Geodetic and Alignment Concepts for Proton Improvement Plan-II at Fermilab

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Proton Improvement Plan-II (PIP-II) Goals

- **Proton Improvement Plan-II (PIP-II)** is Fermilab’s plan for upgrading the accelerator complex.

- PIP-II goal is to support long-term physics research objectives as outlined in the P5 plan, by delivering world-leading beam power to the U.S. neutrino program and providing a platform for the future:
  - Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations.
  - Support the ongoing 8 GeV program including Mu2e, g-2, and short-baseline neutrinos.
  - Provide an upgrade path for Mu2e.
  - Provide a platform for extension of beam power to LBNF to >2 MW.
  - Provide a platform for extension of capability to high duty factor/higher beam power operations.

- Proposed schedule: Initiate operations in newly-configured complex in ~2025.
Construct a modern 800-MeV superconducting linac, of CW-capable components, operated initially in pulsed mode
- Increase Booster/Recycler/Main Injector per pulse intensity by ~50%

Increase Booster repetition rate to 20 Hz
- Maintain 1 MW down to 60 GeV or,
- Provide factor of 2.5 increase in power to 8 GeV program

Modest modifications to Booster/Recycler/Main Injector
- Accommodate higher intensities and higher Booster injection energy

This approach as described in the Reference Design Report:
- Builds on significant existing infrastructure
- Capitalizes on major investment in superconducting RF technologies
  - Fermilab is one of the leading SRF laboratories in the world
- Existing linac removed from service upon completion of PIP-II
- Siting is consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector (PIP-III)

S. Holmes
Fermilab’s accelerator complex supports a diverse program:

- **Neutrinos**
  - NuMI
  - BNB
  - LBNF

- **Muons**
  - g-2
  - Mu2e

- **Test Beams**

- **Fixed Target**
## PIP-II Performance Goals

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>PIP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Beam Energy</td>
<td>800    MeV</td>
</tr>
<tr>
<td>Linac Beam Current</td>
<td>2      mA</td>
</tr>
<tr>
<td>Linac Beam Pulse Length</td>
<td>0.54   msec</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>20     Hz</td>
</tr>
<tr>
<td>Linac Beam Power to Booster</td>
<td>17     kW</td>
</tr>
<tr>
<td>Linac Beam Power Capability (@&gt;10% Duty Factor)</td>
<td>~200   kW</td>
</tr>
<tr>
<td><strong>Mu2e Upgrade Potential (800 MeV)</strong></td>
<td>&gt;100   kW</td>
</tr>
<tr>
<td>Booster Protons per Pulse</td>
<td>$6.5 \times 10^{12}$</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>20     Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>166    kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program (max)</td>
<td>83     kW</td>
</tr>
<tr>
<td>Main Injector Protons per Pulse</td>
<td>$7.5 \times 10^{13}$</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 60-120 GeV</td>
<td>0.7-1.2 sec</td>
</tr>
<tr>
<td><strong>LBNF Beam Power @ 60-120 GeV</strong></td>
<td>1.0-1.2 MW</td>
</tr>
<tr>
<td><strong>LBNF Upgrade Potential @ 60-120 GeV</strong></td>
<td>&gt;2     MW</td>
</tr>
</tbody>
</table>
PIP-II Site Layout
PIP-II connection to Booster and Muon Campus
• The 800 MeV linac will be located in an underground 210 m long tunnel
• It will use superconducting RF accelerating cavities at three different frequencies
• Beam focusing is provided by quadrupoles and solenoids
• A 300 m long transfer line connects to the Booster

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq (MHz)</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ</td>
<td>162.5</td>
<td>0.03-2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HWR ($\beta_{opt}=0.11$)</td>
<td>162.5</td>
<td>2.1-10.3</td>
<td>8/8/1</td>
<td>HWR, solenoid</td>
</tr>
<tr>
<td>SSR1 ($\beta_{opt}=0.22$)</td>
<td>325</td>
<td>10.3-35</td>
<td>16/8/2</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR2 ($\beta_{opt}=0.47$)</td>
<td>325</td>
<td>35-185</td>
<td>35/21/7</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>LB 650 ($\beta_{g}=0.61$)</td>
<td>650</td>
<td>185-500</td>
<td>33/22/11</td>
<td>5-cell elliptical, doublet*</td>
</tr>
<tr>
<td>HB 650 ($\beta_{g}=0.92$)</td>
<td>650</td>
<td>500-800</td>
<td>24/8/4</td>
<td>5-cell elliptical, doublet*</td>
</tr>
</tbody>
</table>

