An 800 MeV Superconducting Linac to Support Megawatt Proton Operations at Fermilab

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Outline

• Fermilab accelerator complex
• PIP-II goals and parameters
• SC linac and subsystems
• PXIE – frontend test
• Summary
Fermilab Accelerator Complex

- Main Injector
- Recycler Ring
- Fixed-Target Experiments, Test Beam Facility
- Booster
- Muon Delivery Ring
- Linac
- Ion Source
- Neutrino Experiments
- Muon Experiments
From Project X to PIP-II

- Project X was conceived as a facility supporting large number of intensity frontier experiments ($\nu$, $\mu$, $K$)
- PIP-II
  - Will support for the world leading $\nu$ experiments
  - Favorably positions Fermilab into the future
From PIP to PIP-II

• PIP - Proton Improvement (next few years)
  – Fermilab Booster upgrade to support NoVA at 700 kW
    • 7 Hz -> 15 Hz

• PIP-II (construction: 2019-2024?)
  – Next step in the power increase
    • Major goals
      – 700 kW -> 1.2 MW at 120 GeV (LBNF)
      – More power for 8 GeV program: 80 ->160 kW (SBNE, …)
  – New SC linac to increase $E_{\text{inj}}$ (400 -> 800 MeV)
    • Particles per pulse extracted from Booster: $(4.3 \rightarrow 6.5) \cdot 10^{12} \times 1.5$
    • Pulsed operation to reduce cost (reuse Tevatron infrastructure)
  – An experiment in near reach
    • $\mu$-to-e upgrade at 15-30% duty factor (7 kW -> 100 kW)
      – Requires new beam line
Future Directions

• The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements
  – multi-MW to LBNF (1.2 -> 2.4 MW)
  – CW capability brings us to other Project X experiments
    • 0.8 GeV (up to 1.6 MW total, RF separ. -> multiple experiments)
      – μ-to-e upgrade – step 0
      – Other experiments with muons (μ->3e, ...)
      – Experiments with neutrons (n-nbar, ...)
      – Nuclear physics & EDMs
    • 3 GeV
      – Kaons
      – Front end for a muon-based facility
• The details will be determined by future HEP programmatic choices (~10 years down the road)
FNAL Accelerator Complex Beyond PIP-II

• PIP-II limitations:
  – Slip-stacking in the Recycler is questionable at intensities beyond PIP-II
    • Beam loss and stability at slip-stacking
  – Booster intensity is limited to $\sim 7 \times 10^{12}$ ppp by impedance and transition crossing

• That sets the strategy for next steps
  – A new 8 GeV source is necessary
  – Possibilities
    • 1.5-2 GeV linac + conventional RCS
    • Lower energy linac + ‘supersmart RCS that mitigates beam losses (integrable optics? R&D into space charge effects is initiated)
    • 8 GeV linac
      – Presently looks as more expensive
      – Higher injection energy – Higher beam loss ?
PIP-II Design Choices

• Future program with rare decays requires SRF linac
• That sets further choices
  – Relative to the Project X the PIP-II scope & cost are reduced
  – SRF technology map is unchanged
    • Makes future upgrades easier
  – The scope changes
    • CW linac energy: 3 GeV -> 0.8 GeV
    • Linac operates in pulsed regime
      – To avoid construction of new cryo-plant
        ⇒ significant cost reduction (collaboration with India can change this)
    • All other systems are CW compatible
      – creates many possibilities in the future
  – Booster is used to accelerate to 8 GeV
    • upgraded to higher $E_{inj}$ and rep. rate
  – Booster and MI upgrades are not parts of PIP-II project
## PIP-II versus PIP

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>PIP</th>
<th>PIP-II</th>
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<tbody>
<tr>
<td>Linac Beam Energy</td>
<td>400 MeV</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Linac Beam Current</td>
<td>25 mA</td>
<td>2 mA</td>
</tr>
<tr>
<td>Linac Beam Pulse Length</td>
<td>0.03 ms</td>
<td>0.55 ms</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15 Hz</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Linac Upgrade Potential</td>
<td>N/A</td>
<td>CW</td>
</tr>
<tr>
<td>Booster Protons per Pulse (extracted)</td>
<td>$4.2 \times 10^{12}$</td>
<td>$6.5 \times 10^{12}$</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>15 Hz</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>80 kW</td>
<td>160 kW</td>
</tr>
<tr>
<td>8 GeV Beam Power to MI (LBNE)</td>
<td>-</td>
<td>80-120* kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program</td>
<td>-</td>
<td>80-40* kW</td>
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<tr>
<td>Main Injector Protons per Pulse (12 batches; extr.)</td>
<td>$4.9 \times 10^{13}$</td>
<td>$7.6 \times 10^{13}$</td>
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<tr>
<td>Main Injector Cycle Time @ 120 GeV</td>
<td>1.33 sec</td>
<td>1.2 sec</td>
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<tr>
<td>Main Injector Cycle Time @ 60 GeV</td>
<td>N/A</td>
<td>0.8 sec</td>
</tr>
<tr>
<td>Beam Power @ 60 GeV (LBNE)</td>
<td>N/A</td>
<td>0.9 MW</td>
</tr>
<tr>
<td>Beam Power @ 120 GeV</td>
<td>0.7 MW</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Upgrade Potential @ 60-120 GeV</td>
<td>-</td>
<td>&gt;2 MW</td>
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</table>
Linac Structure

