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

Building for Discovery: The PIP-II Project

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ORNL Virtual Seminar

4 February 2021

A Partnership of:

US/DOE

India/DAE

Italy/INFN

UK/UKRI-STFC

France/CEA, CNRS/IN2P3

Poland/WUST

Outline

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

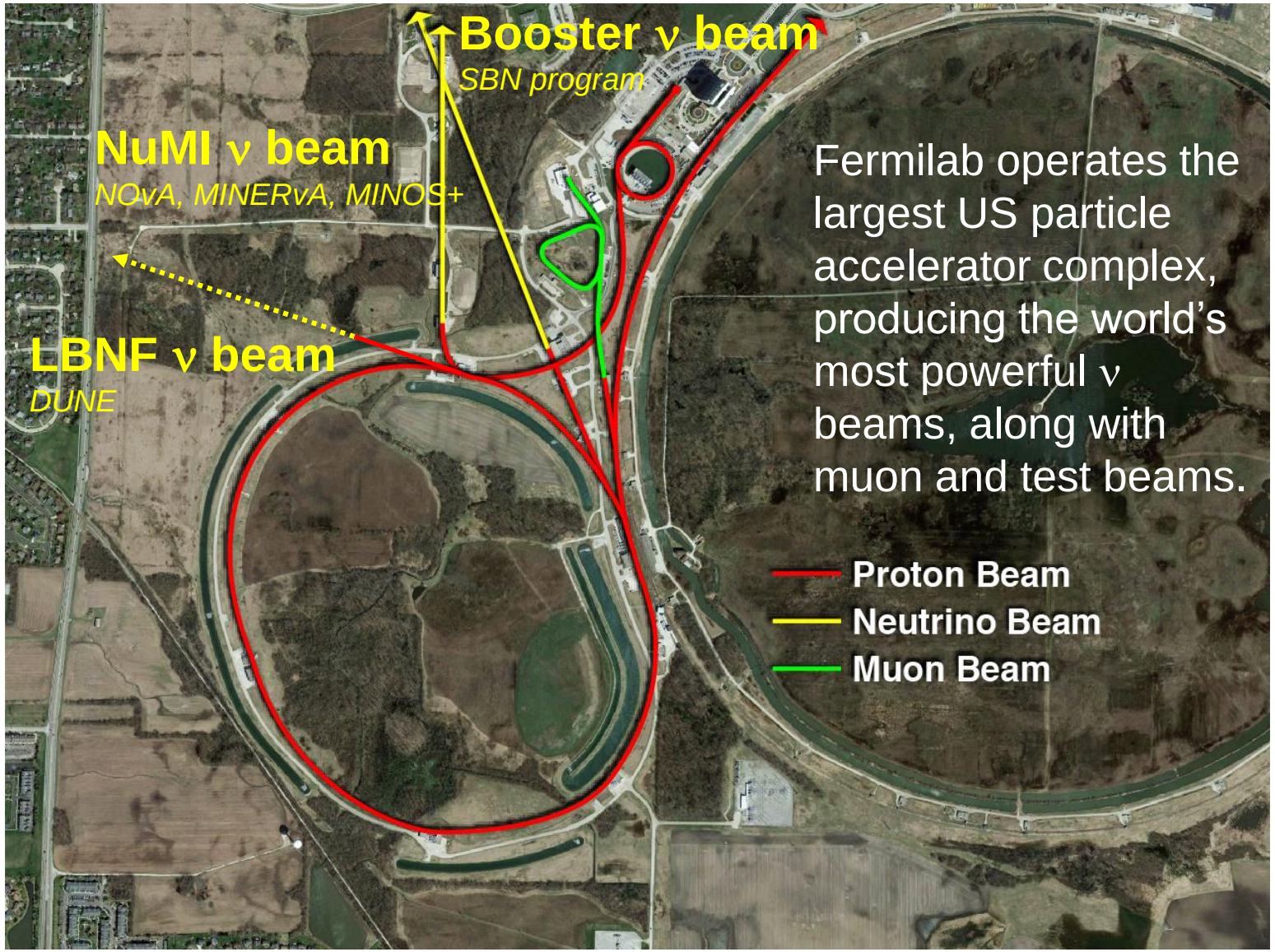
Fermilab at a Glance

America's particle physics and accelerator laboratory

- ~1,800 staff
- 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: operates at >750 kW; enables diverse Particle Physics Program with a Flagship

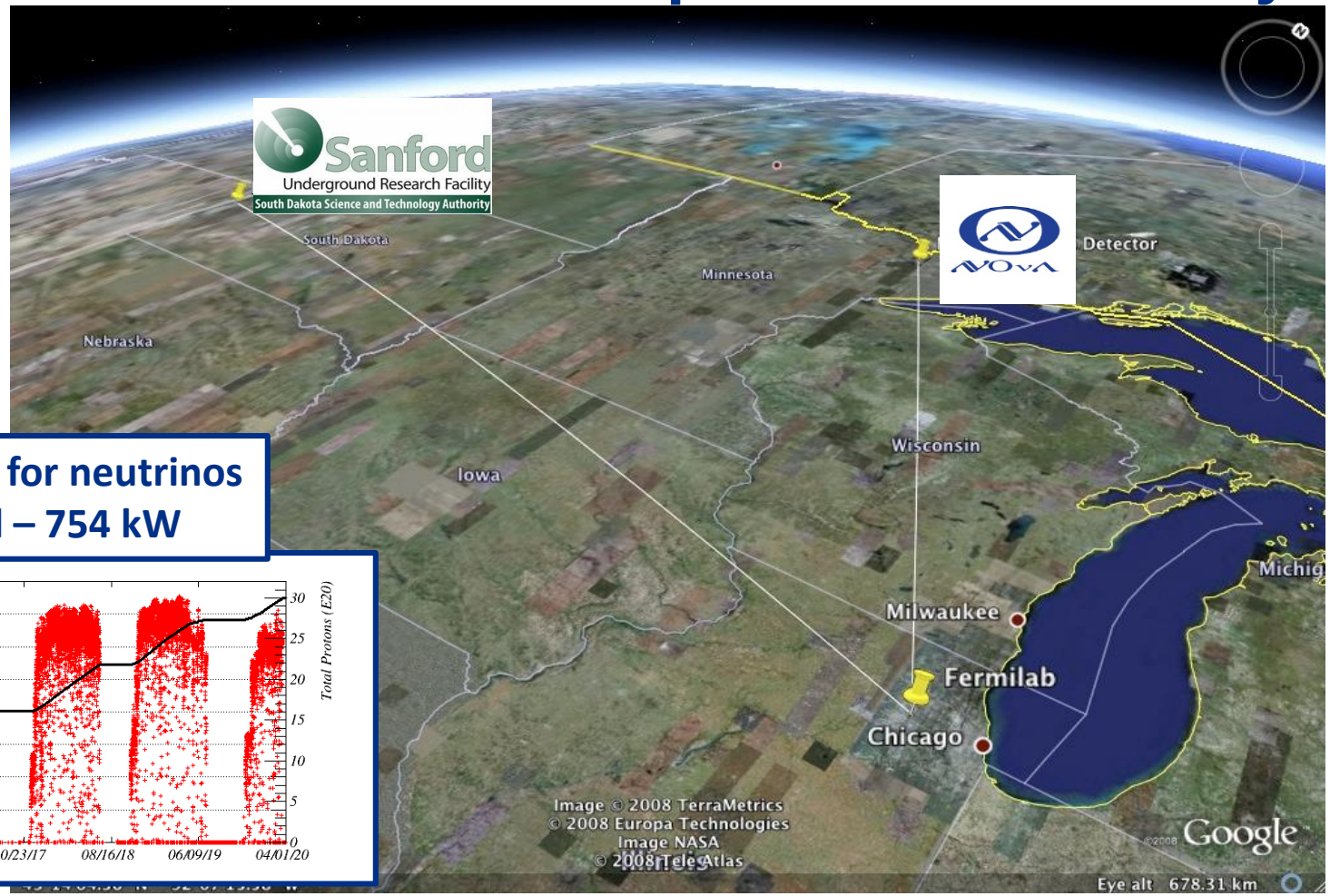


Neutrinos to Minnesota… NOνA:

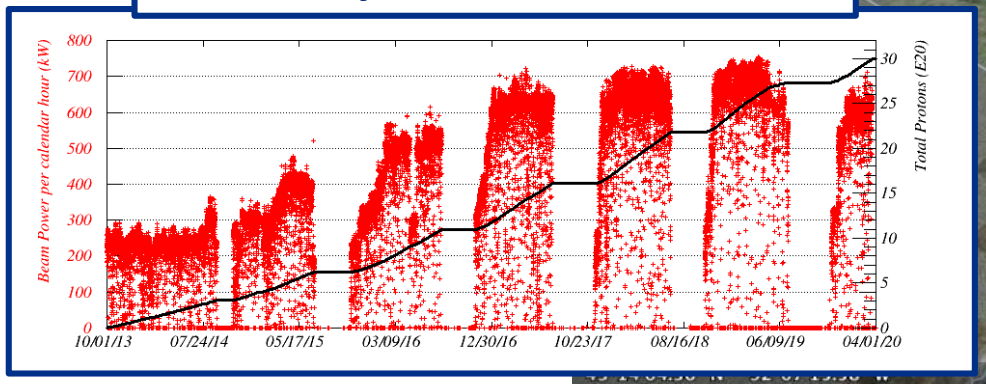
Fermilab's present flagship neutrino experiment

