Proton Improvement Plan II

Steve Brice, on behalf of Shekhar Mishra and the PIP-II Team
ICHEP 2014
3 July 2014
Program Goals

Our goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

• Neutrinos
  – MINERvA, MINOS+, NOvA @ 700 kW
  – LBNF @ >1-2 MW
  – SBN @ 10’s kW

• Muons
  – Muon g-2 @ 17-25 kW
  – Mu2e @ 8-100 kW

• Longer term opportunities

  This requires more protons!
Physics Opportunities

- **LBNF**
  - 1.2 MW of beam power on day one; 2.4 MW ultimately
  - Flexible proton beam energy (60-120 GeV)

- **NuMI**
  - Options for >1MW beam power under investigation

- **Mu2e**
  - 30-50% increase in beam power immediately*
  - Potential for ~25-100 kW at 800 MeV
    - Current Mu2e configuration limits to 25-30 kW

- **SBN**
  - 30-50% increase in beam power immediately*

* Possible extension of Booster operations to 20 Hz is under consideration, but not incorporated into these estimates
**PIP-II Goals**

*Proton Improvement Plan-II supports these long term physics research goals while providing a platform for the future*

**Design Criteria**

- Deliver 1.2 MW of beam power at 120 GeV, with power approaching 1 MW at energies down to 60 GeV, at the start of LBNF operations
- Support the current 8 GeV program, including Mu2e, g-2, and the suite of short-baseline neutrino experiments
- Provide 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
- At an affordable cost to DOE
PIP/PIP-II Strategy

• PIP
  – Increase Booster beam repetition rate to 15 Hz (PIP)
    • 700 kW to NOvA concurrent with 8 GeV program

• PIP-II
  – Increase Booster/Main Injector per pulse intensity by 50%; decrease MI cycle time modestly
  – Increase Booster injection energy to 800 MeV
    • Modest modifications to Booster/Recycler/MI to accommodate higher intensities and higher Booster injection energy
PIP-II

- We believe the most cost-effective means of achieving these goals is via an **800 MeV superconducting pulsed linac**, extendible to support >2 MW operations to LBNF and upgradable to continuous wave (CW) operations
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting rf technologies
  - Uses CW capable components
  - Eliminates significant operational risks inherent in existing linac
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector

- Whitepaper available at [projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232](http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232)
### PIP-II Performance Goals

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>PIP</th>
<th>PIP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Beam Energy</td>
<td>400</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Linac Beam Current</td>
<td>25</td>
<td>2 mA</td>
</tr>
<tr>
<td>Linac Beam Pulse Length</td>
<td>0.03</td>
<td>0.5 msec</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Linac Beam Power to Booster</td>
<td>4</td>
<td>13 kW</td>
</tr>
<tr>
<td>Linac Beam Power Capability (@&gt;10% Duty Factor)</td>
<td>4</td>
<td>~200 kW</td>
</tr>
<tr>
<td>Mu2e Upgrade Potential (800 MeV)</td>
<td>NA</td>
<td>&gt;100 kW</td>
</tr>
<tr>
<td>Booster Protons per Pulse</td>
<td>$4.2 \times 10^{12}$</td>
<td>$6.4 \times 10^{12}$</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>15</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>80</td>
<td>120 kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program (max)</td>
<td>32</td>
<td>40 kW</td>
</tr>
<tr>
<td>Main Injector Protons per Pulse</td>
<td>$4.9 \times 10^{13}$</td>
<td>$7.5 \times 10^{13}$</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 120 GeV</td>
<td>1.33</td>
<td>1.2 sec</td>
</tr>
<tr>
<td>LBNF Beam Power @ 120 GeV*</td>
<td>0.7</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>LBNF Upgrade Potential @ 60-120 GeV</td>
<td>NA</td>
<td>&gt;2 MW</td>
</tr>
</tbody>
</table>

*LBNF beam power can be maintained to ~80 GeV, then scales with energy*
PIP-II Site Layout (provisional)
PIP-II Status and Strategy

- PIP-II is currently pre-CD-0
  - Complete concept exists
    - Documented in whitepaper; technical backup in PX RDR
  - R&D program underway
    - Front end (PXIE) and superconducting rf development
- Strong endorsement from P5
  - Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.
    - Applies in all budget scenarios considered.
- Discussions with P5, Fermilab, and DOE/OHEP management have been in context of FY19 construction start
  - Consistent R&D deliverables list established
  - Preliminary discussions on potential international in-kind contributions
  - Aligned with LCLS-II and LBNF activities
- Goals for the next year
  - Release PIP-II specific RDR
  - Maintain PXIE and SRF development on established schedules
  - Support DOE in the development of Mission Need Statement
  - Establish PIP-II Office
PXIE will address the following:

- Low Energy Beam Transport (LEBT) pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Bunch extinction
- Medium Energy Beam Transport (MEBT) beam absorber
- MEBT vacuum management
- Operation of Half Wave Resonator (HWR) in close proximity to 10 kW absorber
- Operation of Single Spoke Resonator (SSR) with beam, including resonance control
- Emittance preservation and beam halo formation through the front end
Collaborators
ANL: HWR
LBNL: LEBT, RFQ
SNS: LEBT
India (BARC): MEBT
### PIP-II Linac Technology Map

#### Section

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq</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>b=0.11</td>
<td></td>
</tr>
<tr>
<td>HWR ((b_{\text{opt}}=0.11))</td>
<td>162.5</td>
<td>2.1-11</td>
<td>8/8/1</td>
<td>HWR, solenoid</td>
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<tr>
<td>SSR1 ((b_{\text{opt}}=0.22))</td>
<td>325</td>
<td>11-38</td>
<td>16/8/2</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR2 ((b_{\text{opt}}=0.51))</td>
<td>325</td>
<td>38-177</td>
<td>35/21/7</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>LB 650 ((G=0.61))</td>
<td>650</td>
<td>177-480</td>
<td>30/20/5</td>
<td>5-cell elliptical, doublet</td>
</tr>
<tr>
<td>HB 650 ((G=0.9))</td>
<td>650</td>
<td>480-800</td>
<td>24/10/4</td>
<td>5-cell elliptical, doublet</td>
</tr>
</tbody>
</table>

**Note:**
- \(b_{\text{opt}}\) and \(G\) are parameters specific to each section, indicating the optimal or 5-cell elliptical elliptical parameters.
SRF R&D: Q0

Nitrogen-doped 9-cell cavities vs typical 120C bake (2K)

This improvement in cavity performance corresponds to tens of $M saving in cryo infrastructure.

$Q_0$ vs $E_{acc}$ [MV/m]
PIP-II Collaboration

- Collaboration MOUs for the R&D phase (through CD-2):

<table>
<thead>
<tr>
<th>National</th>
<th>IIFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL</td>
<td>ORNL/SNS</td>
</tr>
<tr>
<td>BNL</td>
<td>PNNL</td>
</tr>
<tr>
<td>Cornell</td>
<td>UTenn</td>
</tr>
<tr>
<td>Fermilab</td>
<td>TJNAF</td>
</tr>
<tr>
<td>LBNL</td>
<td>SLAC</td>
</tr>
<tr>
<td>MSU</td>
<td>ILC/ART</td>
</tr>
<tr>
<td>NCSU</td>
<td></td>
</tr>
<tr>
<td>BARC/Mumbai</td>
<td></td>
</tr>
<tr>
<td>IUAC/Delhi</td>
<td></td>
</tr>
<tr>
<td>RRCAT/Indore</td>
<td></td>
</tr>
<tr>
<td>VECC/Kolkata</td>
<td></td>
</tr>
</tbody>
</table>

- Ongoing collaboration/contacts with RAL/FETS (UK), ESS (Sweden), SPL (CERN), RISP (Korea), China/ADS

- Annual Collaboration Meeting (June 3-4 at Fermilab)

https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confid=8365
PIP-II International Contributions

• Discussions at agency and laboratory levels indicate that an 800 MeV SC linac could attract significant in-kind contributions from India/Europe/Asia
  – SC accelerating structures
  – RF sources
  – Instrumentation
  – Magnets/power supplies

• Significant R&D collaboration for >5 years with India
  – Discussions at DOE-DAE level on potential Indian in-kind contributions
Flexible Platform for the Future

- PIP-II Inherent Capability
  - ~200 kW @ 800 MeV
  - ×10 Mu2e sensitivity

- 2 MW to LBNF

- Flexibility for future experiments
  - Muons, Kaons @100’s kW
  - Platform for expansion to multi-MW CW capability
Summary

- The Fermilab accelerator complex can be upgraded to establish LBNF as the leading long-baseline program in the world, with >1 MW at startup (2025)
- The Proton Improvement Plan-II (PIP-II) is a complete, integrated, cost effective concept, that meets this goal, while
  - leveraging U.S. superconducting rf investment,
  - attracting international partners,
  - providing a platform for the long-term future
- PIP-II retains flexibility to eventually realize the full potential of the Fermilab complex
  - LBNF >2 MW
  - Mu2e sensitivity x10
  - MW-class, high duty factor beams for rare processes experiments
- We have received a positive recommendation from P5 and are working with Fermilab and OHEP management to move forward.
# Neutrino Beam Delivery over the Past 15 Years

