Status of FNAL and the PIP-II project

Lia Merminga
3rd J-PARC Symposium
September 23-26, 2019
Tsukuba, Japan

In partnership with:
India/DAE
Italy/INFN
UK/STFC
France/CEA/Irfu, CNRS/IN2P3
Outline

- Fermilab at a Glance
- LBNF/DUNE/PIP-II: Context and Science Objectives
- PIP-II Project Overview
- International Partnerships
- Summary
As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.
Fermilab accelerator complex:
operating at >750 kW now

Fermilab operates the largest US particle accelerator complex, producing the world’s most powerful neutrino beams, along with muon and test beams.

NuMI neutrino beam
NOvA, MINERvA, MINOS+

DUNE neutrino beam

Booster neutrino beam
SBN program

Proton Beam
Neutrino Beam
Muon Beam
Diverse Particle Physics Program with a Flagship

- Fermilab performs experiments around the globe
- Experiments are interrelated and address the main questions of the field
Neutrinos to Minnesota…generation 2 → 3 (DUNE)

NOvA…our present flagship neutrino experiment

Why Underground?

- The target location for LBNE is at the 4850' level of the Homestake mine
- Same location as the cavern that housed the Davis experiment that discovered the solar neutrino problem
- The rock between the cavern and the surface reduces the background from cosmic rays to be 3 million times smaller than at the surface
- Depth allows us to look for neutrinos and other phenomena not associated with the beam (more later)
Accelerator operations…excellent

- World record performance in proton beam power for neutrinos achieved – 754 kW
  - Record was broken three weeks in a row in January.
- New targets and booster improvements needed to go higher and ensure readiness for PIP-II
The U.S. is well positioned to host a world leading neutrino physics program. Its centerpiece would be a next generation long-baseline neutrino facility (LBNF).

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest priority large project in its timeframe.

LBNF would combine a high-intensity neutrino beam and a large-volume precision detector sited underground a long distance away to make accurate measurements of the oscillated neutrino properties, … search for proton decay and neutrinos from supernova bursts. A powerful, wideband neutrino beam would be realized with Fermilab’s PIP-II upgrade project, which provides very high intensities in the Fermilab accelerator complex.

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.
**PIP-II / LBNF / DUNE**

- **Powerful proton beams (****PIP-II**)**
  - 1.2 MW upgradable to multi-MW (2.4 MW Phase 2) to enable world’s most intense neutrino beam with **wideband** capability

- **Dual-site detector facilities (****LBNF**)**
  - Deep underground cavern (1.5 km) of 70kt liquid argon fiducial volume
  - A long baseline (1300 km)

- **Deep Underground Neutrino Experiment (****DUNE**)**
  - Liquid Argon – the next-generation neutrino detector
DUNE – A Global Collaboration

1075 collaborators from 184 institutions in 31 countries + CERN
Science Objectives

Neutrinos – most ubiquitous matter particle in the universe, yet the least understood. Opportunities for game changing physics discoveries:

• **Origin of matter**
  Investigate leptonic CP violation, mass hierarchy, and precision oscillation physics
  ➢ Discover what happened after the big bang: Are neutrinos the reason the universe is made of matter?

• **Neutron Star and Black hole formation**
  Ability to observe supernovae events
  ➢ Use neutrinos to look into the cosmos and watch the formation of neutron stars and black holes in real time

• **Unification of forces**
  Investigate nucleon decay targeting SUSY-favored modes
  ➢ Move closer to realizing Einstein’s dream of a unified theory of matter and energy
PIP-II: a new accelerator to generate neutrinos
**PIP-II** will enable the world’s most intense beam of neutrinos to the international LBNF/DUNE project, and a broad physics research program, powering new discoveries for decades to come.

**PIP-II linac will provide:**

**Beam Power**
- Meeting the needs for the start of DUNE (1.2 MW proton beam)
- Upgradeable to multi-MW capability

**Flexibility**
- Compatible with CW-operations which greatly increases the linac output
- Customized beams for specific science needs
- High-power beam to multiple users simultaneously

**Reliability**
- Fully modernizing the front-end of the Fermilab accelerator complex

*Building the world’s most powerful neutrino beam cost-effectively*
**PIP-II Scope Overview**

The PIP-II scope enables the accelerator complex to reach 1.2 MW proton beam on LBNF target.