Neutrinos to South Dakota… DUNE:

International neutrino experiment hosted by Fermilab



Proton beam power for neutrinos already achieved – 754 kW



PIP-II

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

- Build a world-class neutrino program
- Host it as a global project
- Upgrade Fermilab accelerator complex to provide >1 MW proton beam

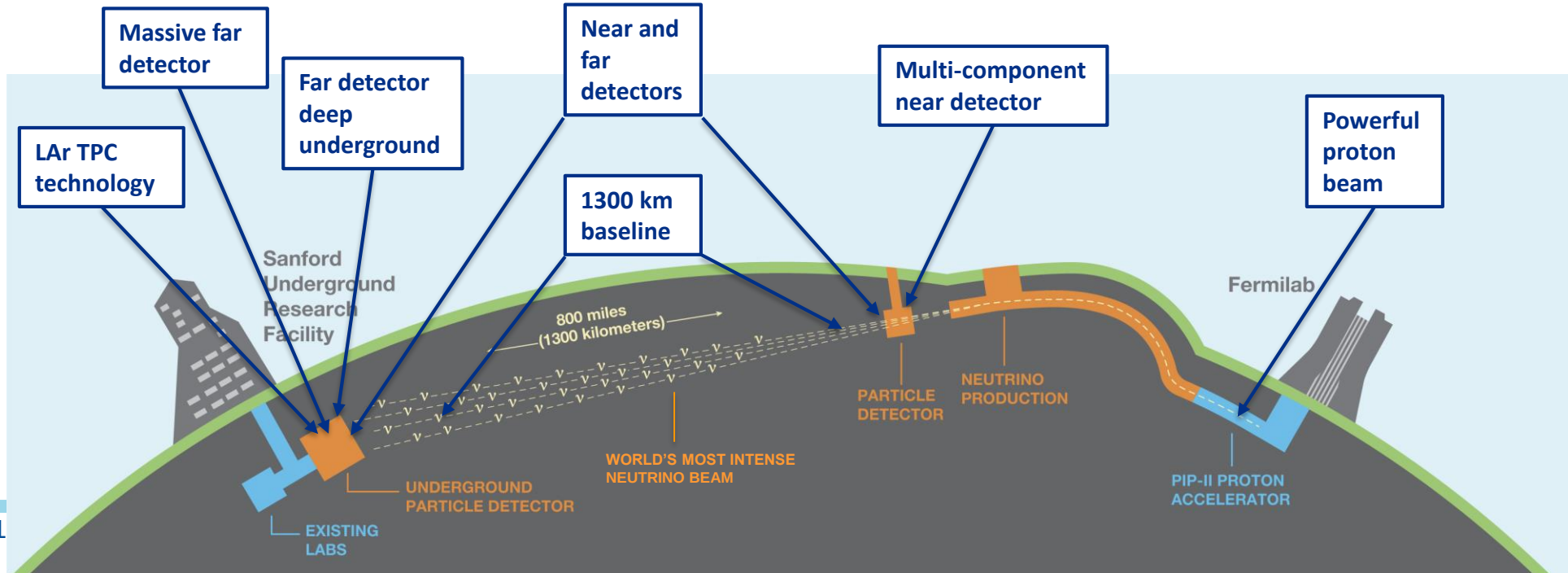
Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest priority large project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

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

PIP-II / LBNF / DUNE meets P5 requirements

- Powerful proton beams (**PIP-II**)
  - 1.2 MW upgradable to multi-MW in energy range of 60-120 GeV to enable world's most intense neutrino beam
- Dual-site detector facilities (**LBNF**)
  - Deep underground caverns (1.5 km) to support 4 x 17 kt liquid argon volume detectors
  - A long baseline (1300 km) neutrino beam, with wideband capability
- Deep Underground Neutrino Experiment (**DUNE**)
  - The next-generation neutrino experiment



DUNE – A Global Collaboration

~1,214 collaborators

202 institutions

33 countries (including 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, 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 Mission

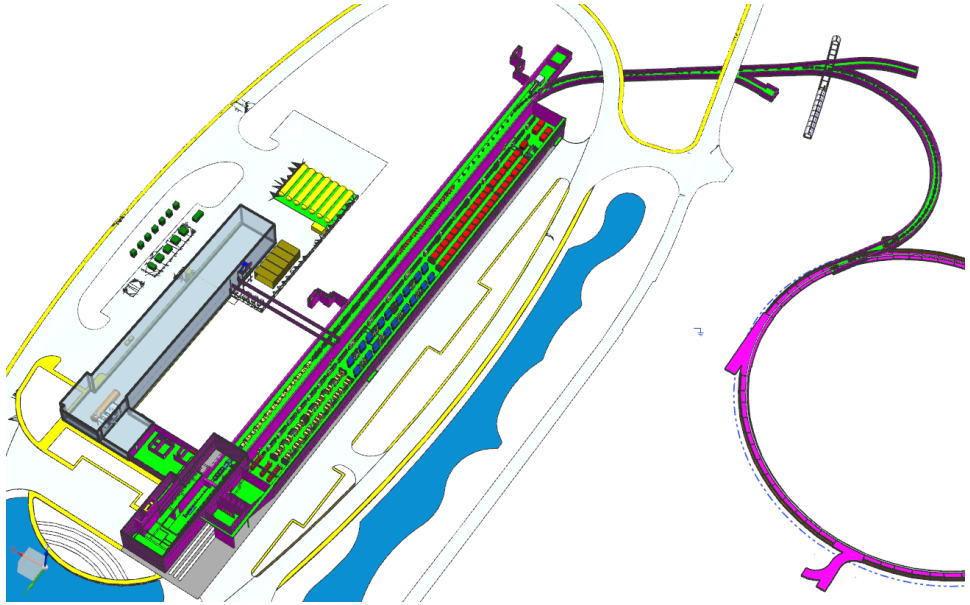
PIP-II will enable the world's most intense beam of neutrinos to the international LBNF/DUNE project, and a broad physics research program, powering new discoveries for decades to come.

PIP-II linac capabilities

Beam Power
- 1.2 MW proton beam
- Upgradeable to multi-MW

Flexibility and multi-user capability
- Compatible w/ CW-operations
- Customized beams
- Multi-user delivery

Reliability



PIP-II Scope

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

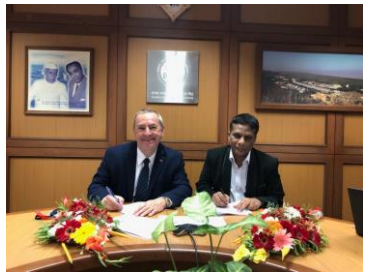
Upgraded Recycler, Main Injector
- RF in both rings

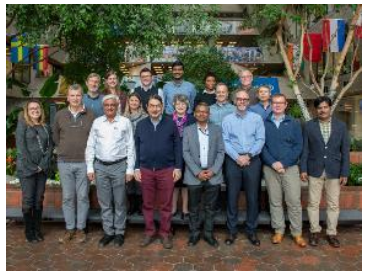
Conventional facilities, incl.
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

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


Main Injector
Transfer Line
PIP-II
SRF Linac
Booster

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 magnets for LHC;
2 GeV synch light source

Italy, INFN (started 2016)

Internationally recognized leader in superconducting RF technologies
SRF cavity and cryomodule fabrication for XFEL; SRF cavities for ESS

UK, STFC UKRI (started 2017)

Substantial engineering and manufacturing experience; Construction, operation of synch 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

Poland, WUST, WUT, TUL (started 2018)

