# SRF Cryomodules for PIP-II at Fermilab

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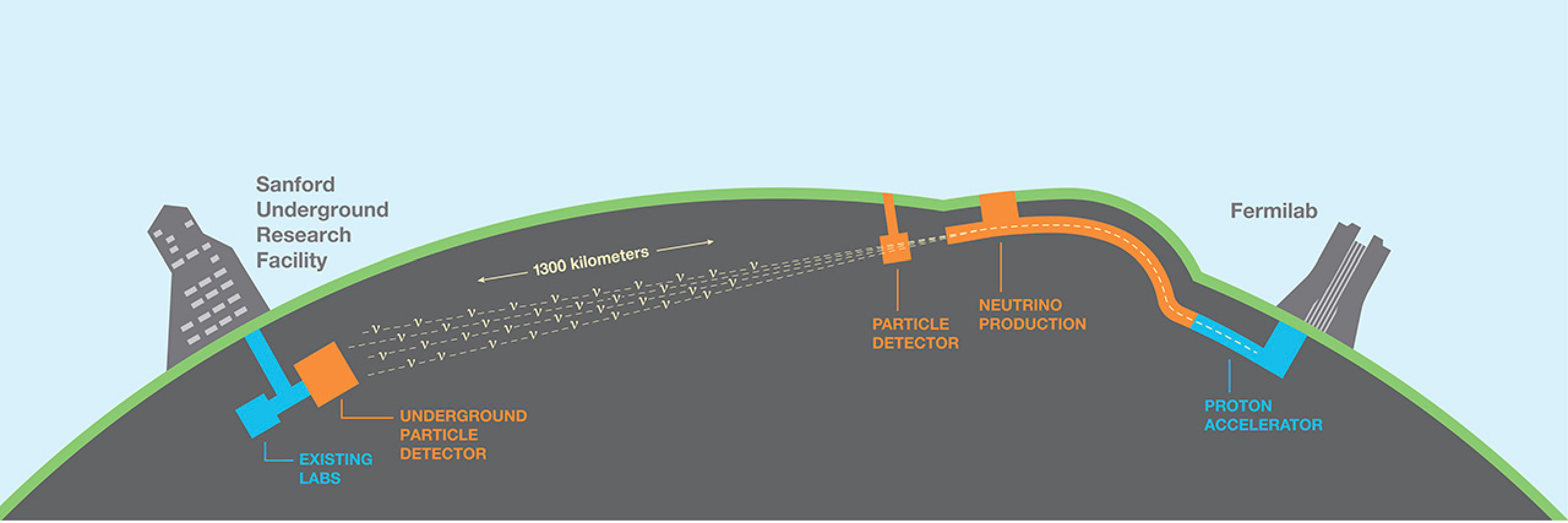
SRF2019

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

# Outline

- Introduction
- Design Overview
- Technical Challenges
- Recent Progress
- Summary

# LBNF / DUNE / PIP-II




Long Baseline Neutrino Facility (LBNF) is the facility for the Deep Underground Neutrino Experiment (DUNE), a dual-site experiment for neutrino science and proton decay studies.

- Hosted at Fermilab (Batavia, IL) and SURF (Lead, SD)

The facility is an internationally designed, coordinated and funded program, a first of its kind for the US DOE.


# 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

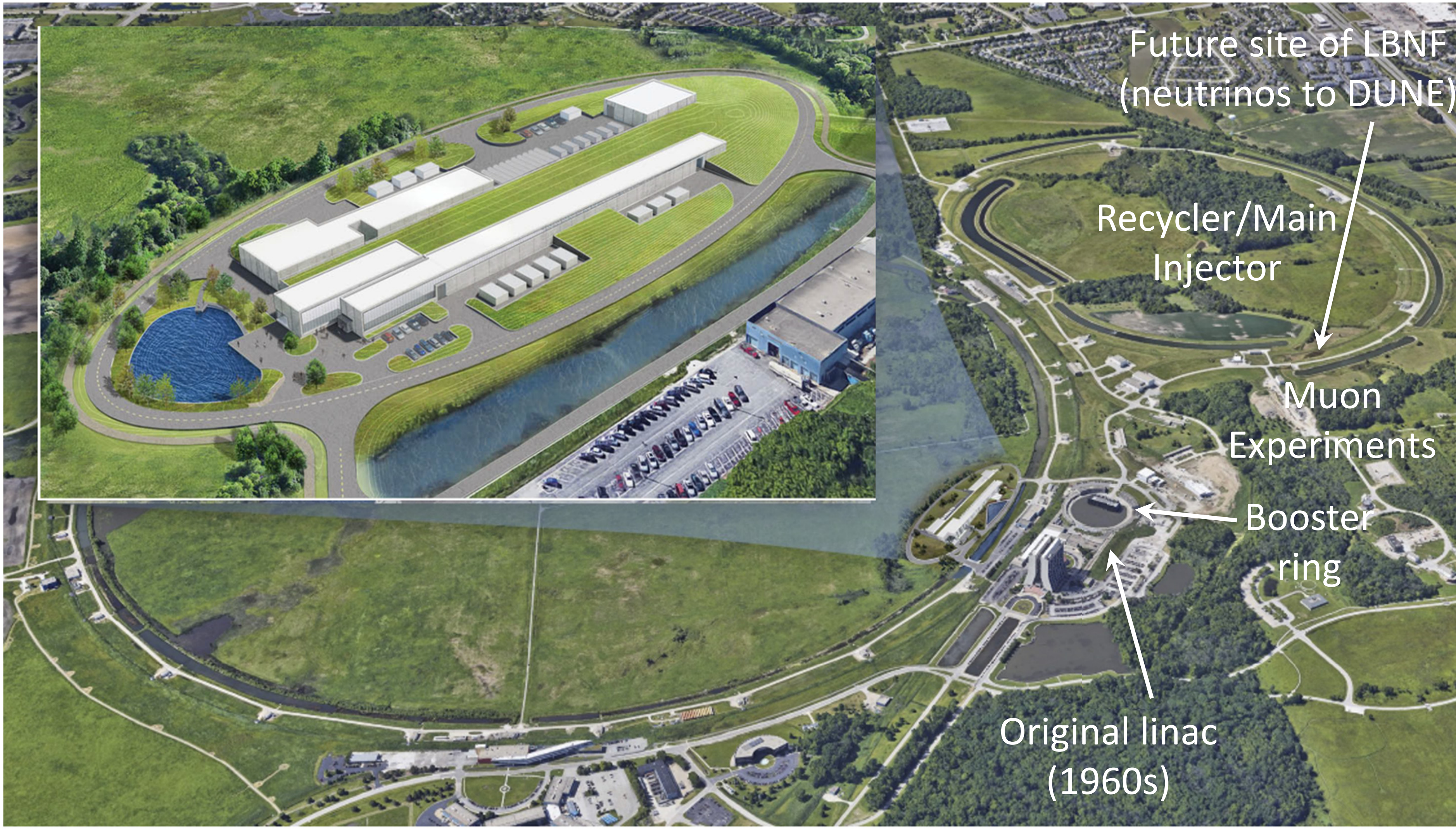
- Compatible with CW-operations which greatly increases the linac output
- Customized beams for specific science needs
- High-power beam to multiple users simultaneously

