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**

**Linac**

- **Length (m)**: 200
- **Pulse Frequency**: 15 Hz
- **Kinetic Energy (MeV)**: 0.750 - 4
- **Frequency (MHz)**: 201 & 804
- **Current (operational)**: 33 ma (Historical low)
- **Linac Lattice**: LE ? HE - Photo
- **N° 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (units)</th>
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<tbody>
<tr>
<td>Energy</td>
<td>35 – 750 (keV)</td>
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<tr>
<td>Frequency</td>
<td>201.25 (MHz)</td>
</tr>
<tr>
<td>Length</td>
<td>120 (cm)</td>
</tr>
<tr>
<td>Design current</td>
<td>60 (mA)</td>
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<tr>
<td>Peak cavity power</td>
<td>~ 140 (kW)</td>
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<tr>
<td>Radial aperture</td>
<td>0.3 (cm)</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>0.12%</td>
</tr>
</tbody>
</table>
Booster Overview

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

### Booster

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<td>Circumference (m)</td>
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<tr>
<td>Harmonic Number</td>
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<tr>
<td>Kinetic Energy (GeV)</td>
<td>0.4 - 8</td>
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<tr>
<td>Momentum (GeV/c)</td>
<td>0.954 - 8.9</td>
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<tr>
<td>Revolution period (μsec)</td>
<td>(\tau_{(inj)} = 2.77 - \tau_{(ext)} = 1.57)</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>37.9 - 52.8</td>
</tr>
<tr>
<td>Batch size</td>
<td>4.5 E12</td>
</tr>
<tr>
<td>Focussing period</td>
<td>FDooDFo (24 total)</td>
</tr>
</tbody>
</table>

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

Loss limited until 2010 then cycle rate limited

Where PIP started

Run II
NuMI slipstacking Jan '08
NuMI May '05
Rbar slipstacking Aug '04
MiniBooNE April '02

Integrate Protons

NOvA shutdown

Protons Delivered per hour

Normalized Booster BLMs

Lin. p/hr: 1.8E+11

Minimun values: -2.57 at 1992

Run 1B
Requested Proton Flux

![Graph showing proton flux over time with labels for existing capability, NOvA shutdown, 15Hz pulse, 15Hz beam, 8 GeV ν, 120 GeV ν (NOvA, LBNx), g-2, and Mu2e.]
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

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,

[Signature]

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

Loss Monitors’ Responses

Beam Intensity

RF Capture

700 MeV Notch

Transition

Extraction

Y= B:IRMCHG E12
B:BLMS14 R/S
B:BLML13 R/S
B:BLMO26 R/S

.75
3.75
.75
2.25

.5
2.5
.5
1.5

< 13 KHz
< 10 KHz
< 10 KHz
< 8 KHz

.25
1.25
.25
.75

WAIT FOR EVENT

Seconds Trig = EVENT 17 engineering units
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
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.

Activation decrease of ~1200mrem/hr
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
  - 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

\[
\begin{align*}
60kV & \quad 30kV \\
35 \text{ amp} & \quad 100-350 \text{ A} \\
\text{DC PS} & \quad 10-35kV \\
& \quad 0.6MW \\
\end{align*}
\]

\[
\begin{align*}
\text{Modulator F1123} & \quad \text{3 triodes} \\
& \quad 3.5MW \\
\text{FPA 7835 plate} &
\end{align*}
\]
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
**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

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**FNAL/Linac - 7835 inventory**

Projected years of operation

- no rebuild available
- Average lifetime past 5 years

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

5.0 MW
- 122 kV, 85.2 A
- \( P_{\text{in}}: 340 \text{ W} \)

Peak power (MW)

Drive power \( P_{\text{in}} \) (kW)

51
50
49
48
47
46
45
44
43
42
41
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5
4
3
2
1
0

Gain (dB)
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

RF Cavity Refurbishment Projections

- Number of Certified Refurbished Cavities

- Cavity Certified
- Cavity Decertified
- Cavity Recertified
- Cavity Number 20
- 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

