MegaWatt Proton Beams for Particle Physics at Fermilab

Steve Holmes
P5 Meeting/BNL
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The Fermilab accelerator complex can be upgraded to establish LBNE 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. investment in superconducting rf,
- 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

- LBNE >2 MW
- Mu2e sensitivity x10
- MW-class, high duty factor beams for rare processes experiments

We look forward to a positive recommendation from P5, and are in a position to move forward expeditiously.
Outline

- Program Goals
- Proton Improvement Plan
- Proton Improvement Plan-II
  - Goals
  - Strategy
  - Description of PIP-II
  - Cost Estimate
  - Platform for the Future
Program Goals

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

- Neutrinos
  - MINOS+, NOvA @700 kW (now)
  - LBNE @ >1 MW (2025)
  - LBNE @ >2 MW (>2030)
  - Short baseline neutrinos

- Muons
  - Muon g-2 @ 17 kW (2017)
  - Mu2e @ 8 kW (2020)
  - Mu2e @ 100 kW (>2023)

- Longer term opportunities
  ⇒ This will require more protons!
Fermilab Accelerator Facts of Life

Every proton delivered to a target at Fermilab must be accelerated through the (40-year-old) Linac and Booster

- **Linac**
  - $2 \times 10^{13}$ protons (35 mA x 100 µsec) to 400 MeV @ 15 Hz
  - Drift Tube section represents a significant operational risk
    - Many components either no longer available, or available from a single vendor operating in a minimal market

- **Booster**
  - $4.2 \times 10^{12}$ protons to 8 GeV @ 7.5 Hz
  - Magnets cycle at 15 Hz
    - Beam cycle rate limited by rf system
  - Pulse intensity limited by space-charge at injection
    - Strongly dependent on injection energy
  - Booster represents a modest operational risk

⇒ **Booster injection is the primary intensity bottleneck**
Proton Improvement Plan (2011 - 2018)

The Proton Improvement Plan supports NOvA, g-2, Mu2e, and short-baseline neutrino goals by doubling the Booster beam repetition rate to 15 Hz, while addressing reliability concerns

- **Goals**
  - $4.2 \times 10^{12}$ protons per pulse at 15 Hz (2.2E17/hour)
  - Linac/Booster availability > 85%
  - Residual activation at acceptable levels
  - Useful operating life through 2025

- **Scope**
  - Increase Booster beam rep rate to 15 Hz
    - RF upgrades/refurbish
  - Replace components with high availability risk
    - DTL rf $\Rightarrow$200 MHz klystrons/modulators
    - Additional Booster rf cavities
  - Double proton flux while maintaining current levels of activation
    - RFQ, dampers, collimators/absorbers

⇒ 700 kW to NOvA at 120 GeV, concurrent with 8 GeV program
Proton Improvement Plan-II

Goals

*Proton Improvement Plan II supports longer term physics research goals by providing increased beam power to LBNE while providing a platform for the future*

- **Design Criteria**
  - Deliver 1.2 MW of proton beam power from the Main Injector to the LBNE target at 120 GeV, with power approaching 1 MW at energies down to 60 GeV, at the start of LBNE operations.
  - Continue support for the current 8 GeV program, including Mu2e, Muon g-2, and the suite of short-baseline neutrino experiments; provide upgrade path for Mu2e.
  - Provide a platform for eventual extension of beam power to LBNE to >2 MW.
  - Provide a platform for extension of capability to high duty factor/higher beam power operations.
Proton Improvement Plan-II

Strategy

- Increase Booster/Recycler/Main Injector per pulse intensity by ~50%.
  - Requires increasing the Booster injection energy
- Select 800 MeV as preferred Booster injection energy
  - 30% reduction in space-charge tune shift w/ 50% increase in beam intensity
  - Provides margin for lower beam loss at higher intensities
- Modest modifications to Booster/Recycler/Main Injector
  - To accommodate higher intensities and higher Booster injection energy

⇒ Cost effective solution:

800 MeV superconducting pulsed linac, extendible to support >2 MW operations to LBNE and upgradable to continuous wave (CW) operations

