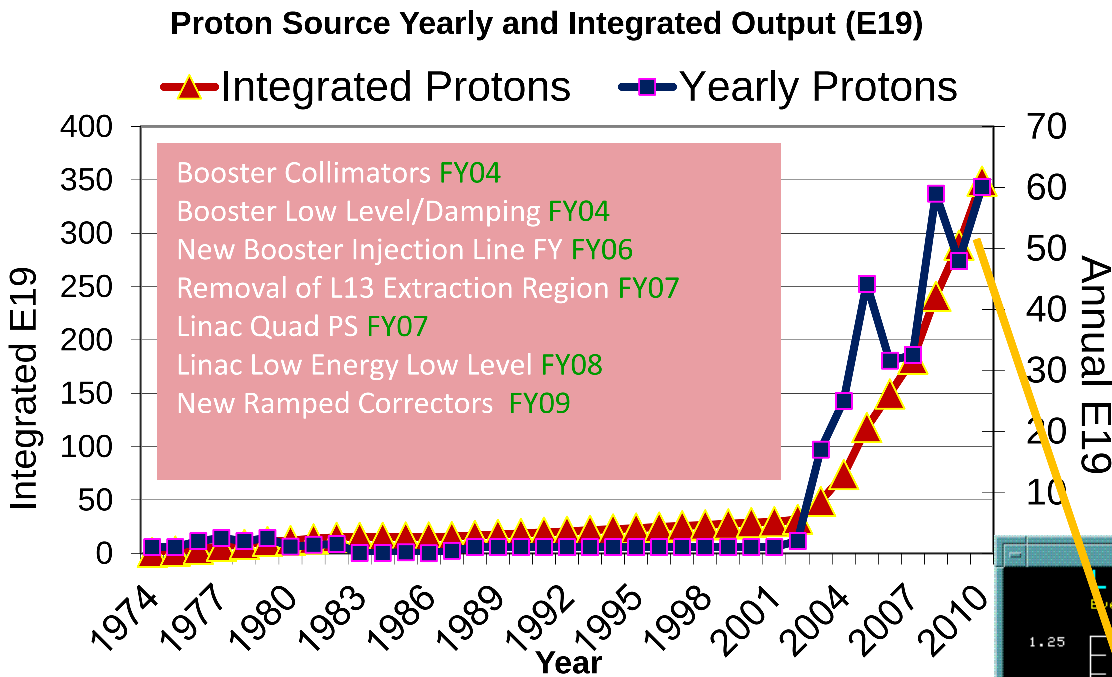
Parameter	**Value**	Units
Particle Species	Protons	
Input (H^{-}) Beam Energy (Kinetic)	400	MeV
Output Beam Energy (Kinetic)	8.0	GeV
Protons per Pulse (injected)	4.7×10^{12}	
Protons per Pulse (extracted)	4.3×10^{12}	
Beam Pulse Repetition Rate	15	Hz
RF Frequency (injection)	37.2	MHz
RF Frequency (extraction)	52.8	MHz
Injection Time	0.02	msec
Injection Turns	~10	
Beam Emittance (95%, normalized)	15	π mm-mrad
Laslett Tune Shift at Injection (33% B.F.)	-0.47	
Delivered Longitudinal Emittance (95%)	0.08	eV-sec
Delivered Momentum Spread (95% full height)	±8	MeV/c

Updated Proton Delivery Scenario (approximate no shutdowns shown)



Proton Source – Flux delivery plans



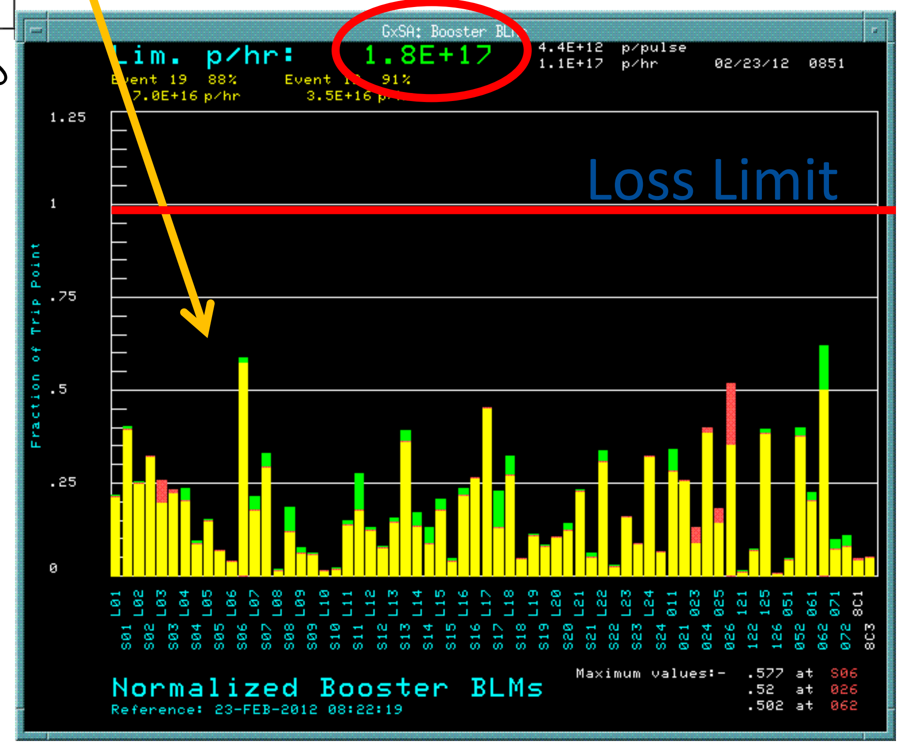


Beam loss limits were set at levels with personnel safety (ALARA) first – flux output increases came with efficiency….

(from ~68% to over 90%)

A ten-fold increase in hourly rates, lower loses and higher uptime. The flux ramp-up for the intensity frontier took time, money and labor….

Almost 8 years of effort before the PS was able to exceed beam requests.

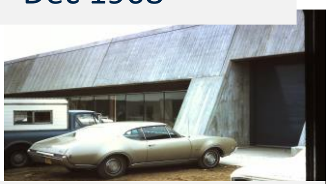


Fermilab

FNAL Linac timeline

1960 1970 1990

Linac ground breaking
Dec 1968



Linac 1st NAL permanent building
Dec 1969

The Village Crier
national accelerator laboratory
Vol. 2 No. 22
August 21, 1970

TEXANS AID IN BUILDING LINAC

The development and construction of the National Accelerator Laboratory requires the skills of men and women from many places and with diverse backgrounds. Pictured (at right) are engineers from Dallas, Texas, who have spent a number of months at NAL. They are employees of the Continental Electronics Manufacturing Corporation, of Dallas.