- Room T acceleration to 2.1 MeV
  - 5 types of SC cavities
  - Solenoidal focusing for first 3 types
  - Doublet focusing for LB & HB
  - HW & SSR1 operate in CW other in pulsed regime
**PIP-II Warm Frontend**

- “Standard” scheme for beam acceleration
  - 30 kV ion source (5 mA nominal, 10 mA max)
    - 2 sources and dipole switch
  - LEBT with beam pre-chopping for machine tuning
    - 3 solenoids, good differential pumping
  - 2.1 MeV CW RFQ
    - $f=162.5$ MHz set by bunch-by-bunch chopping
  - MEBT ($\sim 10$ m)
    - Bunch-by-bunch chopper
      - 2 kickers with $\mu=180^\circ$ to minimize voltage; $V \approx \pm 250$ for bipolar feeding
    - 3 RF cavities, 8 periods, quads (7 triplets, 2 doublets), instrumentation
    - Beam absorber (20 kW) & differential pumping
**PIP-II SC Linac**

- Tight solenoidal focusing in first 3 cryomodules
  - Space charge
  - Variation of cavity $\perp$ defocusing along bunch
- External doublet focusing for LB&HB
  - Beam collimation and instrumentation between cryomodules

<table>
<thead>
<tr>
<th>Section</th>
<th>Energy (MeV)</th>
<th>$\Delta E$/cav (MeV)</th>
<th>$R/Q$ ($\Omega$)</th>
<th>Cav/CM</th>
<th>CM config.</th>
<th>CM length (m)</th>
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</thead>
<tbody>
<tr>
<td>HWR</td>
<td>2.1-11</td>
<td>1.7</td>
<td>272</td>
<td>8/1</td>
<td>8 x (sc)</td>
<td>5.93</td>
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<tr>
<td>SSR1</td>
<td>11-38</td>
<td>2.05</td>
<td>242</td>
<td>16/2</td>
<td>4 x (csc)</td>
<td>5.2</td>
</tr>
<tr>
<td>SSR2</td>
<td>38-177</td>
<td>4.98</td>
<td>275</td>
<td>35/7</td>
<td>sccsccsc</td>
<td>~6.5</td>
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<tr>
<td>LB650</td>
<td>177-480</td>
<td>11.6</td>
<td>378</td>
<td>30/10</td>
<td>(ccc)-(fd)</td>
<td>~3.9</td>
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<tr>
<td>HB650</td>
<td>480-800</td>
<td>17.7</td>
<td>638</td>
<td>24/4</td>
<td>(cccccc)-(fd)</td>
<td>~9.5</td>
</tr>
</tbody>
</table>

**Diagram:**

- Tight solenoidal focusing
- External doublet focusing
- Beam collimation
- Instrumentation

**Fermilab**

Valeri Lebedev | Linac 2014 09/02/2014
Beam Dynamics in SC linac

- Same as for the Project X linac
  - Moderate emittance growth in the course of acceleration
  - Beam loss is dominated by intrabeam stripping (<0.15 W/m)
The average RF power has 2 contributions:
- the energy transferred to the beam (~10%)
- the energy required to fill and discharge the cavities (90%)
  - It does not depend on the peak RF power
For fixed average power the cost of RF grows with peak power
- therefore RF cost achieves minimum with minimum peak power
- i.e. power equal to the power required for beam acceleration

=> Duty factor for the RF power amplifiers ≈15%
Microphonics and Lorentz Force Detuning (LFD)

- Low beam loading (2 mA) ⇒ narrow cavity bandwidth ⇒ microphonics issues
- Microphonics Control Strategies
  - RF power reserve
  - Good regulation of LHe pressure
  - Reduced sensitivity of resonant frequency to LHe pressure
  - Minimizing external vibrations and sensitivity to them
  - Fast tuner driven by sophisticated feedback
- Pulsed operation complicates keeping cavity at resonance due to fast Lorentz force detuning
  - R&D is initiated

