Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science

PIP-II: Powering Discoveries in High Energy Physics

Lia Merminga

Fermilab

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

LLRF Workshop 2019

September 29 - October 3, 2019 Chicago, IL

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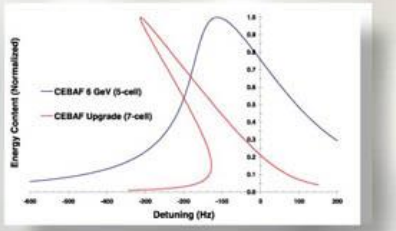
WORKSHOP ON LOW-LEVEL RF CONTROLS FOR SUPERCONDUCTING CAVITIES

Jefferson Lab
Newport News, Virginia, USA

April 25 - 27, 2001

http://www.jlab.org/LLRF
email: llrf@jlab.org

The Workshop will explore the present state and future directions of Low-Level RF (LLRF) control systems for superconducting cavities, investigate in-depth common design issues, such as algorithms and implementation, and attempt to initiate collaborative efforts among institutions.



Topics to be discussed include:

- Control of SRF Cavity Field and Resonance Frequency in the Presence of:
  - High Gradient
  - High or Moderate Q_L
  - Heavy or Negligible Beam Loading
  - Pulsed or CW (RF/Beam)
  - One Klystron/One Cavity or One Klystron/Multiple Cavities
  - Relativistic or Non-relativistic Particle Acceleration
- Analog vs. Digital Systems: Directions, Limitations
- Feedback and Feedforward Techniques
- Design and Development Tools
- Operability Issues

Specific applications of interest include CEBAF Upgrade, SNS/NSP (JAERI), RIA, TESLA, Energy Recovery Linacs (ERLs) and ERL-based FELs.

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Workshop Administrator: Sherry Thomas; Tel. (757) 269-7078; Fax. (757) 269-7658; email: llrf@jlab.org

Outline

- Fermilab at a Glance
- LBNF/DUNE/PIP-II: Context and Science Objectives
- PIP-II Project Overview
- International Partnerships
- Summary

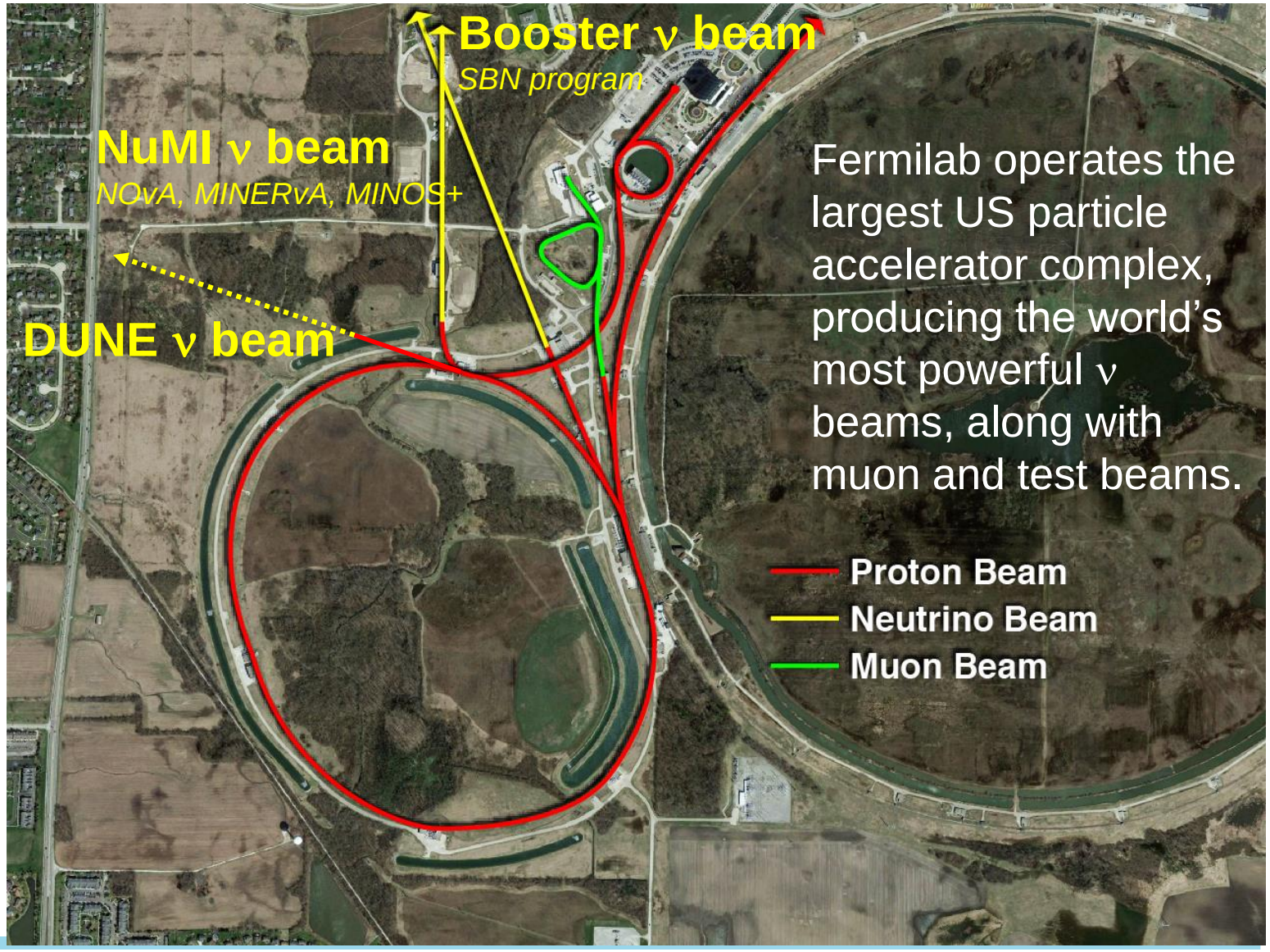
Fermilab at a Glance

- America's particle physics and accelerator laboratory

- ~1,800 staff at $550M/yr
- 6,800 acres of federal land
- 4,000 scientists from >50 countries use Fermilab facilities