Substantial engineering / manufacturing experience; CDS, LLRF, QC for XFEL, ESS

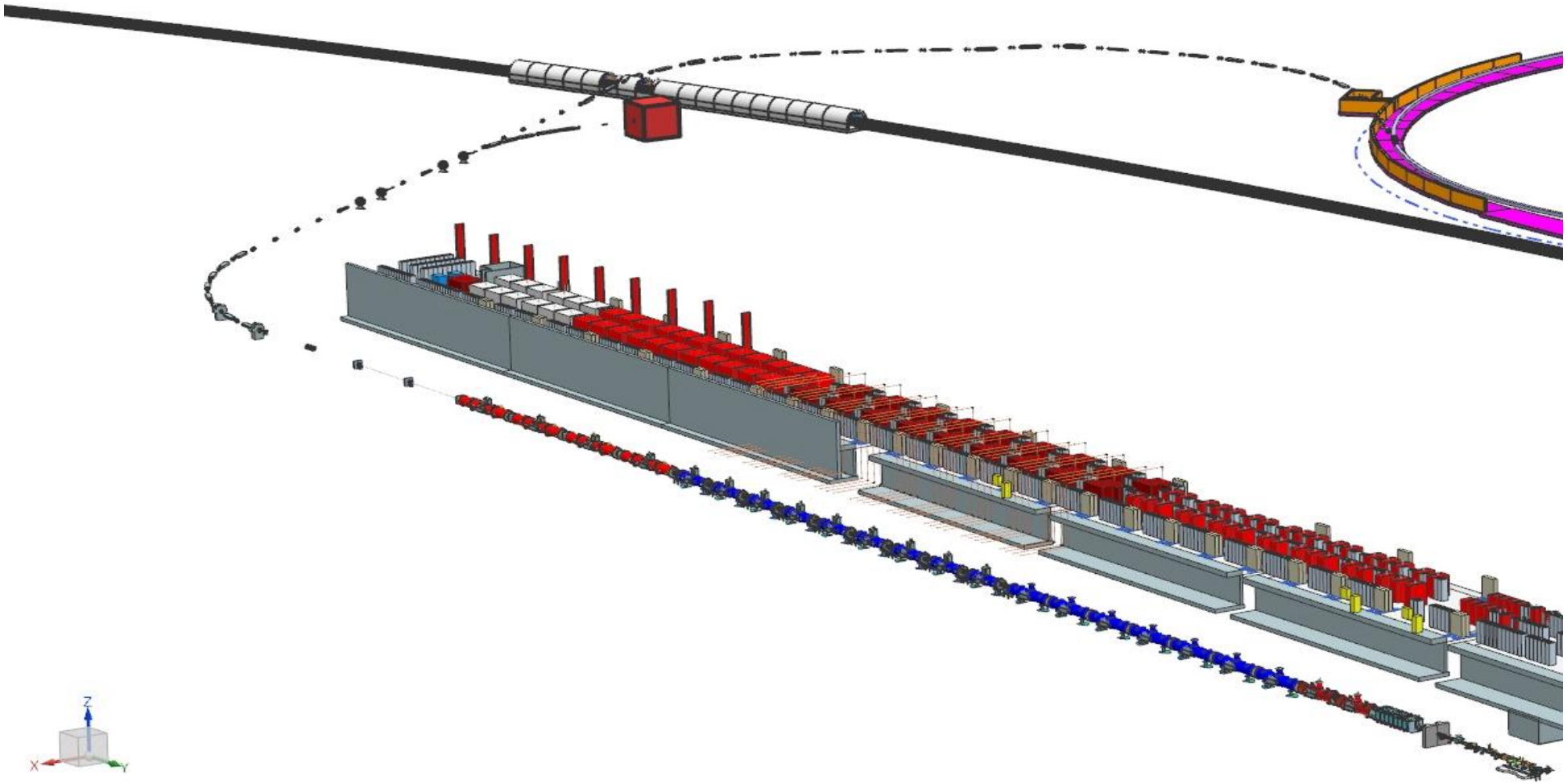
PIP-II Project benefits from world-leading expertise, facilities.
"Timing is perfect"

Major International In-Kind Contributions

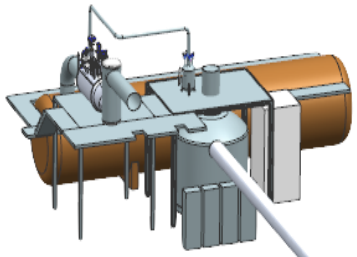
Subsystem (count)	Cavities	Cryomodules	RF & Cryo Systems
HWR (1)	DOE		
SSR1 (2)	DAE		
SSR2 (7)	CNRS/ IN2P3		
LB650 (9)	INFN	CEA	
HB650 (4)	UKRI		
Cryoplant (1)			
CDS			WUST

International partnerships are essential for the success of PIP-II

Technical Systems Progress



PIP-II Superconducting RF CW Linac, 800 MeV Consists of Five Types of Cryomodules



Cryoplant

CDS

HWR
8 Cavities
162.5 MHz

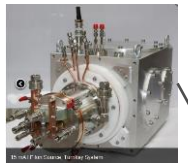
Single Spoke
SSR1 X 2
16 Cavities
325 MHz

Single Spoke
SSR2 X 7
35 Cavities
325 MHz

Elliptical
LB650 X 9
36 Cavities
650 MHz

Elliptical
HB650 X 4
24 Cavities
650 MHz

H- Ion source



RFQ

2.1 MeV

10 MeV

32 MeV

177 MeV

516 MeV

833 MeV

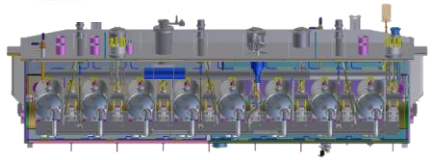
Superconducting

Room Temperature

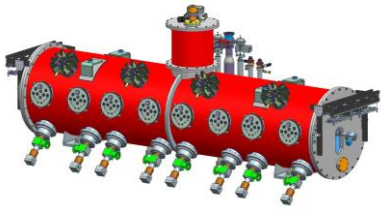
PIP-II Linac is technically complex, state of the art superconducting RF accelerator

PIP-II is the world's highest energy and power CW proton linac, and the U.S. first accelerator project to be built with major international contributions