In the photo are (left to right) Ken
Brown, Herman Swann
y have just com-
f the radio-fre-
d by their firm.
at NAL since Feb-
nce April and Andy
rips from Dallas to
xperience with Conti

rf amplifying cavit
as. Donald Young,

Linac 200 MeV DTL
1970

Linac RF equipment installation & commissioning
April-Aug 1970

Linac 400 MeV Upgrade
1993

2000 2010 2020 2030

FNAL Linac topology

35 keV | 750 keV | 750 keV | 116 MeV | 400 MeV

H- | RFQ | buncher | DTL | SCCL transition | SCCL

Magnetron ion source
35 kV
extractor

Radio Frequency Quadrupole
201.25 MHz
1.2 m
1 tetrode
175 kW

Buncher dual-gap cavity
201.25 MHz
0.2 m
1 pentode
5 kW

Drift Tube Linac
201.25 MHz
73 m
5 tanks
5 triodes
5 MW
200 EQM

Side-Coupled Cavity Linac
805 MHz
4 m
2 modules
2 klystrons
200 kW
4 EQM

Side-Coupled Cavity Linac
805 MHz
65 m
7 modules
7 klystrons
12 MW
28 EQM

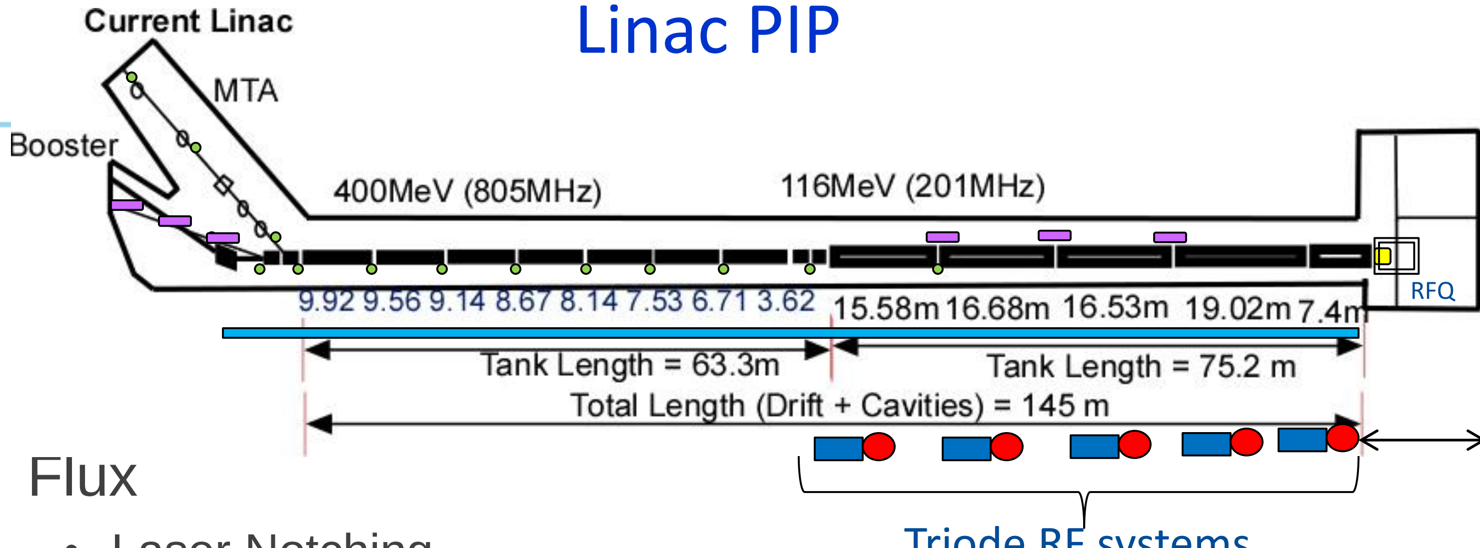
Total Linac: 145 m
5 triodes
9 klystrons

Duty cycle:
0.5% RF
0.04% beam

3 different structures
(RFQ, DTL, SCCL)
2 frequencies

Beam current:
25 mA (avg. in pulse)

Linac PIP



Modulator &
7835 Tube Socket

- Flux
  - Laser Notching
  - Beam Physics
  - Upgraded diagnostics/software
    - BPMs
    - Toroids
- Vulnerability
  - Modulators, Driver Solid State RF source
  - Burle 7835 tube system
  - Utilities
    - Vacuum (Roughing stations, pumps, valves…)
    - LCW (pumps, plumbing)
    - Power (transformers, MCC, breakers, distribution)

Low Energy Linac

Linac Utilities

The Linac power distribution system is under powered, has obsolete parts and is largely buried in the Linac lower gallery – new system will replace only part of present system.

Substation Enclosure >18,000 lbs

Critical vacuum systems update such as the LE roughing stations – along with flanges and valves.

Will be lowered through hatch (FY15?)

Linac Roof Hatch

Updated Roughing Pumps

Linac Diagnostics BPM and Toroid upgrade completed

Crate #	Location		IP Address Decimal	Name	BPM Names Master		Slave 1		Slave 2		Slave 3		Slave 4		Slave 5	
1	Low-Energy Linac	Tank 2	131.225.131.199	LNBP01	LEL 2 Out	33										
2		Tank 3	131.225.131.205	LNBP02	LEL 3 In	19	LEL 3 Out	12								
3		Tank 4	131.225.131.207	LNBP03	LEL 4 In	14										
4		Tank 5	131.225.131.209	LNBP04	LEL 5 In	43	LEL 5 Out	57								
5	Diagnostics Room	LDR-0	131.225.131.249	LNBP05	HEL 0-2	23	HEL 0-3	54	HEL 0-4	30	HEL 1-1	39	HEL 1-2	21	HEL 1-3	13
6		LDR-0	131.225.131.218	LNBP06	HEL 2-1	31	HEL 2-2	34	HEL 2-3	48	HEL 3-1	59	HEL 3-2	44	BP201	27
7		LDR-0	131.225.131.242	LNBP07	HEL 3-4	28	HEL 4-1	53	HEL 4-2	45	HEL 4-3	52	HEL 4-4	56	HEL-3-3	17
8		LDR-1	131.225.131.243	LNBP08	HEL 5-1	22	HEL 5-2	60	HEL 5-3	49	HEL 5-4	35	HEL 6-1	29	HEL 6-2	2
9		LDR-1	131.225.131.248	LNBP09	HEL 6-3	40	HEL 6-4	6	HEL 7-1	58	HEL 7-2	26	HEL 7-3	36	HEL 7-4	55
10	400 MeV Line	LG1-RR2-3	131.225.138.107	MTABP7	BP204	38	BP203	5	BP202	25	??	16				
11		LG1-RR4-1	131.225.138.108	MTABP8	Q1	15	Q2	10	LAM	41	Q3	89	Q4	63	Q5	70
12		GR24-RR6-1	131.225.138.109	MTABP9	Q6	73	Q7	71	Q8	68	Q9	51				
13		GR24-RR6-3	131.225.138.110	MTABP10	Q10	90	V-Q11	11	Q12	18	DEB	42	Q13	24		
14		GR24-RR6-3	131.225.138.111	MTABP11	Q15	3	Q16	69	Q14	8	Q17	92	SEPU	86	HSEPD	
15		GR24-RR6-3	131.225.138.025	MTABP12	PFOIL	9	L1D	67	S01	64	L1U	66	S24	72		

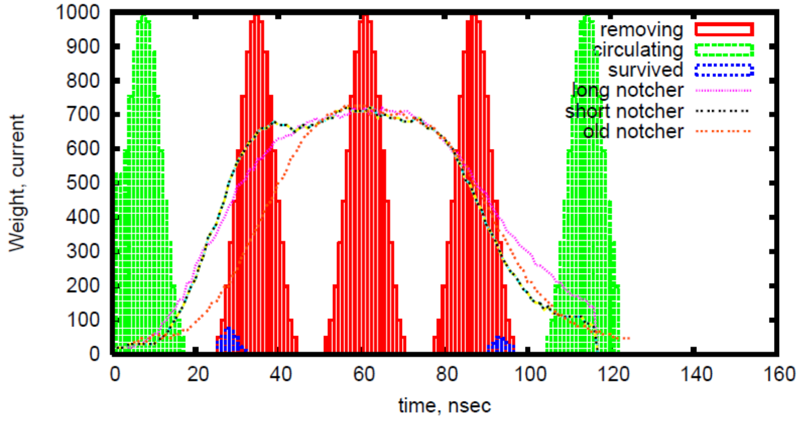
15 Crates – over 60 BPMs

The new digital BPM system is commissioned:
ACNET and Java applications
Hardware/Diagnostics software