- Builds on significant existing infrastructure
- Capitalizes on major investment in superconducting rf technologies
- 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
# Proton Improvement Plan-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>0.6 msec</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Linac Beam Power Capability (10-15% DF)</td>
<td>~200 kW</td>
</tr>
<tr>
<td>Mu2e Upgrade Potential (800 MeV)</td>
<td>&gt;100 kW</td>
</tr>
<tr>
<td>Booster Protons per Pulse</td>
<td>$6.4 \times 10^{12}$</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>120 kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program (max)</td>
<td>40 kW</td>
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<tr>
<td>Main Injector Protons per Pulse</td>
<td>$7.5 \times 10^{13}$</td>
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<tr>
<td>Main Injector Cycle Time @ 120 GeV</td>
<td>1.2 sec</td>
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<tr>
<td>Main Injector Cycle Time @ 80 GeV</td>
<td>0.8 sec</td>
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<tr>
<td>LBNE Beam Power @ 80-120 GeV</td>
<td>1.2 MW</td>
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<tr>
<td>LBNE Upgrade Potential @ 60-120 GeV</td>
<td>&gt;2 MW</td>
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<tr>
<td>Section</td>
<td>Freq</td>
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<tr>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>RFQ</td>
<td>162.5</td>
</tr>
<tr>
<td>HWR (β_{opt}=0.11)</td>
<td>162.5</td>
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<td>SSR1 (β_{opt}=0.22)</td>
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<td>SSR2 (β_{opt}=0.51)</td>
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<tr>
<td>LB 650 (β_G=0.61)</td>
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<tr>
<td>HB 650 (β_G=0.9)</td>
<td>650</td>
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</tbody>
</table>
Proton Improvement Plan-II
Site Layout (provisional)
Proton Improvement Plan-II
Booster/Recycler/MI Requirements

- **Booster**
  - New injection girder to accept 800 MeV and enable transverse beam painting
  - Additional rf voltage (3-4 cavities) to support transition crossing manipulations
  - Upgrades to damper and collimator systems

- **Recycler**
  - RF cooling upgrade for operations at <1.2 sec cycle
  - Collimator upgrade

- **Main Injector**
  - RF power upgrade; new power amplifiers
Proton Improvement Plan-II
Cost Estimate

- Starting point is the Project X/Stage 1 estimate:
  - Estimates of major systems and components
    - M&S (FY13 dollars) and person-years
  - Fermilab (FY13) labor rates applied to effort
  - Overheads applied
  - Across the board 40% contingency
  - Original cost reviewed in March 2010
    - Updates to major component estimates since
  - Benchmark to SNS linac good to ~10%
Proton Improvement Plan-II Cost Estimate

- **PIP-II estimate**
  - **Scope =** Linac + beam transfer line + R&D + ProjMan + civil
    - LBNE target/horn system managed/funded by LBNE
    - Booster, Recycler, Main Injector upgrades managed through operating departments and funded as AIPs
  - Reutilize components from the PX/PIP-II development program
  - Estimate of cryogenic systems based on new concept for low duty factor operations*
  - Estimate of civil construction based on new siting*
  - Estimate of rf for lower duty factor operations (modest savings)
  - Efficient project schedule: 7 years from CD-0 to CD-4
  - Escalated to FY20 dollars

⇒ **DOE/TPC metric**


*Substantial savings from PX*
# Proton Improvement Plan-II Cost Estimate

## PIP-II Major Cost Component

<table>
<thead>
<tr>
<th>PIP-II Major Cost Component</th>
<th>Estimate ($M)</th>
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</thead>
<tbody>
<tr>
<td>R&amp;D</td>
<td>$27</td>
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<tr>
<td>Project Management</td>
<td>$26</td>
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<tr>
<td>Accelerating Cavities and Cryomodules</td>
<td>$70</td>
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<tr>
<td>RF Sources</td>
<td>$29</td>
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<tr>
<td>Cryogenic Systems (reuse existing CHL)</td>
<td>$14</td>
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<tr>
<td>Civil Construction</td>
<td>$66</td>
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<tr>
<td>Instrumentation</td>
<td>$12</td>
</tr>
<tr>
<td>Controls</td>
<td>$13</td>
</tr>
<tr>
<td>Mechanical Systems</td>
<td>$3</td>
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<tr>
<td>Electrical Systems</td>
<td>$2</td>
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<tr>
<td>Beam Transport</td>
<td>$5</td>
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<tr>
<td>Sub-total (direct, FY2013 dollars)</td>
<td>$266</td>
</tr>
<tr>
<td>Indirects, Contingency (40%), escalation (18%)</td>
<td>$276</td>
</tr>
<tr>
<td><strong>TOTAL PROJECT COST (FY2020 Dollars)</strong></td>
<td><strong>$542</strong></td>
</tr>
</tbody>
</table>
Proton Improvement Plan-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
  - $150-200M (TPC metric) plausible

