PIP-II

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

# PIP-II Overview and Status

Rich Stanek, Project Director
for the PIP-II Team

SRF 2023 MOIXA02

PIP-II is a partnership of:

- US-DOE
- India-DAE
- Italy-INFN
- UK-STFC-UKRI
- France-CEA, CNRS/IN2P3
- Poland-WUST, WUT, TUL

# Outline

- PIP-II Mission & Scope
- International Partners
- Design and Quality Control
- Challenges
- Project Status
- ASPIRE Program
- Summary

# PIP-II Mission

**PIP-II** is an essential upgrade to Fermilab accelerator complex to enable the world's most intense beam of neutrinos to LBNF/DUNE, and a broad physics research program for decades to come.

## PIP-II Capabilities

### Beam Power

- 1.2 MW proton beam
- Upgradeable to multi-MW

### Flexibility, multi-user capability

- CW-compatible
- Customized beams
- Multi-user delivery

### Reliability

- Modernizes Fermilab accel complex


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

## PIP-II Scope

### 800 MeV H− SRF linac

CW RF Operations

### Linac-to-Booster transfer line

### Accelerator Complex Upgrades

Booster
Recycler
Main Injector

### Conventional Facilities

Space reserved for two CMs for 1 GeV Upgrade

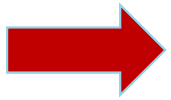
# CD-4 Key Performance Parameters Unchanged
## Demonstrated at Project Completion

| # | Scope | Threshold KPPs | Objective KPPs |
|---|---|---|---|
| 1 | Linac Beam Energy | Accelerate H- beam to 600 MeV | 1. Accelerate H- beam to 700 MeV<br>2. Linac systems required to accelerate beam to 800 MeV installed and tested |
| 2 | Linac Beam Intensity | Beam delivered to Beam Dump at the end of Linac | Beam with intensity of 1.3E12 particles per pulse (H-) at 20 Hz delivered to Beam Line Dump |
| 3 | Booster/ Recycler/ Main Injector upgrades | Booster, Recycler, and Main Injector Upgrades to support operations with beam power of 1.2 MW on the LBNF target are installed and tested without beam | Linac beam injected and circulated in Booster |

Objective KPPs are aligned with the baseline project scope and assure that the accelerator facility as constructed is capable of meeting the scientific needs of the Fermilab program.

# Beam Performance Goals and Partial Component List

| Performance Parameter | Value | Units |
|---|---|---|
| Delivered Beam Energy | 800 | MeV |
| Beam Particles | H- | |
| Beam Pulse Length | 0.54 | ms |
| Particles per Pulse | 6.7 | $10^{12}$ |
| Pulse repetition Rate | 20 | Hz |
| Average Beam Current | 2 | mA |
| Maximum Bunch Intensity | 1.9 | $10^{8}$ |
| Maximum Bunch Rep Rate | 162.5 | MHz |
| Bunch Pattern | Prog and Arbitrary | |
| RF Frequency | 162.5 harmonic | |
| Bunch Length (RMS) | < 4 | ps |
| Transverse Emittance | ≤ 0.3 | mm-rad |
| Longitudinal Emittance (RMS) | ≤ 0.3 | mm-rad |



| Component | Number Required |
|---|---|
| SSR1 cryomodules | 2 |
| SSR2 cryomodules | 8 |
| LB650 cryomodules | 10 |
| HB650 cryomodules | 4 |
| 7 kW SSA | 16 |
| 20 kW SSA | 35 |
| 40 kW SSA | 36 |
| 70 kW SSA | 24 |
| ORBUMP magnets | 6 |
| Gradient magnets | 6 |
| Painting magnets | 10 |
| Gamma-t Quad magnets | 18 |
| Superconducting solenoids | 33 |
| Beam Current Monitors | 48 |
| Beam Position Monitors | 126 |
| Beam Loss Monitors | 235 |
| Beam Profile Monitors | 47 |


Work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under U.S. DOE Contract No. DE-AC02-07CH11359

***PIP-II will provide a highly capable, reliable, upgradeable and expandable scientific infrastructure with significant savings to DOE***

# PIP-II International Partners, Expertise and Capabilities

## India, Department of Atomic Energy (DAE) (started 2009)
## BARC, RRCAT, VECC; and 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)

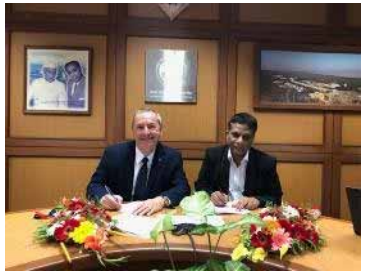
Substantial engineering and manufacturing experience; Construction, operation of synch light & neutron sources SRF cavity processing and testing for ESS