Provide average Position, Intensity, & Relative Phase over each beam pulse for every BPM @15Hz

Notching System

- Booster is h=84
- Booster extraction & MI injection kickers' rise times are ~50ns
- Transfer kickers' rise time corresponds to 3 RF buckets
- No notching done for many years
  - Booster extraction kicker sprayed beam…
- Three 1 meter notcher-kickers introduced a dozen ago dumped beam before acceleration
  - Most activated region in Booster
    - ~40% of total power loss
  - Notching occurs early in cycle
    - 400 MeV for non-cogged cycles
    - 700 MeV when radial cogging
- Notching Goal
  - 15ns rise and fall times with 3 bucket flat top



Fermilab

Notching System – PIP Work

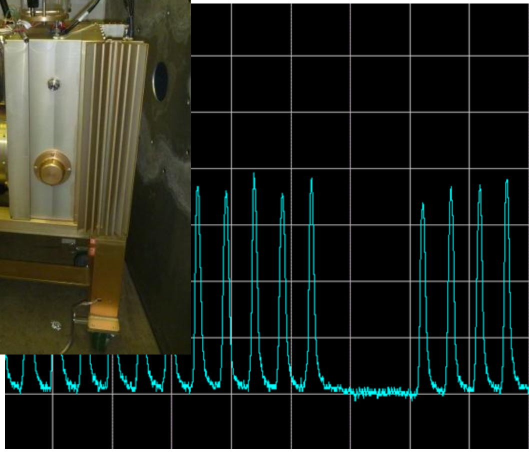
- Moved notcher-kickers & installed engineered absorber
  - Ran 2013-14
    - next slide for reduced activation
- Replace notcher-kicker system
  - Six half-meter notcher-kickers

Absorber

Short Kickers – drop in replacements – two in operation for 2014 summer

    - Remaining 4 just installed
  - New power supply system
    - Partial system ran in summer
    - Entire power system installed

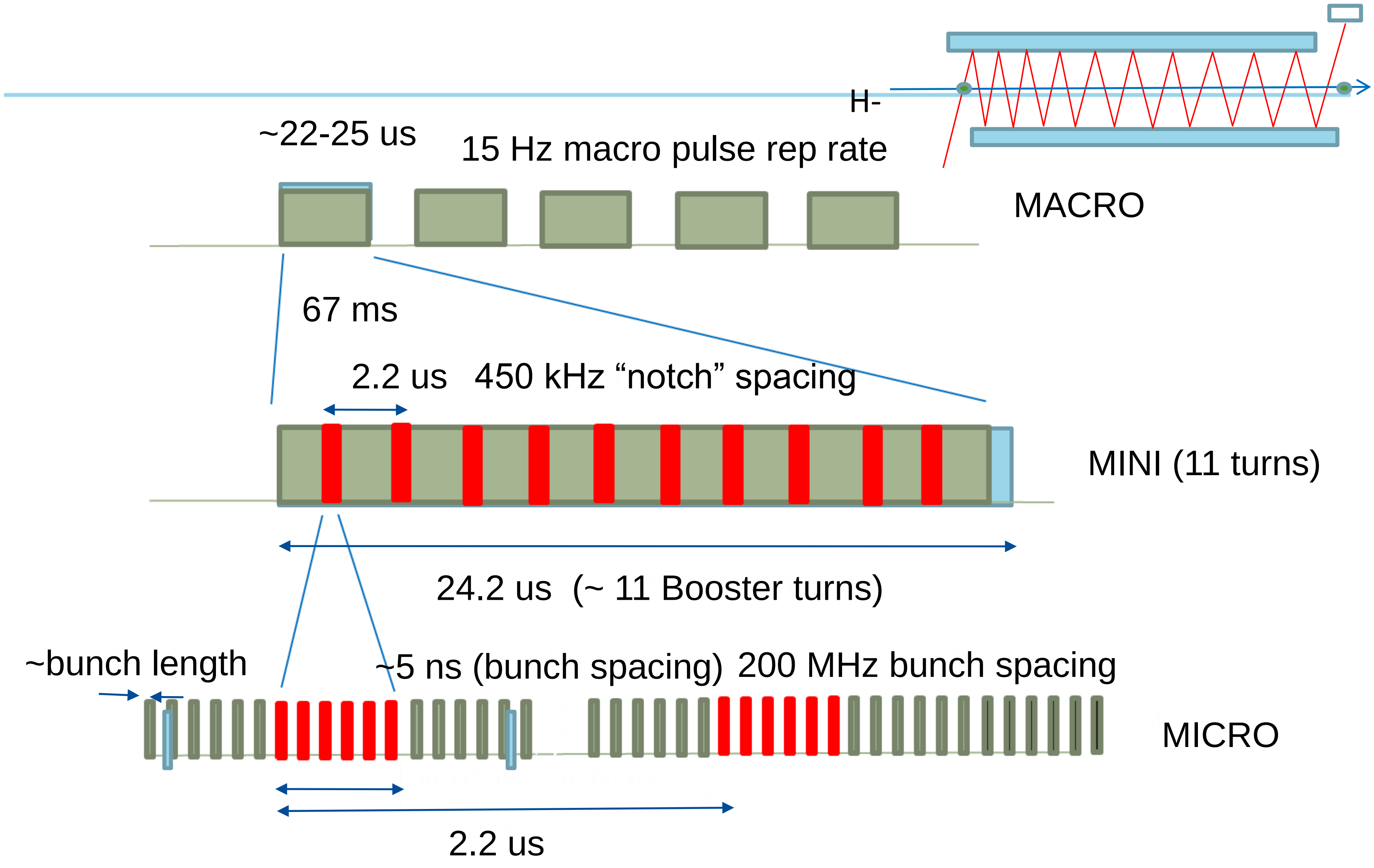
NoVA Style



Requirements and Technique of Laser Notching of H-

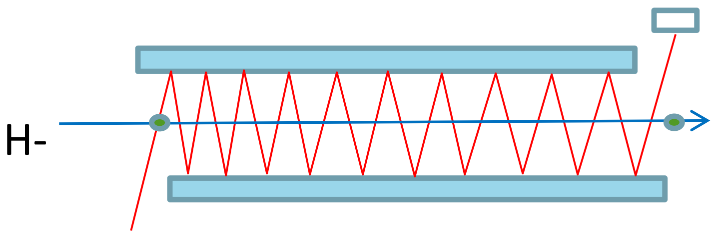
- **Requirements**
  - All ions in bunch should see the same photon density
  - The 201.25 MHz laser pulses must be phased with the RFQ
  - The laser pulse length =/> bunch length ~1.5 to 2 ns
  - Uniform temporal profile
  - The burst of 201.25 MHz pulses must match the Booster inj rev. freq.
  - The 450 kHz burst must have appropriate timing within the linac pulse
  - The pulse energy should neutralize > 99% of ions in each bunch

- **Technique**
  - Utilize a CW seed laser and wave-guide modulator to create required laser pulse pattern (both 200 MHz and 450 kHz) at low pulse energies (pJ)
  - Amplify pulse pattern using a three-stage fiber amplifier (nJ to uJ)
  - Further amplify using a free-space solid state amplifier (mJ)
  - Create a spatially uniform photon beam
  - Insert laser pulse into a linear zig-zag interaction cavity where the laser reflections inside the cavity match the ion velocity
    - to reduce required pulse energy by the number N of reflections in the cavity.