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



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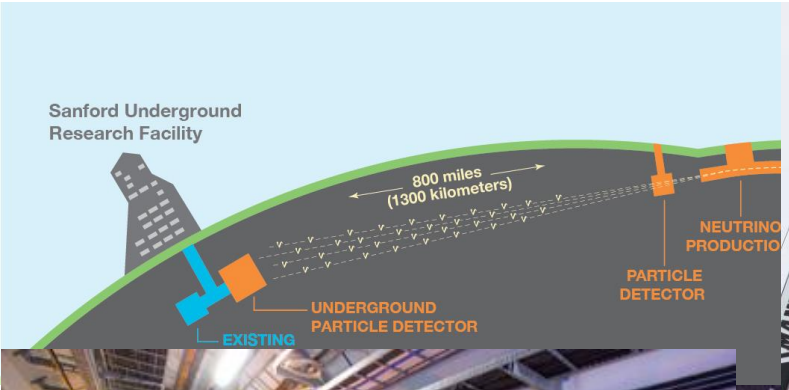
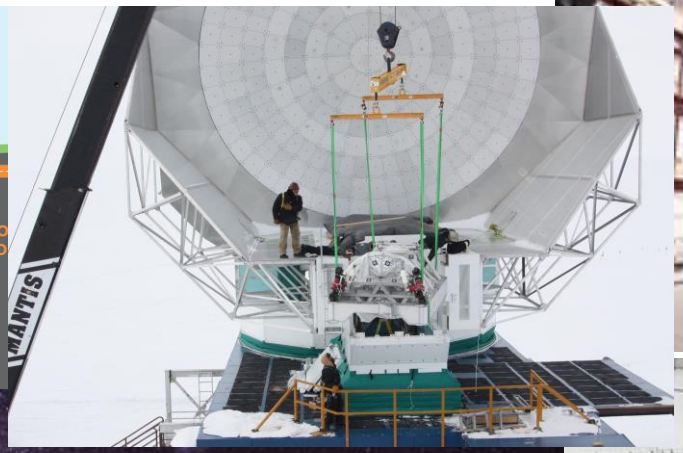
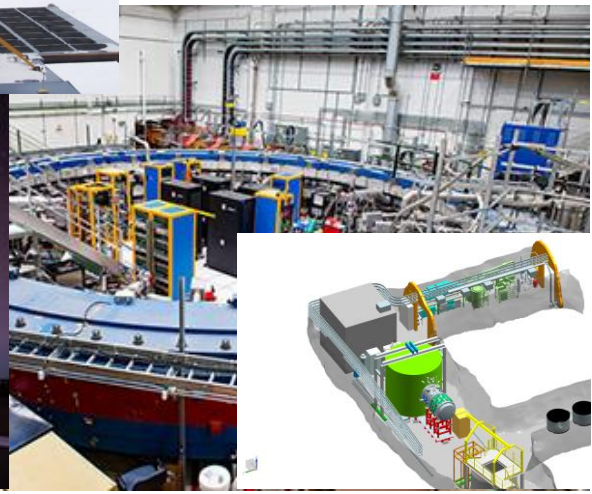
Diverse Particle Physics Program with a Flagship

- Fermilab performs experiments around the globe
- Experiments are interrelated and address the main questions of the field







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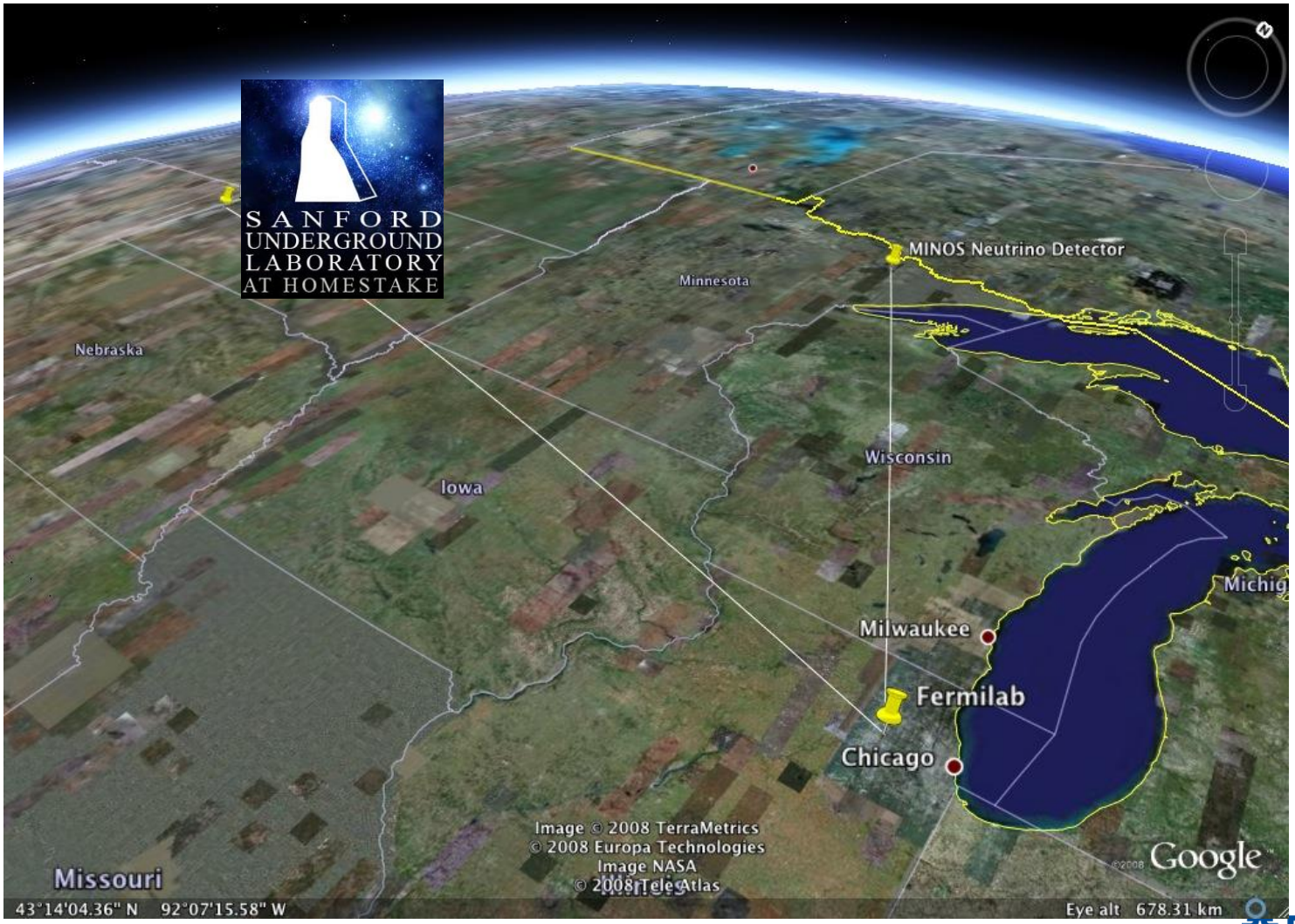
Neutrinos to Minnesota…generation 2 → 3 (DUNE)