The state-of-the-art PIP-II Superconducting RF Systems



5.9 m

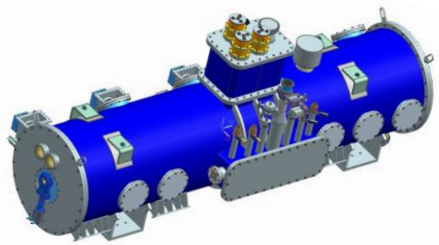


5.3 m

2023

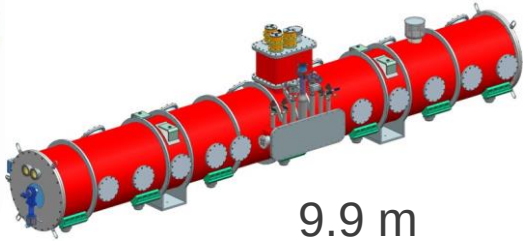
6.5 m

2023

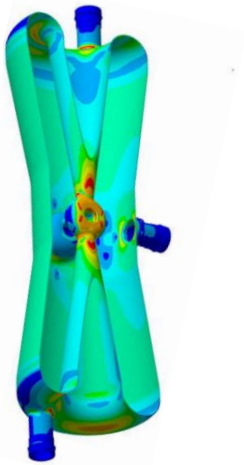


5.5 m

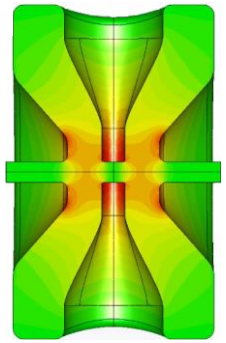
2021-22



9.9 m

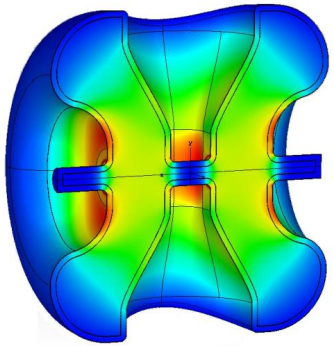


Half Wave Resonator
β=0.11 Q_0 =0.85x10^{10}

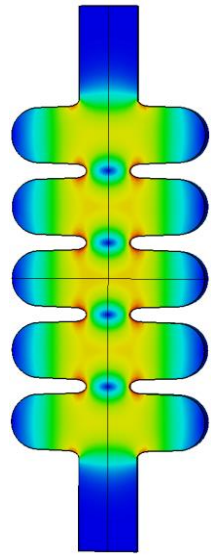


Single Spoke
SSR1
β=0.22 Q_0 =0.82x10^{10}

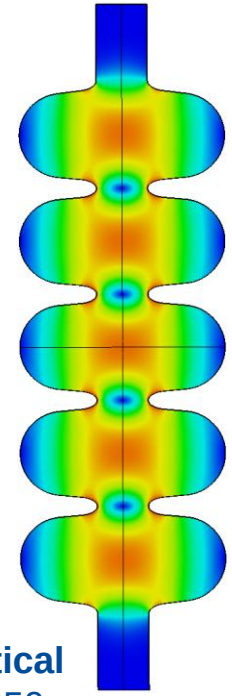
2022



Single Spoke
SSR2
β=0.47 Q_0 =0.82x10^{10}



Elliptical
LB650
β=0.61 *Q_0 =2.4x10^{10}



Elliptical
HB650
β=0.92 *Q_0 =3.3x10^{10}

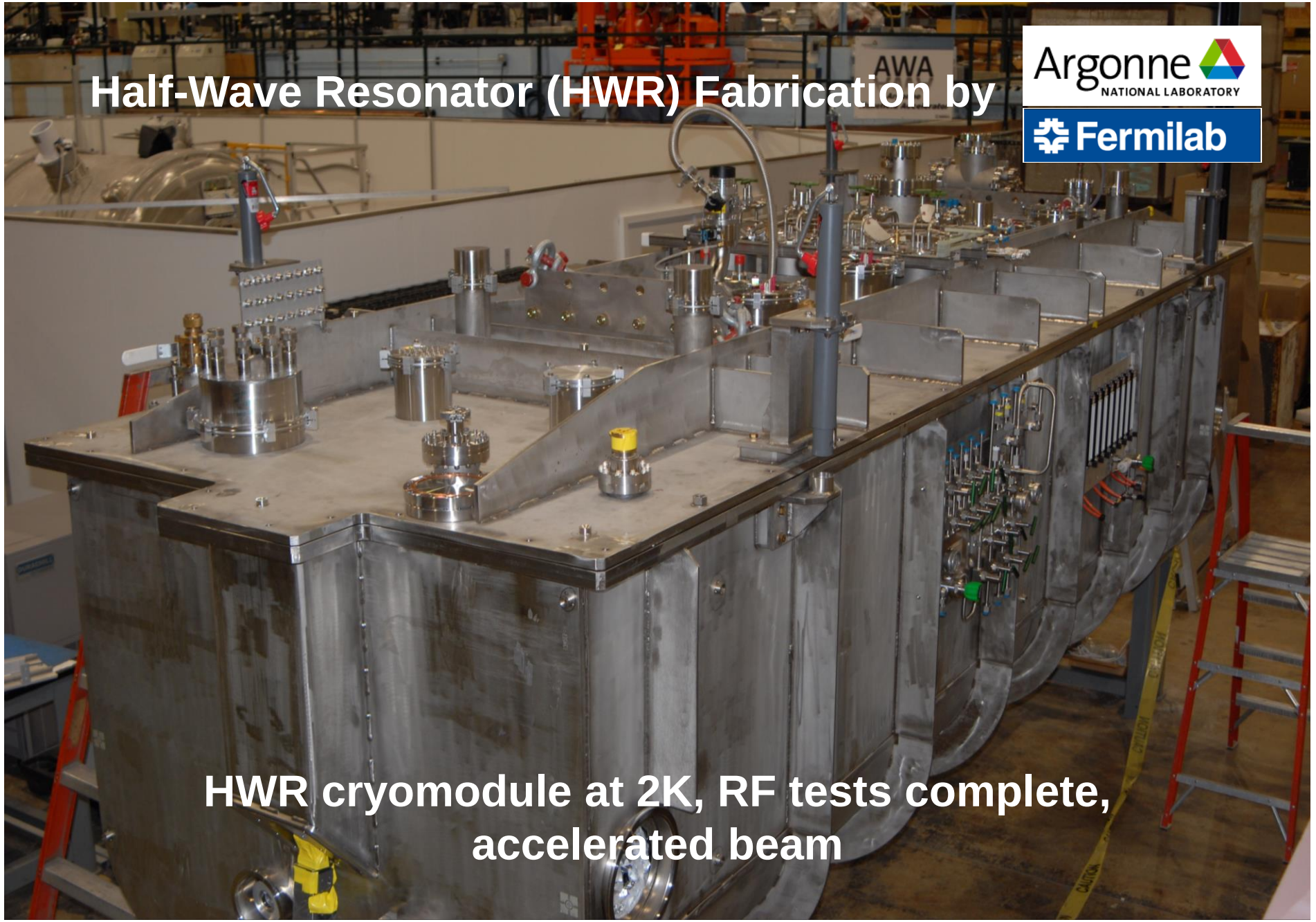
✓ Performance validated ✓ Testing in progress Dates: component built

*unprecedented performance requirement

Half-Wave Resonator (HWR) Fabrication by

Argonne NATIONAL LABORATORY

Fermilab



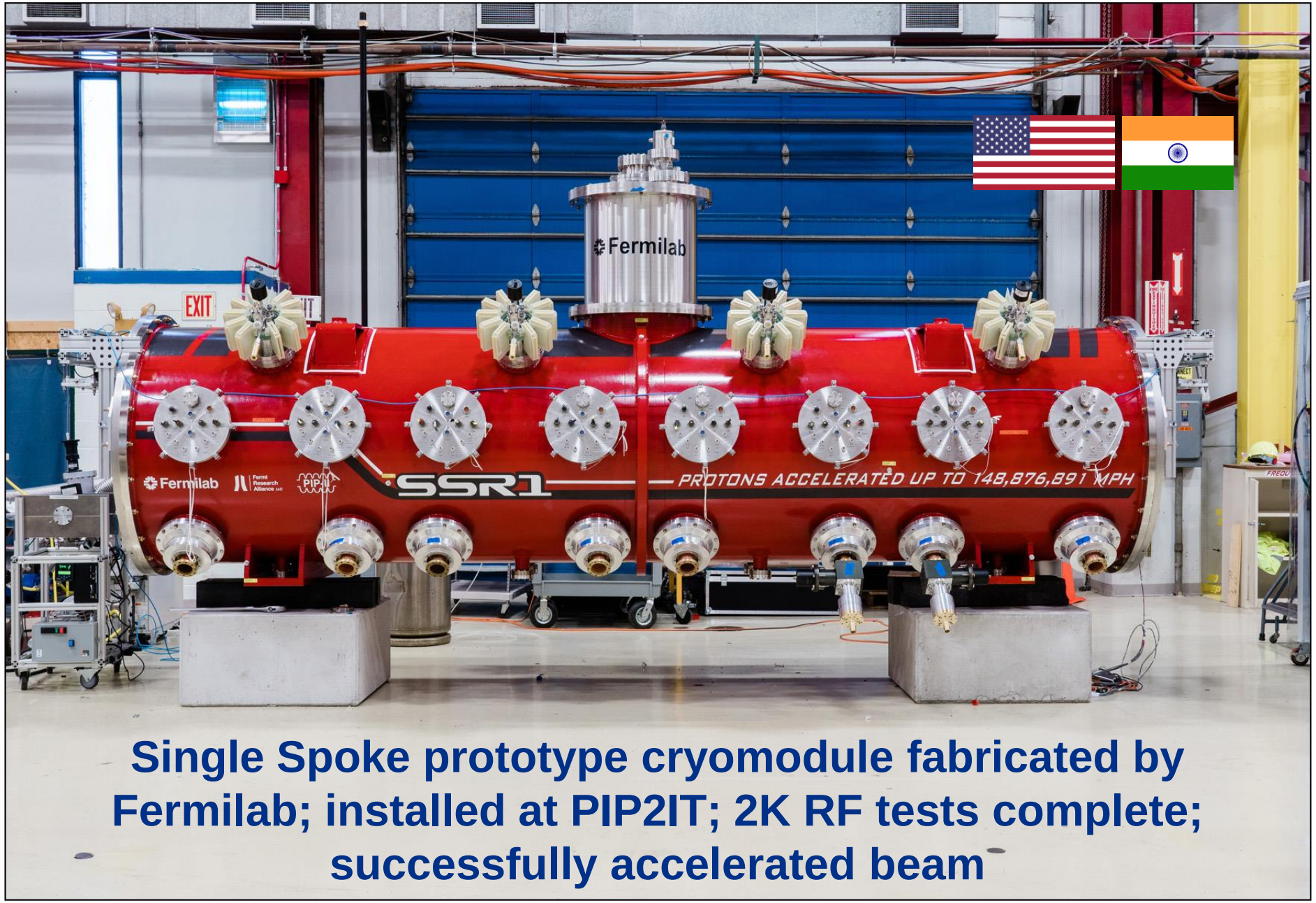
HWR cryomodule at 2K, RF tests complete, accelerated beam

PIP-II

HWR Cryomodule Tests

- Operated all cavities to the full nominal field (9.7 MV/m) and at least 10% above the nominal maximum gradient for extended time.
- Average Quality Factors exceeded specification of 8.5e9 (measured as an ensemble).
- Solenoids all met specification, exceed operational requirements
- All cavities (except 3, untested) operated in GDR mode (LLRF control demonstrated)