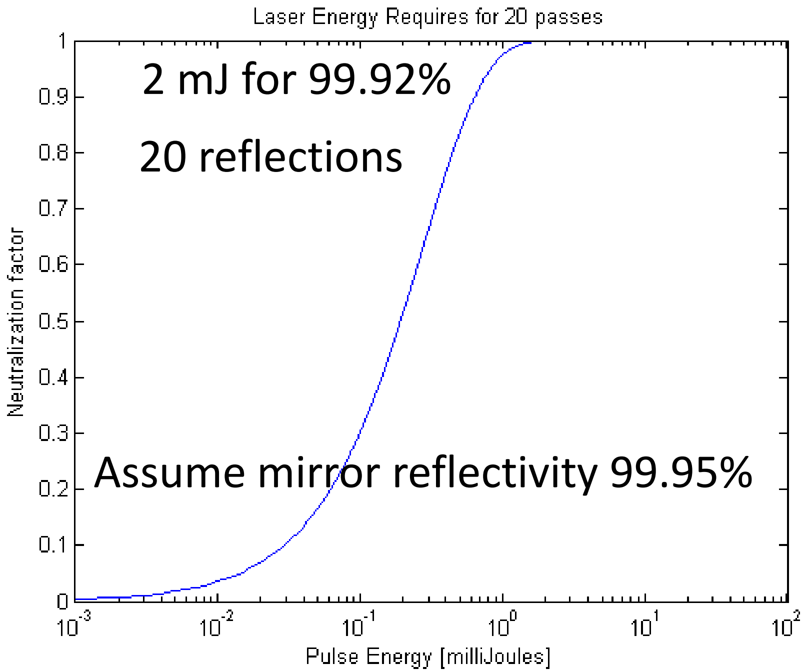

H-
~22-25 us
15 Hz macro pulse rep rate
MACRO
67 ms
2.2 us
450 kHz “notch” spacing
MINI (11 turns)
24.2 us (~ 11 Booster turns)
~bunch length
~5 ns (bunch spacing)
200 MHz bunch spacing
MICRO
2.2 us

Reduction of Pulse Energy

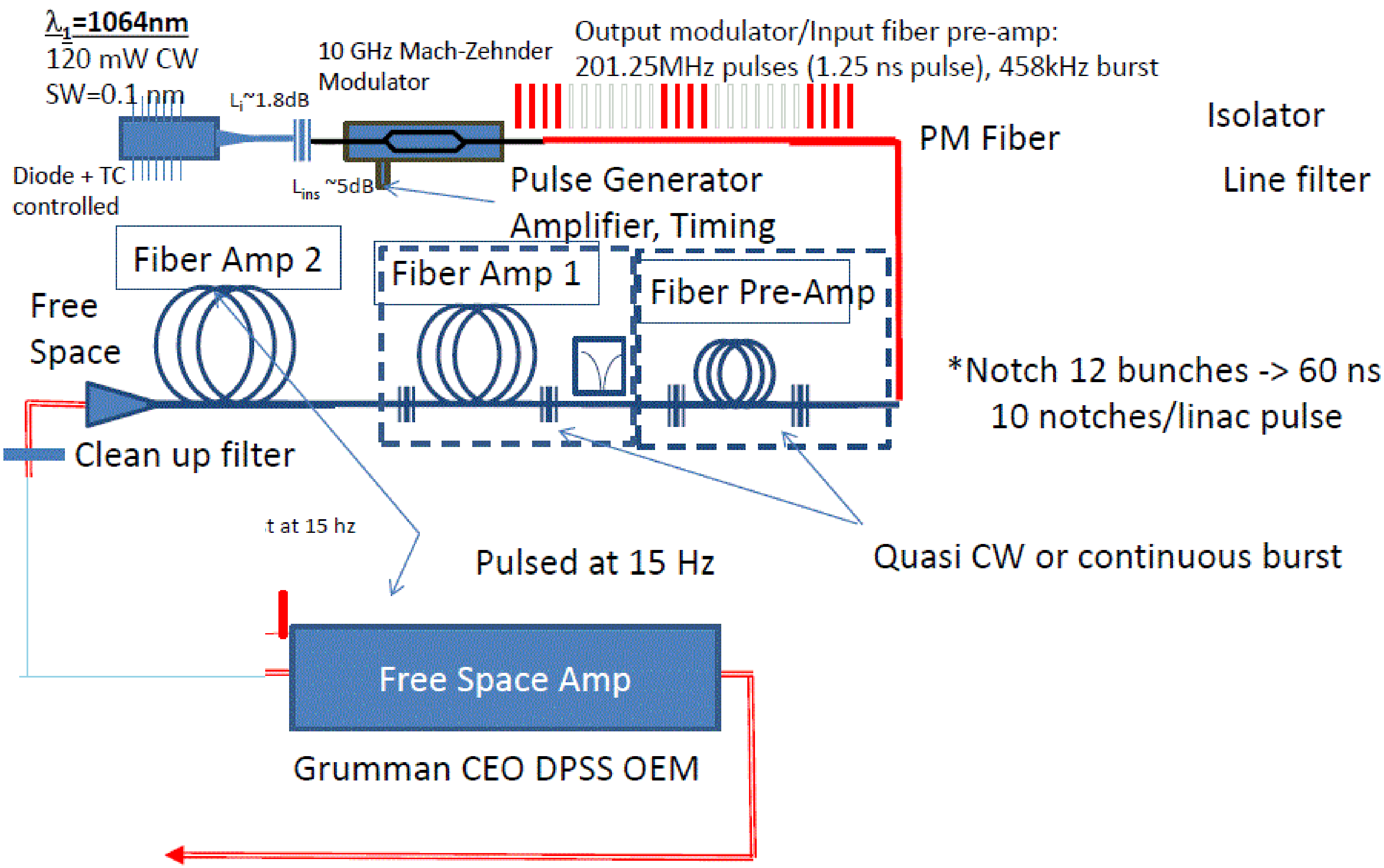
- To reduce the required pulse energy we can effectively increase the interaction time by utilizing an optical cavity such that the laser interacts with the ion beam multiple times.



- Laser follows ion to interact many times
- Cavity length proportional to numbe of interactions
- Laser pulse length = notch length
- Cavity dimensions determined by ion velocity and bunch spacing
- Reduces required laser pulse energy by ~ number of interactions



Burst mode seed pulses to Fiber Amplifier followed by Free Space Amp

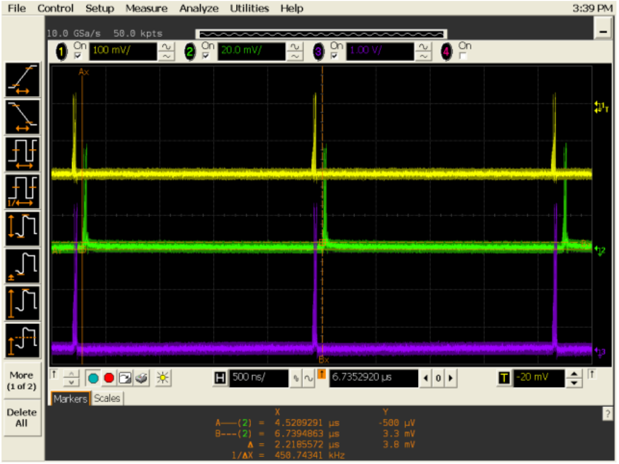


TRANSPORT BEAM SHAPING OPTICS & OPTICAL CAVITY

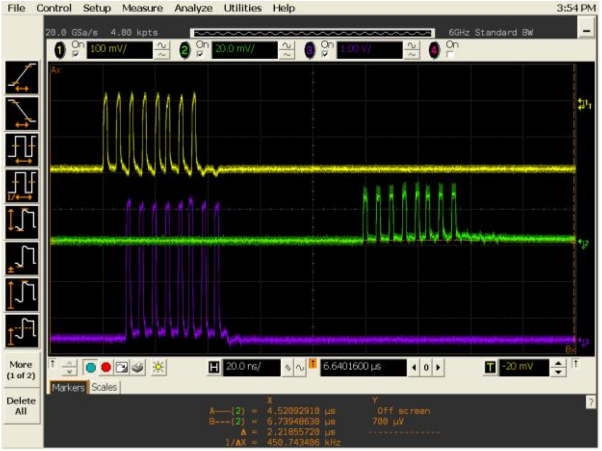
Optical Pattern Generator

Yellow- AWG   Purple- RF Amp out
Green – signal form 1.2 GHz (free-space)PD → laser pulses out of fiber pre-amplifier