### Reliability

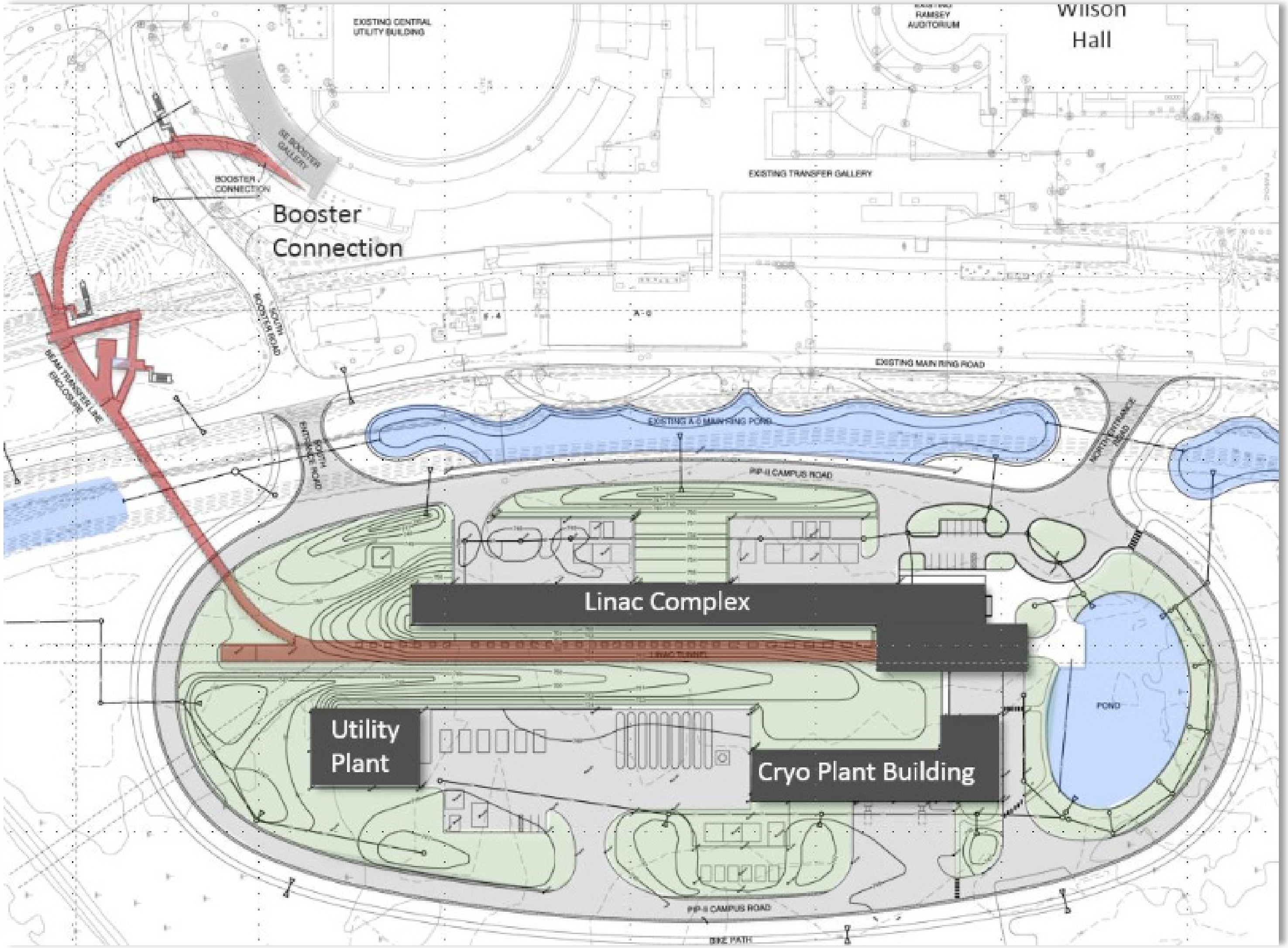
- Fully modernizing the front-end of the Fermilab accelerator complex