NOvA…our present flagship neutrino experiment



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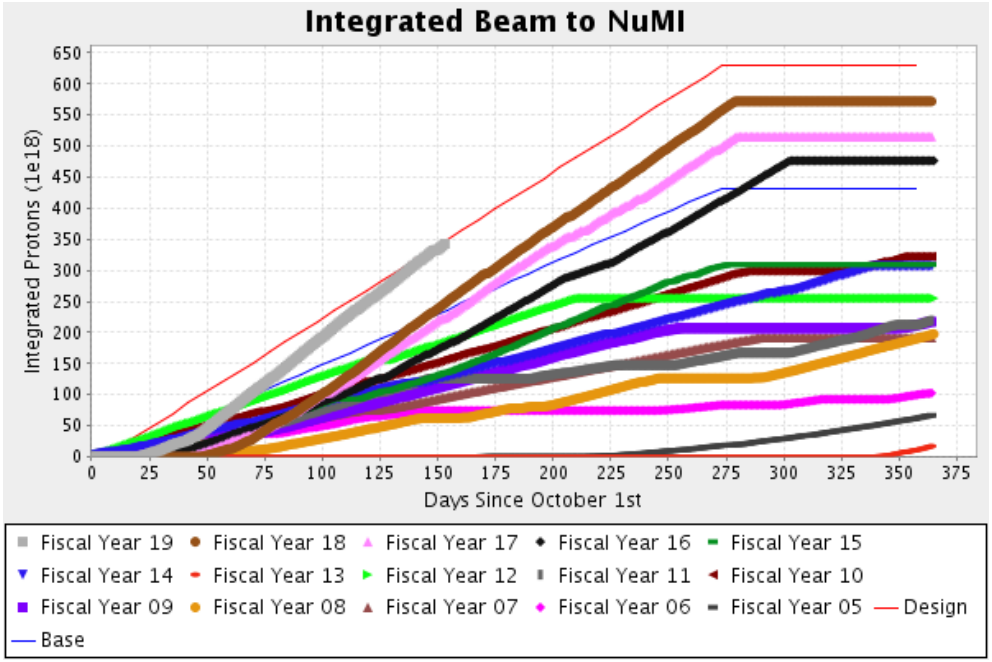
Accelerator operations….excellent

- **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



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2014 P5 Report

"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**)."

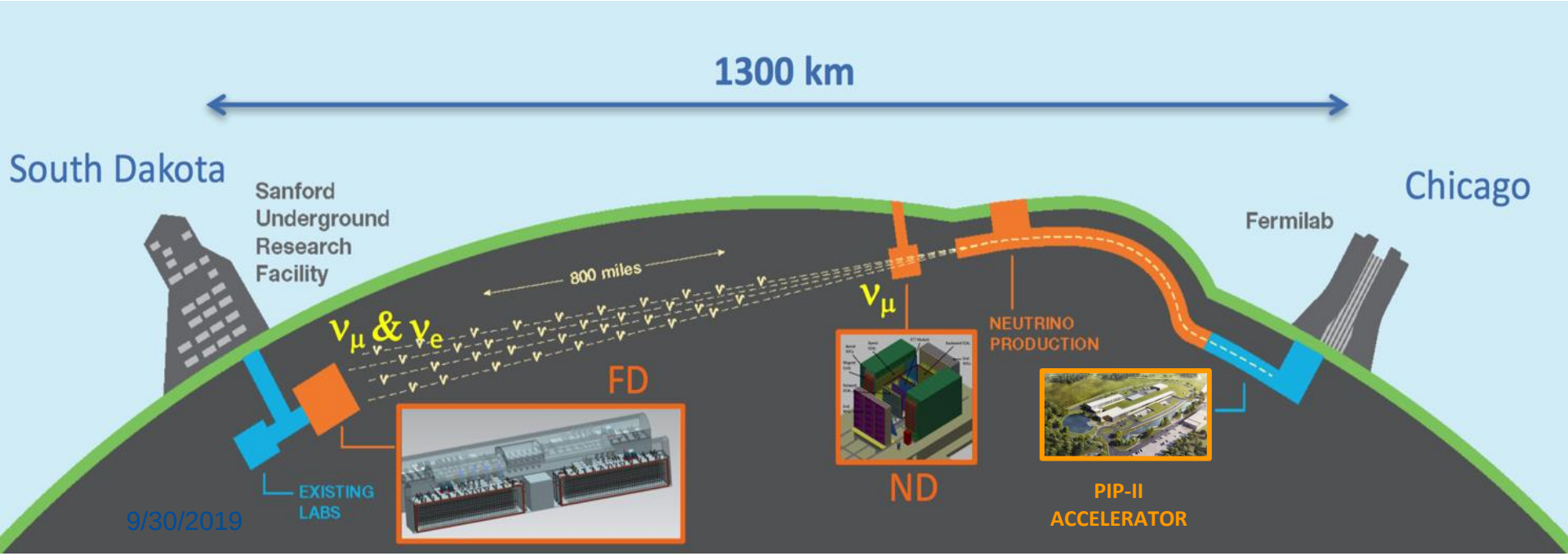
Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest priority large project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