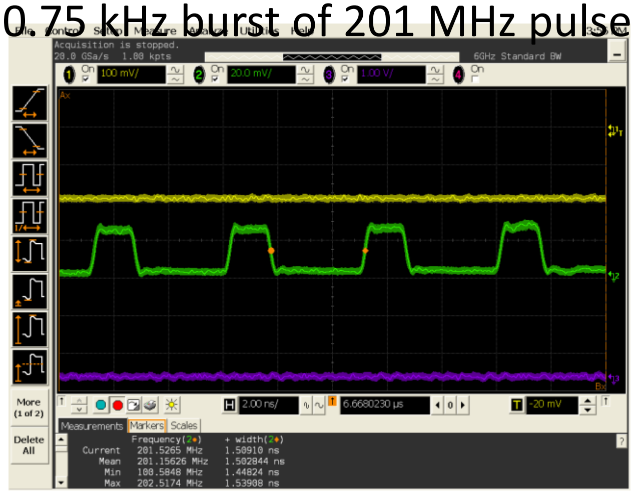
AWG: Chase Scientific DA12000 & CG6000 module



450.75 kHz burst of 201 MHz pulses



One set of 201.25 MHz pulses

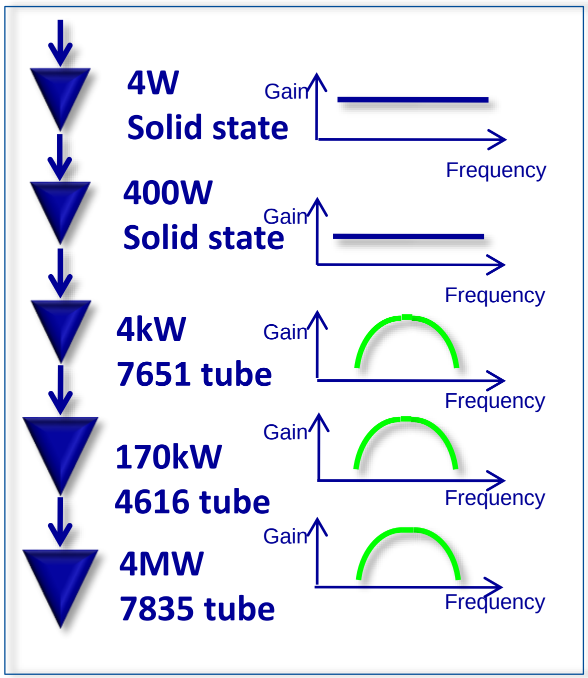


Individual 201.25 MHz temporally uniform pulses

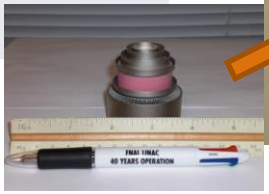
PIP – Linac 200 MHz RF system

RF drive chain – consists of variety of solid state amplifiers, pentode, tetrode and triode vacuum tubes

DTL system requires ~~75~~ 68 tubes with ~~10~~ 9 different types



Manufacturer: Photonis Industries
Av.Lifetime (past 5 years) : ~ 1.5 years
Operational Needs: 7

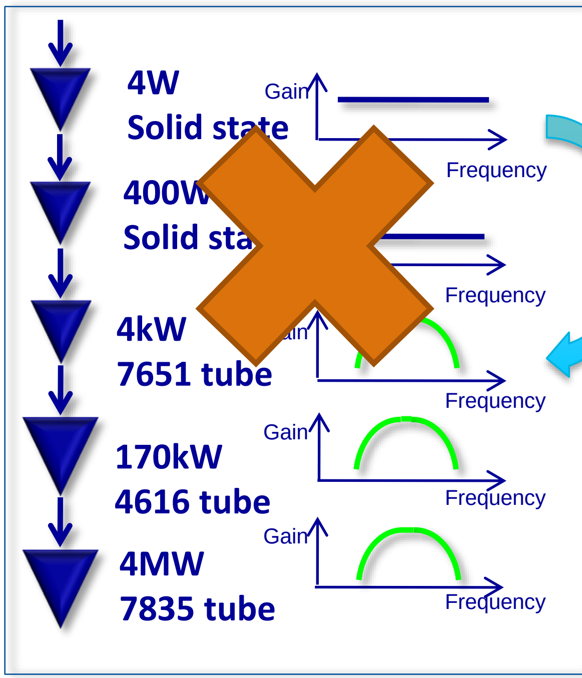


Fermilab

PIP – Linac 200 MHz RF system

RF drive chain – consists of variety of solid state amplifiers, pentode, tetrode and triode vacuum tubes

DTL system requires ~~75~~ 68 tubes with ~~10~~ 9 different types



Manufacturer: Photonis Industries
Av.Lifetime (past 5 years) : ~ 1.5 years
Operational Needs: 7

7651 system

Solid State Amplifier

Repaired cavity (part of +3 cavities)

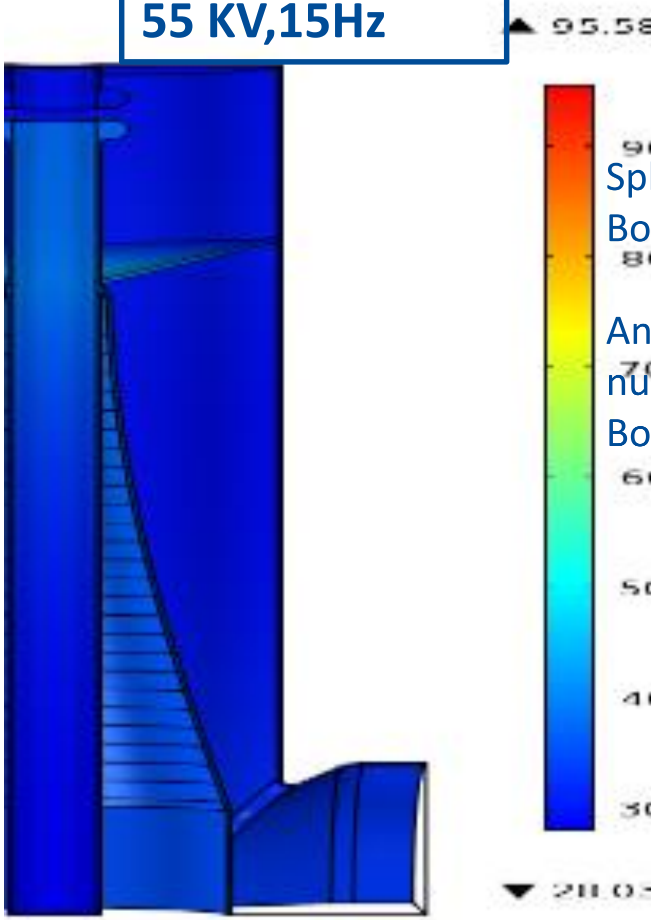
- Tested successfully
- Installed in late August
- Ran for the last two weeks before the shutdown

This was an original cavity - rejected due to mechanical issues. Redone with spare components and machining. This will allow for 20 stations to operational upon completion of refurbishment.
This has been installed and running in Booster in Aug 2014 for about 2 weeks before shutdown.