*Warm doublets external to cryomodules

All components CW-capable
PIP-II Linac SRF Section

The PIP-II superconducting section will occupy ~150 m of the linac enclosure with:

1. **1 CM (8 cavities) HWR @ 162.5 MHz** => at ANL
   - Cavities fabrication and testing in progress
   - Cryomodule assembly in FY17
2. **9 CM (51 cavities) SSR1 & SSR2 @ 325 MHz** => at Fermilab
   - SSR1 cavities completed and referenced
   - SSR1 Cryomodule assembly in FY17
The PIP-II superconducting section will occupy ~150 m of the linac enclosure with:
- 15 CM (57 cavities) LB & HB @ 650 MHz
  - Cavities and cryomodules in the design phase
PIP-II R&D: PIP-II Injector Test

- PIP2IT in progress at the CM Test Facility (CMTF) building
- Will demonstrate the front end of the PIP-II linac by accelerating H- ions up to 25 MeV in about 40 m length
  - H- ion source: 30 kV, 10 mA
  - LEBT - pre-chopping
  - RFQ - 2.1 MeV, CW mode
  - MEBT – bunch-by-bunch chopper with beam absorber, vacuum management
  - Operation of HWR in close proximity to 10 kW absorber
  - Operation of SSR1 with beam - CW and pulsed, resonance control and LFD compensation in pulse mode

Collaborators
- ANL: HWR
- LBNL: LEBT, RFQ
- SNS: LEBT
- BARC: MEBT
- IUAC: SSR1

- 2015
  - 30 kV
  - LEBT

- Now
  - 2.1 MeV
  - RFQ

- 2017
  - 10 MeV
  - MEBT

- 2018
  - 25 MeV
  - HWR

- 2019
  - SSR1

40 m, ~25 MeV
• LEBT, RFQ and MEBT beamline components currently aligned < ± 0.25 mm
### Alignment Tolerances

- **Relative tolerances between components (RMS):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity X,Y misalignment wrt CM</td>
<td>± 0.5 mm</td>
</tr>
<tr>
<td>Solenoid X,Y misalignment wrt CM</td>
<td>± 0.5 mm</td>
</tr>
<tr>
<td>BPM X,Y misalignment wrt CM</td>
<td>± 0.5 mm</td>
</tr>
<tr>
<td>Quadrupole, solenoids, RFQ X,Y misalignment wrt. Linac</td>
<td>± 0.25 mm</td>
</tr>
<tr>
<td>Cryomodule X,Y misalignment wrt Linac</td>
<td>± 0.3 mm</td>
</tr>
<tr>
<td>Cavity Z misalignment wrt. CM</td>
<td>± 0.5 mm</td>
</tr>
<tr>
<td>Solenoid Z misalignment wrt CM</td>
<td>± 0.5 mm</td>
</tr>
<tr>
<td>BPM Z misalignment wrt. CM</td>
<td>± 2 mm</td>
</tr>
<tr>
<td>Quadrupole, solenoids, RFQ Z misalignment wrt Linac</td>
<td>± 2 mm</td>
</tr>
<tr>
<td>Cryomodule Z misalignment wrt. Linac</td>
<td>± 2 mm</td>
</tr>
<tr>
<td>Cavity tilt misalignment</td>
<td>± 1 mrad</td>
</tr>
<tr>
<td>Solenoid tilt misalignment</td>
<td>± 0.5 mrad</td>
</tr>
<tr>
<td>BPM tilt misalignment</td>
<td>± 3 mrad</td>
</tr>
<tr>
<td>Quadrupole, solenoids tilt misalignment wrt Linac</td>
<td>± 1 mrad</td>
</tr>
<tr>
<td>RFQ tilt misalignment wrt Linac</td>
<td>± 0.05 mrad</td>
</tr>
<tr>
<td>Cryomodule tilt misalignment</td>
<td>± 0.05 mrad</td>
</tr>
</tbody>
</table>
• Provides the basis for construction surveys and for the precision underground control networks
• Existing Fermilab control network (accuracy < 2 mm @ 95% confidence level)
  o vertical datum = North American Vertical Datum of 1988 (NAVD 88)
  o geoid model = NGS model Geoid93 (upgrade to Geoid12B)
• Includes 4 monuments tied to CORS and IL HARN
• Add 10 new geodetic monuments (densification around project site)
• ~400 GPS and terrestrial observations
• **expected error ellipses in millimeter range** (@ 95% confidence level)

