PIP-II Goals, Status, and Strategy

Steve Holmes
DOE Independent Project Review of PIP-II
15 November 2016
Steve Holmes

• Role on PIP-II
  – Project Manager
  – IIFC Technical Coordinator (FNAL, delegated)

• Relevant Experience
  – Main Injector Project Manager
  – Accelerator Division Head
  – Associate Laboratory Director for Accelerators
Charge Elements

1. Technical Design: Is the conceptual design for the PIP-II linac sound and likely to meet the specified technical performance requirements? Are R&D efforts being effectively managed to maximize benefits and minimize technical risks to the project?

2. Scope: Is the project's scope sufficiently well-defined to support the preliminary cost and schedule estimates?

3. Cost and Schedule: Are the cost and schedule estimates sufficiently well-defined and of adequate maturity to support the forecasted critical decision milestones and cost range?

4. Management: Is the project being properly managed at this stage? Does the management team possess the skills, expertise and experience necessary to successfully execute the project? Are plans to identify and allocate staffing and resources consistent with current funding guidance?

5. Environment, Safety, and Health: Is environment, safety, and health being properly addressed given the project's current stage of development?

6. India Institutions and Fermilab Collaboration (IIFC): Is the collaboration proceeding satisfactorily towards meeting the goals outlined in the Joint R&D document? Will the deliverables outlined in the Joint R&D document position India for a successful contribution to the PIP-II construction phase?
Since June 2015 IPR

- First hardware deliverables arrive from DAE  July 2015
- Seven DAE engineers/scientists arrive for  October 2015
  2-year residencies
- MNS approved and CD-0 issued  November 2015
- Project accounting initiated  January 2016
- Joint IIFC Meetings  January/July 2016
- North American elliptical cavity vendors  March/August 2016
  close shop
- Associate Project Manager for  April 2016
  Planning and Reporting on-board
- RFQ commissioned with beam  February-November 2016
- Wetlands delineation report received  July 2016
- Analysis of Alternatives submitted for review  July 2016
  - Review committee validation/to OHEP  September 2016
- Draft CDR Released  October 2016
- Responses to all Action Items  October 2016
  - See website
Goals/Mission Need

The goal of PIP-II is to support long-term physics research goals 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

• Mission Need Statement/CD-0 approved November 2015
  – Based on Reference Design/cost estimate (June 2015 IPR)
  – India collaboration was critical

• Capability gap/mission need
  – Reduce time required for LBNF/DUNE to achieve world-first results
  – Sustain high-reliability operations of the Fermilab accelerator complex

• Construction period FY2019-FY2025

• Cost range: $465-$650M
  – (Cost to U.S. DOE after international contributions)
Proposed Technical Approach

• Construct a modern 800-MeV superconducting linac, of CW capable components, operating initially in pulsed mode
  – Ameliorate space-charge forces at Booster injection, allowing an increase Booster/Recycler/Main Injector per pulse intensity of ~50%, while preserving transverse & longitudinal emittance at current levels

• Accompanied by modifications to Booster/Recycler/Main Injector to accommodate higher intensities and higher Booster injection energy

• 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

• Described in the draft Conceptual Design Report
Proposed Technical Approach/Site Layout
## 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>0.54 msec</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Linac Beam Power to Booster</td>
<td>4</td>
<td>17 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>4.3×10^{12}</td>
<td>6.5×10^{12}</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>15</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>80</td>
<td>166 kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program (max)</td>
<td>32</td>
<td>83 kW</td>
</tr>
<tr>
<td>Main Injector Protons per Pulse</td>
<td>4.9×10^{13}</td>
<td>7.5×10^{13}</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 60-120 GeV</td>
<td>1.33**</td>
<td>0.7-1.2 sec</td>
</tr>
<tr>
<td>LBNF Beam Power @ 60-120 GeV</td>
<td>0.7**</td>
<td>1.0-1.2 MW</td>
</tr>
<tr>
<td>LBNF Upgrade Potential @ 60-120 GeV</td>
<td>NA</td>
<td>&gt;2 MW</td>
</tr>
</tbody>
</table>

**NOvA operations at 120 GeV

* India in-kind cryoplant would support CW operations on day-1
Scope

The scope of PIP-II includes all management, permitting, design, development, fabrication, construction, and procurement activities associated with the construction and commissioning of:

- An 800-MeV superconducting linac, constructed of CW-capable accelerating structures and cryomodules, operating with a peak current of 2 mA and a beam duty factor of 1.1%;
- Beam transport from the end of the SC Linac to the new Booster injection point, and to a new 800-MeV beam dump;
- Upgrades to the Booster to accommodate 800-MeV injection, and acceleration of $6.5 \times 10^{12}$ protons per pulse;
- Upgrades to the Recycler to accommodate slip-stacking of $7.7 \times 10^{13}$ protons delivered in twelve Booster batches;
- Upgrades to the Main Injector to accommodate acceleration of $7.5 \times 10^{13}$ protons per pulse to 120 GeV with a 1.2 second cycle time, and to 60 GeV with a 0.7 second cycle time.
- All associated conventional facilities and infrastructure
**Scope/Technology Map**

<table>
<thead>
<tr>
<th>IS</th>
<th>LEBT</th>
<th>RFQ</th>
<th>MEBT</th>
<th>β</th>
<th>Cav/mag/CM</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

**DC**
- 0.03 MeV
- 0.03 - 10.3 MeV

**162.5 MHz**
- 0.03 - 2.1 MeV
- 10.3 - 185 MeV

**325 MHz**
- 10.3 - 800 MeV

**650 MHz**
- 185 - 800 MeV

- **RFQ**
  - Freq: 162.5 MHz
  - Energy (MeV): 0.03 - 2.1

- **HWR (β_{opt}=0.11)**
  - Freq: 162.5 MHz
  - Energy (MeV): 2.1 - 10.3
  - Cav/mag/CM: 8/8/1
  - Type: HWR, solenoid

- **SSR1 (β_{opt}=0.22)**
  - Freq: 325 MHz
  - Energy (MeV): 10.3 - 35
  - Cav/mag/CM: 16/8/2
  - Type: SSR, solenoid

- **SSR2 (β_{opt}=0.47)**
  - Freq: 325 MHz
  - Energy (MeV): 35 - 185
  - Cav/mag/CM: 35/21/7
  - Type: SSR, solenoid

- **LB 650 (β_g=0.61)**
  - Freq: 650 MHz
  - Energy (MeV): 185 - 500
  - Cav/mag/CM: 33/22/11
  - Type: 5-cell elliptical, doublet*

- **HB 650 (β_g=0.92)**
  - Freq: 650 MHz
  - Energy (MeV): 500 - 800
  - Cav/mag/CM: 24/8/4
  - Type: 5-cell elliptical, doublet*

*Warm doublets external to cryomodules

**All components CW-capable**

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[Image of Scope/Technology Map with IS, LEBT, RFQ, MEBT, β values, and Cav/mag/CM specifications for each section.]

11/15/2016
R&D

• The goal is to mitigate risk: Technical/cost/schedule

• Technical Risks
  – Front End
    • Delivery of beam with required characteristics and reliability
  – Operate (high Q_L) SC Linac in pulsed mode at low current
    • Primary issue is resonance control in cavities
  – Booster/Recycler/Main Injector beam intensity
    • 50% per pulse increase over current operations
    • Longitudinal emittance from Booster for slip-stacking
    • Transition crossing
    • Beam loss/activation
  – Develop requisite capabilities of partners and vendors

• Cost Risks
  – Superconducting RF: Cavities, cryomodules, RF sources represent major portion of construction costs
  – Cavity Q_0: plays a critical role in the capital and operating costs of the cryoplant

Current funding profile will support R&D completion in early FY2020
R&D Strategy

We would like to have the following prototypes and/or demonstrations completed at the time of CD-3

- **PIP2IT**
  - Beam accelerated and characterized through the SSR1 prototype cryomodule
  - Demonstration of effective microphonics/LFD mitigation

- **SRF**
  - HWR and SSR1 cryomodules tested with beam
  - SSR2 and LB650 dressed cavities tested at full rf power
  - HB650 prototype cryomodule tested at full rf power
  - All utilizing associated RF power and RF controls systems

- **Main Injector/Recycler**
  - Selection and demonstration of MIRF power amplifier
  - Gamma-t jump prototype magnet
R&D: PIP-II Injector Test

40 m, ~25 MeV

PIP2IT will address the address/measure the following:

- **LEBT pre-chopping**: Demonstrated
- **Vacuum management in the LEBT/RFQ region**: Demonstrated
- **Validation of chopper performance**
  - Bunch extinction, effective emittance growth
- **MEBT beam absorber**
  - Reliability and lifetime
- **MEBT vacuum management**
- **CW operation of HWR**
  - Degradation of cavity performance
  - Optimal distance to 10 kW absorber
- **Operation of SSR with beam**
  - CW and pulsed operation
  - Resonance control and LFD compensation in pulsed operations
- **Emittance preservation and beam halo formation through the front end**

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

Derwent et al.
Cost Range

• Point estimate developed for the June 2015 IPR:

<table>
<thead>
<tr>
<th>PIP-II</th>
<th>Cost Est</th>
<th>Int’l Contrib</th>
<th>DOE TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct, FY13$</td>
<td>$347M</td>
<td>$108M</td>
<td>$239M</td>
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<tr>
<td>Overheads</td>
<td></td>
<td></td>
<td>$84M</td>
</tr>
<tr>
<td>Escalation (to FY20$)</td>
<td></td>
<td></td>
<td>$59M</td>
</tr>
<tr>
<td>Contingency</td>
<td></td>
<td></td>
<td>$134M</td>
</tr>
<tr>
<td>TOTAL PROJECT COST</td>
<td></td>
<td></td>
<td>$516M</td>
</tr>
</tbody>
</table>

• Propose cost range based on DOE Cost Estimating Guide (DOE G 413.3 – 21) for class 3/4 project maturity
  – Range: -10% to +26%

  **Mission Need Statement Cost Range:** $465M – $650M

• Cost estimate will be updated as part of the development of the Resource Loaded Schedule in advance of CD-1
Schedule

Resource Loaded Schedule (RLS) under development in P6

- **WBS established**
  - Segregates OPC and TEC funds
  - Will support EVMS reporting

- **T0, 1, 2, 3, 4 milestones established for project duration**
  - I3, I4 milestones: International contributions lie outside DOE scope, but essential to track

- **Resource loading for R&D phase in process; major activities have been loaded**
  - PIP2IT
  - SSR2, HB650
  - RF Sources
  - Cryogenic distribution syste (PIP2IT)
  - Conventional Facilities
High Level Schedule

Charge Item: #3
Lari
Schedule/Funding Profile

• Currently working with the following profile:

<table>
<thead>
<tr>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
<th>FY23</th>
<th>FY24</th>
<th>FY25</th>
</tr>
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<tbody>
<tr>
<td>$15.7</td>
<td>$18.2</td>
<td>$25.0</td>
<td>$40.0</td>
<td>$60.0</td>
<td>$100.0</td>
<td>$100.0</td>
<td>$100.0</td>
<td>$100.0</td>
<td>$91.1</td>
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</table>

– Sums to upper cost range

• Associated CD dates:

<table>
<thead>
<tr>
<th>CD-0</th>
<th>MNS</th>
<th>Early</th>
<th>T0/T1</th>
</tr>
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<tbody>
<tr>
<td>Q1FY16</td>
<td>Q1FY16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD-1</td>
<td>FY17</td>
<td>Q4FY17</td>
<td>Q4FY18</td>
</tr>
<tr>
<td>FY18</td>
<td>Q1FY19</td>
<td>Q1FY20</td>
<td></td>
</tr>
<tr>
<td>CD-3</td>
<td>FY20</td>
<td>Q4FY20</td>
<td>Q4FY21</td>
</tr>
<tr>
<td>FY26</td>
<td>Q3FY26</td>
<td>Q1FY29</td>
<td></td>
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</table>

RLS required to reconcile funding profile and CD dates
Organization

- DOE Office of Science
  - Director (Project Management Executive)

- Office of High Energy Physics
  - Associate Director (Project Owner)
    - PIP-II Program Manager

- Fermi Site Office
  - PIP-II Federal Project Director

- Fermi National Accelerator Laboratory
  - Accelerator Division
    - PIP-II Project Office
      - PIP-II Project Manager

- Indian Institutions and Fermilab Collaboration (IIFC)

- Indian Department of Atomic Energy (DAE)
Critical mass of persons experienced in accelerator development, construction, operations; and in DOE and international projects
- Main Injector, NOvA, US LHC Accelerator, PIP, and SBN projects
- LHC and ESS projects
- Tevatron, CEBAF, NOvA operations
Project Strategy/Staffing Requirements

- We are able to generate total resource requirements based on FTE estimates gathered as part of the point estimate*. 