Booster PIP - New Cavities and Harmonic Cavity

Specifications for Design of New Accelerating Cavities for the Fermilab Booster underway with testing of current cavities to confirm modeling.

55 KV,15Hz

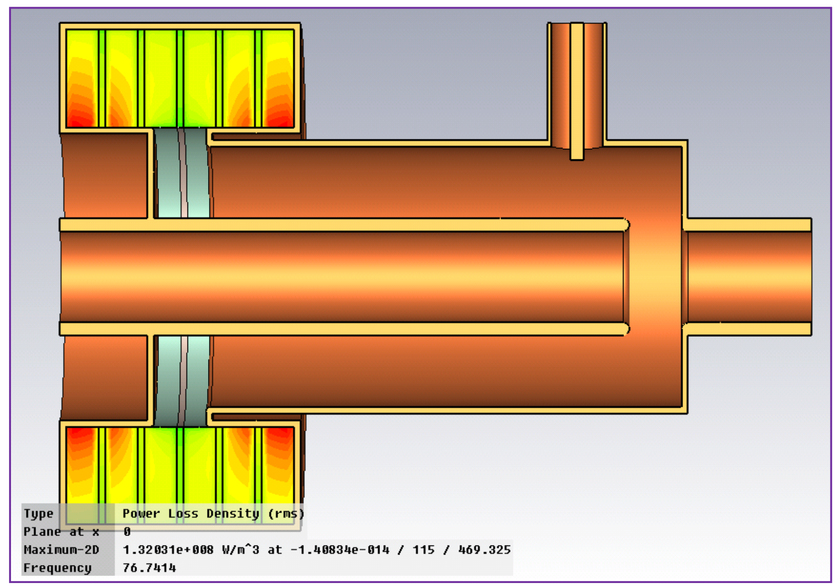


Split Image view of Booster Cavity

Anticipate increasing number of cavities in Booster from 19 to 22

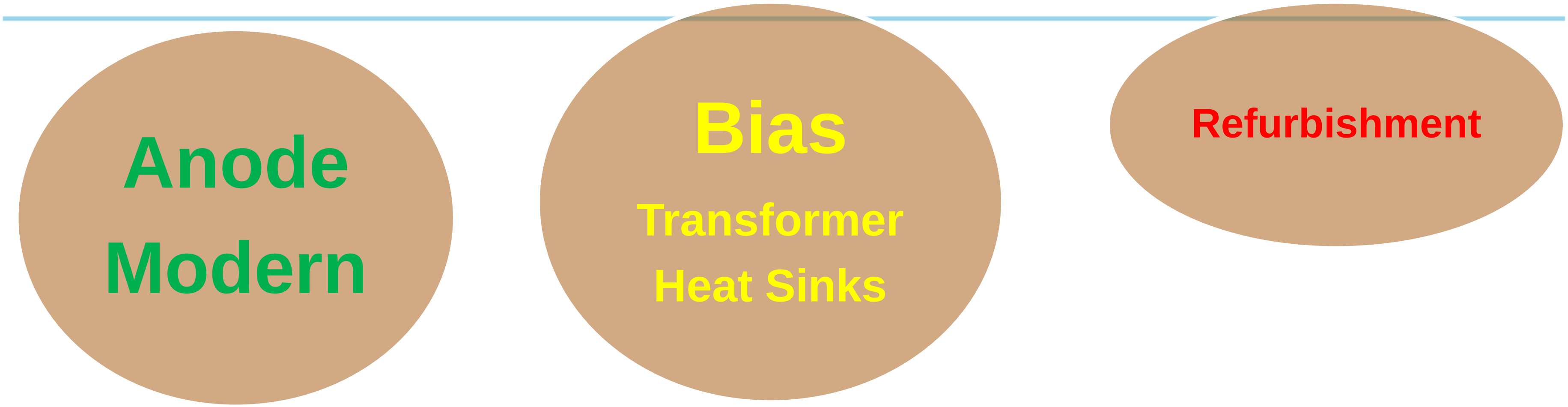
Thermal Profile (F)

- Harmonic cavity work is underway to help with beam capture, transition and possibly extraction.
  - Based upon work at TRIUMF and LANL
  - Simulations look promising
  - University interest – Illinois Institute of Technology



Magnetic loss density (100 kV)

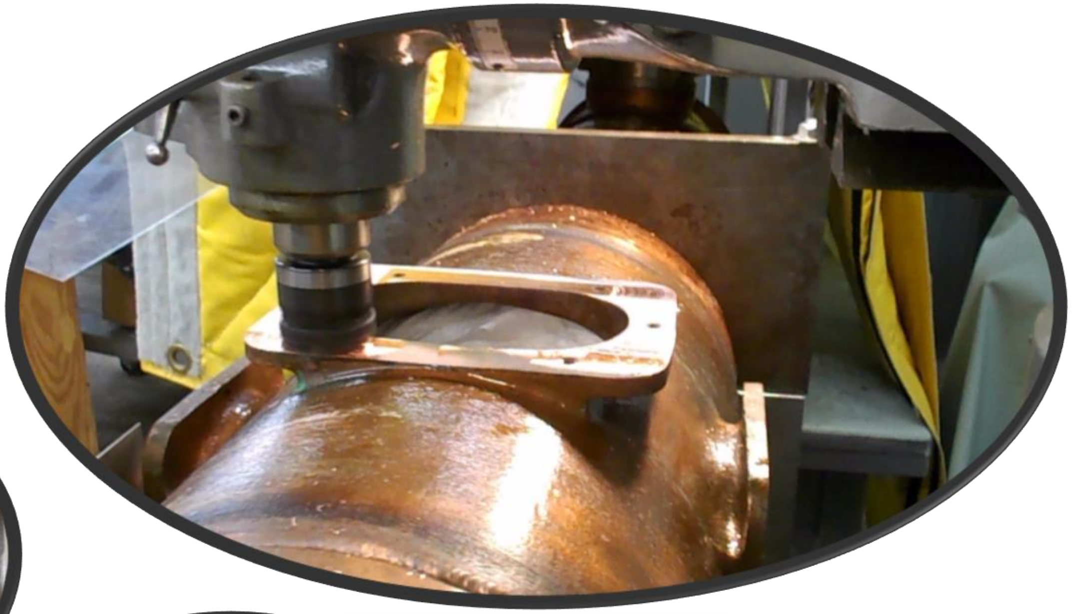
Anode Supplies and Bias Supplies (15 Hz operation)

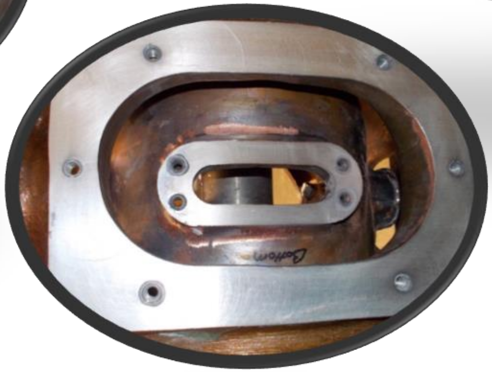


Design is nearly complete
Install this summer both anode supplies: (EE / RF Dept.)