– 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

P5 Report defines PIP-II Mission

***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

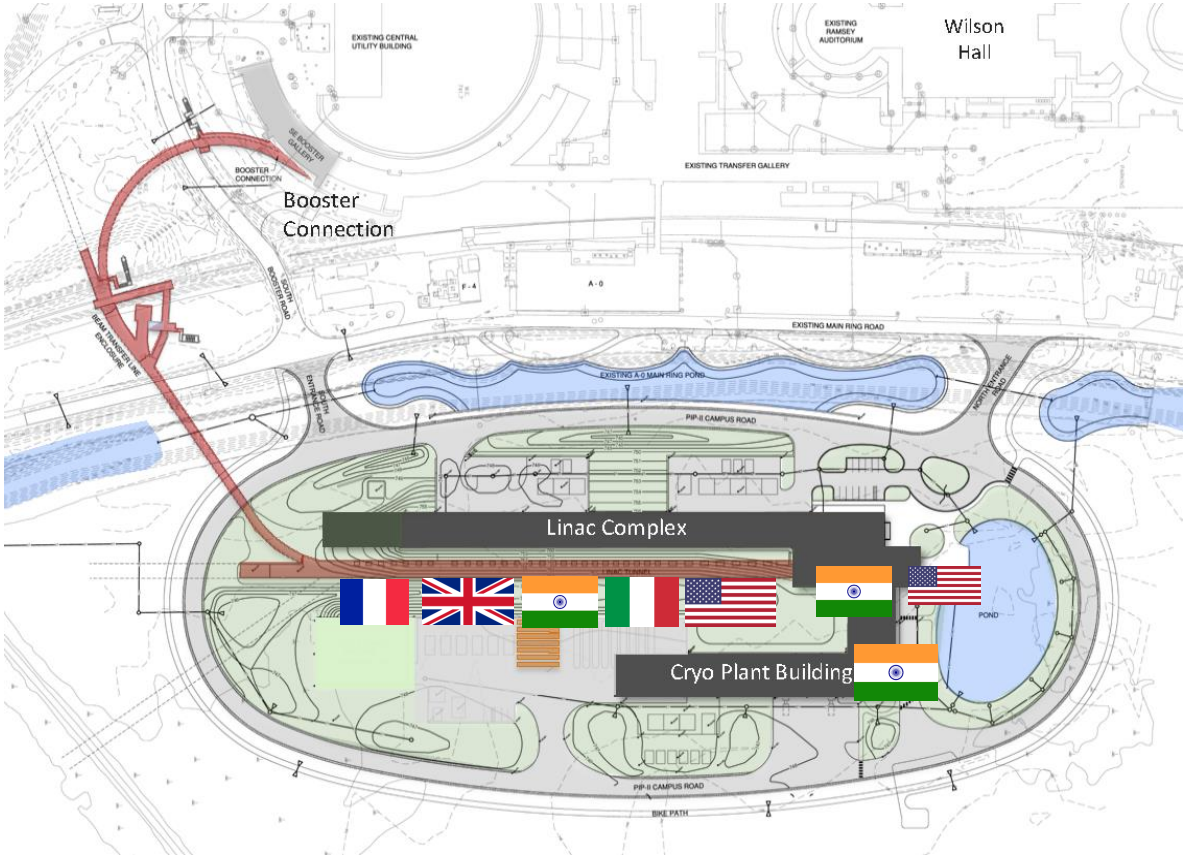
- Compatible with CW-operations which greatly increases the linac output
- Customized beams for specific science needs
- High-power beam to multiple users simultaneously

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



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

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

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PIP-II Site

PIP-II Site - Aerial View

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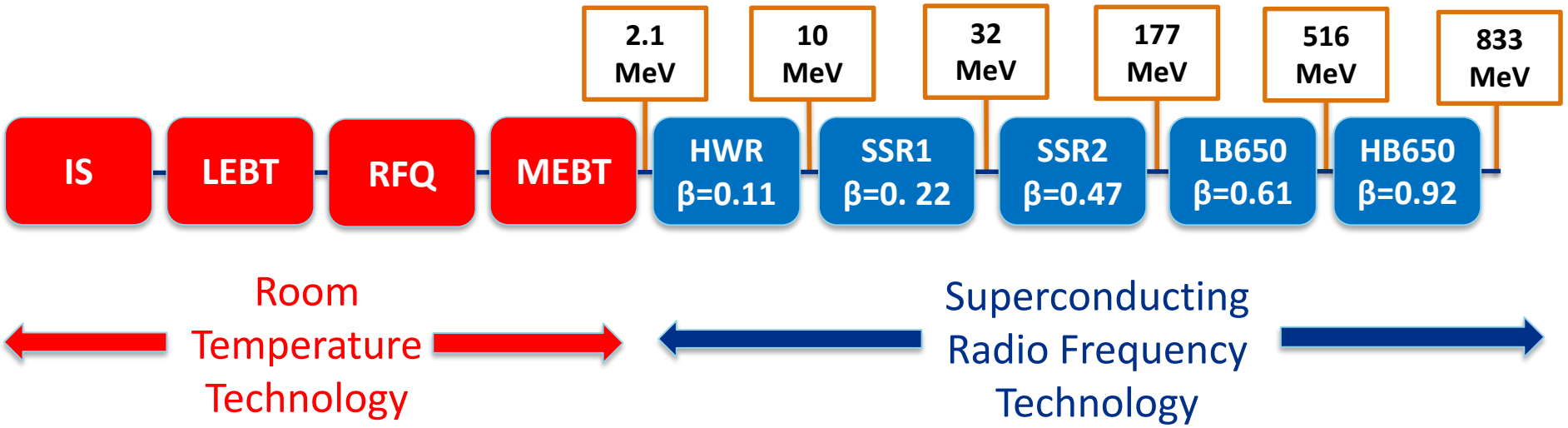
The PIP-II 800 MeV Linac