<table>
<thead>
<tr>
<th>Resource</th>
<th>R&amp;D Phase</th>
<th>Construction Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FTE-years</td>
<td>FTE-years</td>
</tr>
<tr>
<td></td>
<td>Total Effort</td>
<td>Int'l Visitors</td>
</tr>
<tr>
<td>Accelerator Physicists</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Computer Professionals</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Conventional Facility Engineers</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cryogenic Engineers</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Electrical/Electronics Engineers</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Mechanical Engineer</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>Project Management</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>RF Engineers</td>
<td>28</td>
<td>8</td>
</tr>
<tr>
<td>Technicians</td>
<td>41</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>178</strong></td>
<td><strong>24</strong></td>
</tr>
</tbody>
</table>

*Does not include contingency

- Note: PIP-II current utilization is 53-59 FTE
• Accelerator Safety Requirements
  – PIP2IT operations conform with laboratory policies and procedures
    • Shielding assessments
    • Interlocked enclosure as required
    • ODH (eventually)
    • Operations permits specify beam intensity authorization
  – Exemption from DOE O 420.2C as a “room-sized accelerator”

• National Environmental Policy Act (NEPA)
  – Monthly strategy meeting established with FSO, ESH Section, and PIP-II Project
  – Environmental Evaluation Notification Form (EENF) drafted and shared with FSO
  – Wetlands delineation study complete (summer 2016)
  – Environmental Assessment (EA) to be launched late FY17/early FY18 (funding dependent)
    – Require FONSI prior to CD-2

• Expect to appoint APM/ESHQ at end of FY2017
International Partners/India

- Indian Institutions and Fermilab Collaboration (IIFC) established in 2009
  - Collaborative development of technologies associated with high intensity superconducting proton accelerators
  - Critical to achieving CD-0

- High-level management via two (DOE & DAE) Principal Coordinators, supported by (Fermilab & DAE) Technical Coordinators

- Technical integration of work via Fermilab SPMs and Indian SPCs
  - Weekly teleconferences providing coordination

- Joint R&D document: defines scope of work and deliverables dates
  - Fermilab has proposed revision to the deliverables dates to provide consistency with the current RLS for the R&D phase. Not yet formally accepted by PCs

- Semi-annual reviews of progress

- Seven Indian engineers/scientists at Fermilab for 2-year residencies
  - Plus multiple short term visits

- DAE observers/presenters at this review:
  - Ranajit Kumar/Head, DAE Nuclear Control and Planning Wing
  - Satish Joshi/Head, Proton Linac and Superconducting Cavities Division, RRCAT
  - Srinivas Krishnagopal/High Intensity Proton Linac Section, BARC
  - Vikas Jain/RRCAT, Fermilab Guest Engineer
Other Partners/Europe

- Partnership forming with INFN
  - LB650 prototype cavity design and fabrication
  - Led by INFN/Milano

- UK institutions proposal to STFC for support of LBNF/PIP-II
  - PIP-II: HB650 cryomodules
  - To be led by CI/ASTeC (Daresbury)

- The prospects for European deliverables should be clear later this fall

- Review observer
  - Carlo Pagani (INFN/Milano)
Summary

• PIP-II conceptual design meets the requirements outlined in the Mission Need Statement
  – Concept is mature; will provide ≥1.2 MW of beam power at LBNF/DUNE startup
  – Flexible platform for the future

• R&D activities are aligned with the technical and cost risks associated with the conceptual design
  – PIP2IT retires risks associated with the front end and resonance control
  – SRF program retires risks associated with the superconducting accelerating modules
  – R&D program is run jointly with our Indian collaborators
  – Major accomplishments over the last year

• PIP-II project scope is well defined
  – 800-MeV superconducting linac
  – Modifications to the Booster/Recycler/Main Injector
  – Site layout established

• Resource Loaded Schedule under development
  – WBS and high level milestones established
  – Major R&D elements are incorporated
  – Will provide consistency with funding profile

• Targeting completion of R&D program/initiation of construction (CD-3) in 2020
Summary

• An experienced management team is in place that can be expected to successfully execute the PIP-II project.
  – Recent addition of Associate Project Manager for Planning and Reporting

• Staffing requirements are understood for both R&D and construction phases
  – Competition for resources with other projects will require careful coordination at the laboratory level

• Laboratory safety policies and procedures are governing beam operations at PIP2IT

• NEPA strategy developed and being implemented
  – Wetlands delineation complete
  – EENF in draft

• The collaboration with India/DAE is in the R&D phase
  – Deliverables defined in Joint R&D document
  – Scope aligned with potential DAE contributions to the construction phase
  – Actively managed by DOE/Fermilab/DAE

• Potential for Italy/INFN and/or UK/STFC contribution to the construction phase

• Next Step: CD-1!*
Backups
Design Criteria

• 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

Goal: Initiate operations in newly-configured complex in ~2025
Cost Estimate

- Point estimate constructed for June 2015 IPR
  - Estimate starts in FY16
  - Estimate as if everything constructed by Fermilab
  - M&S estimates for all major systems, conventional facilities, project management, and R&D
    - Scope: Superconducting linac + beam transfer line + required modifications to Booster, Recycler, Main Injector
    - Includes component fabrication and installation
    - Estimates in direct FY13$
  - Effort estimated for above in person-years by skills type
    - Includes EDIA
    - Translated to SWF at Fermilab FY13 labor rates
  - Remove costs for international contributions
  - Apply published Fermilab overhead rates
  - Apply escalation of 18.2% (FY13 to FY20 @ 2.4%/year)
  - Apply across-the-board 35% contingency
Future Directions