***Building the world's most powerful neutrino beam cost-effectively***

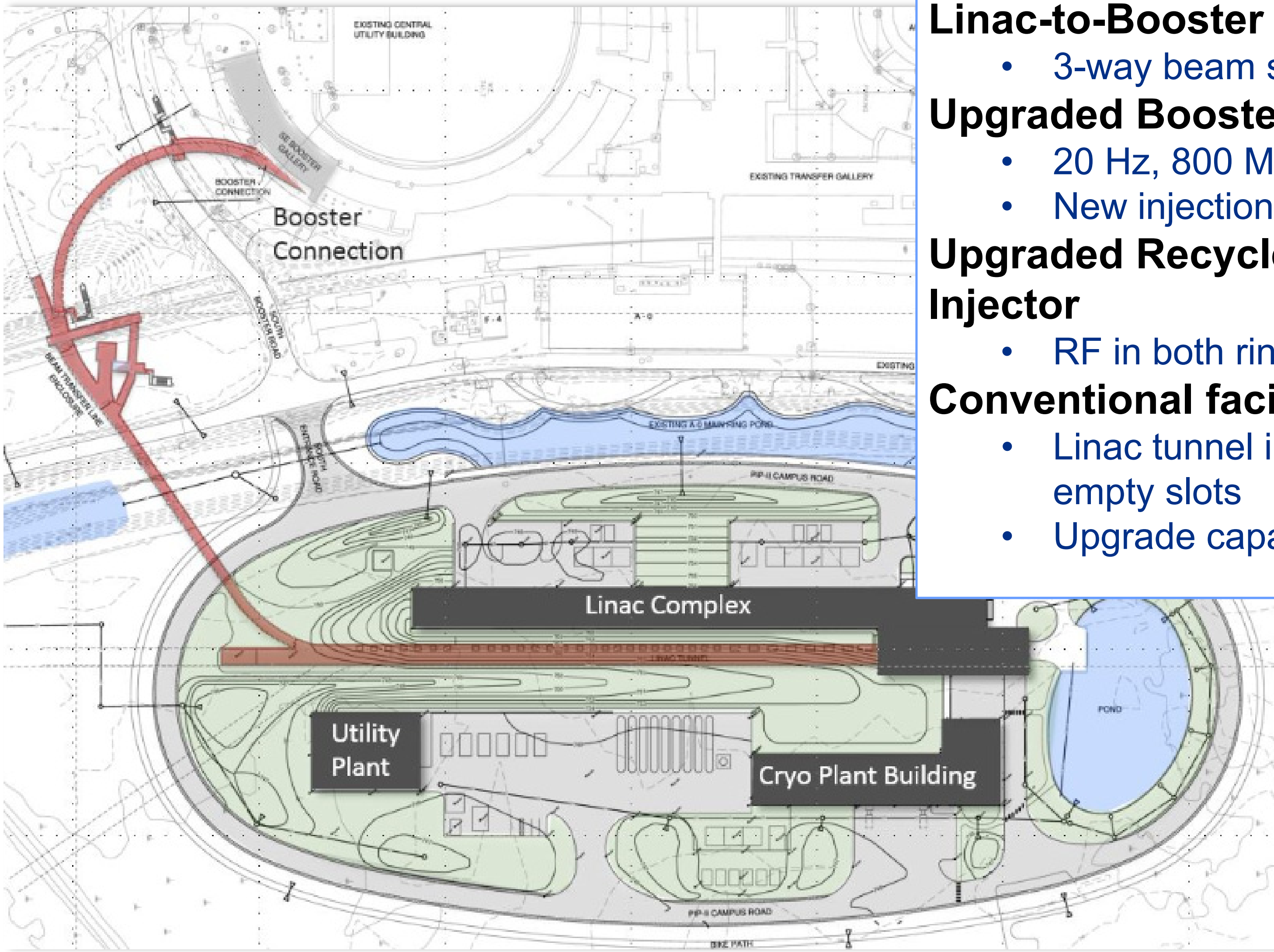
# PIP-II at Fermilab Site



# PIP-II Project Scope



# PIP-II Project Scope




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

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

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

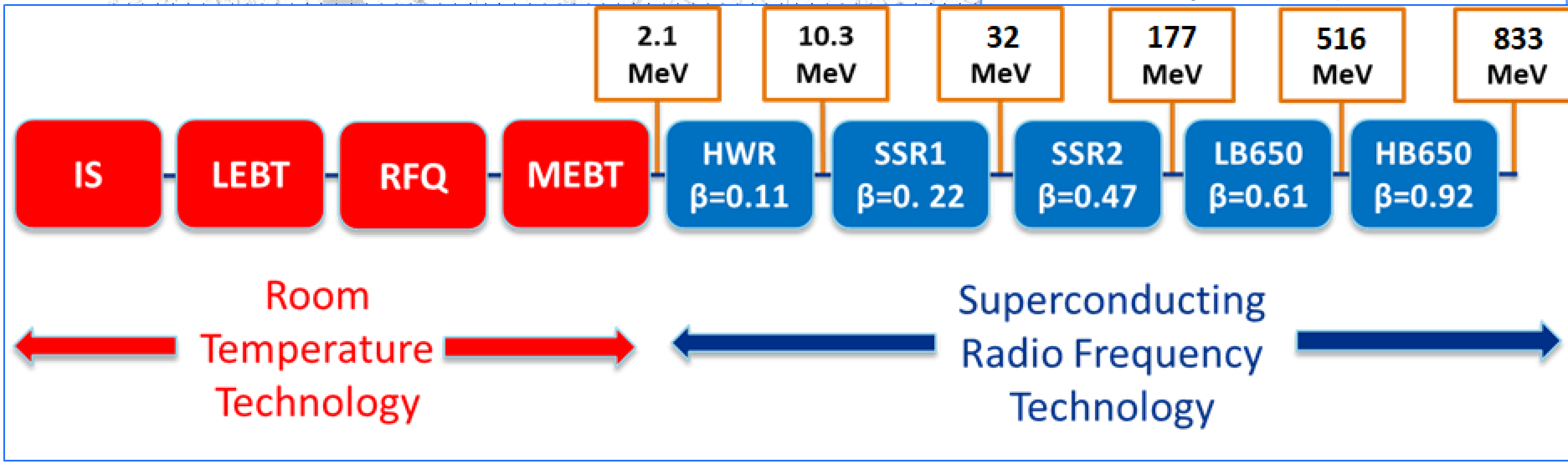
**Upgraded Recycler & Main Injector**
- RF in both rings

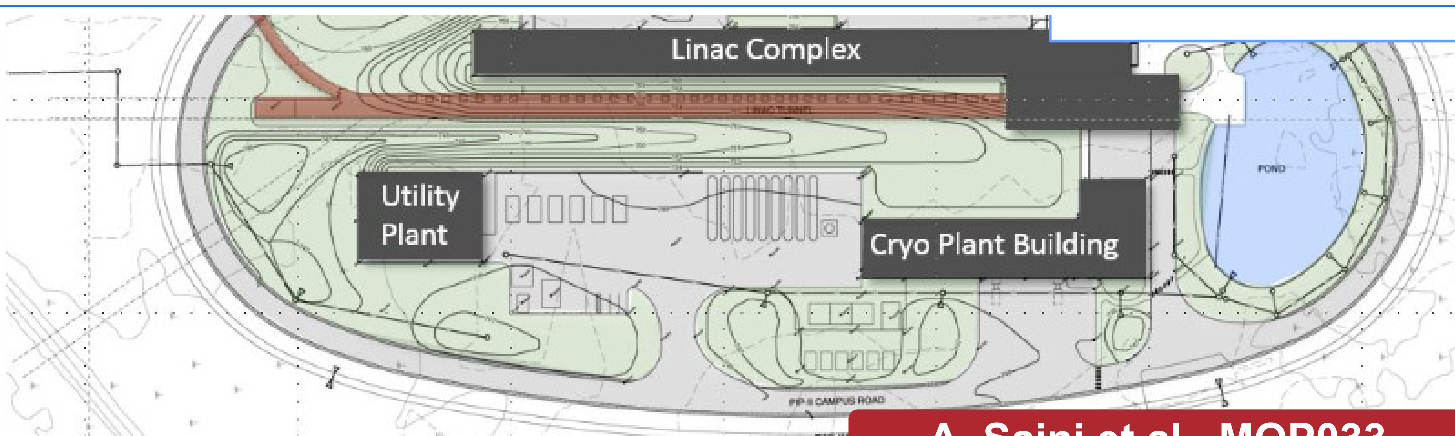
**Conventional facilities**
- Linac tunnel includes 2 empty slots
- Upgrade capability to 1GeV