<table>
<thead>
<tr>
<th></th>
<th>Protons on Target ($\times 10^{20}$)</th>
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<tbody>
<tr>
<td>K2K</td>
<td>0.92</td>
</tr>
<tr>
<td>T2K</td>
<td>6.70</td>
</tr>
<tr>
<td>OPERA/ICARUS</td>
<td>1.81</td>
</tr>
<tr>
<td><strong>Total Asia + Europe</strong></td>
<td>9.43</td>
</tr>
<tr>
<td>NuMI</td>
<td>18.00</td>
</tr>
<tr>
<td>BNB</td>
<td>17.50</td>
</tr>
<tr>
<td><strong>Total Fermilab</strong></td>
<td>35.50</td>
</tr>
</tbody>
</table>
Proton Demand

15 Hz (after PIP)
Total beam thru Booster

7.5 Hz
NuMI

g-2
SY120 "tax"

BNB
mu2e

POT/quarter, (x10^{20})

FY

Steve Brice
3 July 2014
SRF R&D

HWR

SSR1

SSR2

LB650

HB650
<table>
<thead>
<tr>
<th>Cavity</th>
<th>Frequency</th>
<th>Cavity Type</th>
<th>Beta</th>
<th>Collaboration?</th>
<th>Cavity EM Design Complete</th>
<th>Cavity Mech Design Complete</th>
<th>Single Cell / Prototype Ordered</th>
<th>Full Cavity Prototype Received</th>
<th>Prototype Tested</th>
<th>Cavities for CM Ordered</th>
<th>Cavities for CM Received</th>
<th>Cavities for CM Tested</th>
<th>Cavities for CM Dressed</th>
<th>CM Cold Mass Design</th>
<th>CM Parts Ordered</th>
<th># of CM Assembled</th>
<th>Est % complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Wave Resonator (HWR)</td>
<td>162.5 MHz</td>
<td>1-HWR CW</td>
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<td>ANL</td>
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<td>yes</td>
<td>yes</td>
<td>not started</td>
<td>8</td>
<td>all parts</td>
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<td>not started</td>
<td>yes</td>
<td>WIP</td>
<td>not started</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Single Spoke Resonator 1 (SSR1)</td>
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<td>1-spoke CW</td>
<td>0.22</td>
<td>India</td>
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<td>yes</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>1</td>
<td>80%</td>
<td>WIP</td>
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<td>50</td>
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<td>1-spoke CW</td>
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<td>India</td>
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<td>yes</td>
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<td>not started</td>
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<td>not started</td>
<td>not started</td>
<td>not started</td>
<td>not started</td>
<td>10</td>
</tr>
<tr>
<td>Low Energy 650 (LE 650)</td>
<td>650 MHz</td>
<td>5-cell CW</td>
<td>0.6</td>
<td>India, JLAB</td>
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<td>not started</td>
<td>not started</td>
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<td>not started</td>
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<td>not started</td>
<td>not started</td>
<td>10</td>
</tr>
<tr>
<td>High Energy 650 (HE 650)</td>
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<td>5-cell CW</td>
<td>0.9</td>
<td>India</td>
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<td>yes</td>
<td>5 of 10</td>
<td>4</td>
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<td>9</td>
<td>4</td>
<td>not started</td>
<td>not started</td>
<td>WIP</td>
<td>not started</td>
<td>not started</td>
<td>20</td>
</tr>
</tbody>
</table>
Cryogenic System

- Required to support 5% cryogenic duty factor
  - Configuration capable of 10-15% with more pumping
  - 160 – 240 kW beam power at 800 MeV
Mu2e w/ PIP-II

• Can operate PIP-II linac up to ~15% duty factor with cryogenic system as designed
• RF system as designed can support 2 mA (averaged over 1 msec) at 15% duty factor
• RFQ can supply 10 mA
• MEBT chopper can provide arbitrary bunch patterns for separation at downstream end of linac.
• Mu2e Operations:
  – 10% micro-duty factor (100 ns×1 MHz)
  – 13.5% macro-duty factor (9 ms×15 Hz)
  – 10%×13.5%×10mA×800 MeV = 108 kW
Mu2e w/PIP-II

9 ms, 1 mA (Mu2e)

1 ms, 2 mA (Boo)

67 ms

100 ns, 10 mA

6 ns

1 ms