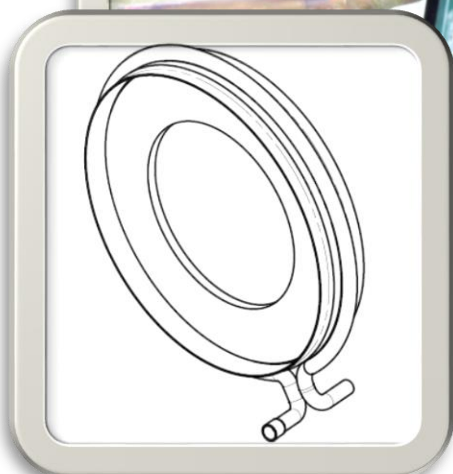
East gallery complete
West gallery supplies work underway but slow – will be finished FY15

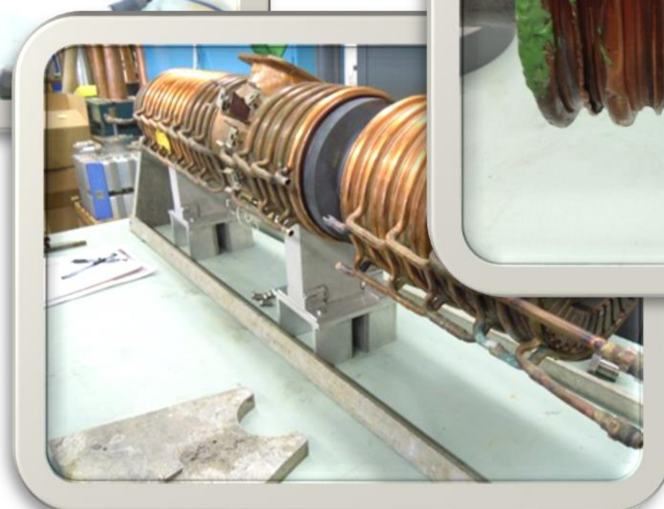
Cavity RF flange refurbishment





Tuner refurbishment





Fun Facts

You need all cavities in tunnel to be refurbished before higher rep rate operations

After refurbishment is completed – higher flux will require time

After refurbishment is completed – the cavities will still be OLD

There is likely to be failures as cavities are run harder

Roughing Station (1 of 4)

Replacing Original Equipment

Vacuum:
Turbos, Roughing Stations, Ion pumps and Valves

2 Utility Substations (1000kva) Breakers & MCC

Isolation Valve

LCW: Valves, New plumbing, Pumps, Hoses, Bypasses in galleries and general repairs