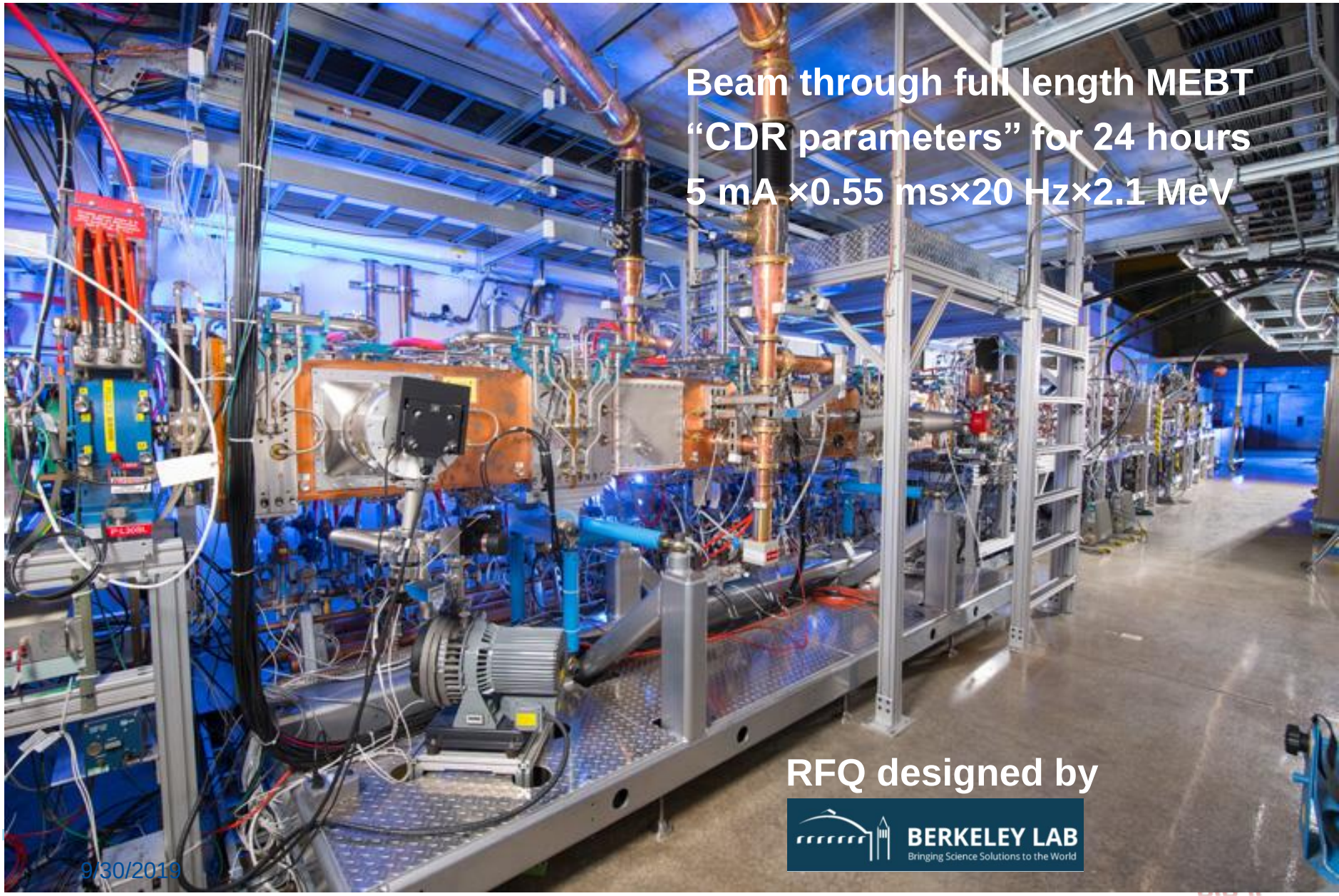


PIP-II Injector Test Facility (PIP2IT)

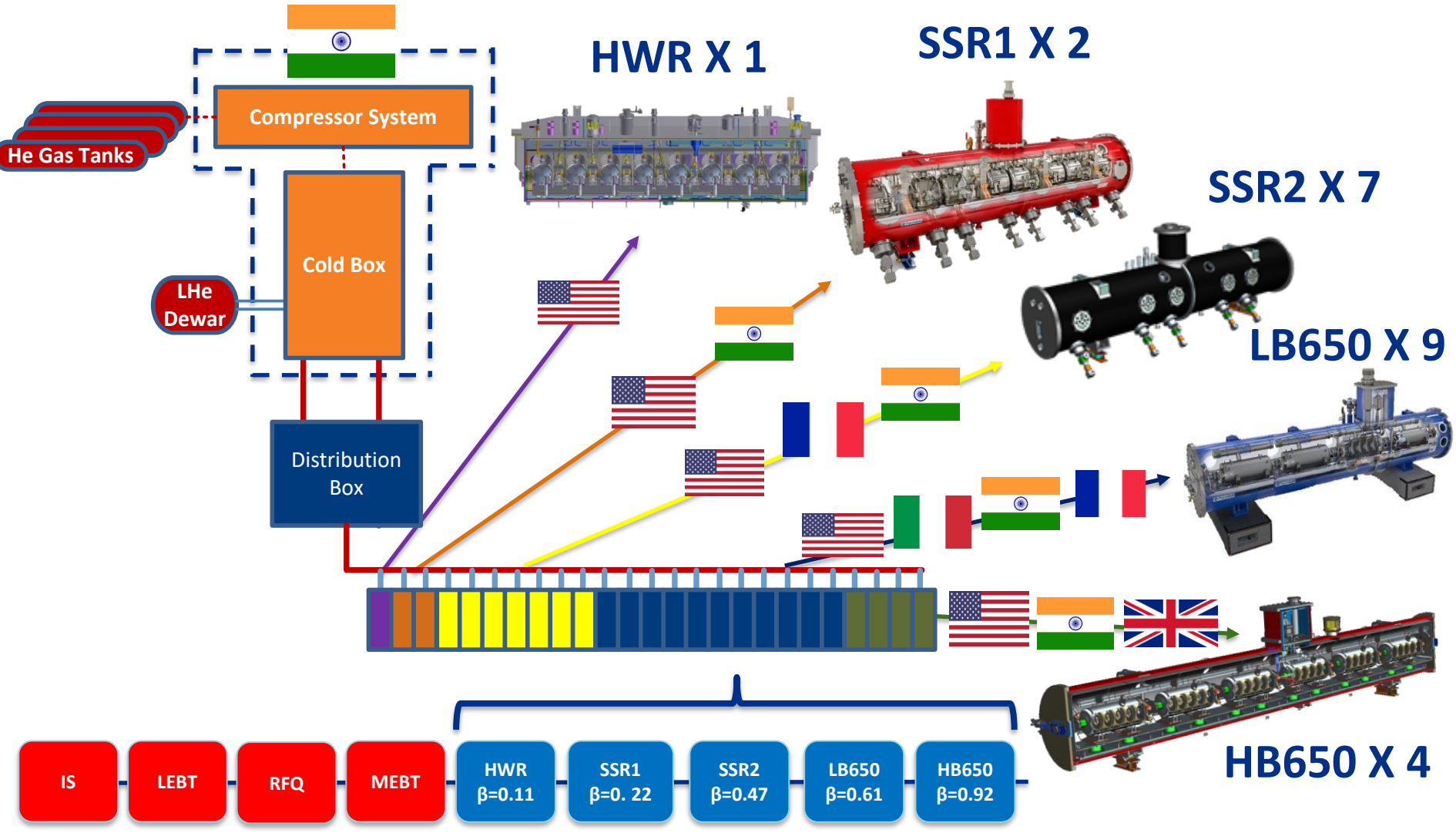
After FY20 will be repurposed to PIP-II CM test facility

PIP-II Injector Test Facility retires a significant number of technical risks – complete in FY20

PIP-II Injector Test Facility (PIP2IT)



PIP-II SRF Linac & Areas of International Interest



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.