RF Leak on Refurbishment Cavity - no longer certified

Cavity recertified
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
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
Enhancements of the Fermilab Booster to Reduce Losses and Extend Lifetime: 
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Robert Zwaska
11 November 2014
HB2014
## PIP Booster Beam Parameters

(At Completion)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Particle Species</td>
<td>Protons</td>
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<tr>
<td>Input (H$^+$) Beam Energy (Kinetic)</td>
<td>400</td>
<td>MeV</td>
</tr>
<tr>
<td>Output Beam Energy (Kinetic)</td>
<td>8.0</td>
<td>GeV</td>
</tr>
<tr>
<td>Protons per Pulse (injected)</td>
<td>4.7 x 10^{12}</td>
<td></td>
</tr>
<tr>
<td>Protons per Pulse (extracted)</td>
<td>4.3 x 10^{12}</td>
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</tr>
<tr>
<td>Beam Pulse Repetition Rate</td>
<td>15</td>
<td>Hz</td>
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<tr>
<td>RF Frequency (injection)</td>
<td>37.2</td>
<td>MHz</td>
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<tr>
<td>RF Frequency (extraction)</td>
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<td>MHz</td>
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<tr>
<td>Injection Time</td>
<td>0.02</td>
<td>msec</td>
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<tr>
<td>Injection Turns</td>
<td>~10</td>
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<tr>
<td>Beam Emittance (95%, normalized)</td>
<td>15</td>
<td>π mm-mrad</td>
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<tr>
<td>Laslett Tune Shift at Injection (33% B.F.)</td>
<td>-0.47</td>
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<tr>
<td>Delivered Longitudinal Emittance (95%)</td>
<td>0.08</td>
<td>eV-sec</td>
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<tr>
<td>Delivered Momentum Spread (95% full height)</td>
<td>±8</td>
<td>MeV/c</td>
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</table>
Updated Proton Delivery Scenario (approximate no shutdowns shown)

- 15 Hz
- Total beam thru Booster
- 7.5 Hz
- NuMI
- g-2
- BNB
- mu2e
- SY120
- Summer Shutdown
- Updated Proton Delivery Scenario (approximate no shutdowns shown)
Proton Source – Flux delivery plans

- NOvA: ~ 1.3 E17 pph
- Mu2e Muon Production: ~ 2.0 E16 pph
- BOOSTER NEUTRINO BEAMLINE: ~ 3 to 8 E16 pph
- Fixed Target: ~ 2.0 E14 pph
- g-2 Muon Production: ~ 6.0 E16 pph
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.
FNAL Linac timeline

1960
- Linac ground breaking
  Dec 1968

1970
- Linac 200 MeV DTL
  1970
- Linac 1st NAL permanent building
  Dec 1969
- Linac RF equipment installation & commissioning
  April-Aug 1970

1990
- Linac 400 MeV Upgrade
  1993

2000

2010

2020

2030
FNAL Linac topology

- **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

**Beam current**: 25 mA (avg. in pulse)

**3 different structures**: (RFQ, DTL, SCCL)
- 2 frequencies
Linac PIP

- 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)
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.

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

Substation Enclosure >18,000 lbs

Will be lowered through hatch (FY15?)

Updated Roughing Pumps

Linac Roof Hatch
Linac Diagnostics BPM and Toroid upgrade completed

<table>
<thead>
<tr>
<th>Crate #</th>
<th>Location</th>
<th>IP Address</th>
<th>BPM Names</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Tank 2</td>
<td>131.225.131.199</td>
<td>LEL 2 Out 33</td>
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<tr>
<td>2</td>
<td>Tank 3</td>
<td>131.225.131.205</td>
<td>LEL 3 In 19</td>
</tr>
<tr>
<td>3</td>
<td>Tank 4</td>
<td>131.225.131.207</td>
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<td>4</td>
<td>Tank 5</td>
<td>131.225.131.209</td>
<td>LEL 5 In 43</td>
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<td>5</td>
<td>LDR-0</td>
<td>131.225.131.249</td>
<td>HEL 0-2 23</td>
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<td>6</td>
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<td>7</td>
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<td>Q1 15 Q2 10</td>
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<td>12</td>
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<td>Q6 73 Q7 71</td>
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<td>PFOIL 9 L1D 67</td>
</tr>
</tbody>
</table>