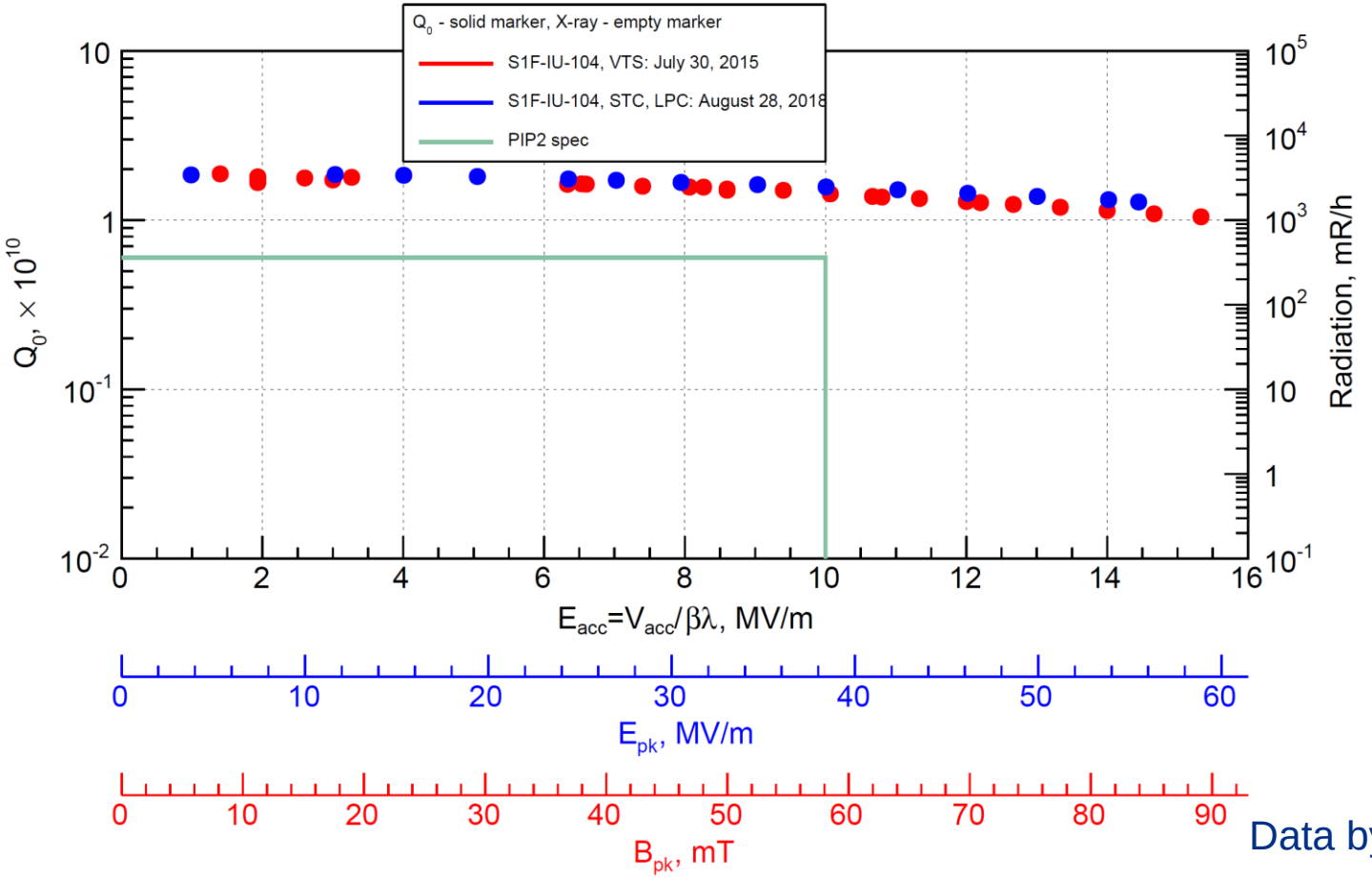
Cavity Position	Cavity Serial #	Nominal gradient required (MV/m)	Maximum gradient (MV/m)	Cavity Q_0	Note
CAV1	#P1	1.6	10.6	>1.4e10	No FE, no MP
CAV2	#P2	2.5	10.9	>1.4e10	No FE, no MP
CAV3	#2	3.5	6.5		Need to replace warm window
CAV4	#3	4.8	11.2	>1.4e10	No FE, no MP
CAV5	#4	6.5	10.5	>1.4e10	No FE, no MP
CAV6	#5	8.7	11.0		No FE, no MP
CAV7	#7	9.4	10.7	>1.4e10	No FE, no MP
CAV8	#1	9.7	10.8	>1.4e10	No FE, no MP



Single Spoke prototype cryomodule fabricated by Fermilab; installed at PIP2IT; 2K RF tests complete; successfully accelerated beam

SSR1 – Indian Cavity Performance

STC* test with low power coupler



Data by A. Sukhanov

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

*STC= Spoke Test Cryostat

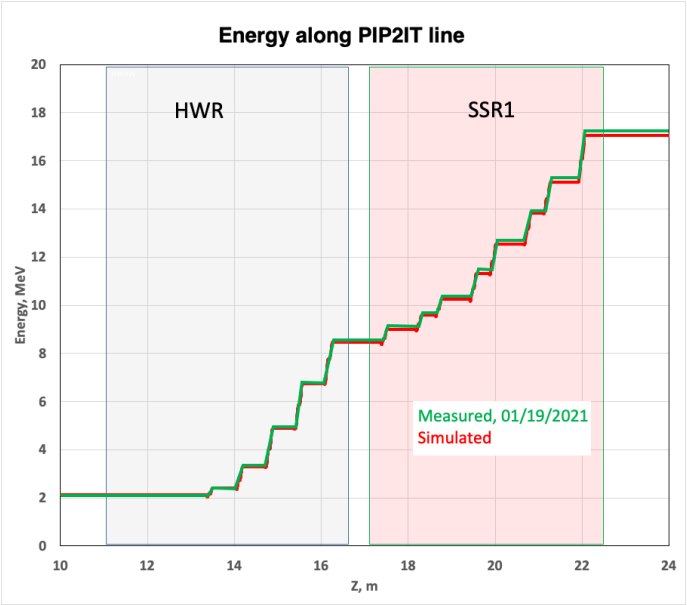
SSR1 Prototype Cryomodule Tests: Phase 1 Gradients achieved

- All eight SSR1 cavity gradients measured, exceed Phase 1 requirements.
  - Phase 2 test, Qo measurements in March.
- Completed first heat load measurement with all cavities and solenoids at nominal field/current.

Cavity Position	Cavity Serial #	Phase 1 gradient required (MV/m)	Phase 2 gradient required (MV/m)	Cavity gradient measured (MV/m)	Notes
CAV1	S1H-NR-106	**4.88**	10.00	**11.5**	Phase 2 admin limit, FE onset 10.5 MV/m.
CAV2	S1H-NR-110	**4.63**	8.78	**5.3**	Phase 1 admin limit
CAV3	S1H-NR-112	**4.78**	8.05	**5.5**	Phase 1 admin limit
CAV4	S1H-NR-109	**7.32**	10.00	**8.4**	Phase 1 admin limit, FE onset 5.5 MV/m
CAV5	S1H-NR-114	**7.80**	9.76	**9.0**	Phase 1 admin limit
CAV6	S1F-IU-104	**7.56**	10.00	**8.7**	Phase 1 admin limit
CAV7	S1H-NR-113	**7.32**	8.54	**8.4**	Phase 1 admin limit
CAV8	S1H-NR-111	**10.00**	10.00	**11.0**	Phase 1 admin limit, FE onset 10.5 MV/m.

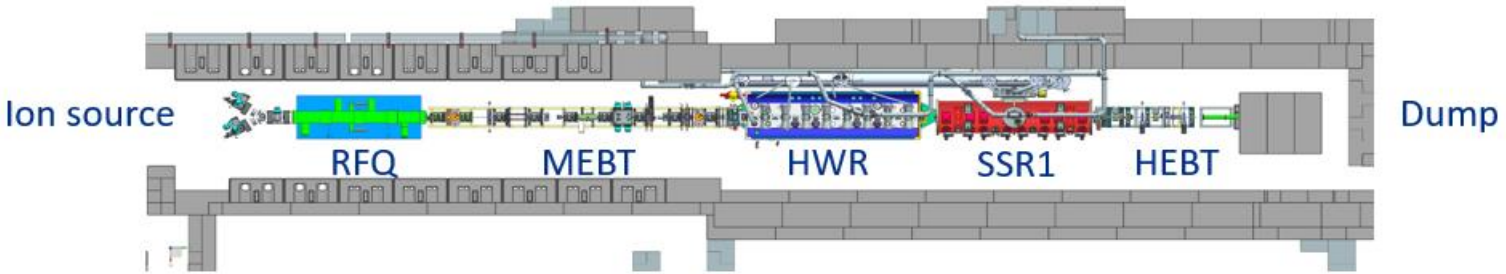
Phase 1: first SSR1 slot; Phase 2: second SSR1 slot

PIP-II Cryomodules accelerate beam to 17 MeV!



17.2 MeV achieved

Beam energy evolution with 5 HWR and 8 SSR1 cavities



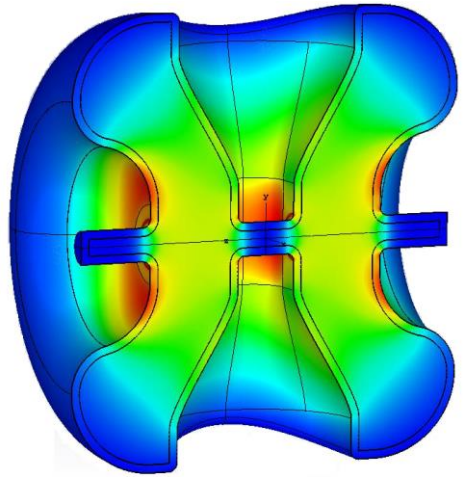
PIP2IT to be converted to PIP-II Cryomodule Test Facility

Significant Milestone: SRF cryomodules and battery of accelerator systems demonstrate solid performance; design requirements are being validated; international partners' deliverables seamlessly integrated. New era of SRF proton acceleration at Fermilab

SSR2 Cavities, Pre-Production Cryomodule

Cavity

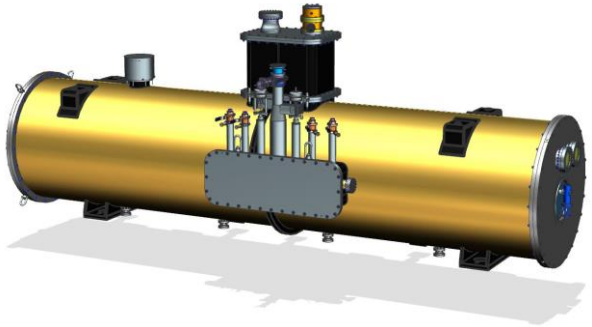
- Integrated design team: Fermilab, IN2P3 and DAE
- Niobium production at vendor completed
- Prototype jacketed cavity procurement in progress
- Coupler procurement in progress