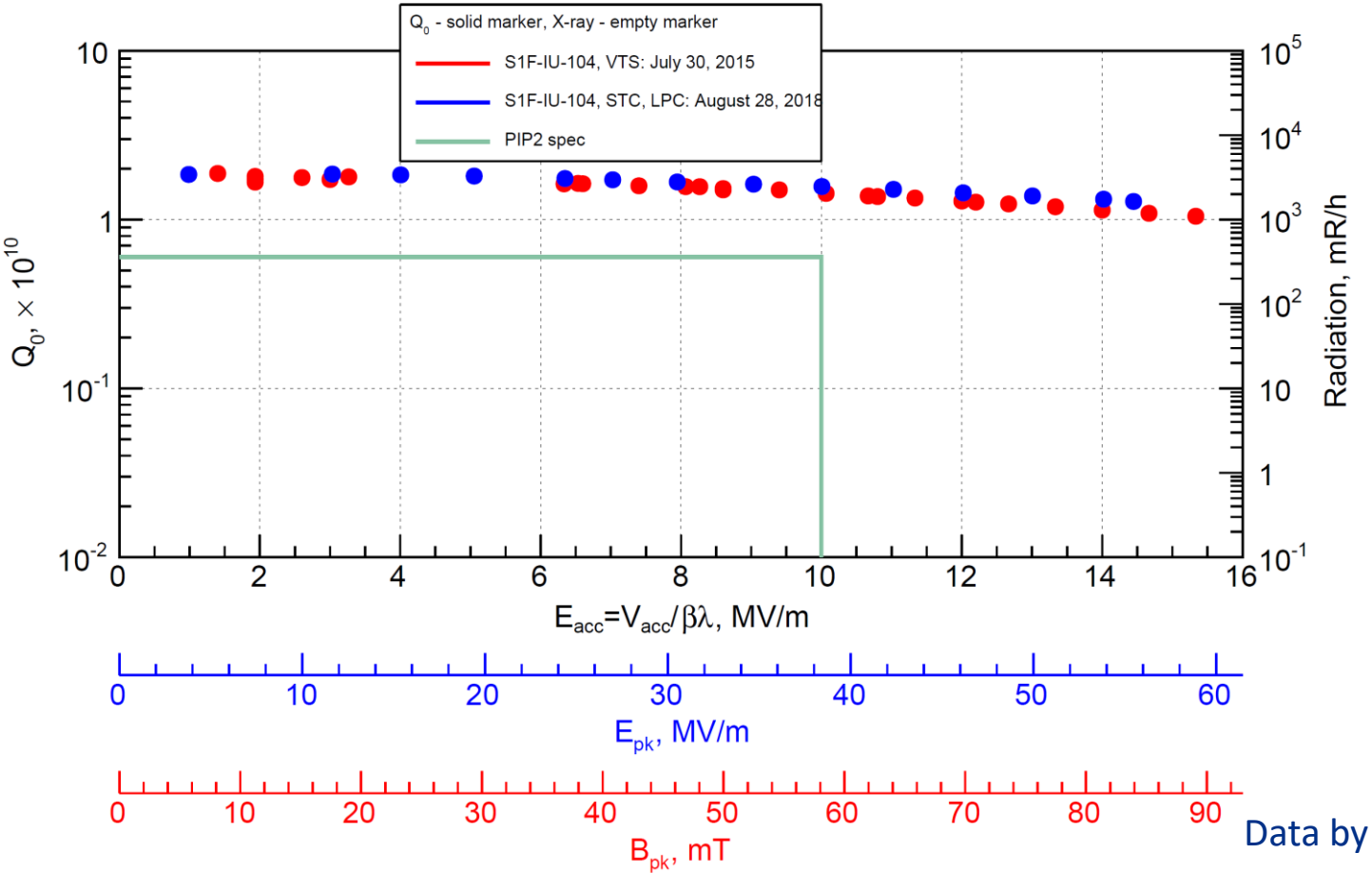
HWR will be transported to PIP2IT end of October for RF and beam tests

SSR1 Assembly Nearly Complete

String assembly complete - includes one cavity from DAE. Transport to PIP2IT in November 2019

SSR1 – Indian Cavity Performance

STC* test with low power coupler



Data by A. Sukhanov

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

*STC= Spoke Test Cryostat

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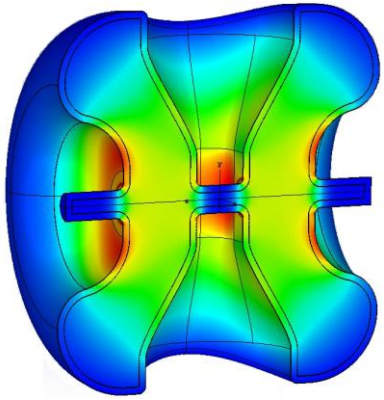
SSR2

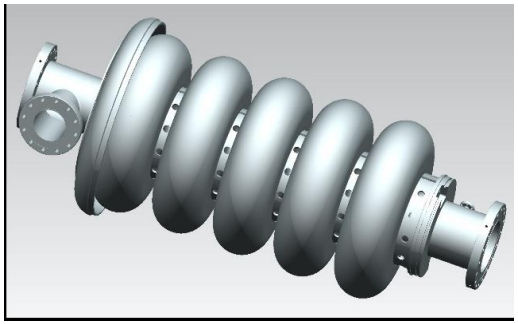
- Cavity RF and mechanical design complete
  - Nb ordered
- Prototype cavities expected in FY20