• The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements to the Fermilab proton complex
  – >2 MW to LBNF
  – 100’s kW for a rare processes program
    • CW capability at 0.8 – 3 GeV
  – Front end for a muon-based facility

• The natural next steps would be upgrading the PIP-II linac to CW operations and replacement of the Booster with higher performance accelerator (PIP-III)
India is planning on providing, as an in-kind contribution, a cryoplant of sufficient capacity to support CW operations.

PIP-II front end can produce arbitrary bunch patterns subject to the following constraints:
- Peak current \( \leq 10 \) mA
- Average current \( \leq 2 \) mA

This provides an opportunity for delivering 800-MeV protons directly from the SCL to a second generation Mu2e.
**PIP-II and Next Generation Mu2e**

- Possible beam structure:
  - Beam pulse length: \(~20\) nsec
  - Pulse repetition period: \(1.6\) \(\mu\)sec
  - Beam power: **100 kW**
  - Three-year run achieves single event sensitivity of \(2 \times 10^{-18}\)
2.4 MW requires $1.5 \times 10^{14}$ particles from MI every 1.2 s @ 120 GeV
   - Every 0.6 sec @ 60 GeV

Slip-stacking in Recycler is not an option at these intensities
   - Need to box-car stack $6 \times 2.5 \times 10^{13}$ protons in less than 0.6 sec
   - >10 Hz rep-rate
   - Or inject a long (linac) pulse directly into Main Injector

Booster is not capable of accelerating $2.5 \times 10^{13}$ no matter what the injection energy, or how it is upgraded: many issues…

**Achieving 2+ MW will require replacement of the Booster with either a 6-8 GeV pulsed linac or a rapid cycling synchrotron (RCS) fed by a $\geq 1.5$ GeV linac**

**PIP-III: 20 Hz operations of a new RCS at $\sim 2.5 \times 10^{13}$ ppp**
   - Deliver 2.4 MW @ 60-120 GeV from the Main Injector to the LBNF beamline in support of the DUNE experiment
   - Deliver up to 80 kW @ 8 GeV to support g-2, Mu2e, and short-baseline neutrinos
   - Deliver ~100 kW @ 800 MeV to support a second generation Mu2e
## Possible Parameters for post-PIP-II Complex

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RCS</th>
<th>Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton Source</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle Type</td>
<td>p</td>
<td>H-</td>
</tr>
<tr>
<td>Beam Kinetic Energy</td>
<td>8.0</td>
<td>8.0 GeV</td>
</tr>
<tr>
<td>Protons per Pulse</td>
<td>$2.5 \times 10^{13}$</td>
<td>$1.5 \times 10^{14}$</td>
</tr>
<tr>
<td>Beam Pulse Length</td>
<td>0.0016</td>
<td>10 msec</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>20</td>
<td>3.33 Hz</td>
</tr>
<tr>
<td>Pulses to Recycler</td>
<td>6</td>
<td>NA</td>
</tr>
<tr>
<td>Pulses to Main Injector</td>
<td>NA</td>
<td>1</td>
</tr>
<tr>
<td>Beam Power at 8 GeV (Total)</td>
<td>640</td>
<td>640 kW</td>
</tr>
<tr>
<td>Beam Power to Main Injector*</td>
<td>160/320</td>
<td>160/320 kW</td>
</tr>
<tr>
<td>Beam Power Available to 8 GeV Program*</td>
<td>480/320</td>
<td>480/320 kW</td>
</tr>
<tr>
<td><strong>Main Injector</strong></td>
<td></td>
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<tr>
<td>Beam Kinetic Energy*</td>
<td>120/60</td>
<td>120/60 GeV</td>
</tr>
<tr>
<td>Main Injector Protons per Pulse</td>
<td>$1.5 \times 10^{14}$</td>
<td>$1.5 \times 10^{14}$</td>
</tr>
<tr>
<td>Main Injector Cycler Time*</td>
<td>1.2/0.6</td>
<td>1.2/0.6 sec</td>
</tr>
<tr>
<td>LBNF Beam Power*</td>
<td>2.4/2.4</td>
<td>2.4/2.4 MW</td>
</tr>
</tbody>
</table>

* First number refers to 120 GeV MI operations; second to 60 GeV
PIP-III (~2030)