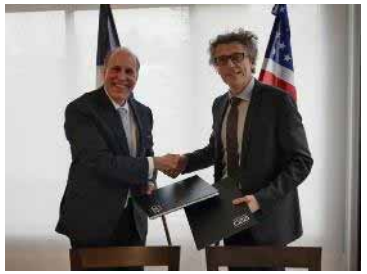
## France, CEA, CNRS/IN2P3 (started 2017)

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 is the U.S. first accelerator project to be built with major international contributions; benefits from world-leading expertise, capabilities***



PIP-II

# Other U.S. Institutions are Involved

- PIP-II Partnerships not limited to international institutions
  - Argonne National Lab (ANL) built the HWR
  - Low Level RF Collaboration
    - Lawrence Berkeley National Lab (LBNL)
    - Thomas Jefferson National Lab (JLab)
    - Stanford Linear Accelerator Center (SLAC)
- Large projects require collaborations – *rare to be able to do one on your own*
  - Makes efficient use of government investments in SRF infrastructure
  - Improves ability to resolve issues (technical, schedule)

# Linac Scope

PIP2IT successfully demonstrated 17 MeV beam through the first SSR1 CM with parameters required for LBNF/DUNE operations

**Cryoplant**
2.5kW @ 2K

**CDS**

**HWR**
162.5 MHz

**Single Spoke 1**
SSR1 x (1 + 2)
325 MHz

**Single Spoke 2**
SSR2 x (1 + 7)
325 MHz

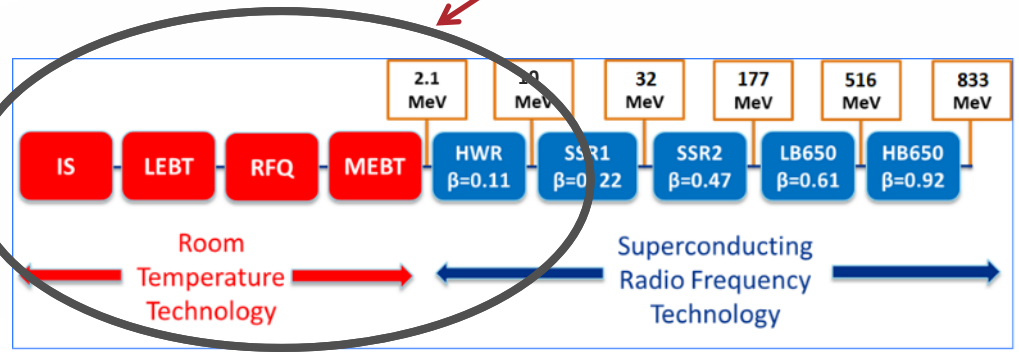
**Elliptical**
LB650 x (1 + 9)
650 MHz

**Elliptical**
HB650 x (1 + 4)
650 MHz

SRF technology

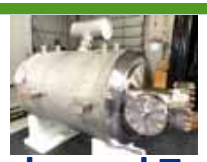
Room temperature technology

Tested at PIP2IT

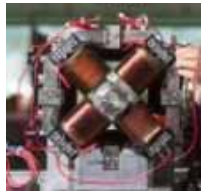
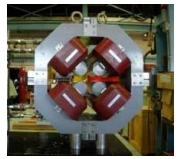
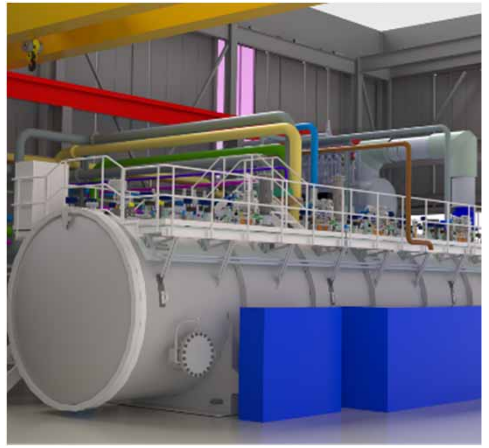
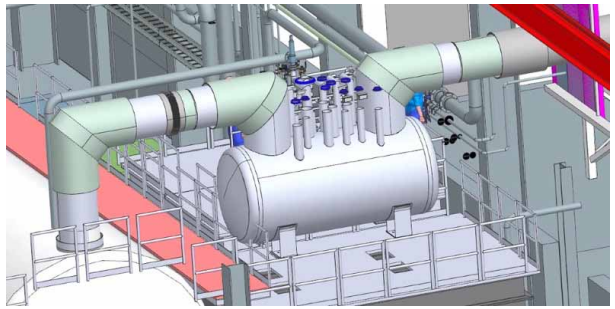



*PIP-II technology map*

# Overview of Construction IKC for PIP-II – CryoModules (CM)

| | SSR1 | SSR2 | LB | HB |
|---|---|---|---|---|
| DAE | 9  + Coupler and Tuners | 33 SSR solenoids  1 CM set, assembly @FNAL | 4  + Coupler and Tuners | 1  CM set, assembly @FNAL |
| cea | | | 10  | |
| CNRS IN2P3 | |  Cavity Tests | | |
| INFN | | | 40  | |
| UKRI | | | | 3  |