# PIP-II Project Scope

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

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



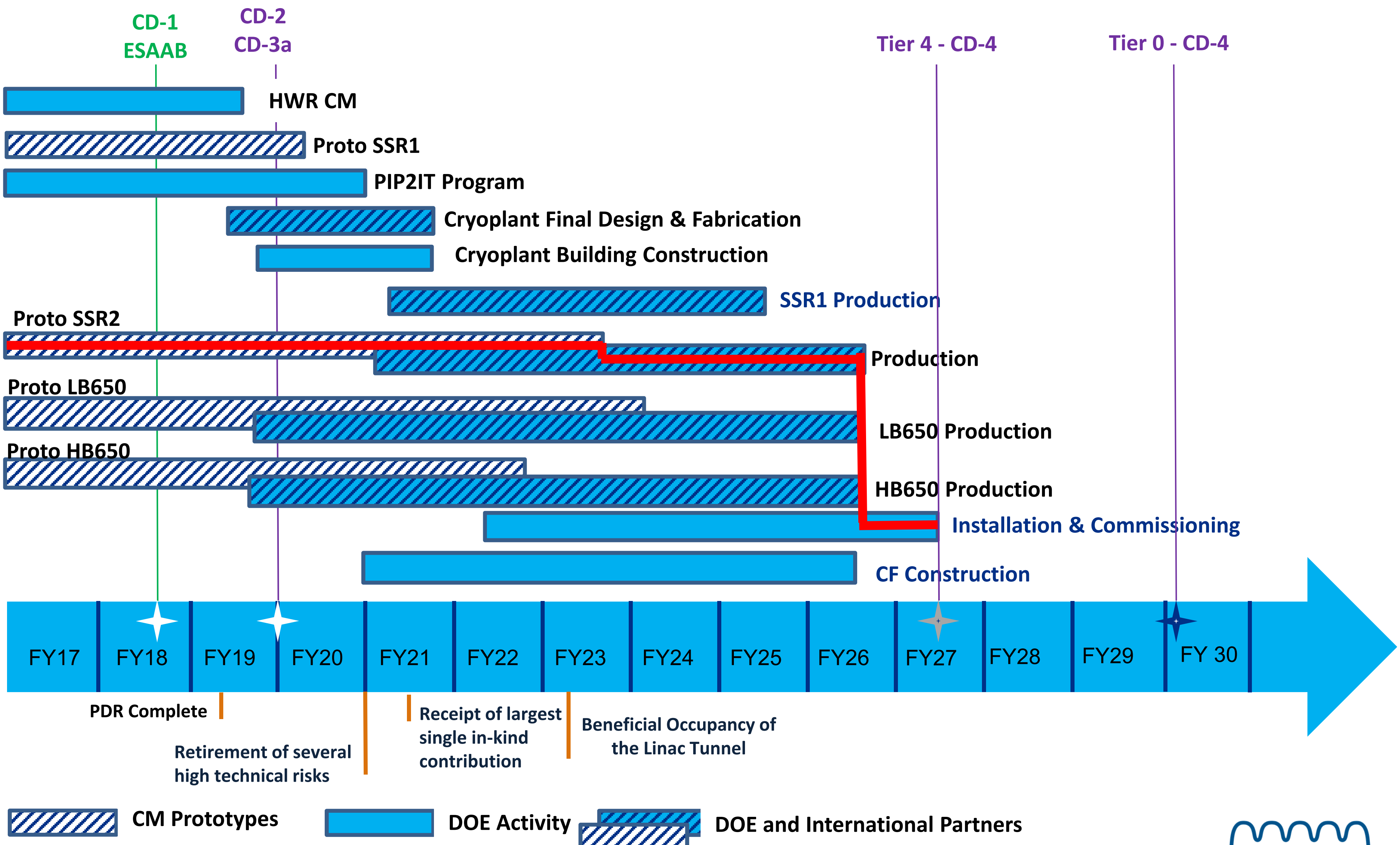




A. Saini et al., MOP033

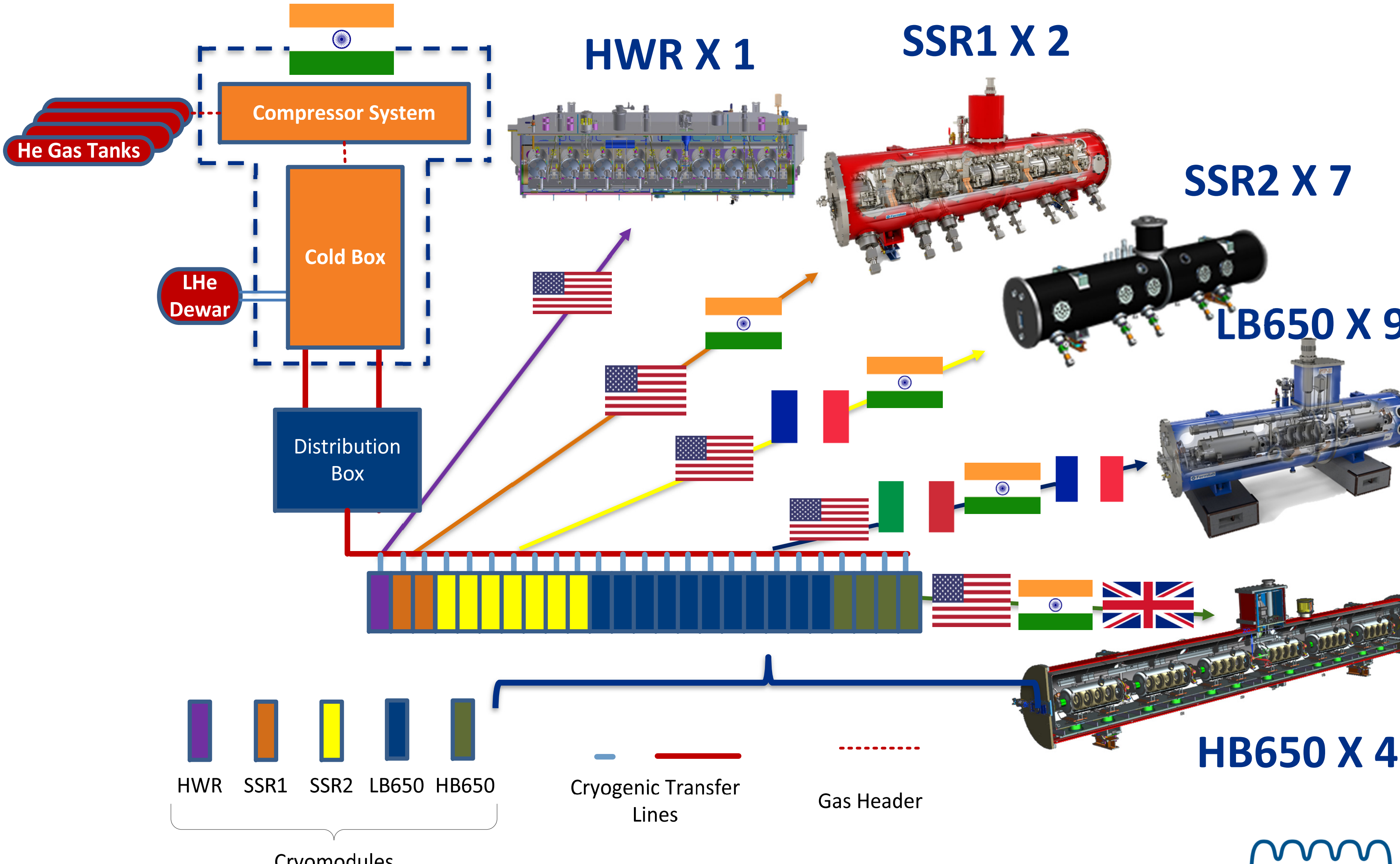


PIP-II

# PIP-II Technical Driven Schedule (Draft)



# PIP-II SRF Linac & Areas of International Interest



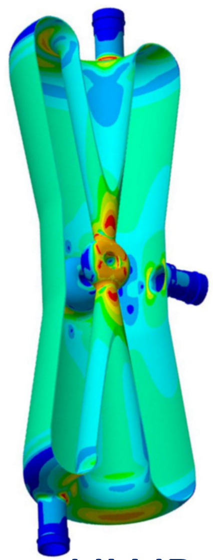
# In-kind Contribution (Cryomodule Components)

| Item | US DOE | In-kind |
|---|---|---|
| HWR Cryomodule | ANL builds cryomodule, FNAL tests. | |
| SSR1 Cryomodules | FNAL builds and tests all Cryomodules | • Some prototype cavities<br>• Production cavities, tuners and solenoids |
| SSR2 Cryomodules | FNAL builds and tests all Cryomodules | • Some prototype cavities<br>• Production cavities, tuners and solenoids |
| LB650 Cryomodules | FNAL tests all cryomodules | Prototype and production cryomodules including all sub components |
| HB650 Cryomodules | • FNAL builds prototype cryomodule and transportation tests<br>• FNAL tests all cryomodules | • Production cryomodules including all subcomponents<br>• Transportation design |
| Cryoplant | FNAL installation, integration and commissioning | Cryoplant Procurement |
| Cryogenic Distribution | FNAL design, procurement, installation and commissioning | |

