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 $5 \times 10^{12}$ (typically $4.3 \times 10^{12}$) in 1.5 us
  - Ramps at 15 Hz
    - Historically $\ll= 7$ Hz with beam

- **Main Injector produces 120 GeV protons (NuMI)**
  - Bunched at 53 MHz
  - Up to $5 \times 10^{13}$ (typically $3.7 \times 10^{13}$)
    - 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>200</td>
</tr>
<tr>
<td>Pulse Frequency</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Kinetic Energy (MeV)</td>
<td>0.75 - 4</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>201 &amp; 804</td>
</tr>
<tr>
<td>Current (operational)</td>
<td>33 ma (Historical low)</td>
</tr>
<tr>
<td>Linac Lattice</td>
<td>LE ? HE - Photo</td>
</tr>
<tr>
<td>No of cavities</td>
<td>5 DTLs, 7 SC, 3 small</td>
</tr>
</tbody>
</table>

LE Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat top</td>
<td>350 usec</td>
</tr>
<tr>
<td>Raise Fall time</td>
<td>75 usec</td>
</tr>
<tr>
<td>Average Axial Field</td>
<td>1.5 MV/m</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>RF Peak Power</td>
<td>3.5 MW</td>
</tr>
<tr>
<td>Peak Current</td>
<td>35 mA</td>
</tr>
<tr>
<td>Beam width</td>
<td>20 usec</td>
</tr>
<tr>
<td>Power to the beam</td>
<td>787.50 KW</td>
</tr>
<tr>
<td>Average RF Power</td>
<td>19.16 KW</td>
</tr>
<tr>
<td>Peak Power</td>
<td>3.50 MW</td>
</tr>
</tbody>
</table>

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>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>35 – 750 (keV)</td>
</tr>
<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>
</tr>
<tr>
<td>Peak cavity power</td>
<td>~ 140 (kW)</td>
</tr>
<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>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>474</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>84</td>
</tr>
<tr>
<td>Kinetic Energy (GeV)</td>
<td>0.4 - 8</td>
</tr>
<tr>
<td>Momentum (GeV/c)</td>
<td>0.954 - 8.9</td>
</tr>
<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…
Loss limited until 2010 then cycle rate limited

Booster loss profile

Run II
NuMI May '05
NuMI slipstacking Jan '08
Pbar slipstacking Aug '04
MiniBooNE April '02
Run 1B
NOvA shutdown
Integrate Protons
Requested Proton Flux

- Main Injector
- Booster Neutrinos
- g-2
- mu2e
- Total

- Protons/Hour
- 2.50E+17
- 2.00E+17
- 1.50E+17
- 1.00E+17
- 5.00E+16
- 0.00E+00


- NOvA Shutdown
- Existing Capability
- 120 GeV $\nu$
- (NOvA, LBNx)
- 15Hz pulse
- 15Hz beam
- 8 GeV $\nu$
- g-2
- 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

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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,

Sergei Nagaitsev  
Chief Accelerator Officer  
Fermi National Accelerator Laboratory

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

Beam Intensity

Loss Monitors’ Responses
PIP : Notching

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

Bucket spacing at extraction energy ~ 19 nsec

Absorber L13 (2013)
The plot above shows the difference between two radiation activation surveys after running similar flux for a week. The new system has greatly reduced residual activation in several areas of Booster.

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

• Neutralize a portion of the Linac beam with a pulsed laser
  – Remove the majority of the loss from the Booster entirely

• Prototype of the laser front-end is operating
  – Atypical laser
    • Multiple timescales
    • High-pulse power
    • Moderate average power (few W)

• Interaction region installed in Linac
PIP – Accelerator Physics: Linac Laser Notch

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

System internal review - Aug’14
APT Seminar – Mar’14
Final installation expected FY15
PIP – Linac 200 MHz RF system: issues & risks

• The 201.25 MHz RF power system has been a big concern for over a decade in regards **long term operational reliability and viability**

• The **issue** of retaining the 201.25 MHz RF system is
  – specialized maintenance required and extensive downtime generated by the tube modulator
    • F1123 discontinued production for over 10 years
  – short lifetime, high-cost & limited market of the final power amplifier

• The **risk** of retaining the 201.25 MHz RF system is that
  – power tubes could become unobtainable to support operations until 2025
  – additional vacuum tubes could become obsolete in the modulator &
    • F1123 no longer be rebuilt -> years of operation ~ **6 years**

• **PIP plan** to address these issues is
  – build-up 4 year in-house inventory of the 7835
  – develop a workable plan to replace the final amplifier in case tube line production is discontinued
  – replace the high voltage modulator with present day technology
PIP – Linac 200 MHz RF system: Modulator

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

```
<table>
<thead>
<tr>
<th>60kV</th>
<th>30kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 amp</td>
<td>350 A</td>
</tr>
<tr>
<td>DC PS</td>
<td>Modulator F1123 3 triodes</td>
</tr>
</tbody>
</table>

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
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 201.25 MHz 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**

- **Gain (dB)**
  - Drive power Pin (kW)
  - 51
  - 45
  - 40
  - 0
  - 100
  - 200
  - 300
  - 400
  - 500
  - 5.5
  - 2.5
  - 0

- **Peak power (MW)**
  - Courtesy:
  - 5.0 MW
  - 122 kV, 85.2 A
  - Pin 340 W

- **f0: 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**

**Graph:**
- **Drive power P_{in} (kW) vs. Peak power (MW)**
  - 5.0 MW
  - 122 kV, 85.2 A
  - Pin 340 W

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

**Timeline:**
- Award PO SBK
- PDR
- CDR
- Manufacturer
- First Acceptance Test
- FNAL receive
- Final Test
- Today

**DTL**
- f_{0}: 201.25 MHz
- Saturated efficiency: > 48%
- Perveance: 2.0 mA/V^{1.5}
- PRF: 15 Hz
- Pulse length: 450 msec
- J_{cath}: 1 A/cm^2
- Expected lifetime: > 200 hrs
Booster RF cavity

Designed in 1969 – several small modifications but largely original cavity
- 19 stations
- 2 gaps @ ~ 24 kV
- Tunable 24 – 53 MHz
- Power amplifier system already upgraded to solid-state in PIP
Booster PIP - Refurbishment of 40 year old cavities

(Weeks)

Cool-down
Remove Tuners
Cavity Removal

Rebuild - Cones & Tuners

Rebuild Stems/Flanges
Re-Assemble
Testing

Cavity Removal - Stripping
Tuners Rebuild
Rebuild and Test
**Booster refurbishment**

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

RF Cavity Refurbishment Projections

Number of Certified Refurbished Cavities

Cavity recertified
RF Leak on Refurbishment Cavity - no longer certified

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
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
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