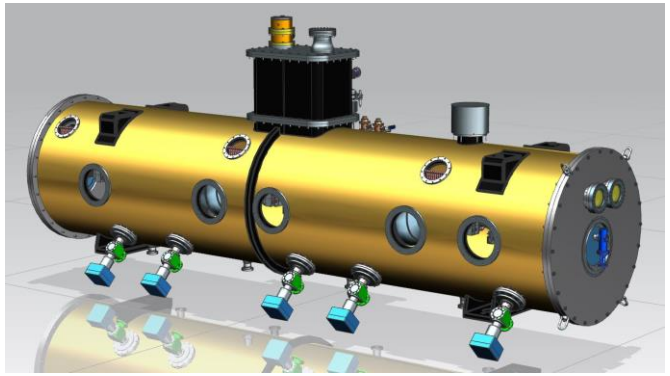


Parameters	SSR2 v 3.1
Optimal beta β_{opt}	0.472
Aperture [mm]	40
Frequency [MHz]	325
Effective length $2\beta_{opt}\lambda/2$ [m]	0.436
E_{peak}/E_{acc}	3.51
B_{peak}/E_{acc} [mT/(MV/m)]	6.75
G [Ohm]	115
R/Q [Ohm]	305.2
E_{peak} [MV/m] @ 5 MeV	40.2
B_{peak} [mT] @ 5 MeV	77.4
Max energy gain [MeV]	5.0
Max gradient [MV/m]	11.47

Cryomodule

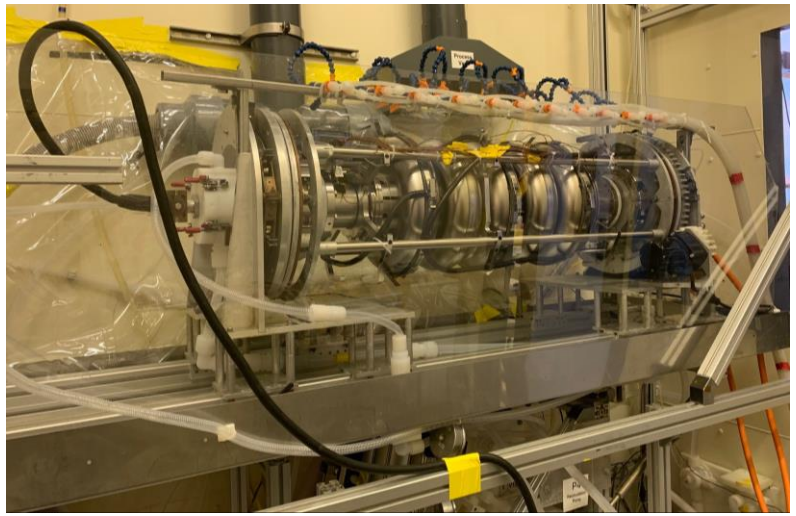
- Design in progress by Fermilab, DAE



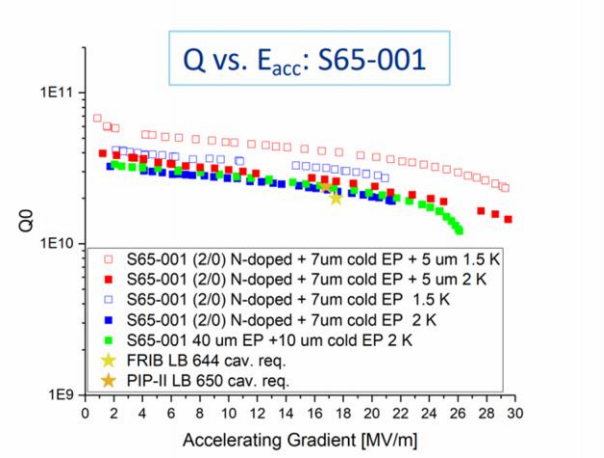


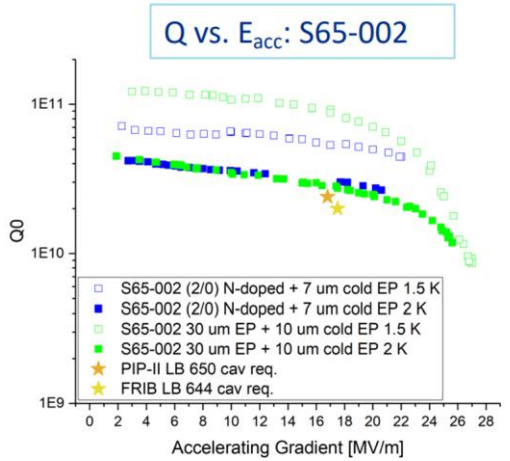
LB650 Cavities

- Q_0, Gradient → 2.4 x10^{10} and 16.8 MV/m - unprecedented for β <1
- Cavity RF design completed led by INFN
  - First prototype bare cavity INFN contribution arrived in May 2020
  - RF testing in progress
- MSU 644 MHz cavities tested, meet PIP-II Q_0, gradient specs



B61-EZ-001 on ANL EP stand





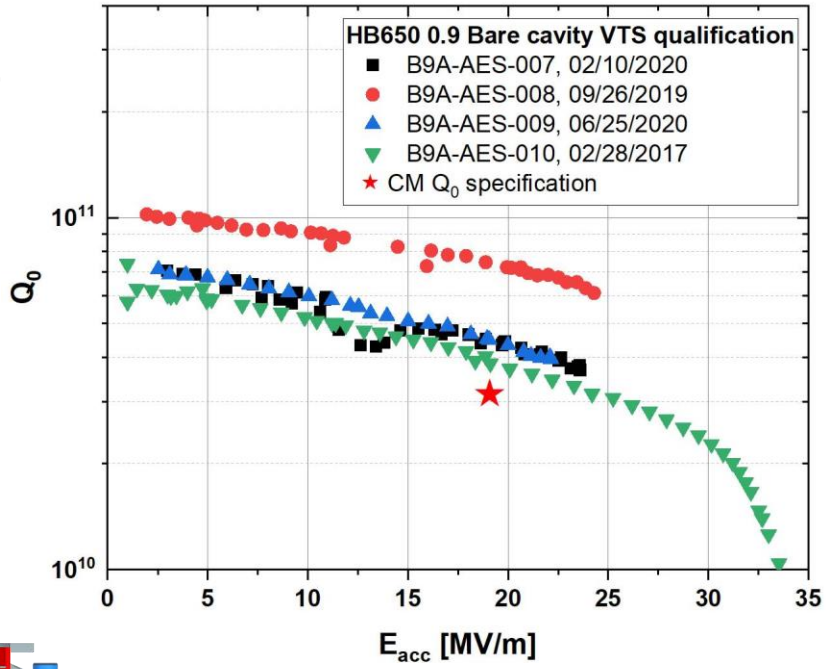
MSU cavities are directly scaled from PIP-II LB650 cavity design.

Courtesy: *Martina Martinello*

HB650 Prototype Cryomodule

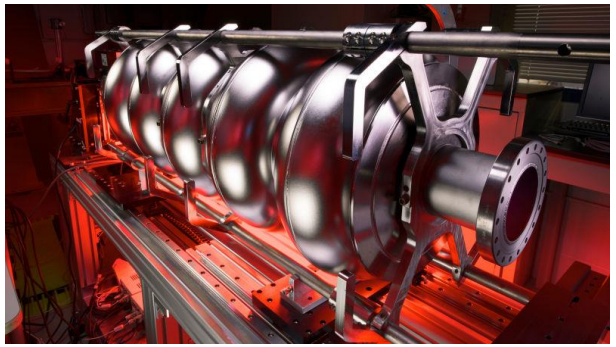
Cavity

- Q_0, Gradient → 3.3 x10^{10} and 18.7 MV/m - unprecedented for β <
  - N-doping optimization is required
- All four HB650 Fermilab cavities exceeded cryomodule Q_0 spec
- RRCAT cavity reached max gradient 29 MV/m, met PIP-II specs
- Cavity, coupler procurement awarded



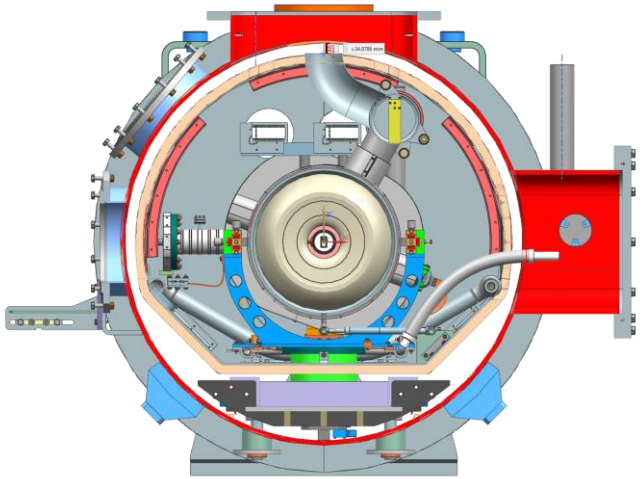
Cryomodule

- FDR was successfully completed in 7/29-31/2020
- Successful HB650 Transportation FDR on 9/22/2020 led by UKRI