- 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
- x10 Mu2e sensitivity
- 2 MW to LBNE
- Flexibility for future experiments
Summary

- The Fermilab accelerator complex can be upgraded to establish LBNE 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
  - LBNE >2 MW
  - Mu2e sensitivity x10
  - MW-class, high duty factor beams for rare processes experiments
- We look forward to a positive recommendation from P5, and are in a position to move forward expeditiously.
Backups
Proton Improvement Plan

Proton Demand

- **Main Injector**
- **Booster Neutrinos**
- **$g$-2**
- **$\mu$2e**
- **Total**

![Proton Demand Graph]

- **NOvA**
- **8 GeV $\nu$**
- **g-2**
- **Mu2e**

Fermilab
Proton Improvement Plan Projection

- Main Injector
- Booster Neutrinos
- g-2
- mu2e
- Total
- PIP Minimum
- PIP Maximum

Protons/Hour

- 8 GeV ν
- NOvA
- g-2
- Mu2e

Proton Improvement Plan-II Options

- **Plan A - Superconducting Linac**
  - 800 MeV pulsed SC linac
  - Constructed from CW-capable accelerating modules
  - Operated initially at low duty factor
  - Sited in close proximity to Booster and to significant existing infrastructure

- **Plan B - Afterburner**
  - 400 MeV pulsed linac appended to existing 400 MeV linac
  - 805 MHz accelerating modules
  - Requires physical relocation of existing linac upstream ~50 m
  - ~1 year interruption to operations
  - Less expensive than Plan A
## Proton Improvement Plan-II

### Pluses and Minuses

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Plan A: PIP-II</th>
<th>Plan B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power to LBNE</td>
<td>1.2 MW</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Cost to DOE (FY2020 $M)</td>
<td>$350-400</td>
<td>$250</td>
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<tr>
<td>R&amp;D aligned with efforts to date</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Upgradable to 2 MW to LBNE</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>High Duty Factor Capable</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Proton Driver for Muon Facility</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Upgrade paths utilize 1.3 GHz infrastructure &amp; capabilities</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Retires significant reliability risks</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Interruption to operations</td>
<td>~2 months</td>
<td>&gt;12 months</td>
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<tr>
<td>International contribution &amp; collaboration</td>
<td>Significant</td>
<td>Minimal</td>
</tr>
<tr>
<td>Reutilization of existing infrastructure</td>
<td>Significant</td>
<td>Modest</td>
</tr>
<tr>
<td>Status of technical development/understanding</td>
<td>Advanced conceptual</td>
<td>Pre-conceptual</td>
</tr>
</tbody>
</table>
Linac Length Compare

- Length of existing linac enclosure
  - 400 MeV: 145 m

- Length of PIP-II
  - 800 MeV: 190 m
  - 540 MeV: 145 m
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

Flexible Beam Formats

1 GeV

\(f_0/2\)

\[1 \text{ mA}\]

\[0.91 \text{ mA}\]

\[0.09 \text{ mA}\]

1 \(\mu\text{sec}\)
2+ MW

- Require $1.5 \times 10^{14}$ particles from MI every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Slip-stacking is not an option at these intensities
  - Need to box-car stack $6 \times 2.5E13$ protons in less than 0.6 sec $\Rightarrow >10$ Hz rep-rate
  - Either Recycler (8 GeV) or MI (6-8 GeV)
2+ MW

