PIPll-Machine Protection System

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Outline

• What is PIP-II
• Technical Machine Description
  ▪ Technology Layout
  ▪ PXIE Components
  ▪ MPS Design Goals
  ▪ MPS Technical Challenges
• Required R&D
• Summary
The Proton Improvement Plan (PIP) is an ongoing project to modernize and improve the proton source’s capability for the already-approved user program.

- PIP is underway starting FY11 and should finish this decade.
- Many of the PIP upgrades are prerequisites for PIP-II.
Motivation/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!
Design Criteria

Support long 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, 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
  - At an affordable cost to DOE
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
  ▪ Building on significant existing infrastructure
  ▪ Capitalizing on major investment in superconducting RF technologies
  ▪ Eliminating 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
# 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 (extracted)</td>
<td>6.4×10^{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>
</tr>
<tr>
<td>Main Injector Protons per Pulse (extracted)</td>
<td>7.5×10^{13}</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 120 GeV</td>
<td>1.2 sec</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 80 GeV</td>
<td>0.8 sec</td>
</tr>
<tr>
<td>LBNE Beam Power @ 80-120 GeV</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>LBNE Upgrade Potential @ 60-120 GeV</td>
<td>&gt;2 MW</td>
</tr>
</tbody>
</table>
Siting History – 2013 Version

[Map diagram showing various stages and components of a site, including Muon Hall, Wilson Hall, Linac, Tevatron, and different energy levels such as 0-1 GeV, 1-3 GeV, and 3-8 GeV Pulsed Linac. Legend includes stages and existing beamline enclosures.]
Site Layout (provisional)
### Linac Technology Map

<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 (β_{opt}=0.11)</td>
<td>162.5</td>
<td>2.1-11</td>
<td>8/8/1</td>
<td>HWR, solenoid</td>
</tr>
<tr>
<td>SSR1 (β_{opt}=0.22)</td>
<td>325</td>
<td>11-38</td>
<td>16/8/2</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR2 (β_{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 (β_{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 (β_{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>
Warm Front End Function

- **PIP-II**: 800 MeV SRF linac *operated* at low duty factor but *designed* and *constructed* for CW operation

- Hence, the warm front end:
  - Provides $\text{H}^-$ beam to the first superconducting module
    - Ion Source ($30 \text{ keV, DC}$) $\rightarrow$ LEBT (*commissioning with pulsed beam, machine protection system*) $\rightarrow$ RFQ ($2.1 \text{ MeV, } 162.5 \text{ MHz}$) $\rightarrow$ MEBT ($2 \text{ mA average current, bunch pattern selection}$)
    - Beam must be formatted for injection into the Booster
      - *Pulse length: 0.6 ms @ 15 Hz*
      - *Achieved by a combination of the LEBT and MEBT chopping systems*
  - Operates CW
    - i.e. no change with respect to Project X designed operation
Performance Requirements

• Beam requirements
  ▪ Output energy: 2.1 MeV (±1%)
  ▪ Output beam current: 2 mA
  ▪ Must be capable of:
    ❖ Create the appropriate bunch structure for Booster injection
    ❖ Bunch-by-bunch selection for future upgrades
      ❖ i.e. Project X requirement

• Losses/vacuum management
  ▪ Extinction of removed bunches in MEBT: < 10^{-4}
  ▪ Beam loss (un-removed bunches) in MEBT: < 5%
  ▪ Pressure upstream of the HWR: < 10^{-9} torr
Ion Source

- DC H⁻ ion source
  - Up to 10 mA at 30 keV
    - 5 mA nominal
  - < 0.2 mm·mrad, rms, normalized
  - ≤ 4×10⁻³ torr l s⁻¹ gas load to LEBT

- Acquired ion source from D-Pace, Inc.
  - H⁻, up to 15 mA at 30 keV
  - Designed for DC operation
  - Meets PIP-II beam requirements
    - Measured at TRIUMF and LBNL
    - Downstream chopping system will deliver the proper beam structure to SRF and beyond
  - Shortcoming:
    - Short lifetime (~300 hours)
LEBT Design Concept - Motivation