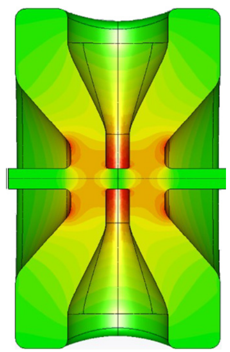


PIP-II

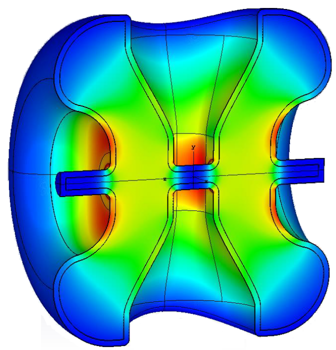
# Design Overview – Cavities



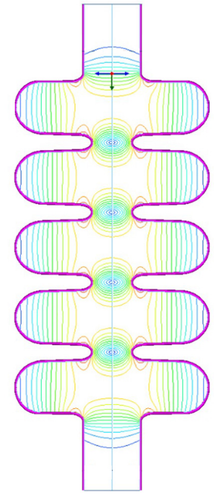
HWR



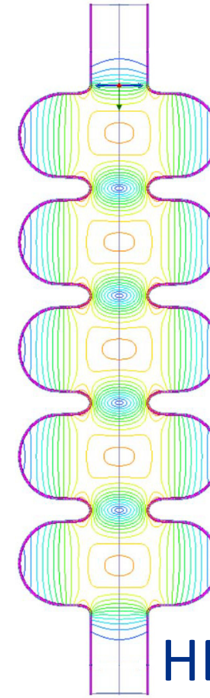
SSR1



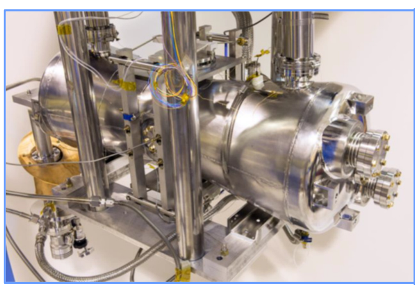
SSR2

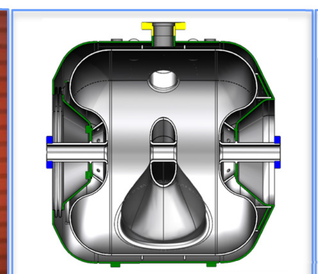
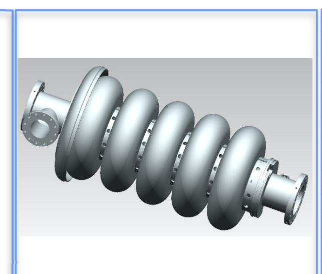
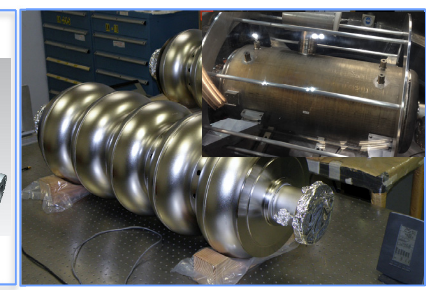


LB650



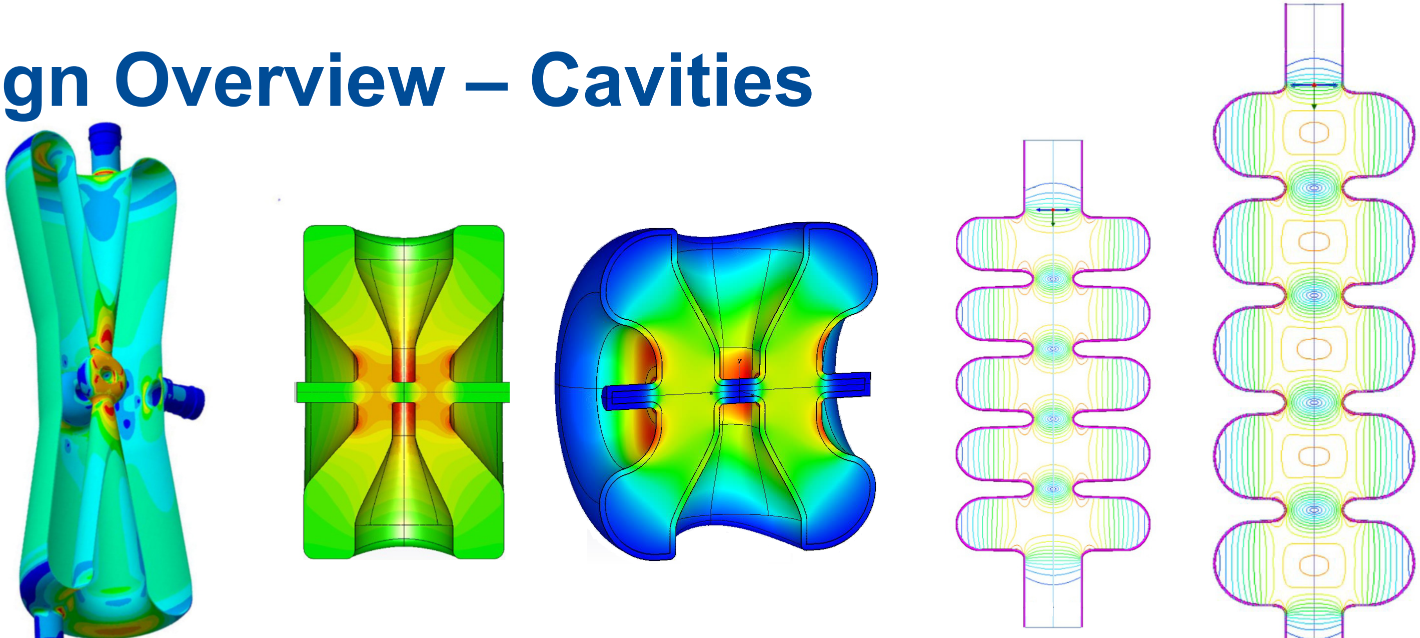
HB650



Preliminary Design
Completed

# Design Overview – Cavities

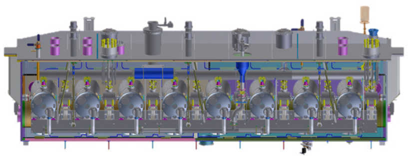


| Cavity | β | Frequency [MHz] | Aperture [mm] | Effective Length [mm] | Accelerating Gradient [MV/m] | $E_{peak}$ [MV/m] | $B_{peak}$ [mT] | R/Q [Ω] | G [Ω] |
|---|---|---|---|---|---|---|---|---|---|
| HWR | 0.11 | 162.5 | 33 | 20.7 | 9.7 | 44.9 | 48.3 | 272 | 48 |
| SSR1 | 0.22 | 325 | 30 | 20.5 | 10 | 38.4 | 58.1 | 242 | 84 |
| SSR2 | 0.47 | 325 | 40 | 43.8 | 11.4 | 40 | 64.5 | 297 | 115 |
| LB650 | 0.61 | 650 | 88 | 70.3 | 16.9 | 40.3 | 74.6 | 341 | 193 |
| HB650 | 0.92 | 650 | 118 | 106.1 | 18.8 | [illegible] | 72.1 | 610 | 260 |

**M. Bertucci, et al., MOP057** **R. Paparella, et al., MOP060** **M. Parise, TUP014**

**P. Berrutti, TUP066**

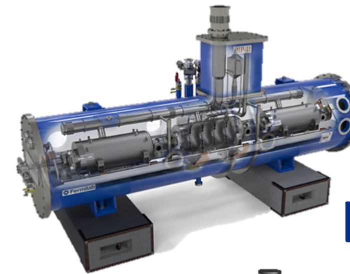
# Design Overview – Cryomodules



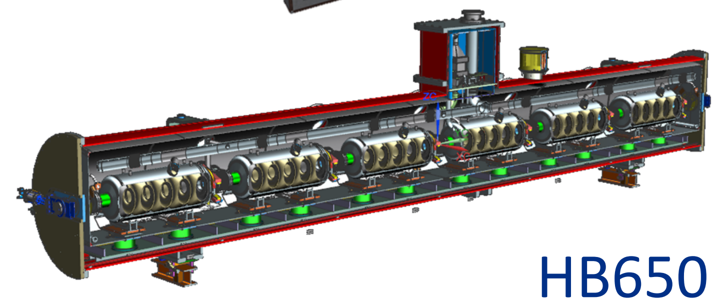
HWR

SSR1

SSR2



LB650



HB650

| Cryomodule | CM # | Cavity # | String Assy. | CM Length [m] | $Q_0$ @ 2K [$x10^{10}$] | $R_s$ [$\Omega$] | $Q_L$ [$x10^6$] |
|---|---|---|---|---|---|---|---|
| HWR | 1 | 8 | 8 x (SC) | 5.93 | 0.5 | 9.6 | 2.3 |
| SSR1 | 2 | 8 | 4 x (CSC) | 5.3 | 0.8 | 14 | 3.0 |
| SSR2 | 7 | 5 | SCCSCCSC | 6.5 | 1.0 | 14.4 | 5.1 |
| LB650 | 9 | 4 | CCCC | 5.52 | 2.2 | 9.0 | 10.4 |
| HB650 | 4 | 6 | CCCCCC | 9.92 | 3.0 | 8.7 | 9.9 |