- Booster is not capable of accelerating $2.5 \times 10^{13}$ no matter how it is upgraded
  - Requires ~0.1% beam loss
  - High impedance
  - Transition crossing
  - Poor magnetic field quality
  - Poor vacuum
  - Inadequate shielding

⇒ **Achieving 2+ MW from Main Injector will require construction of a $\geq 1.5$ GeV linac**
  - Can feed Main Injector via either a 6-8 GeV pulsed linac or rapid cycling synchrotron (RCS)
# 2+ MW to LBNE

Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Type</td>
<td>H⁻</td>
</tr>
<tr>
<td>Beam Kinetic Energy</td>
<td>8.0 GeV</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>10 Hz</td>
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<tr>
<td>Pulse Width</td>
<td>$6 \times 4.3$ msec</td>
</tr>
<tr>
<td>Particles per cycle to Recycler/MI</td>
<td>$2.5 \times 10^{13}$</td>
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<tr>
<td>Beam Power @ 8 GeV</td>
<td>320 kW</td>
</tr>
</tbody>
</table>

Main Injector/Recycler

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Kinetic Energy (maximum)</td>
<td>60/120 GeV</td>
</tr>
<tr>
<td>Cycle time</td>
<td>0.6/1.2 sec</td>
</tr>
<tr>
<td>Particles per cycle</td>
<td>$1.5 \times 10^{14}$</td>
</tr>
<tr>
<td>Beam Power at 60-120 GeV</td>
<td>2400 kW</td>
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</tbody>
</table>
# PX Reference Design Performance

**CW Linac**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Particle Type</td>
<td>H⁻</td>
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<tr>
<td>Beam Kinetic Energy</td>
<td>3.0 GeV</td>
</tr>
<tr>
<td>Average Beam Current (@ 1 GeV)</td>
<td>2 mA</td>
</tr>
<tr>
<td>Average Beam Current (@ 3 GeV)</td>
<td>1 mA</td>
</tr>
<tr>
<td>Beam Power to 1 GeV program</td>
<td>1000 kW</td>
</tr>
<tr>
<td>Beam Power to 3 GeV program</td>
<td>2870 kW</td>
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</table>

**Pulsed Linac**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Type</td>
<td>H⁻</td>
</tr>
<tr>
<td>Beam Kinetic Energy</td>
<td>8.0 GeV</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>6×4.3 msec</td>
</tr>
<tr>
<td>Particles per cycle to Recycler/MI</td>
<td>2.7×10¹³</td>
</tr>
<tr>
<td>Beam Power</td>
<td>340 kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV program</td>
<td>170 kW</td>
</tr>
</tbody>
</table>

**Main Injector/Recycler**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Kinetic Energy (maximum)</td>
<td>60/120 GeV</td>
</tr>
<tr>
<td>Cycle time</td>
<td>0.6/1.2 sec</td>
</tr>
<tr>
<td>Particles per cycle</td>
<td>1.5×10¹⁴</td>
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<tr>
<td>Beam Power at 120 GeV</td>
<td>2400 kW</td>
</tr>
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R&D Program

- The goal is to mitigate risk: technical/cost/(schedule)

**Technical Risks**
- Front End (PXIE)
- H- injection system
  - Booster in Stage 1, 2; Recycler in Stage 3
- High Intensity Recycler/Main Injector operations
- High Power targets

**Cost Risks**
- Superconducting rf
  - Cavities, cryomodules, rf sources – CW to long-pulse
  - Q0 is a primary cost driver in CW sections

- Nearly all elements are in play at PIP-II

⇒ *Goal is to be prepared for a construction start in 2018*
R&D Hardware Status

- PXIE
  - Ion source operational and characterized (LBNL→FNAL)
  - LEBT emittance scanner procurement initiated (SNS)
  - LEBT solenoids delivered (FNAL)
  - RFQ design complete; fabrication initiated (LBNL)
  - HWR cavity design complete and procurements initiated; CM design in process (ANL)
  - Nine qualified SSR1 cavities now in hand; CM design in process (FNAL)
  - Chopper proof-of-principle prototypes and driver development (FNAL)
  - Shielded enclosure under construction at CMTF

- SRF
  - Major progress on HWR, SSR1, 650 MHz ellipticals, and high Q0
Project X Injection Experiment PXIE