**800 MeV H⁻ linac**
- Warm Front End
- SRF section

**Linac-to-Booster transfer line**
- 3-way beam split

**Upgraded Booster**
- 20 Hz, 800 MeV injection
- New injection area

**Upgraded Recycler & Main Injector**
- RF in both rings

**Conventional facilities**
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection
PIP-II Site - Aerial View
The PIP-II 800 MeV Linac

Room Temperature Technology

Superconducting Radio Frequency Technology

PIP-II Injector Test Facility (PIP2IT)

**Room Temperature Technology**
- **IS**
- **LEBT**
- **RFQ**
- **MEBT**

**Superconducting Radio Frequency Technology**
- **HWR** $\beta=0.11$
- **SSR1** $\beta=0.22$
- **SSR2** $\beta=0.47$
- **LB650** $\beta=0.61$
- **HB650** $\beta=0.92$

**PIP-II Injector Test Facility (PIP2IT)**

**PIP-II Injector Test Facility retires a significant number of technical risks – complete in FY20**
Beam through full length MEBT
“CDR parameters” for 24 hours
5 mA × 0.55 ms × 20 Hz × 2.1 MeV
PIP-II is the first U.S. accelerator project to be built with major international contributions
Half-Wave Resonator Cryomodule Fabrication by Argonne National Laboratory

HWR cryomodule arrived at Fermilab 16-Aug-2019
HWR will be transported to PIP2IT end of October for RF and beam tests
String assembly complete - includes one cavity from DAE. Transport to PIP2IT in November 2019

9/27/2019
SSR1 – Indian Cavity Performance

STC* test with low power coupler

High Q at high gradient and field emission free
BARC cavity has the best cavity Q performance up to date

Data by A. Sukhanov

*STC= Spoke Test Cryostat
SSR2

• Cavity RF and mechanical design complete
  – Nb ordered
• Prototype cavities expected in FY20

LB650

• Cavity RF and mechanical design complete
• Two prototype cavities will be delivered in 2019

HB650

• First HB650 jacketed cavity
• HB650 high Q R&D completed, design validation started
• Cryomodule design is in progress
R&D Challenges in SRF

- High $Q_0$ and High Gradient $\Rightarrow 3 \times 10^{10}$ and 20 MV/m
  - Nitrogen-doping evolved from discovery to proven technology for LCLS-II
  - Tests at 650 MHz show that an additional doping optimization is desirable (relative to doping developed for 1.3 GHz)

- Suppression of Microphonics
  - Maximum detuning < 20 Hz ($\sigma<3$ Hz)
    - Passive means
      - Cryomodule design
    - Active means
      - Adaptive Detuning Control Algorithm
Linac Installation & Commissioning: PIP2IT

- Nearly full scale PIP-II 2.1 MeV normal conducting front-end
- Support HWR and SSR1 CM commissioning with beam
- After FY20 will be repurposed to PIP-II CM test facility
Fermilab’s Path to 1.2 MW on LBNF Target

- Increase the number of protons per Booster pulse from 4.3e12 (present) to 6.5e12
- Increase of Booster rep. rate from 15 Hz to 20 Hz
- Reduce Main Injector cycle from 1.33 s to 1.2 s

Increases in Booster injection energy, pulse intensity and repetition rate require upgrades to Booster, Recycler Ring (RR), and Main Injector (MI).

Collaboration with J-PARC experts critical to successful upgrade of Fermilab synchrotrons
Accelerator Complex Upgrades

- Upgrades to Booster, Recycler, and Main Injector (MI) required to accommodate:
  - increased injection energy (400 MeV to 800 MeV)
  - increased intensity (4.3E12 to 6.5E12 Booster, 5E13 to 7.5E13 MI)
  - higher repetition rate (15 Hz to 20 Hz)

- Scope of Ring upgrades:
  - New Booster Injection girder
  - New 53 MHz Recycler cavities
  - Upgraded Main Injector RF Cavities
    - Two Power Amplifiers (PA) operation of MI RF cavity
  - New beam line from the superconducting Linac to the Booster, new beam absorber line and beam dump
PIP-II Groundbreaking – 15 March 2019
Conventional Facilities

Site Clearing Complete
Under special authorization prior to CD-2/3a granted by DOE

Cryogenics Plant Building
Design Complete; Ready for Procurement

Linac Complex
Conceptual Design update underway, scheduled for completion in November 2019. Will form the basis of final design
Schedule Overview

- **CD-1 Approval**
- **CD-2**
- **CD-3a**
- **CD-3**
- **HWR assembly**
- **Proto SSR1**
- **PIP2IT Program**
- **Cryoplant Final Design & Fabrication**
- **Cryoplant Building Construction**
- **SSR1 Production**
- **SSR2 Production**
- **LB650 Production**
- **HB650 Production**
- **Installation & Commissioning**
- **Linac Complex Civil Construction**