INFN 3D model of LB650 cavity

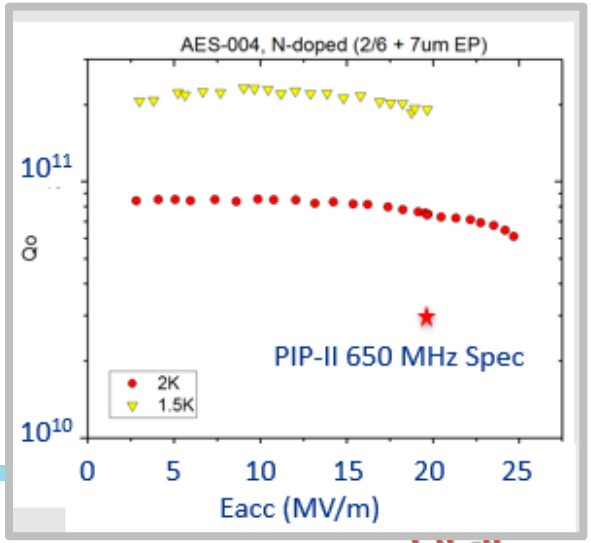
LB650

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

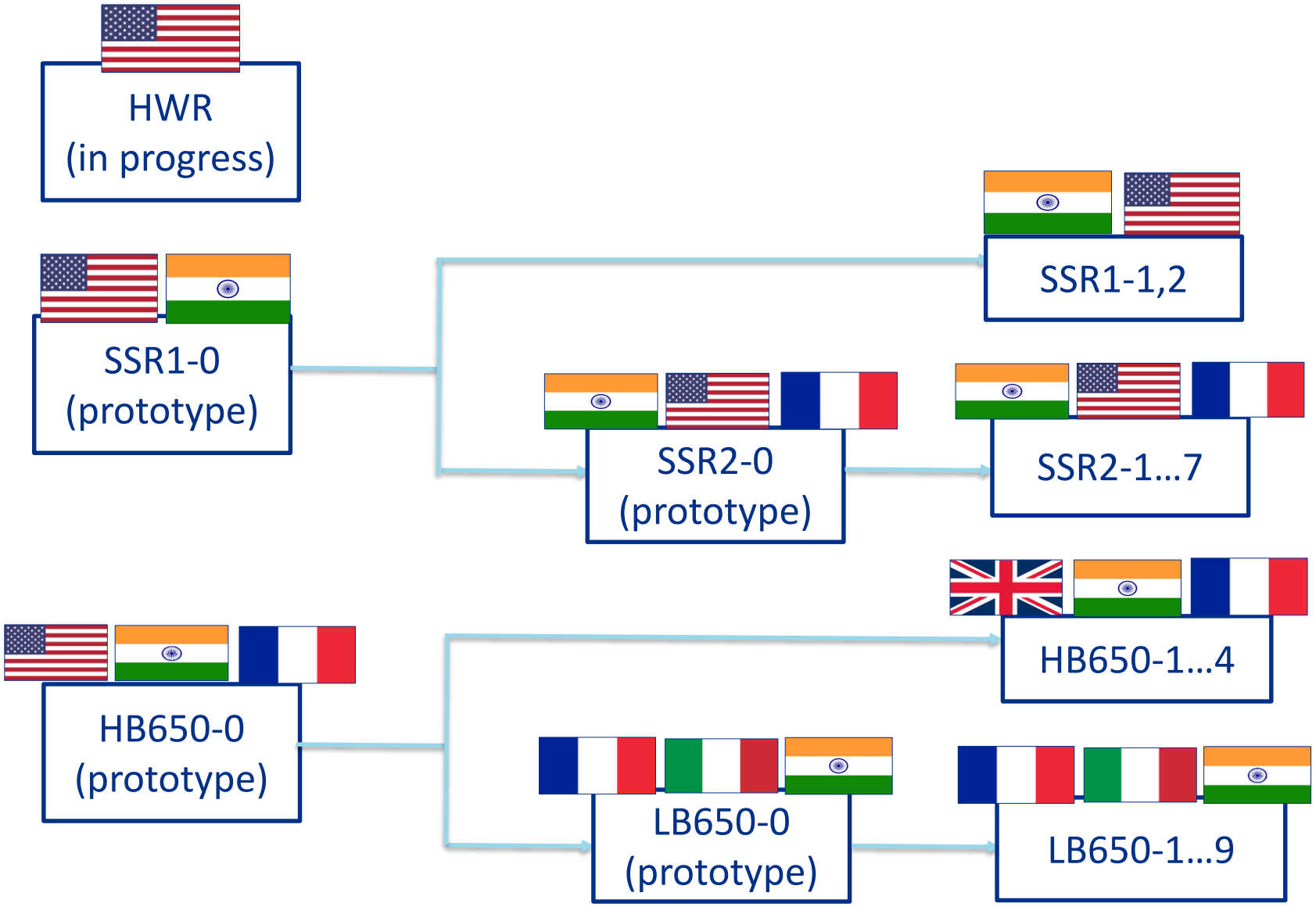


HB650

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



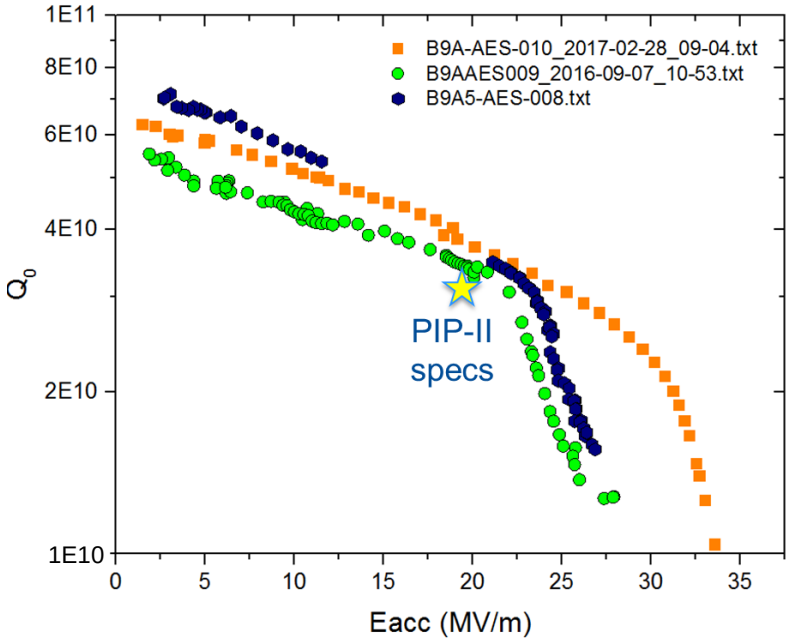
Cryomodule (CM) Development Path



SRF plan includes four prototype CMs to retire or mitigate major technical risks, including transportation