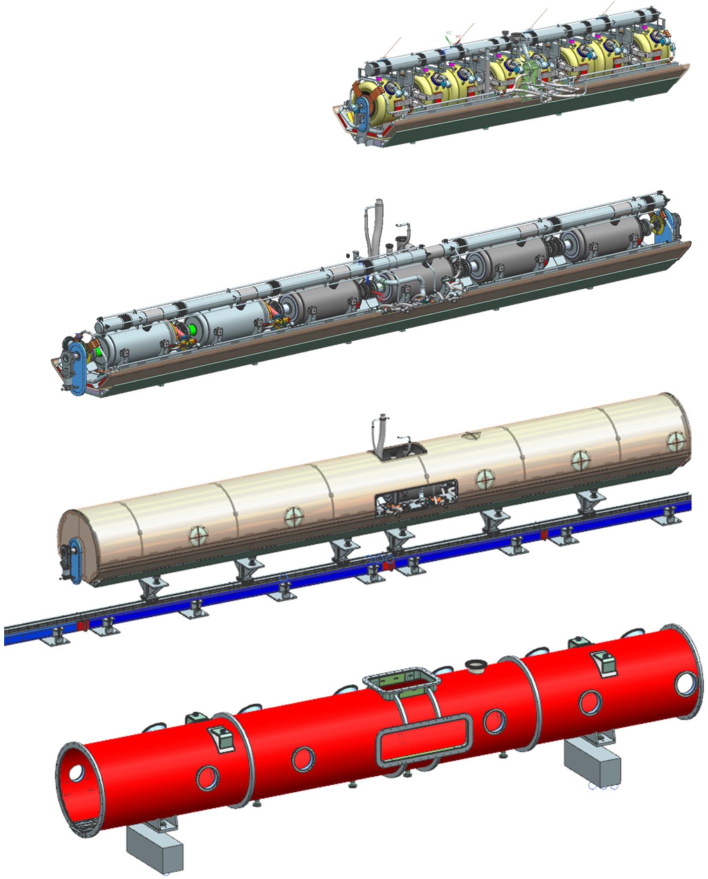
23 Cryomodules + 4 Prototypes C = Cavity, S = Solenoid

# Design Overview – Cryomodules Standardization

Except HWR

- All cryomodules have cavities supported by room temperature strong back.
- Same size of thermal shield, support post and vacuum vessel.
- Same tooling and assembly procedure.

- SSR1/SSR2 common design and components
- LB650/HB650 common design and components



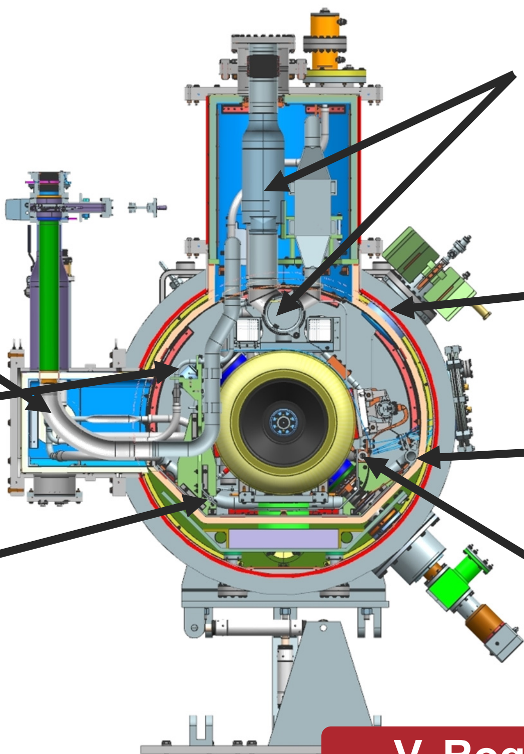
**V. Roger et al., MOP094**

# Design Overview – Cryomodules

All cryomodules have the same layout and the same pressure design values.

All cryomodules need to be compatible with a fast cool down:

- Above 20 K/hour through the Q-disease regime 90 - 175 K.
- Above 120 K/hour through the superconducting transition at 9.2 K