• Requirements
  - < 0.25 mm·mrad, rms, normalized
  - < 10% un-controlled losses
  - Max gas load to RFQ: $10^{-4}$ torr l s$^{-1}$

• Neutralization
  - Commissioning in pulse mode i.e. space-charge dominated transport
    - Transition from space-charge dominated transport to un-neutralized transport (baseline operation DC) may cause difficulties
  - Possibility of pre-chopping the beam
    - Matching to RFQ Twiss parameters difficulties during transition

• Space
  - Allows installation of diagnostics between the last solenoid and the RFQ entrance
  - Allows mounting a dedicated absorber (between the 2 solenoids)
  - Helps vacuum management
LEBT Design Concept

- Three (3) solenoid transport scheme with 2 sections addresses neutralization issues
  - Neutralized/compensated transport
    - From ion source to 2nd solenoid
  - Space-charge dominated transport
    - Last ~1 m before RFQ
  - Accommodates 2 ion sources to ensure high availability
    - Switching magnet (slow) between 1st and 2nd solenoid
      - Also part of the Personnel Safety system
  - Note: Lattice compatible with neutralized transport over the entire length of the LEBT
RFQ Design (LBNL)

- 4-vane CW RFQ
  - Frequency: 162.5 MHz
  - Input energy: 30 keV
    - Reduces length of RFQ adiabatic buncher
  - Output energy: 2.1 MeV
    - Below neutron production threshold for most materials
    - Sufficiently large to mitigate space-charge effects in MEBT
  - RF + Beam power: 100 kW
  - Power loss density at vanes: < 8 Watts/cm² CW
    - Thermal management

- Four modules, joined with butt joints
- Detailed simulations of the entire RFQ assembly (3D) in MicroWave Studio
  - E.g.: Vane modulation taken into account during RF design
MEBT Scheme

- Prepare bunch structure for further acceleration
  - $>10^{-4}$ extinction
  - $<5\%$ beam loss (*passing bunches*)

- Vacuum management near SRF

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**Diagram:***

- **Matching from RFQ to MEBT**
- **Measure parameters of the beam coming out of RFQ**
- **Sections with buncher cavities**
- **Measure parameters of the beam coming into SRF linac**
- **Chopping system**
- **Differential pumping and scraping**
MEBT Chopping System

- Largest risk item (*for the whole warm front-end*)
  - Traveling-wave, broadband chopper
    - Any bunch of the 162.5 MHz CW train can either pass or be removed
    - 2 kickers working in-sync: equal and opposite polarity voltage to the two opposing electrodes of each kicker assembly
  - Absorber
    - CW operation requires most of the beam to be deflected onto the absorber
      - *Up to 21 kW focused to a 2 mm radius (rms)*

![Diagram showing two kickers separated by 180° and differential pumping](image)

XMAC, February 2014; Arden Warner
• MPS goals and scope:
  - Protect the accelerator from beam induced damage
    - Safely switch off or reduce beam intensity in case of failures
    - Monitor/control beam intensity
    - Fail Safe design where possible
    - Provide highest machine availability possible
  - Provide overview of machine status
    - Subsystems status (ok/not-ok)
    - Manage and display alarms
    - Performance/fault analysis (i.e. data logging etc.)
    - Determine the operational readiness of the machine
Three functional layers to system:
1. Signal providers
2. Main logic layer (permit system) includes slot ‘0’ interface
3. Actuators

MPS comprises a logic system that takes in low level signals from various beam instruments and interlock systems and drives permits to low energy beam enable devices.
MPS needs to integrate with several subsystems with different time scales of interest:

- Toroids (nsec)
- BLMs (µsec)
- BPMs
- RF interlocks etc. (nsec)
- LLRF (nsec)
- Movable diagnostics (Scrapers, OTR, YAG..) (slow)
- Pneumatics (air, water, gas) dumps
- Beam dumps and kickers
- Rad Safety

Basic instruments fundamental to MPS (i.e. transmission loss etc.) as dedicated systems in addition to being machine tune-up devices

- Magnets (msec)
- Timing
- LCW
- Vacuum (msec)
Operational Modes and Beam Modes

- **Operational Mode:**
  - Defines the beam path through the accelerator
  - A valid beam path through the machine is usually defined by a unique set of critical components (dipole magnets, kickers, beam stops, etc.).
  - The MPS monitors the setting of these components to mask alarms that are outside the chosen beam path.