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

15 Crates – over 60 BPMs
**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
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

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
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.
~22-25 us  15 Hz macro pulse rep rate

67 ms

2.2 us  450 kHz "notch" spacing

~bunch length

~5 ns (bunch spacing)  200 MHz bunch spacing

24.2 us (~11 Booster turns)

~bunch length
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 number 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

Assume mirror reflectivity 99.95%

Laser Energy Requires for 20 passes

2 mJ for 99.92%
20 reflections
Burst mode seed pulses to Fiber Amplifier followed by Free Space Amp

\[ \lambda_2 = 1064 \text{nm} \]
120 mW CW SW=0.1 nm

Diode + TC controlled

Output modulator/Input fiber pre-amp:
201.25MHz pulses (1.25 ns pulse), 458kHz burst

10 GHz Mach-Zehnder Modulator

PM Fiber
Isolator
Line filter

Pulse Generator
Amplifier, Timing

Fiber Amp 1
Fiber Pre-Amp

Fiber Amp 2
Clean up filter

Notch 12 bunches -> 60 ns
10 notches/linac pulse

Pulsed at 15 Hz
Quasi CW or continuous burst

Free Space Amp
Grumman CEO DPSS OEM

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

450.75 kHz burst of 201 MHz pulses

One set of 201.25 MHz pulses

Individual 201.25 MHz temporally uniform pulses

AWG: Chase Scientific DA12000 & CG6000 module
**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 tubes with 10 different types

**Manufacturer: Photonis Industries**

Av.Lifetime (past 5 years) : ~ 1.5 years

Operational Needs: 7
**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 tubes with 10 different types

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Gain</th>
<th>Manufacturer: Photonis Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td>4W</td>
<td>68</td>
<td>Av.Lifetime (past 5 years) : ~ 1.5 years</td>
</tr>
<tr>
<td>400W</td>
<td>9</td>
<td>Operational Needs: 7</td>
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<tr>
<td>4kW</td>
<td>4W</td>
<td>7651 system</td>
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<tr>
<td>7651 tube</td>
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<td>Solid State Amplifier</td>
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<tr>
<td>170kW</td>
<td></td>
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<tr>
<td>4616 tube</td>
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<tr>
<td>4MW</td>
<td></td>
<td></td>
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<tr>
<td>7835 tube</td>
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</tbody>
</table>
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.

- 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

55 KV, 15Hz

Split Image view of Booster Cavity

Anticipate increasing number of cavities in Booster from 19 to 22

Magnetic loss density (100 kV)
Anode Supplies and Bias Supplies (15 Hz operation)

Anode Modern

Bias Transformer Heat Sinks

Refurbishment

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

Completed Power Distribution

Completed LCW

Completed Solid State Drive System
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.
Booster Utilities

Replacing Original Equipment

Vacuum:
- Turbos, Roughing Stations, Ion pumps and Valves

LCW: Valves, New plumbing, Pumps, Hoses, Bypasses in galleries and general repairs
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
Flux increase - Losses

Protons per hour E15

Beam Loss (Operational Limit 525 Watts)

PIP Goal is $270 \times 10^{15}$/hr

2005

2010

2011
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

- **Instabilities**
  - Dampers

- **Injection painting**
  - Optimized radiation shielding
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
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)

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)
7. Instrumentation/Diagnostics (Linac/Booster BPMs, Dampers)
8. Utilities (House Power, LCW, Vacuum) (determined by shutdowns)

Blue: Significant Progress
Purple - Delayed
Green: Completed