# Overview of Construction IKC for PIP-II – other than CM

| | SSAs | LLRF | MEBT/Warm Unit Magnets | Cryoplant and CDS Components |
|---|---|---|---|---|
| | 9  7kW 40 20 kW<br>All<br>40  40kW 31 70 kW |  <br>1 SSR1<br>1 SSR2<br>1 HB650 |  9 MEBT quad<br>91 All<br>   <br>Warm unit magnets |  |
| | | | | CDS for TTL and DVB<br>  |

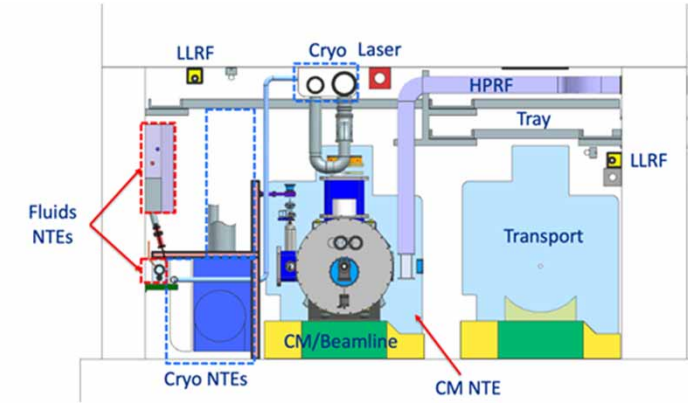
# Partnerships

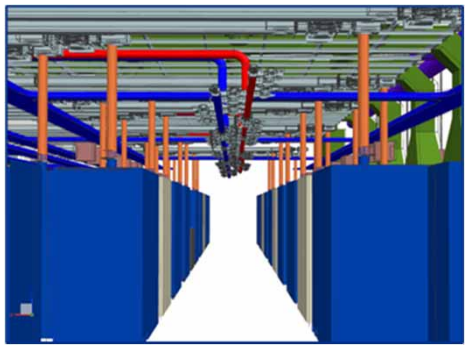
- *Partnerships work when both sides get benefit from the collaboration*
- ***To our Partners: PIP-II would not be successful without you!***
- Partners, both international and at other national labs
  - Add another level of technical expertise and experience
    - *Transparency and communication are the keys*
  - Allow for parallel efforts while reducing infrastructure costs

- Not without possible drawbacks including some additional risks
  - Technical standards/codes may not be the same – adding additional analysis/reviews
  - Quality Control systems probably not consistent – adding extra work to map QC data
  - Number of funding sources increases – adding more uncertainty in fund availability
  - Procurements can be handled differently at different institutions – adding complexity

# Design Control

- Designs are driven by Physics Requirements and Technical Requirements Specifications
- Changes are tracked from the Technical Baseline (per Configuration Management Plan)
- Design Change Board reviews requests (DCR) and approves changes
- Not-to-Exceed envelopes are used initially
  - Eventually actual designs are input to full linac 3D CAD model (Installation Coordinator)
- Per the Systems Engineering Management Plan
  - Level 2 Subsystem Manager is the “Design Authority”
  - Governing institution responsible for final design of component is “Designer of Record”



| Item | Designer of Record Institute(s) | Production Entity Institute(s) |
|---|---|---|
| **CryoPlant** | | |
| CryoPlant | Commercial | DAE - BARC |
| **CDS** | | |
| Distribution Valve Box | WUST | WUST |
| Tunnel Transfer Line Modules | WUST | WUST |
| **SSR1 CM1-2** | | |
| CM | FNAL | FNAL |
| Jacketed Cavities | FNAL | DAE - BARC |
| Couplers | FNAL | FNAL |
| Tuners | FNAL | DAE - BARC |
| SC Solenoids | DAE - BARC | DAE - BARC |
| **SSR2 CM1-7** | | |
| CM (including shipping) | FNAL & DAE - BARC | FNAL & DAE - BARC |
| Jacketed Cavities | FNAL | DAE - BARC & IN2P3 |
| Couplers | FNAL | DAE - BARC & IN2P3 |
| Tuners | FNAL | DAE - BARC & IN2P3 |
| SC Solenoids | DAE - BARC | DAE - BARC |