- **Beam Mode:**
  - Defines range of beam intensity and duty cycle
  - Beam modes define the full range of possible operational beam chopping/intensity scenarios including cycles without beam (no beam) to the MPS.
  - Alarm thresholds may be changed or alarms masked for different beam modes to allow for diagnostic operations.
System Models

Block diagram of SNS MPS system.

- SNS has 1GeV H- SC linac with same average current specified by PXIE. They have a working MPS for their facility. Plan to follow that implementation where applicable
  - Response time < 10 microseconds
- We have experience with MPS system design for SC linac at NML (electron linac).
  - Similar hardware infrastructure and controls interfaces where possible

Block diagram of ASTA MPS system.
Technical Concerns

- **CW Beam:**
  - Losses develop continuously; no large, peak beam intensities to trigger loss monitors.
  - MPS must allow pulsed, diagnostic beam operation when CW losses inhibit normal operation.

- **MEBT Chopper:**
  - Kicks out individual bunches to reduce average current of beam from 5mA to 1mA. Diagnostics needed to insure SRF is not overloaded.

- **Low Energy SRF Transition:**
  - Most loss monitors are ineffective at low energies.
  - Reduced penetration depth of beam energy impacting niobium.
  - Need a way to detect losses before cavities quench.
PXIE Study Plans

- Warm section:
  - Develop understanding of acceptable loss rates in
    - LEBT
    - RFQ
    - MEBT
  - Develop strategy to monitor chopped beam from the MEBT
- Low energy cold section:
  - Detection of beam loss in cryomodules
    - Develop understanding of low energy beam loss mechanisms and their instruments
    - Develop/select sensor technology to directly measure low energy beam loss
    - Understand impact of dark current effects on MPS instruments
MPS Controls Interface and Integration for PXIE

MPS system interfaces. Black arrows illustrate incoming information and red arrows illustrate outgoing control.

Some significant infrastructure and tools already developed for ASTA MPS at NML

MPS Controls requirements can be resolved by the tiers inherent in the control system. These include the (a) top tier applications, (b) the middle tier services and (3) the lowest tier front-ends.

- Applications(1)
  - Configuration control, alarm viewers, post-mortem analyzer etc.
- Services(2)
  - Data loggers, dedicated DAQ, Databases etc.
- Front-end Servers(3)
  - Slot-zero controllers – time-stamps, circular buffers, read-backs, settings etc.
Damage Potential and Timing

- Devices upstream of MEBT chopper exposed to over 10KW of beam power in early stages of Project X development.

- MPS Response time depends primarily on Kicker shut-off time (~100 ns), time of flight (~3µs) and FPGA processing time (1-2 nsec).

- Full scale PIP-II introduces higher damage potentials and using SNS as an example, the design goal for MPS response time would be less than 10 µsec.
Preliminary sCVD Detector Test

CVD diamonds are being investigated because of their sensitivity to single particles, nanosecond time response and the excellent radiation resistivity which makes them perfectly suitable for applications in high-radiation environments. In addition operation in vacuum at both room temperature and 1.8 Kelvin has been demonstrated.

Interest for PIXIE/PIP-II:

1. Develop an effective loss monitor to detect low energy proton losses (2.1 MeV) as a diagnostic to protect the PIXIE cryogenic system at injection.
2. Provide a detector capable of single particle detection as an effective diagnostic for beam extinction measurements in the accelerator.