• PIP-II surface network will have similar density and configuration as NuMI
Primary surface geodetic network at Fermilab
Expected accuracy results

Ellipses of Error in x, y plane
Errors in Height

Ellipses of Error @ 95% confidence level
(bar scale tick = 1 mm)

Histogram of standardized residuals
(bar scale tick = 1 σ)

• PIP-II results are expected to be similar to NuMI
• Provide vertical sight risers for transferring coordinates from the surface to the underground (better and more efficient for controlling error propagation in a weak geometry tunnel network)
• Network simulations => 3 locations for transferring coordinates from the surface
• Designed adequate procedure for precision transfer of surface coordinates underground

Precision underground control networks
Established to support the precision alignment of beamline components

Components alignment wrt Linac and are very similar to MI and NuMI:
- cryomodules, beam magnets and instrumentation aligned to $\pm 0.25$ mm

Components alignment wrt CM and are similar to LCLS-II:
- cavities and solenoids aligned to $\pm 0.5$ mm and 1-0.5 mrad angular

Error budget network requirements $\pm 0.50$ mm at 95% confidence level

Network: continuous from Linac and Transfer Line to Booster

Constraints at underground transfer points: 3 sight risers

Network type: Laser Tracker processed as trilateration

Additional angular and distance measurements to study and control network behaviour

Beam trajectory Azimuth confirmed by precision Gyro $\pm 3$ arcsec (0.015 mrad) between transfer points
Precision underground control network
Expected accuracy results

- Errors Ellipses $\pm 0.45$ mm and histogram of residuals $\sigma = \pm 0.110$ mm @ 95% confidence level

- PIP-II results are expected to be similar to NuMI
Cryomodules alignment

- Components alignment wrt CM and are similar to LCLS-II:
  - Cavities and solenoids aligned to $\pm 0.5$ mm transversal and 1-0.5 mrad angular

- The beam is mainly sensitive to the solenoids angle error: $\pm 0.5$ mrad => $\pm 0.15$ mm pitch/yaw (1$\sigma$)

- Cryomodule error budget analysis (among others) < $\pm 0.5$ mm
  - referencing of cavities/solenoids mechanical and magnetic axis < $\pm 0.10$ mm
  - cavity string alignment = $\pm 0.15$ mm
  - cold mas to vessel alignment and referencing to vessel = $\pm 0.2$ mm
  - string misalignments due to transportation = $\pm 0.2$ mm
  - thermal cycling (warm up, cool down) = $\pm 0.05$ mm

- The FNAL cryomodules alignment procedure is well established and proven to achieve similar accuracy requirements as LCLS-II, well within PIP-II requirements
Partners:

- International: India collaboration is formalized, European collaboration in the discussion stage (CEA/Saclay, Orsay, INFN, STFC),
- National: ANL, LBNL, SLAC most active

**PIP-II current status:**

- Critical Decision 0 (CD-0) - the formal conceptualization of the proposed PIP-II project has been approved in June 2015
- Critical Decision 1 (CD-1) – the preparation phase to develop a conceptual design and cost estimate in progress => review Q3 2017
Future Directions: PIP-III

- The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements to the Fermilab proton complex
  - upgrading the PIP-II linac to CW operations and replacement of the Booster with higher performance accelerator (PIP-III)
  - PIP-III (booster replacement allows multi-MW beams) an essential part of the upgrade to 2.4 MW
Summary

- PIP-II will allow Fermilab to maintain its lead with the most powerful neutrino beam in the world, with >1 MW at startup
- Presents a challenge with respect to the detail and complexity of the geodetic and alignment aspects
- From the Alignment perspective the PIP-II is very similar with MI, NuMI, LCLS-II
- Past experience:
  - The absolute global tolerances have been achieved successfully
  - The relative alignment tolerances of beamline components have been also achieved successfully
- Similar geodetic and alignment concepts are proposed for PIP-II
Thank you