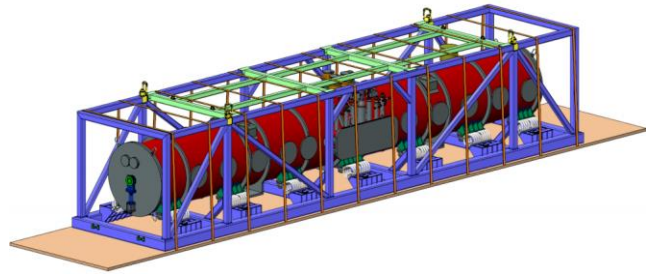


Bare HB650 Cavity

Jacketed HB650 Cavity in STC



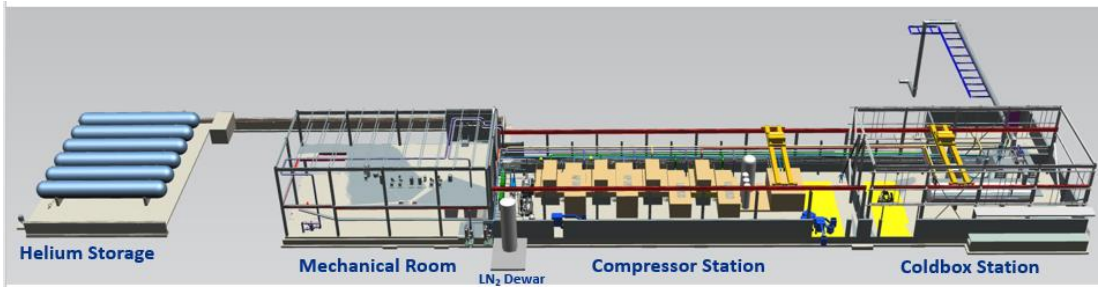
HB650 proto cryomodule

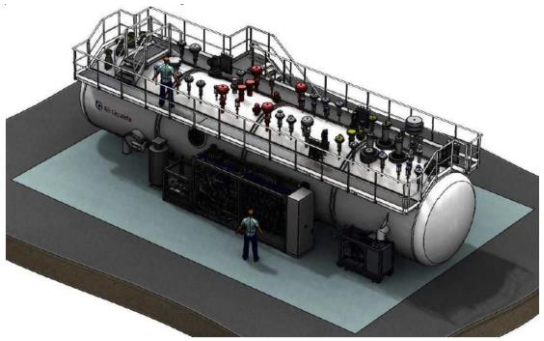


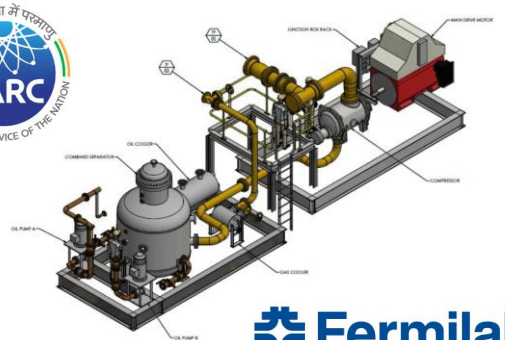
HB650 Transportation Tooling

Cryoplant & Cryogenic Distribution System (CDS)

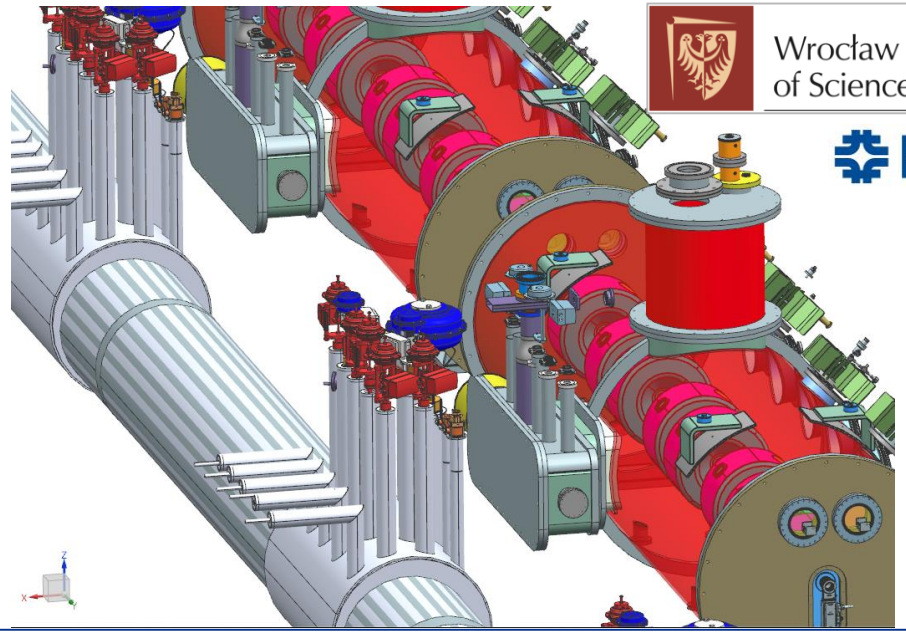
- Jointly developed cryoplant specification between DAE and Fermilab
- DAE issued purchase order for cryoplant



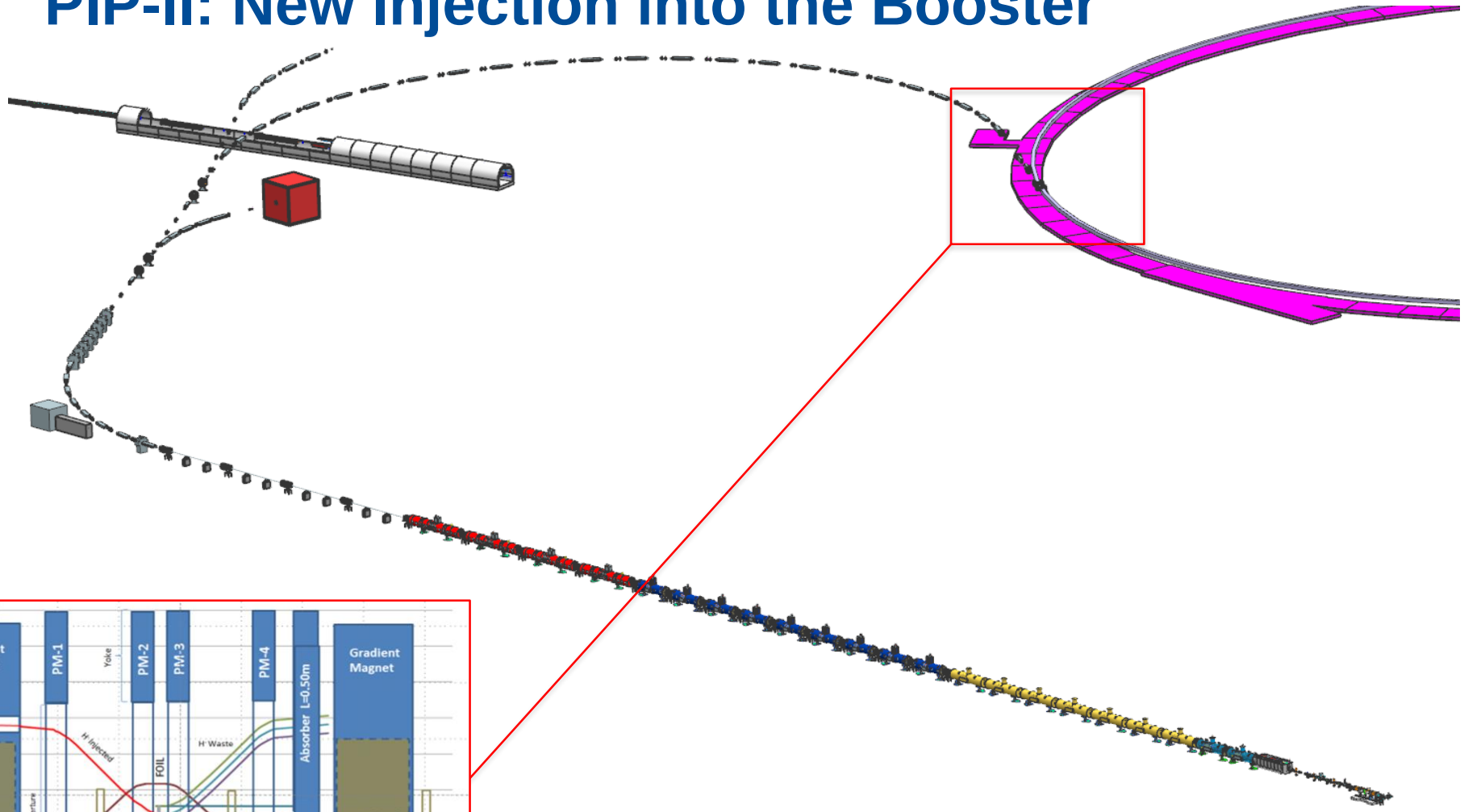


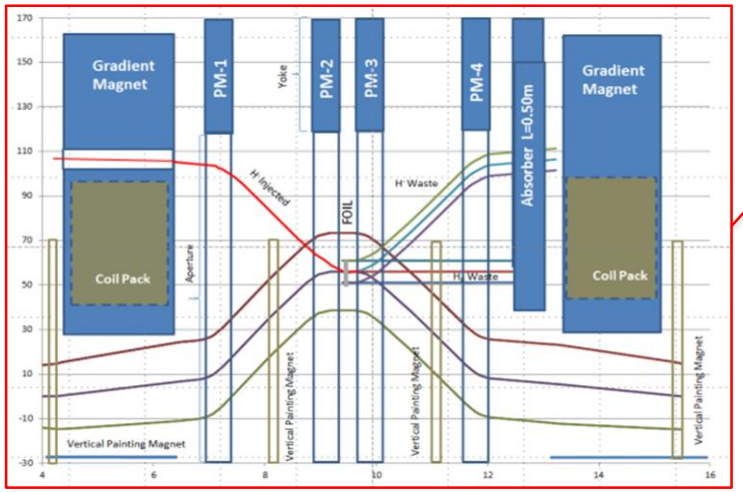


- Designed in collaboration with Fermilab and Wroclaw University of Science and Technology
- Final Design completed
- 3D Models completed
  - Interconnect Transfer Line (ITL)
  - Tunnel Distribution Line (TDL)