Characteristics of crystal that were tested:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate material</td>
<td>sCVD diamond</td>
</tr>
<tr>
<td>Substrate size</td>
<td>4.6 mm x 4.6 mm x 0.5 mm</td>
</tr>
<tr>
<td>Electrode size</td>
<td>4 mm x 4 mm</td>
</tr>
<tr>
<td>Electrode material</td>
<td>Gold</td>
</tr>
<tr>
<td>Detector capacitance</td>
<td>3 pF</td>
</tr>
<tr>
<td>Bias Voltage</td>
<td>500 Volts</td>
</tr>
</tbody>
</table>
CVD General Principle and Characteristics

### Counting Mode

- \( E \)
- \( \nu \)
- \( MIP \)
- \( L_e = \frac{Q \nu}{d} \)
- \( Q/2 \)
- \( L_e = \frac{d}{\nu} \)

### Calorimetric Mode

- \( E \)
- \( \nu \)
- \( \alpha \)
- \( L_e = \frac{Q/2 \nu}{d} \)
- \( Q/2 \)

### Table: Properties of Diamond and Silicon

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
<th>Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>5.5</td>
<td>1.12</td>
<td>Low leakage</td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>( 10^7 )</td>
<td>( 3 \cdot 10^5 )</td>
<td></td>
</tr>
<tr>
<td>Intrinsic resistivity @ R.T. [( \Omega \text{ cm} )]</td>
<td>( &gt; 10^{11} )</td>
<td>( 2.3 \cdot 10^5 )</td>
<td></td>
</tr>
<tr>
<td>Intrinsic carrier density [cm(^{-3})]</td>
<td>( &lt; 10^3 )</td>
<td>( 1.5 \cdot 10^{10} )</td>
<td></td>
</tr>
<tr>
<td>Electron mobility [cm(^2)/Vs]</td>
<td>1900</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td>Hole mobility [cm(^2)/Vs]</td>
<td>2300</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Saturation velocity [cm/s]</td>
<td>( e^-: 0.9 \cdot 10^7 )</td>
<td>( 0.82 \cdot 10^7 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>holes: ( 1.4 \cdot 10^7 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density [g/cm(^3)]</td>
<td>3.52</td>
<td>2.33</td>
<td>Low capacitance</td>
</tr>
<tr>
<td>Atomic number - Z</td>
<td>6</td>
<td>14</td>
<td>Radiation hard</td>
</tr>
<tr>
<td>Dielectric constant - ( \varepsilon )</td>
<td>5.7</td>
<td>11.9</td>
<td>Heat spreader</td>
</tr>
<tr>
<td>Displacement energy [eV/atom]</td>
<td>43</td>
<td>13-20</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity [W/m.K]</td>
<td>( \approx 2000 )</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>3.61</td>
<td></td>
</tr>
<tr>
<td>Interaction length [cm]</td>
<td>12.2</td>
<td>9.36</td>
<td>Low signal, Low Noise</td>
</tr>
<tr>
<td>Spec. Ionization Loss [MeV/cm]</td>
<td>24.5</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>Aver. Signal Created / 100 ( \mu \text{m} ) [( e_0 )]</td>
<td>6.07</td>
<td>3.21</td>
<td></td>
</tr>
<tr>
<td>Aver. Signal Created / 0.1 X0 [( e_0 )]</td>
<td>3602</td>
<td>8892</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4401</td>
<td>8323</td>
<td></td>
</tr>
</tbody>
</table>
Detector located inside the vacuum with the crystal angled toward the dump. 160 µs beam pulses, 200 µA – 3 mA, 2.5 MeV and 500 volt bias on the detector. Window in case exposes crystal to the beam. The ideal crystal should be thin (100 micron limit possible dependent on area). Beam Toroid signal

Single particle detection of scattered electrons and secondary protons from dump

Fast Charge Amplifier: 100 MHz, 4 mV/fC

Reflections due to cable capacitance is understood and correctable

Zoom
Summary

- MPS is an important piece of PIP-II design.
- Have a close model for a working system at SNS (180MeV to 1GeV).
- Have experience with MPS design at NML (electron accelerator).
- Need to establish interfaces between MPS, instrumentation, and control systems.
- Need to examine low energy issues (2.1MeV to 180MeV) and higher energy issues (1GeV to 8GeV).
- PXIE will act as a platform for testing low energy MPS issues.