| Item | Designer of Record Institute(s) | Production Entity Institute(s) |
|---|---|---|
| **LB650 CM1-9** | | |
| CM (including shipping) | FNAL & CEA | CEA |
| Jacketed Cavities | FNAL | INFN & DAE - VECC |
| Couplers | FNAL | DAE - BARC |
| Tuners | FNAL | DAE - BARC |
| **HB650 CM1-6** | | |
| CM (including shipping) | FNAL & DAE - RRCAT | UKRI & DAE - RRCAT |
| Jacketed Cavities | FNAL | UKRI & DAE - RRCAT |
| Couplers | FNAL | UKRI & DAE - RRCAT |
| Tuners | FNAL | UKRI & DAE - RRCAT |
| **HPRF** | | |
| 325MHz-7kW SSAs (SSR1) | DAE - BARC | DAE - BARC |
| 325MHz-20kW SSAs (SSR2) | DAE - BARC | DAE - BARC |
| 650MHz-40kW SSAs (LB650) | DAE - RRCAT | DAE - RRCAT |
| 650MHz-70kW SSAs (HB650) | DAE - RRCAT | DAE - RRCAT |
| **MAGNETS** | | |
| PIP-II Magnets | DAE - BARC | DAE - BARC |
| 650 MHz Warm unit magnets [quads+ correctors] | DAE - BARC | DAE - BARC |

# Quality Assurance and Control

- A Quality Control Coordination Group is established to bring Quality representatives from each Partner together in a forum.
  - This group discusses QA expectations and ensures alignment of QC activities for like contributions.
  - Meets quarterly with individual one on one meetings every month

- Quality Control (QC) Plans are identified and tracked via a QC Plan Tracking Tool and are developed in accordance with the Technical Review Plan.

- Travelers are developed across the Project to document results of QC checks
  - Currently focusing on traveler exchange process and Quality Control Alignment Matrix

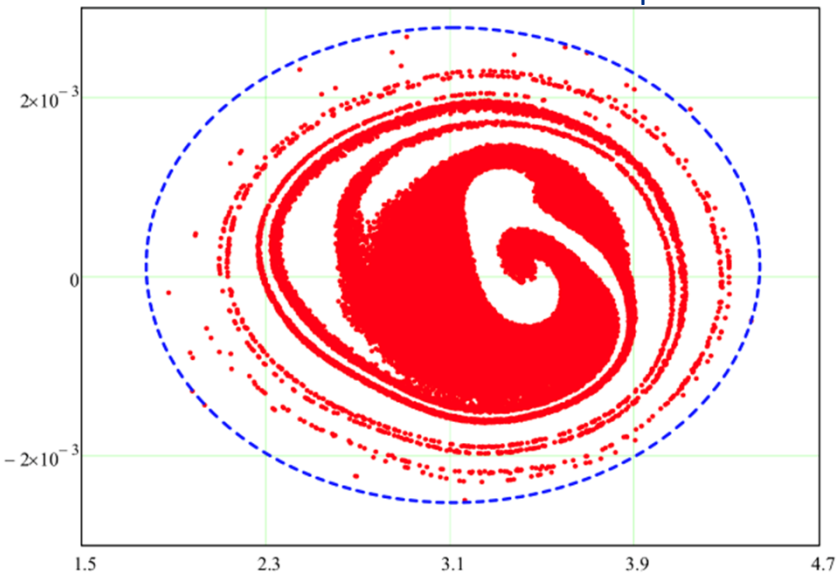
# PIP-II Challenges

- Injecting into an existing machine in the accelerator complex
  - Inject at 800 MeV instead of 400 MeV
  - Inject over 550 microsec instead of 33 microsec with limited injection length in the lattice
  - Operate Booster at 20 Hz instead of 15 Hz
- Variety of SRF cavity types adds complexity
  - Fabrication differences, processing recipe, mechanical stability…
  - CMs have many common features
  - Prototypes are necessary
- Switching to an EPICS-based control system for FNAL accelerator facility
  - Will run hybrid with remnants of ACNET still present
- Integration into overall Lab schedule (2-year shutdown)
  - PIP-II readiness affects entire FNAL program

# Simulations of Beam Dynamics in Booster

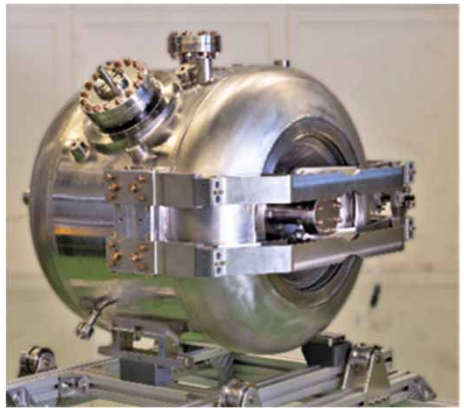
- Booster 400 MeV optics scaled to 800 MeV with modifications for the PIP-II injection was used
- Realistic Linac beam distribution tracked from the RFQ
- Foil model integrated in simulations
- Booster Impedance simulated, measured, used for simulations
- Transition crossing simulated
- PIP-II mitigates intensity limits and losses in Booster:
  - Space charge tune-shift reduced by factor of 2 – 4 at 800 MeV injection
  - Transverse emittances meet requirements
  - Electron cloud simulated, small impact at PIP-II intensity
  - Beam losses at the 2% level with 2-stage collimation in BTL, and increased aperture extraction magnets