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq. $f_0$ (MHz)</th>
<th>Maximal detune (peak Hz)</th>
<th>Minimal Half Bandwidth, $f_0/2Q$(Hz)</th>
<th>Max Required Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR</td>
<td>162.5</td>
<td>20</td>
<td>34</td>
<td>4.8</td>
</tr>
<tr>
<td>SSR1</td>
<td>325</td>
<td>20</td>
<td>45</td>
<td>5.3</td>
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<tr>
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<td>17.0</td>
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<td>29</td>
<td>33.0</td>
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<tr>
<td>HB650</td>
<td>650</td>
<td>20</td>
<td>31</td>
<td>48.5</td>
</tr>
</tbody>
</table>
Cryogenics

• Cost minimization => reusing existing Tevatron cryogenics
  – Cryogenic duty factor is ~6.6%
• Conservative approach for $Q_0$:
  – Total cryogenic heat load at 2K (320 W) is dominated by static load (182 W)
    • It is ~17% of the CW load
• Upgrade to CW will require a new 2K cryogenic plant
• Note that
  • HWR & SSR1 cryomodules designed for CW operation
    – They will operate at CW
    • Negligible addition to the total load
• Success of R&D on $Q_0$ should allow operation at 20-30% duty factor
  – The $\mu$-to-e upgrade without cryo-plant upgrade

<table>
<thead>
<tr>
<th></th>
<th>$Q_0$</th>
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</thead>
<tbody>
<tr>
<td>HWR</td>
<td>$5\times10^9$</td>
</tr>
<tr>
<td>SSR1</td>
<td></td>
</tr>
<tr>
<td>SSR2</td>
<td>$1.2\times10^{10}$</td>
</tr>
<tr>
<td>LB650</td>
<td>$1.5\times10^{10}$</td>
</tr>
<tr>
<td>HB650</td>
<td>$2\times10^{10}$</td>
</tr>
</tbody>
</table>
PXIE

- PXIE represents a complete systems test of the frontend
  - Has to retire major risks
    - CW RFQ, Chopper, MEBT differential pumping, low energy acceleration in SC cavities at high power
  - Test stand for suppression of resonance control and LFD
  - Development of SC linac diagnostics (LPM)
- PXIE accelerates beam to ~25 MeV and includes:
  - Warm front end + 2 SC cryomodules
  - HEBT + 50 kW beam dump
- PXIE status
  - LEBT: in commissioning
  - RFQ: comes this spring
  - MEBT: shortened version will be ready for RFQ test this year
  - Cryomodules: Designed, being built, expected to be ready ~2017
  - Beam commissioning ~2018
Conclusions

• Proton Improvement Plan-II supports long term physics research goals by
  – providing increased beam power to LBNF
  – and setting a platform for the future

• PIP-II is in the pre-CD-0 status
  – It has strong support from P5, OHEP, and Fermilab director
  – Plan presented to P5 and DOE proposes five year construction period starting in FY2019

• Strong endorsement of PIP-II in the P5 Report
  – **Recommendation 14:** Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIPII) 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.
Acknowledgements

**PIP-II Collaboration**

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

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<th>National</th>
<th>IIFC</th>
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<td>ANL</td>
<td>BNL</td>
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<tr>
<td>ORNL/SNS</td>
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<td>Cornell</td>
<td>PNNL</td>
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<td>UTenn</td>
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<td>LBNL</td>
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<td>TJNAF</td>
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<tr>
<td>MSU</td>
<td>NCSU</td>
</tr>
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<td>ILC/ART</td>
<td></td>
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</tbody>
</table>

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

- PIP-II and PXIE posters at LINAC-14:
  - RT: TUPP047, TUPP051, THPP049, THPP055, THPP056
  - SC: MOPP047, MOPP049, MOPP052, MOPP055, MOPP056, TUPP052, TUIOC02, TUPP048, TUPP049; TUPP052, TUPP053, THPP001, THPP048, THPP050, THPP057

Thank you
Backup Slides
PXIE MEBT

- RFQ
- Scrappers
- Bunching cavity
- Absorber
- Kickers
- Triplet
- HW R
## Cryogenic Loads

<table>
<thead>
<tr>
<th>CM type</th>
<th>Number of CM</th>
<th>Static Load per CM at 2K [W]</th>
<th>Dynamic Load per CM at 2K [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td>HWR</td>
<td>1</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>SSR1</td>
<td>2</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>SSR2</td>
<td>7</td>
<td>8.8</td>
<td>43</td>
</tr>
<tr>
<td>LB 650</td>
<td>10</td>
<td>5</td>
<td>73</td>
</tr>
<tr>
<td>HB 650</td>
<td>4</td>
<td>6.2</td>
<td>147</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>182</strong></td>
<td><strong>1651</strong></td>
<td><strong>138</strong></td>
</tr>
</tbody>
</table>

Cryo-plant 490 (margin of ~1.5 times)