**FY27**
- Planned Project Complete (early CD-4)

**FY28**
- Proto SSR1

**FY29**
- HWR assembly

**FY30**
- Cryoplant Building Construction

**Tier 0 - CD-4**

**TPC $873M**

**Contingency 42%**
PIP-II

International Partnerships
PIP-II International Partnership Principles

- Pursue partnerships where broader interests are aligned, specifically technology (SRF) and science (DUNE)

- Bring international institutions in early as Partners
  - Share project planning, R&D to provide joint sense of ownership

- Integrate Partners in PIP-II project management principles

- Establish a multi-layered governance structure (INC, P2LDC, P2PEB*)

- Establish International Agreements

*International Neutrino Council; PIP-II Laboratory Directors Council; PIP-II Project Executive Board
**India, Department of Atomic Energy (DAE) (started 2009)**

BARC, RRCAT, VECC; also IUAC

- Substantial engineering/manufacturing experience
- Superconducting correction magnets for LHC
- Construction & operation of 2 GeV synch light source @ RRCAT

**Italy, INFN (started 2016)**

- Internationally recognized leader in superconducting RF technologies
- SRF cavity and cryomodule (CM) fabrication for XFEL
- SRF cavity fabrication for ESS

**UK, UKRI (started 2017)**

- Substantial engineering and manufacturing experience
- Construction and operation of domestic synchrotron light & neutron sources
- SRF cavity processing and testing for ESS

**France, CEA, CNRS/IN2P3 (started 2017)**

- Internationally recognized leader in large-scale CM assembly
- CM assembly for European XFEL and ESS
- SSR2 cavities and couplers for ESS

**PIP-II Project benefits from world-leading expertise, facilities. “Timing is perfect”**
### Major In-Kind Contribution Production Deliverables

<table>
<thead>
<tr>
<th>Subsystem (count)</th>
<th>Cavities</th>
<th>Cryomodules</th>
<th>RF Systems &amp; Cryoplant</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR (1)</td>
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<td>HB650 (4)</td>
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<tr>
<td>Cryoplant (1)</td>
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<td><img src="logo.png" alt="India" /></td>
<td><img src="logo.png" alt="UK" /></td>
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*International partnerships are essential for the success of the PIP-II Project*
Next Board meeting at IPNO, Orsay on October 11, 2019
Summary

- PIP-II is breaking new ground
  - First DOE accelerator to be built with significant international contributions
  - Highest energy CW SRF proton linac
- PIP-II is the “heart and soul” of Fermilab, and critical to the success of the international neutrino program
- Baseline review is scheduled Jan 2020
- Our world-leading international Partners enable DOE/Fermilab to build a highly capable machine at reduced cost to DOE
- We greatly appreciate the enduring support from DOE and international Partners, and their commitment to our joint success and furthering neutrino science
Thank you!
## PIP-II Project Key Performance Parameters

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Threshold KPP</th>
<th>Objective KPP</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Linac Beam Energy</td>
<td>Accelerate H- beam to 600 MeV</td>
<td>Accelerate H- beam to 700 MeV. Linac systems required to accelerate beam to 800 MeV installed and tested.</td>
</tr>
<tr>
<td>2</td>
<td>Linac Beam Intensity</td>
<td>H- beam delivered to beam absorber at the end of the linac</td>
<td>H- beam with an intensity of $1.3 \times 10^{12}$ particles per pulse at a 20 Hz repetition rate delivered to Beam Transfer Line beam absorber</td>
</tr>
<tr>
<td>3</td>
<td>Booster, Recycler, Main Injector Upgrades</td>
<td>Booster, Recycler, Main Injector upgrades required to support delivery of 1.2 MW onto the LBNF target are installed and tested without beam</td>
<td>Linac beam injected and circulated in Booster</td>
</tr>
</tbody>
</table>

### Design Parameters
- Beam energy: to 800 MeV
- Linac beam intensity: $6.7 \times 10^{12}$ particles per pulse at 20 Hz
- Proton beam power delivered on LBNF target: 1.2 MW
Warm Front End

- 15 mA, 30 kV ion source
- 2 m LEBT (‘slow’ chopper, dif. pumping, envelope match to RFQ)
- 2.1 MeV, 162.5 MHz RFQ
- 14 m MEBT (bunch-by-bunch chopper, shielding wall, envelope match)
- Successful integration of magnets from DAE/BARC.
LBNF: From Illinois to a mile underground in South Dakota

**Illinois:**
- World’s most powerful and advanced neutrino beam
- DUNE “near” detector

**South Dakota:**
- Conventional facilities
- Cryostats - Four massive membrane cryostats to hold liquid argon
- Cryogenic systems – LAr and Nitrogen
- DUNE “far” detectors - four liquid argon detector modules
SRF plan includes four prototype CMs to retire or mitigate major technical risks, including transportation.