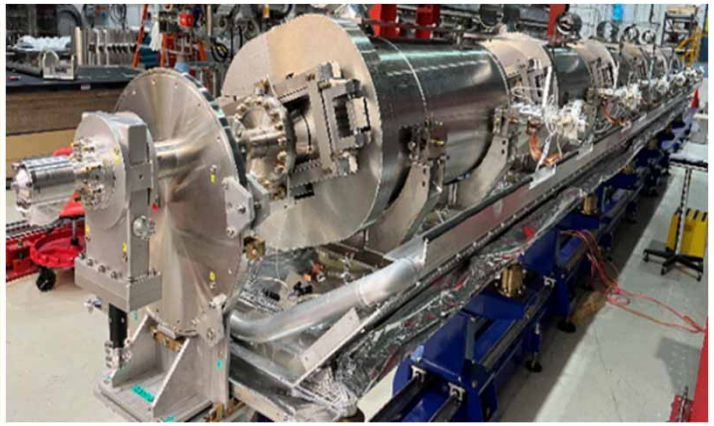
Simulated booster beam distribution at extraction.
The blue line shows the 0.1 eV·s requirement.



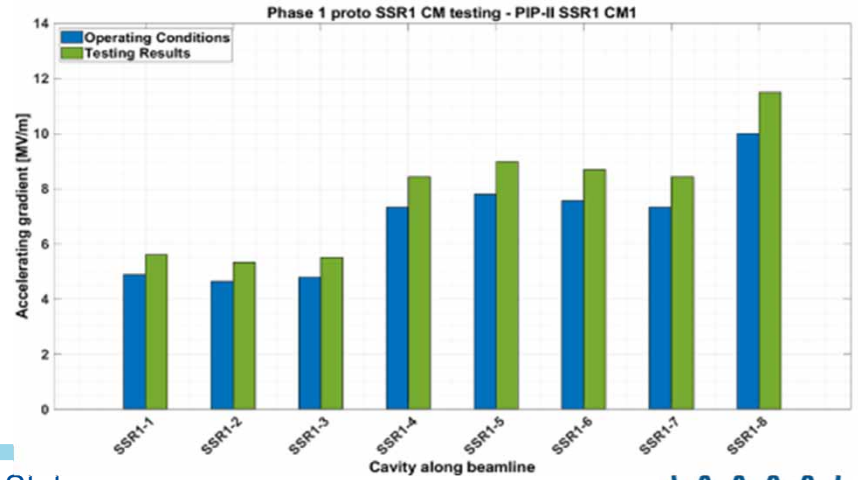
# PIP-II Status - SRF

- *Three CMs have been fabricated and tested (HWR, SSR1 pCM and HB650 pCM)*
  - *HWR (after some minor rework) will be linac ready*
  - *SSR1 pCM linac ready as is*
  - *HB 650 pCM will need to have cavity string rebuilt before use in linac*
- *SSR2 cavities being processed – issue with Field Emission/HPR*
  - *Procurement of components for SSR2 pCM completed, preparing facilities for the assembly*
- *Processing recipes for LB and HB 650 cavities are resolved (pending final testing)*
- *LB650 Nb awarded (INFN) cavity procurement documentation is ongoing*
- *HB650 Nb awarded (UKRI) cavity contract awarded (UKRI)*
- *Procurements for LB650 CMs (CEA/Saclay) and HB 650 CMs (UKRI) ongoing*

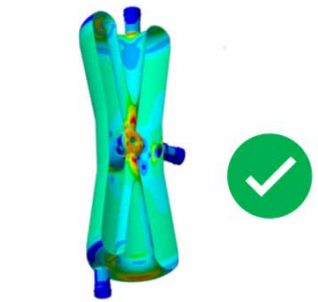


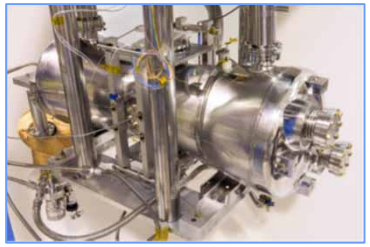


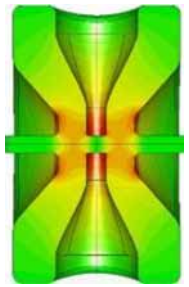
| Cavity Position | Nominal Required Gradient (MV/m) | Maximum Test Gradient (MV/m) | Notes |
|---|---|---|---|
| 1 | 1.39 | 10.8 | No residual FE or MP |
| 2 | 1.89 | 10.9 | No residual FE or MP |
| 3 | 3.91 | 6.5 | Coupler HV Bias failure |
| 4 | 4.79 | 11.2 | No residual FE or MP |
| 5 | 7.19 | 10.5 | No residual FE or MP |
| 6 | 9.70 | 11.0 | No residual FE or MP |
| 7 | 9.70 | 10.7 | No residual FE or MP |
| 8 | 9.70 | 10.6 | No residual FE or MP |