Accessible Filtering

Isolation Valve

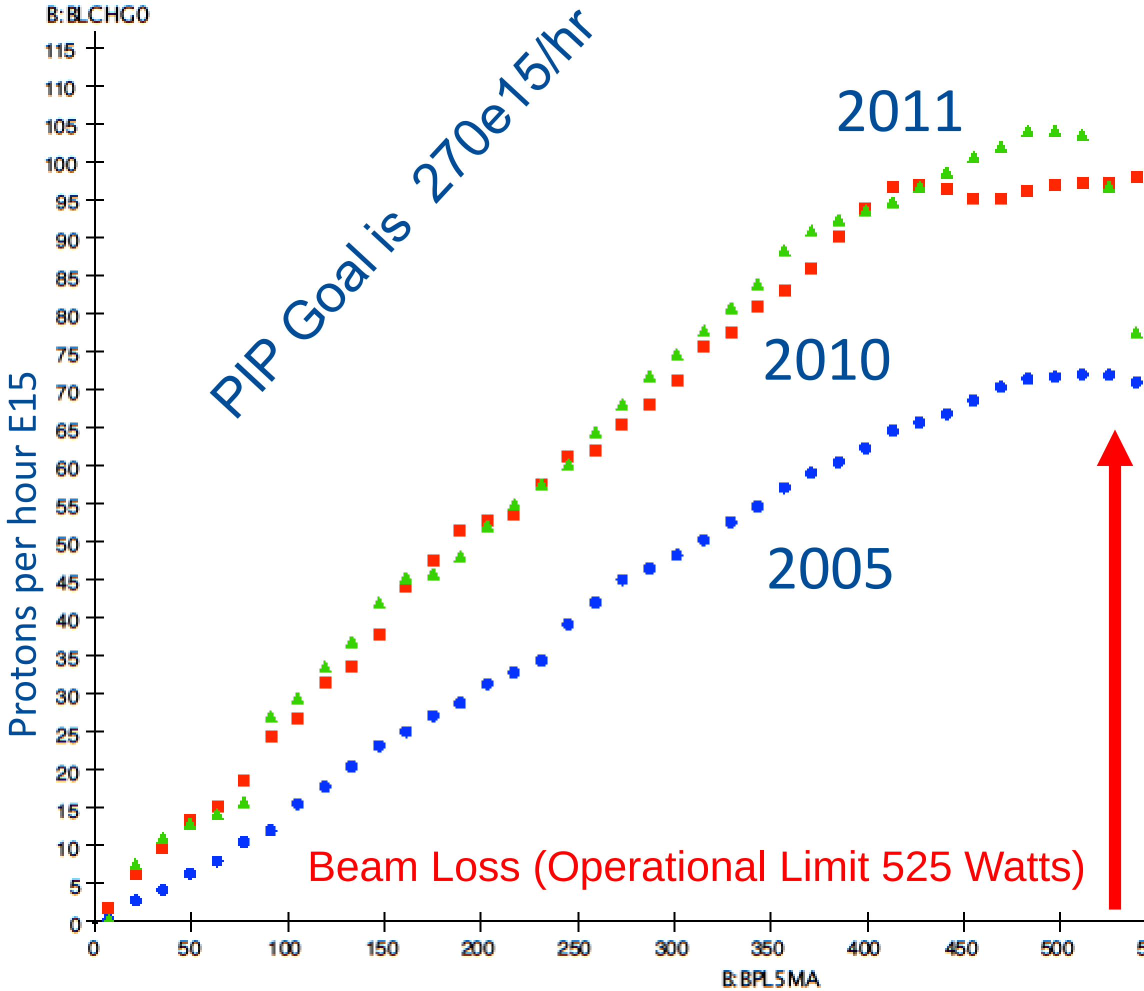
New LCW Return System

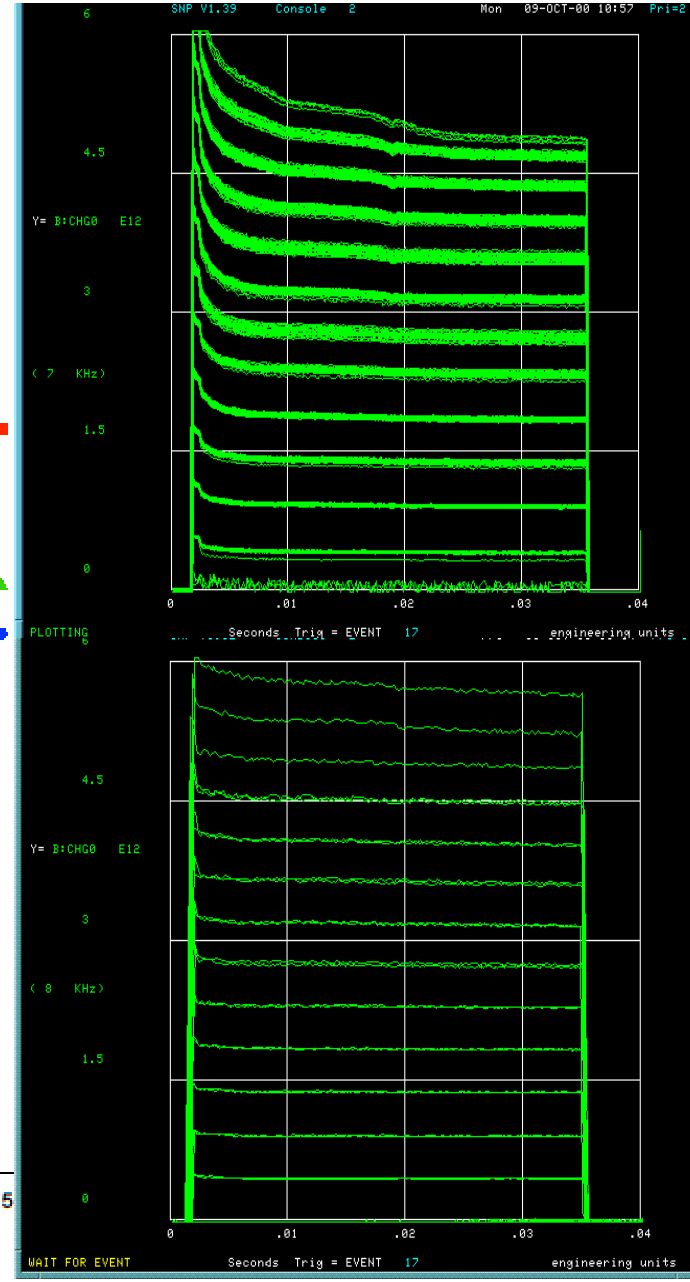
Booster Losses

- Losses at injection
  - Poorly captured beam
- Notch creation
  - Gap for extraction
  - Created with a kicker
  - Lost in gradient magnet
- Slow losses at high-energy
  - Optics issues
  - RF variation
- Transition
  - Occasionally significant, but can usually be tuned away

Fermilab

Flux increase - Losses





Fermilab

Path to Higher Proton Throughput

- Loss reduction
  - Lower linac emittance
    - RFQ & linac lattice improvements
  - Apertures & alignment
    - Comprehensive survey of apertures
    - Alignment where necessary (including within girders)
    - Opening apertures where possible
  - Optics adjustment
    - Comprehensive survey of lattice and coupling
    - Control of tunes and chromaticity
    - Automated orbit and optics smoothing
  - RF improvements
    - Increased voltage from amplifiers
    - Cavity modification/replacements
  - Instabilities
    - Dampers
  - Injection painting

- Orbit Control
  - Magnetic Cogging
    - Prerequisite for other work
- Loss Control
  - Rework of notching in Booster
    - Perform earlier in cycle
    - New notch kickers and absorber
    - Exploration of full or partial notching in Linac
  - Collimation system
    - Operate as true, two-stage system
    - Run beam near primary scatterer
    - Optimize primary scatter thickness
  - Adjust radiation shielding where advantageous

Booster Shielding

Goal – 2.7E17 p/hour

A Booster shielding assessment is underway:

Several rounds of scans have been performed

First round of analysis completed

Preparing for another set of measurements – based upon earlier results

Need to finish by FY15

Assessment Beam Parameters

Shielding Requirements

Longitudinal Shielding Summary

Transverse Shielding Summary

Labyrinths and Penetrations

Air Activation

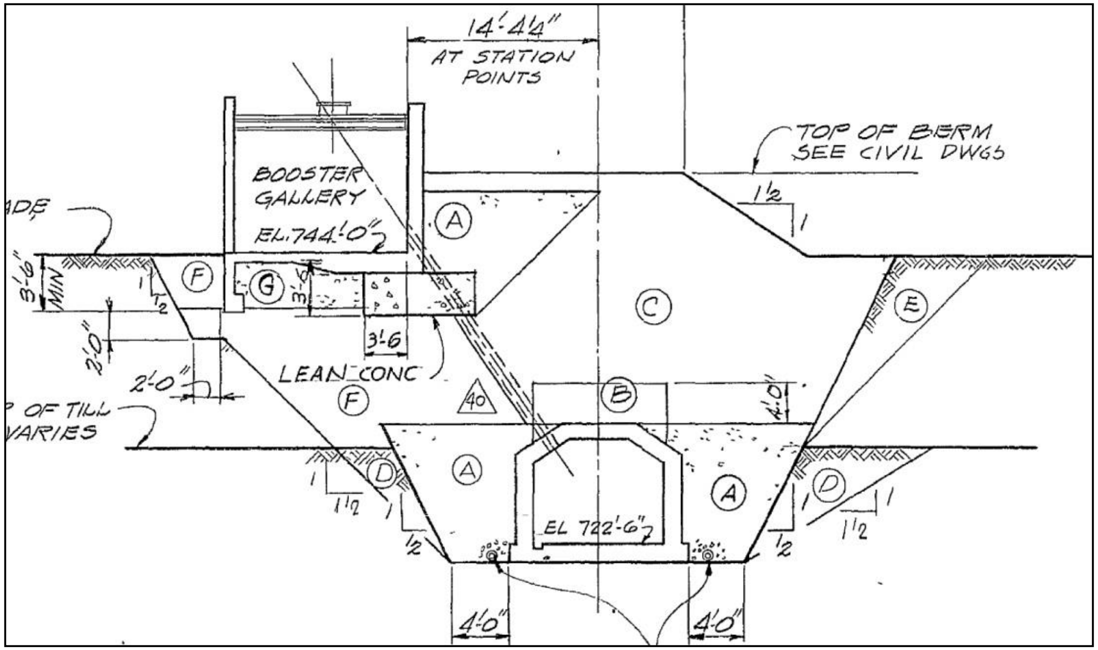
Ground Water and Surface Water

Soil Activation

Muons

Residual Dose Rates

Active Shielding Controls



PIP-II Impacts *The Original PIP* (Need to Evolve & Align)

- Anticipating a PIP-II Linac in 2023
  - Linac needs to operate until 2023
  - Booster needs to operate until at least 2030, and be able to accept the PIP-II beam in 2023
- Studies underway to adjust the PIP plan for PIP-II
  - Some changes made immediately, expect plan to fully settle mid-2015
- Implications:
  - Klystron implementation on hold until need is demonstrated
    - Prototype will be completed and tested to spec
  - Booster cavity strategy evolving
    - Any full replacement to be compatible with PIP-II and later upgrades
    - Requirements to be settled upon in the near future
  - Booster modifications to allow 800 MeV injection
  - Booster 20 Hz operations will be studied
  - Booster infrastructure

Working to integrate into PIP or operational effort – depending on timetable/funding

PIP FY13 – FY14
(Work Prioritized – based upon schedule and resources)

Blue: Significant Progress
Purple - Delayed
Green: Completed

1. Booster solid state – completed on schedule (FY13)
2. Booster 15 Hz operation –
   1. Refurbishment (on schedule FY15)
   2. New Booster Tuners (20 in FY15)
3. Long lead task items – define/initiate necessary work to meet schedule
   1. Linac RF Power Systems (7835 tube risk/replacement option)
   2. Linac Modulator (obsolete tubes and reliability)
   3. New Booster Cavity (several independent tasks)
4. Booster Shielding (completion in FY15 – before high flux operations)
5. Beam Physics
   1. Booster Absorber system (completion this shutdown)
   2. Aperture/Alignment (completed FY14 – may look again under operations)
   3. Cogging (estimate to be completed in Dec FY15)
   4. Linac Laser Notcher (completion in FY15)
6. Booster RF Systems (Anodes, Bias Supplies – completion in FY15)
7. Instrumentation/Diagnostics (Linac/Booster BPMs, Dampers)
8. Utilities (House Power, LCW, Vacuum) (determined by shutdowns)