- PXIE is the centerpiece of the PX R&D program
  - Integrated systems test for front end components
    - Validate concept for Project X front end, thereby minimizing primary technical risk element within the Reference Design
    - Operate at full Project X design parameters

- Systems test goals
  - 1 mA average current with 80% chopping of beam delivered from RFQ
  - Efficient acceleration with minimal emittance dilution through ~30 MeV

- Utilizes components constructed to PX specifications wherever possible
  - Opportunity to re-utilize selected pieces of PXIE in Stage 1

- Collaboration between Fermilab, ANL, LBNL, SNS, India

- DOE Review of PXIE Program (January 2013)
  - “PXIE is a portion of a comprehensive Project X R&D program and...within the broader Project X R&D has the correct emphasis... PXIE allows FNAL to gain experience with an operational SRF hadron accelerator, an important step that will not occur any other way.”

## SRF Development Status

<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>
<td>0.11</td>
<td>ANL</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>not started</td>
<td>8</td>
<td>all parts</td>
<td>not started</td>
<td>not started</td>
<td>yes</td>
<td>WIP</td>
<td>not started</td>
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<td></td>
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<tr>
<td>Single Spoke Resonator 1 (SSR1)</td>
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<td>8</td>
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<td>Single Spoke Resonator 2 (SSR2)</td>
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<td>10</td>
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<td>Low Energy 650 (LE 650)</td>
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<td>5-cell CW</td>
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<tr>
<td>Pulsed Energy 1300 (ILC)</td>
<td>1300 MHz</td>
<td>9-cell pulsed</td>
<td>1.0</td>
<td>DESY, KEK</td>
<td>yes</td>
<td>yes</td>
<td>30</td>
<td>53</td>
<td>43</td>
<td>80</td>
<td>70</td>
<td>43</td>
<td>21</td>
<td>yes</td>
<td>5</td>
<td>2</td>
<td>90</td>
</tr>
</tbody>
</table>
SSR1 Cavity Performance

- 120-150 micron BCP and HPR at ANL/FNAL processing facility then 120 C bake
- Low FE depends on optimized nozzle design for effective HPR of surface
- Two previous SSR1 spoke resonators performed very well in bare cavity tests
- Above are the tests of 9 cavities from U.S. Vendor (Roark) production of 10 cavities
- Performance at 2 K is above requirements for Project X in both $Q_0$ and gradient
- Revised design of helium vessel and tuner are complete
- The first new SSR1 cavity is dressed.
- Measured $df/dP = \sim 10$ Hz/Torr
Linac Beam Dynamics

rms transverse beam envelopes (top), rms bunch length (bottom)

1 GeV
The LBNE target needs to accept 1.2 MW beam power

- Development proceeding in the following areas:

<table>
<thead>
<tr>
<th>System</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Beam Window</td>
<td>Active cooling @2.3 MW; 1.2?</td>
</tr>
<tr>
<td>Target</td>
<td>Higher stress</td>
</tr>
<tr>
<td>Horns</td>
<td>Higher heat load and stress</td>
</tr>
<tr>
<td>Hadron Monitor</td>
<td>Radiation hardening, active cooling</td>
</tr>
<tr>
<td>Remote Handling</td>
<td>Additional short term storage facilities</td>
</tr>
<tr>
<td>Cooling Systems</td>
<td>Expanded capacity</td>
</tr>
<tr>
<td>Target Hall Shielding</td>
<td>0.25 m additional concrete shielding (top)</td>
</tr>
</tbody>
</table>
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 μsec) 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)

100 ns, 10 mA

6 ns

1 μs

67 ms

Collaboration

- Organized as a “national project with international participation”
  - Fermilab as lead laboratory

- Collaboration MOUs for the RD&D phase:

<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>
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<td>Cornell</td>
<td>UTenn*</td>
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<td>Fermilab</td>
<td>TJNAF</td>
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<td>IUAC/Delhi</td>
<td>RRCAT/Indore</td>
</tr>
<tr>
<td>VECC/Kolkata</td>
<td></td>
</tr>
</tbody>
</table>

- *Recent additions bringing capabilities needed for experimental program development, in particular neutron targets and materials applications

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