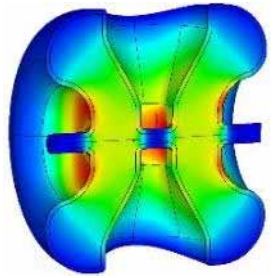
# SRF Cavities



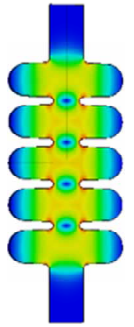


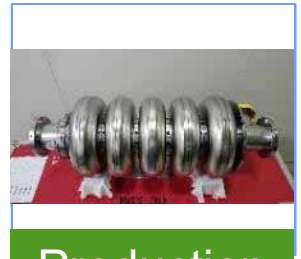


Production

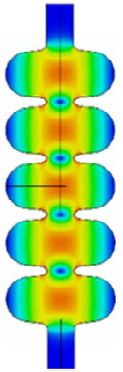


Pre-Production





Production



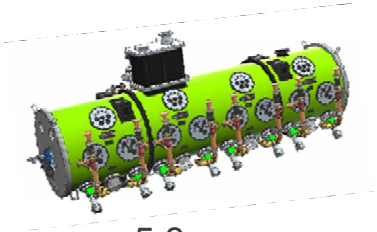
Production

| Name (Qty.) | **HWR (8)** | **SSR1 (16)** | **SSR2 (35)** | **LB650 (36)** | **HB650 (24)** | Units |
|---|---|---|---|---|---|---|
| Type | Half-Wave | Single Spoke | Single Spoke | Elliptical | Elliptical | - |
| $\beta$ | 0.11 | 0.22 | 0.47 | 0.61 | 0.92 | - |
| Frequency | 162.5 | 325 | 325 | 650 | 650 | MHz |
| $Q_0$ | $8.5 \cdot 10^9$ | $8.2 \cdot 10^9$ | $8.2 \cdot 10^9$ | $2.4 \cdot 10^{10}$ | $3.3 \cdot 10^{10}$ | - |
| Gradient | 9.7 | 10 | 11.5 | 16.8 | 18.7 | MV/m |
| Doped | No | No | No | Mid-T bake | Yes | - |

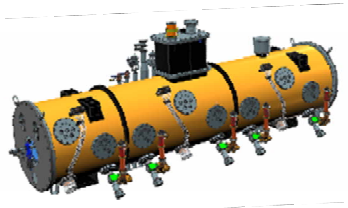
*Prototypes validated* *Ongoing activities*

# SRF Cryomodules

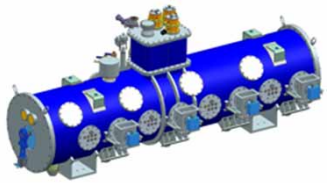
5.9 m



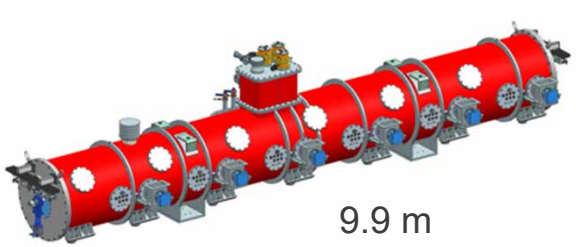
5.3 m



6.5 m



5.5 m



9.9 m

HWR ✓ SSR1 ✓ SSR2 ✓ LB650 ✓ HB650 ✓ (Cold testing is ongoing)