PIP-II: New Injection into the Booster





PIP-II injection mitigates high intensity effects, reduces losses

- Precision PIP-II linac beam allows 3D painting injection
- Increased energy & painting injection reduce space charge tune shift

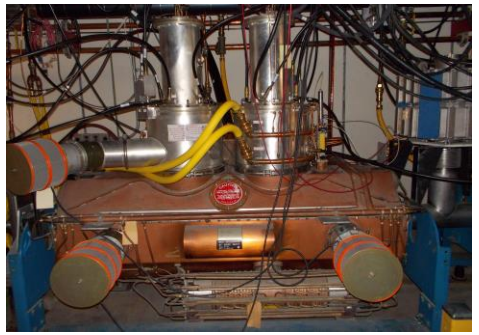
Path to 1.2 MW on LBNF Target

1. Increase number of protons per Booster pulse:
   4.3e12 → 6.5e12
2. Increase of Booster rep. rate:
   15 Hz → 20 Hz
3. Reduce Main Injector cycle:
   1.33 s → 1.2 s

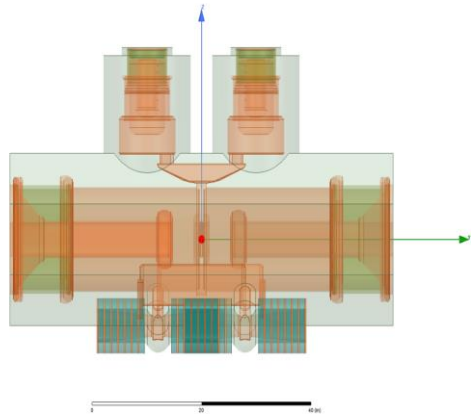
- Upgrades required in:
  - Booster
  - Recycler Ring (RR)
  - Main Injector (MI)

Accelerator Complex Upgrades

- Booster:
  - New Booster Injection girder
  - New Booster Collimators and Dampers
  - New Booster cavities
- Recycler Ring
  - New Recycler cavities
- Main Injector (MI)
  - 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 with two PAs



Cryogenic Plant Building Groundbreaking – July 2020

Conventional Facilities

- Cryoplant Building Construction underway
  - Structural steel erection ongoing until mid-February 2021
  - Precast concrete wall panels installation scheduled for mid-February 2021
  - Completion in December 2021
- Site Work
  - Proposal docs underway; DOE review Feb 21
- Linac Complex Design integrated with technical systems
  - Final design underway
    - 90% review scheduled week of January 25th
    - On track for 100% in April 2021
- Booster Connection
  - Start design in March/April 2021

Cryoplant Building Construction

https://app.truelook.com/?u=fc1599677013#tl_live
https://app.truelook.com/?m=160025008322055655036 47

PIP-II Site Status on 3 February 2021

PIP-II baseline approved by DOE – December 2020

Fiscal Year	2016				2017				2018				2019				2020				2021				2022				2023				2024				2025				2026				2027				2028				2029			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Project Milestones	CD-0 ESAAB Approval								CD-1 ESAAB Approval				ECF CD-2/3 ESAAB Approved																																CD-4 Approval											
																					CD-2 ESAAB Approval																																	
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																													Shutdown Beam to Switchyard 120																							
																																	Shutdown Beam to Experimental Program																	
PIP2IT																	PIP2IT Beam Commissioning																																			
																					Fabricate Test Infrastructure for HB650 CM																																	
																									Fabricate Test Infrastructure for SSR2																							
Linac Complex																					Detailed/Final Design																																	
																									Procurement																							
																													Construction																							
																													T5 MS - AUP High Bay Building				AUP Linac Tunnel																			
CryoModules																									HB650 Prototype CM Integration Fabrication and Testing																							
																																	HB650 Production CryoModule Integration Fabrication and Testing																	
																																	LB650 Pre-Production CM Integration Fabrication and Testing																	
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CryoPlant																					Cryoplant Building Construction																																	
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Installation																																	WFE Installation and Checkout																	
																																	Install 800 MeV Injection System																	
																																	Install and Test Booster 20Hz Components																	
																																	Cryomodule Installation and Checkout																	
Beam Commissioning																																	Beam Commissioning through WFE																	
																																	Linac Beam Commissioning																	
																																	Beam Commissioning through Booster Injection																	

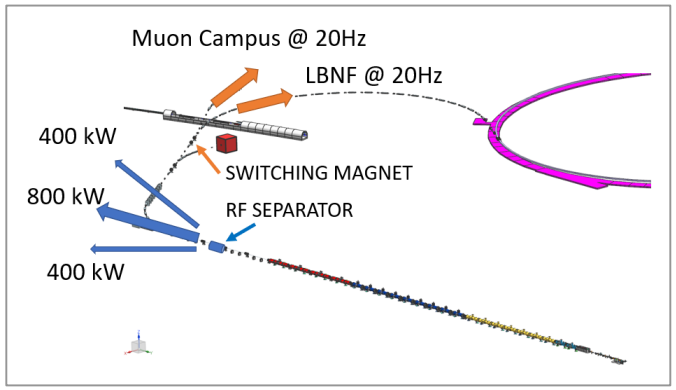
"This approval marks a significant milestone for the project and the start of a new era for Fermilab and the global HEP community. "

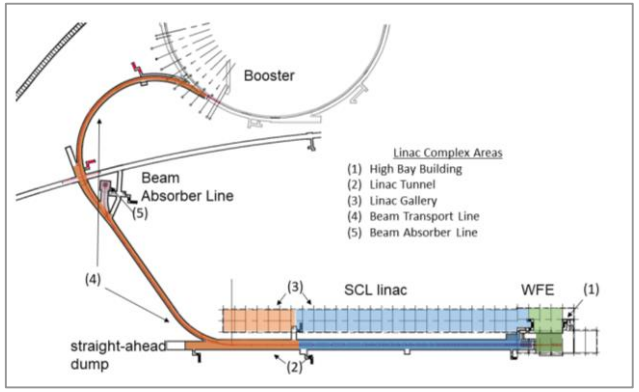
PIP-II 2021 Major Milestones

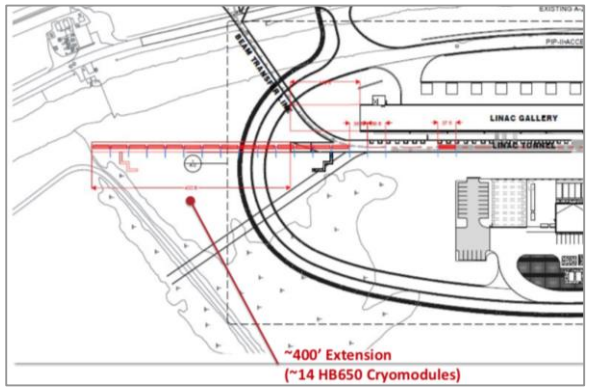
- Receive CD-3A approval for long lead procurements
- Complete beam tests at PIP2IT through HWR and SSR1
- Complete HB650 proto cryomodule integration
- Receive CD-3 Start of Construction/Execution approval
- Complete Cryoplant Building Construction

PIP-II Design Is Compatible With Future Science-Driven Upgrades

- PIP-II is designed for >1 MW over 60 – 120 GeV and 1.2 MW at 120 GeV
- Provides platform for upgrade to >2 MW
- Linac beam power of 1.6 MW (CW), programmable bunch patterns
- Facility enables multi-user, simultaneous, high beam power operations
  - Switch yard to provide beams to Muon Campus in multiuser mode with LBNF
- Linac tunnel includes space and infrastructure to reach 1 GeV and space to add RF separator for beam sharing
- Tunnel extension (by 120 m) compatible with energy 2–2.5 GeV
- Beam current can be increased by a factor of a few by upgrading amplifiers







Summary

- PIP-II is a leading-edge SRF linear accelerator critical to the success of the LBNF/DUNE international neutrino program
- International partnerships are essential for the success of the PIP-II project
- Excellent, experienced project team and strongly committed partners ensure continued technical progress despite pandemic challenges
  - PIP-II baseline is approved
  - Cryoplant building construction is well underway
  - Beam has been accelerated by first two PIP-II cryomodules
- We are building a highly capable accelerator that will power the world's best neutrino experiment!

We greatly appreciate the commitment and strong support from our stakeholders, DOE, and our International Partners!

Thank you!