Pipe B - Pumping line
MAWP: 2.05 bar warm, 4.1 bar cold

Pipe A - 2 K supply
MAWP: 20 bar

Pipe H - Cool down / warm up line
MAWP: 20 bar

Pipe G - 2 phase He & chimney
MAWP: 2.05 bar warm, 4.1 bar cold

Pipe I - Helium guard of the current leads
MAWP: 4.1 bar

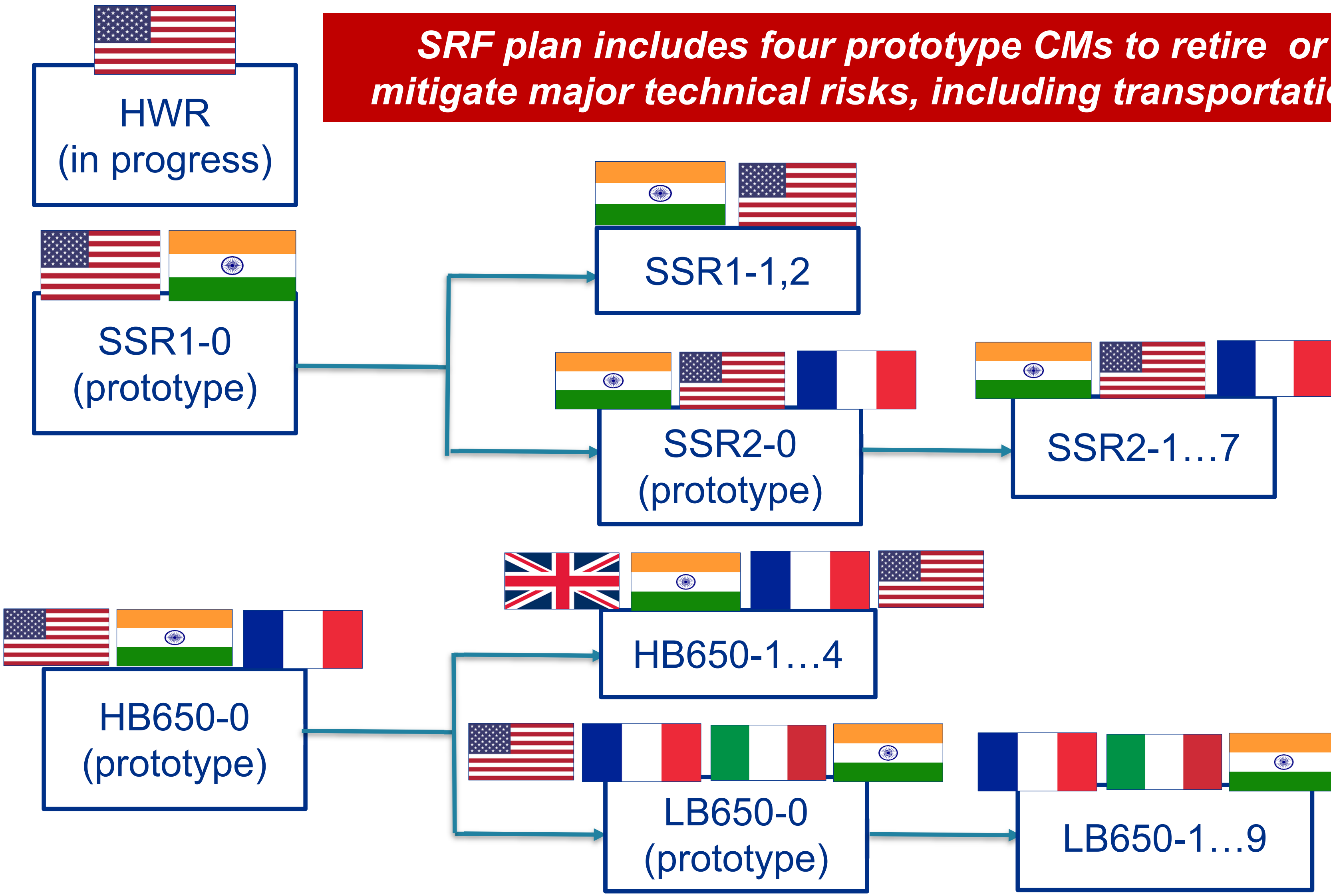
Pipe C & D - 5 K line
MAWP: 20 bar

Pipe E & F - 35-50 K line
MAWP: 20 bar

**V. Roger et al., MOP094**

# Cryomodule (CM) Development Path

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



# Technical Challenges – Cryomodule Heat Loads

- The Cryoplant design is dominated by the 2K heat load
- The 2K heat load is dominated by cavity performance
- Cavity heat loads are based on the expected CM installed $Q_0$ factors and operating gradient

| | HWR | SSR1 | SSR2 | LB650 | HB650 |
|---|---|---|---|---|---|
| Nominal Cavity $Q_0$ [-] | 5E+9 | 8.2E+09 | 1.0E+10 | 2.2E+10 | 3.0E+10 |
| Nominal Gradient [MV/m] | 9.7 | 8.6 | 11.4 | 15.6 | 18.7 |
| Cavities per CM [-] | 8 | 8 | 5 | 4 | 6 |
| Number of CMs [-] | 1 | 2 | 7 | 9 | 4 |
| **Dynamic per CM [W]** | **11** | **16** | **48** | **64** | **128** |
| **Static per CM [W]** | **27** | **18** | **14** | **7** | **9** |

*See ED0008200 for detailed individual cavity parameters

# Cryoplant Capacity Safety Factors

- Safety factors, representing the heat load uncertainty are explicitly defined to avoid mis-sizing
- Under-sizing leads to expensive upgrades or lower operating energy
- Over-sizing can lead to operational issues of capacity control, inefficiencies and unnecessary higher costs

$$Q_C = F_O(F_S Q_S + F_D Q_D)$$

$F_S$ = 1.3, static heat load safety factor
$F_D$ = 1.15, dynamic heat load safety factor
$F_O$ = 1.1, operational safety factor

## Heat Load Summary:

| | 2K (isothermal) | 2K (non-isothermal) | 5K (LTTS) | 40K (HTTS) |
|---|---|---|---|---|
| CM Dynamic [W] | 1466 | 0 | 407 | 1081 |
| CM Static [W] | 274 | 0 | 684 | 3156 |
| CDS [W] | 0 | 250 | 134 | 1971 |
| Total Nominal [W] | 1740 | 250 | 1225 | 6208 |
| **Total with SF [W]** | **2244** | **358** | **1685** | **8699** |

# R&D Goal of Cavity $Q_0$

| Cryomodule | 2K Q0 Specification | 2K Dynamic Heat Load Spec (W) | 2K Q0 R&D Goal | 2K Dynamic Heat Load R&D Goal (W) |
|---|---|---|---|---|
| HWR | 5.0e9 | 11 | | |
| SSR1 | 8.3e9 | 32 | 1.0e10 | 28 |
| SSR2 | 1.0e10 | 337 | 1.5e10 | 239 |
| LB650 | 2.2e10 | 528 | 3.0e10 | 398 |
| HB650 | 3.0e10 | 512 | 4.0e10 | 387 |

Improvement of 359 W

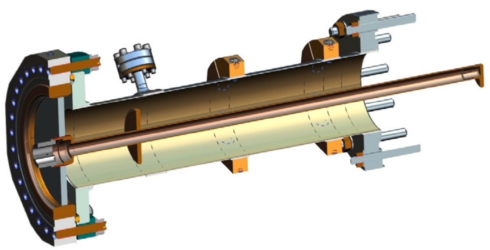
ED0008200 PIP-II Cryogenic Heat Load

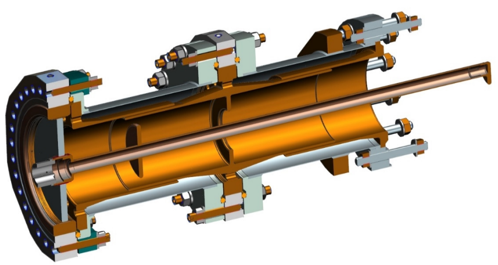
R&D Supported both by Fermilab and partner labs

# Technical Challenges – CW High Power Couplers

## Coupler Design Goals (2 mA CW)

| Cavity | Accelerating Gradient [MV/m] | Power Required [kW] | Power Designed [kW] | $Q_L$ [$\times10^6$] |
|---|---|---|---|---|
| HWR | 9.7 | 5 | 10 | 2.3 |
| SSR1 | 10 | 4.6 | 25 | 3.0 |
| SSR2 | 11.4 | 13.5 | 25 | 5.1 |
| LB650 | 16.9 | 30 | 55 | 10.4 |
| HB650 | 18.8 | 44 | 55 | 9.9 |





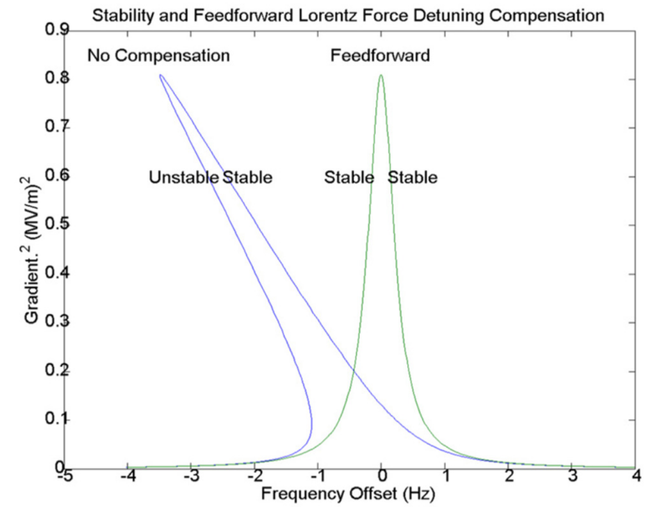
S. Kazakov et al., MOP080

# Technical Challenges – Resonance Control

Initial needs – pulsed beam. Future needs – CW Beam. May operate initially with CW RF and pulsed beam, but exploring pulsed RF for cost saving in operation. Challenges for resonance control!

| Cavity | LFD [Hz/(MV/m)²] | Nominal LFD [Hz] | Half Bandwidth [Hz] |
|---|---|---|---|
| HWR | 1.5* | -122 | 35 |
| SSR1 | 4.4* | -440 | 54 |
| SSR2 | 2.8 | -362 | 32 |
| LB650 | 1.7 | -520 | 32 |
| HB650 | 1.0 | -352 | 33 |