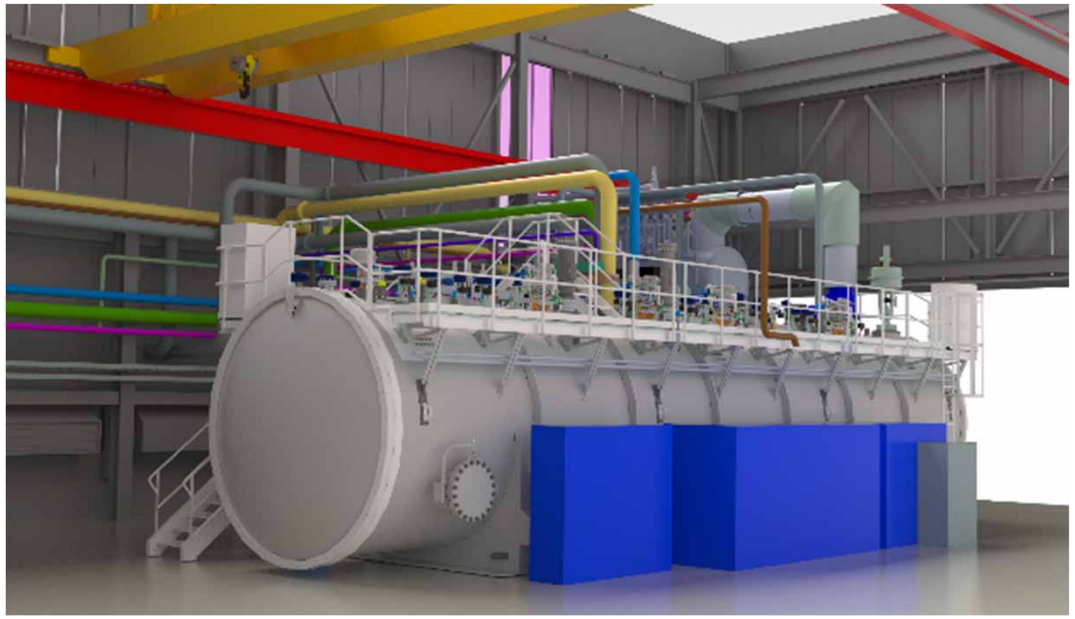
*Pre-Production Cryomodules*

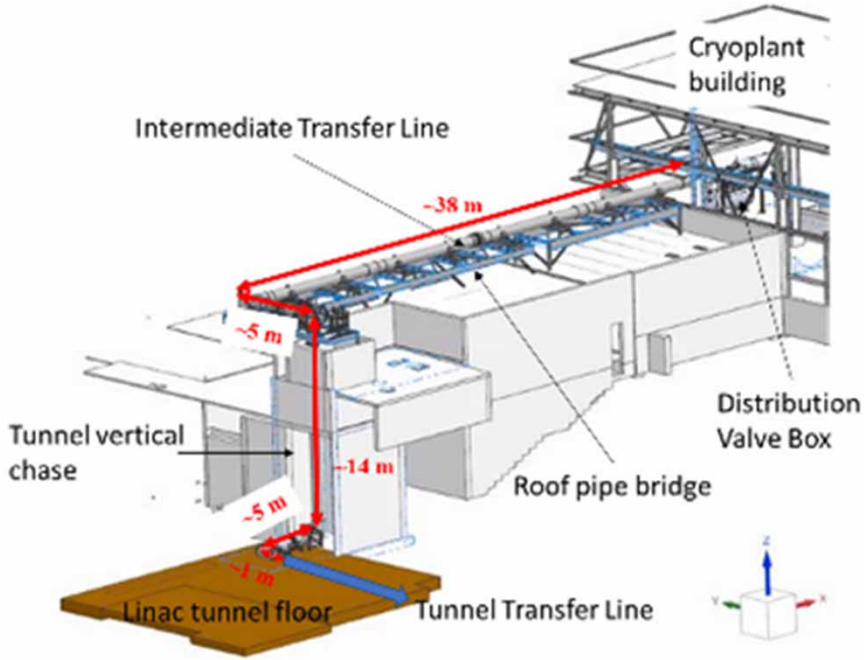


✓ *Prototype designed* ✓ *Prototype built* ✓ *Prototypes validated*

# PIP-II Status - Cryo

- *Cryoplant is on order (BARC) and final design review is complete*
  - *Expected delivery ~Nov/Dec 2024*
  - *2.5 kW @ 2K (50% margin to baseline heat load)*
  - *1.5 kW @ 5K LTTS (120% margin to baseline heat load)*
  - *10.7 kW @ 40K HTTS (70% margin to baseline heat load)*
- *Cryo Distribution System design complete – ready for procurement*





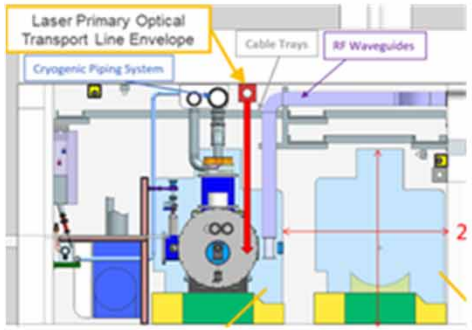
# PIP-II Status - Civil Construction

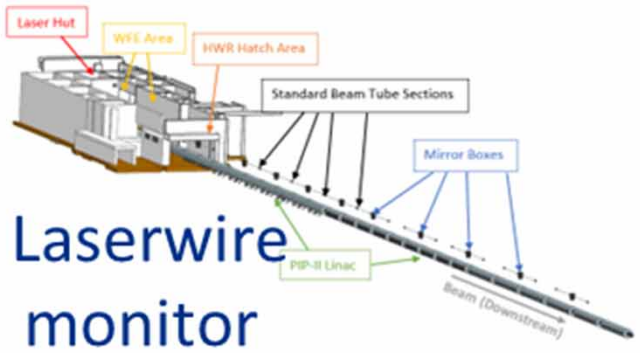
- PIP-II Project requires cryoplant (2,300 $m^2$) and front-end (1,400 $m^2$) buildings, 275 m of linac tunnel, 28 MW electrical power, and 5,700 lpm of cooling water
- Status: completed Site Work, completed Cryoplant Building, and excellent progress on Linac Complex (front-end building and hall)