R&D Challenges in SRF

- High Q_0 and High Gradient → 3 x10^{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)



Vertical test results for 5-cell HB cavity

- Suppression of Microphonics
  - Maximum detuning < 20 Hz (σ<3 Hz)
    - Passive means
      - Cryomodule design
    - Active means
      - Adaptive Detuning Control Algorithm

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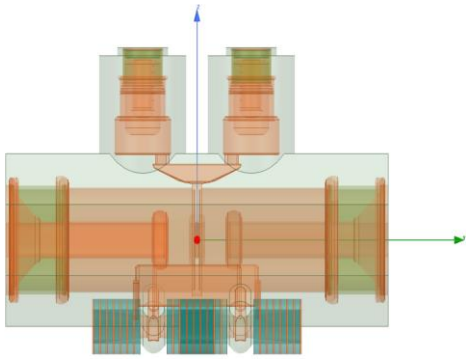
Fermilab's Path to 1.2 MW on LBNF Target

- 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).

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



MI Cavity Model with two PAs

PIP-II Groundbreaking – 15 March 2019

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Conventional Facilities

Site Clearing Complete

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

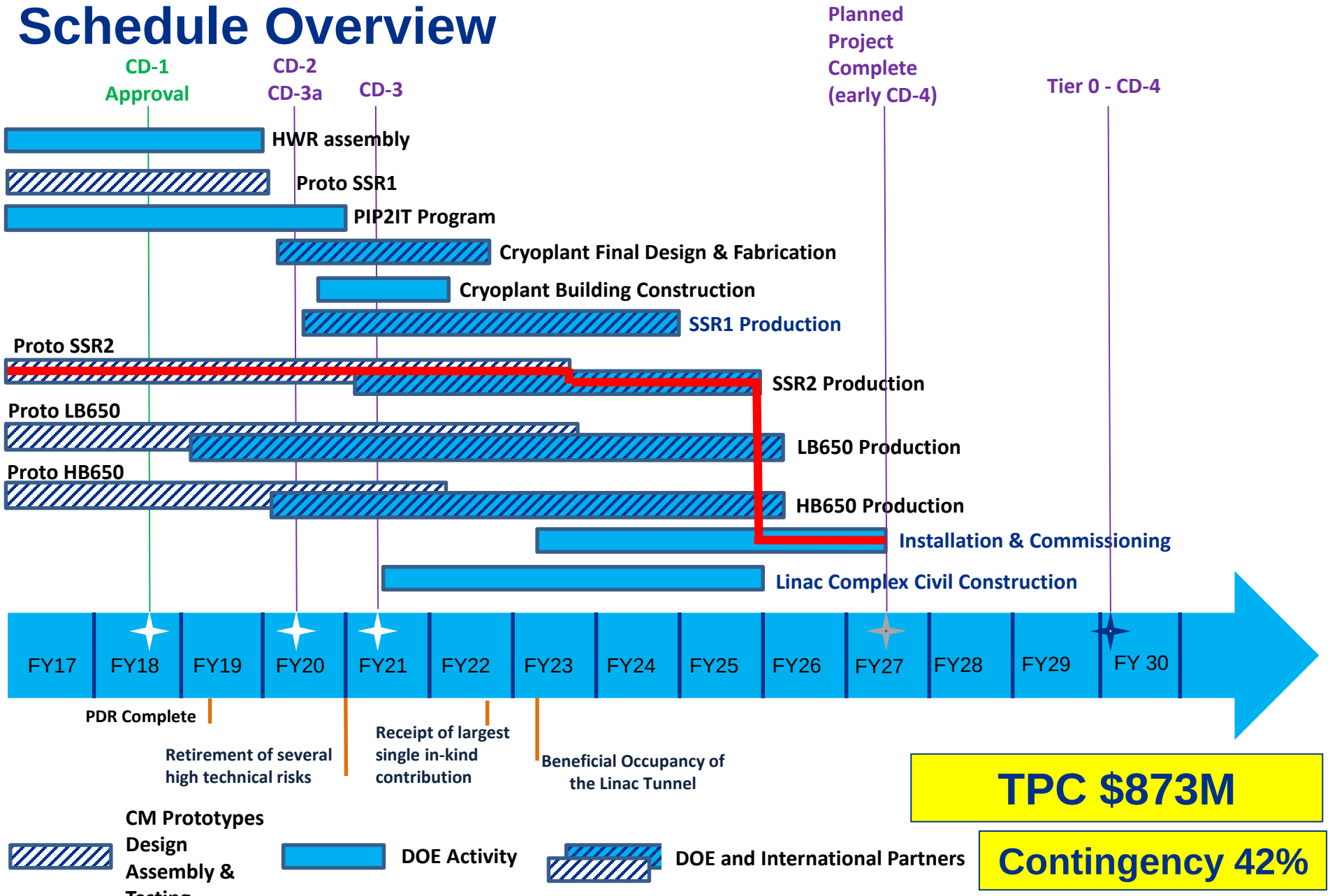
Cryogenics Plant Building

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



TPC $873M

Contingency 42%

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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

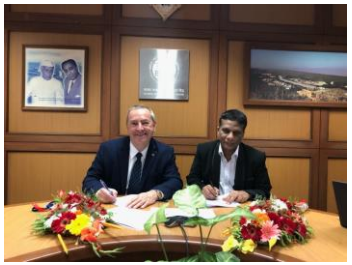
*International Neutrino Council; PIP-II Laboratory Directors Council; PIP-II Project Executive Board

PIP-II International Partners, Expertise and Capabilities

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

Subsystem (count)	Cavities	Cryomodules	RF Systems & Cryoplant
HWR (1)			
SSR1 (2)			
SSR2 (7)	 	 	
LB650 (11)	 		
HB650 (4)	 	 	
Cryoplant (1)			

International partnerships are essential for the success of the PIP-II Project

First PIP-II Project Executive Board Meeting – 3/14/2019

Next Board meeting at IPNO, Orsay on October 11, 2019

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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!