- 25-May: Serious construction accident has shut down the job (until further notice)

# PIP-II Status for Other Systems

- Full front-end test complete: achieved 17 MeV with LBNF/Dune beam parameters
- Several Solid-State Amplifiers, 7kW (BARC) and 40kW (RRCAT) have been delivered and tested – DAE working on contracts for production units
- ~456 pieces of instrumentation in the machine
  - Laser Wire Profile Monitor (most challenging)
- EPICS control system being implemented on CM test stand
  - μTCA selected as electronics platform
- Contracts placed for key linac/accelerator components including:
  - 200 kW amplifier parts and vacuum tubes, Booster RF cavity, collimators, and magnet PS




| Instrument | WFE | SC LINAC | LINAC end | BTL | Total |
|---|---|---|---|---|---|
| BCM – DCCT | 3 | 0 | 1 | 0 | 4 |
| BCM – ACCT | 3 | 2 | 1 | 2 | 8 |
| BCM – RWCM | 1 | 0 | 1 | 0 | 2 |
| BCM - Scrapers – paddles | 16 | 0 | 0 | 0 | 16 |
| BCM - EID - non-ring | 14 | 0 | 0 | 0 | 14 |
| BCM - EID - ring pickups | 4 | 0 | 0 | 0 | 4 |
| BPM - Warm | 11 | 14 | 6 | 58 | 89 |
| BPM – Cold | 0 | 37 | 0 | 0 | 37 |
| BProM – Laser Wire | 1 | 11 | 1 | 0 | 13 |
| BProM – Wire Scanner | 4 | 0 | 0 | 22 | 26 |
| BProM – Emittance Scanner | 6 | 0 | 0 | 0 | 6 |
| BProM – Bunch Shape Monitor | 0 | 0 | 1 | 0 | 1 |
| BProM - Longitudinal – Laser | 1 | 0 | 0 | 0 | 1 |
| BLM - ion | 0 | 46 | 8 | 58 | 112 |
| BLM - PMT | 8 | 63 | 0 | 0 | 71 |
| BLM - neutron | 4 | 46 | 2 | 0 | 52 |

# Key PIP-II Dates

- CD-0 approved – Jan 2016
- CD-1 approved - Jul 2018
- CD-2/3 Early Conventional Facilities Subproject - Jul 2020
- CD-2  Baseline Established - Dec 2020
- CD-3a  Long Lead Procurements - Mar 2021
- CD-3  Start of Project Execution - Apr 2022
- Early CD-4 Finish - Apr 2029
- CD-4  Project Complete - Dec 2032

*Projected dates:*

- *Linac Tunnel Complete (ready for installation) -  Apr 2025*
- *Start of Cryoplant Commissioning – Sep 2025*
- *Start of Beam Commissioning – Dec 2028*

# ASPIRE Fellowship

**A**ccelerator

**S**cience

**P**rogram to

**I**ncrease

**R**epresentation in

**E**ngineering


https://www.fnal.gov/pub/forphysicists/fellowships/aspire/

- … is a Fermilab Fellowship for undergraduate and graduate (masters) students who are underrepresented in STEM disciplines, to develop the next generation of particle accelerator engineers.
- …. aims to further diversify PIP-II and Fermilab workforce and to meet the hiring needs in accelerator engineering disciplines.
- ….is a partnership between Fermilab and Midwest colleges and universities.



*Program is transitioning to EDI Office sponsorship*

# Summary

- PIP-II Team is working very well together
  - Partners are engaged and committed to delivering their components
- PIP-II experienced unprecedented turnover in the management team but we have rebuilt and now have a strong, experienced team in place
- Technical progress at both Fermilab and Partners has been good
  - Contracts for key components are being executed and parts delivered
  - Moving closer to cryomodule production

***Project execution is underway, our technical teams are talented and motivated to deliver the PIP-II Project***

# PIP-II

**Follow us:**

- www.pip2.fnal.gov
- @PIP2accelerator
- /showcase/pip-ii/

# Institutions

- BARC — Bhabha Atomic Research Centre
- CEA — Commissariat à l'énergie atomique
- CNRS/IN2P3 — Centre National de la Recherche Scientifique/Institut national de physique nucléaire et de physique des particules
- FNAL — Fermi National Accelerator Laboratory
- INFN — Istituto Nazionale di Fisica Nucleare
- IUAC — Inter-University Accelerator Centre
- RRCAT — Raja Ramanna Centre for Advanced Technology
- STFC UKRI — Science & Technology Facilities Council UK Research and Innovation
- TUL — Lodz University of Technology
- VECC — Variable Energy Cyclotron Centre
- WUST — Wroclaw University of Science and Technology
- WUT — Warsaw University of Technology