* Measured

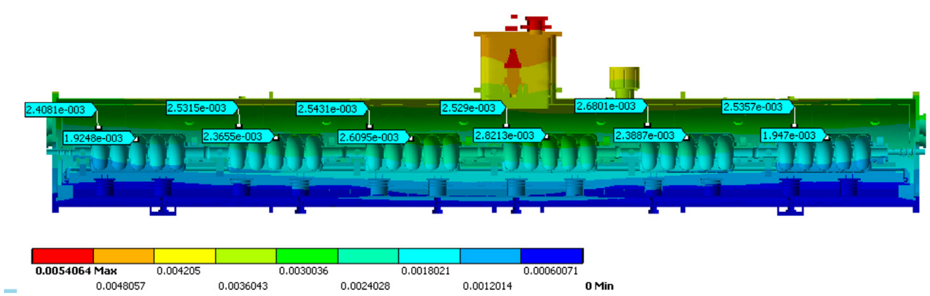


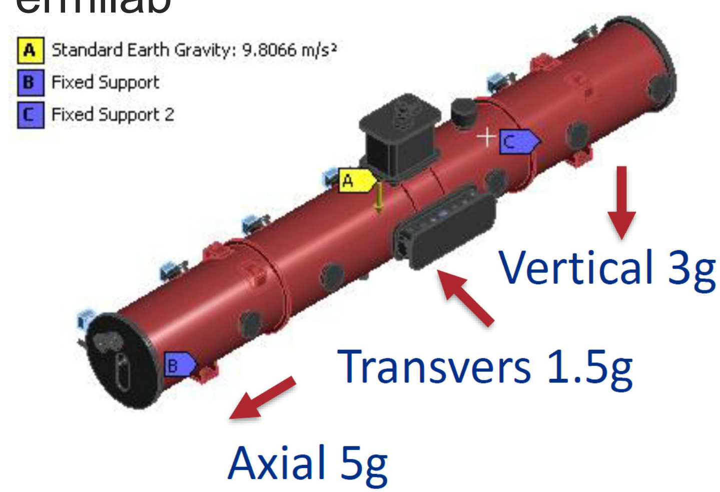

**TUP082. TUP083, TUP084, THP090**

- LLRF Development
- Increase bandwidth
- Increase tuner stiffness

# Technical Challenges – Overseas Transportation

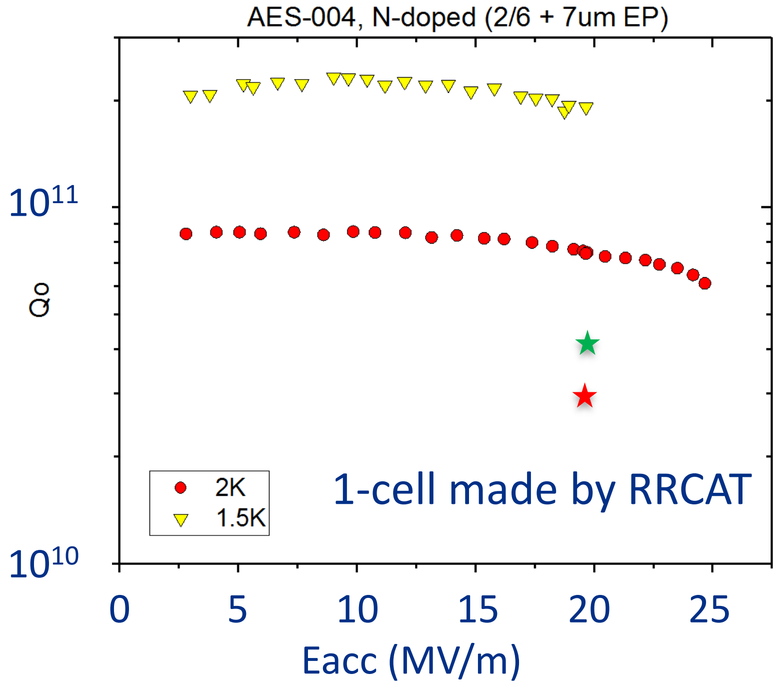
- 13 Cryomodules transport from overseas partner labs to Fermilab
- Transportation is part of the cryomodule prototyping
- Two dummy tests
  - From Fermilab to oversea partner lab
  - From oversea partner lab to Fermilab
- Three prototype cryomodules to be extensively tested
  - HB650 pCM from Fermilab to oversea partner lab
  - HB650 pCM from oversea partner lab to Fermilab
  - LB650 pCM from oversea partner lab to Fermilab

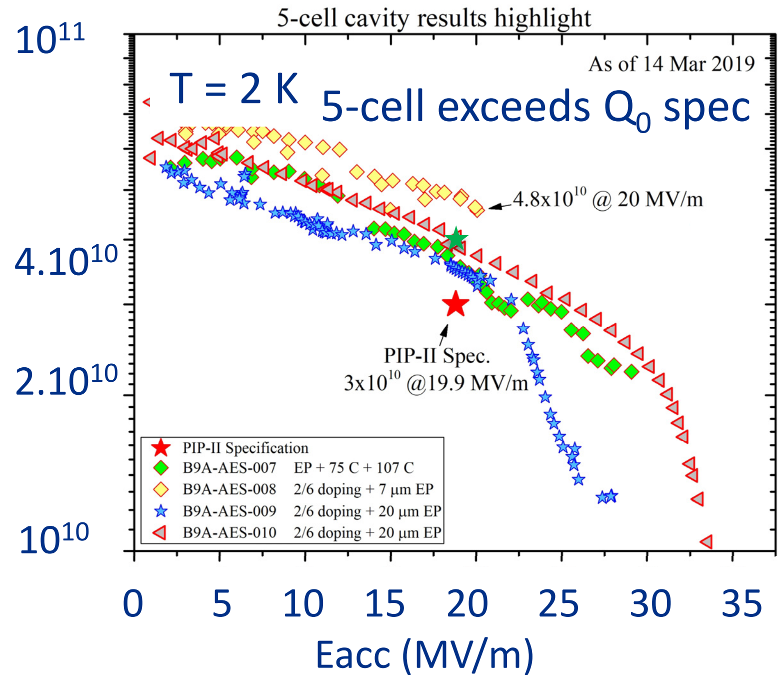



**MOP089, MOP091, MOP094**

# Recent Progress – Cavities




★ PIP-II 650 MHz R&D Goal

★ PIP-II 650 MHz Spec

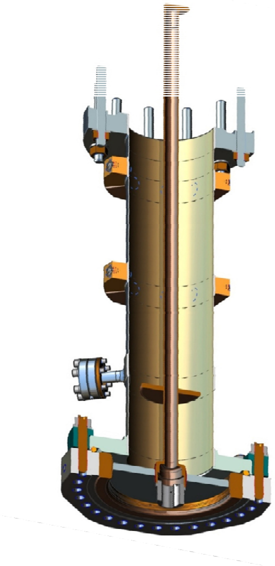
2/6 doped B9AS-RRCAT-301 showed record breaking performance with Quench field >25 MV/m

Cavity B9A-AES-008 vertical testing showed cavity has very high quality factor of 5e10 at 20 MV/m.

**M. Martinello, et al., MOP038**

# Recent Progress – Couplers

- 650 MHz Coupler reached 50 kW CW
  - 55 kW Design goal
  - Limited by test stand, not by couplers. Improvement identified.
- Exceeds the requirement of dressed cavity integrated test in STC (Spoke Test Cryostat, a PIP-II horizontal test cryostat for both spoke and 650 MHz dressed cavities).

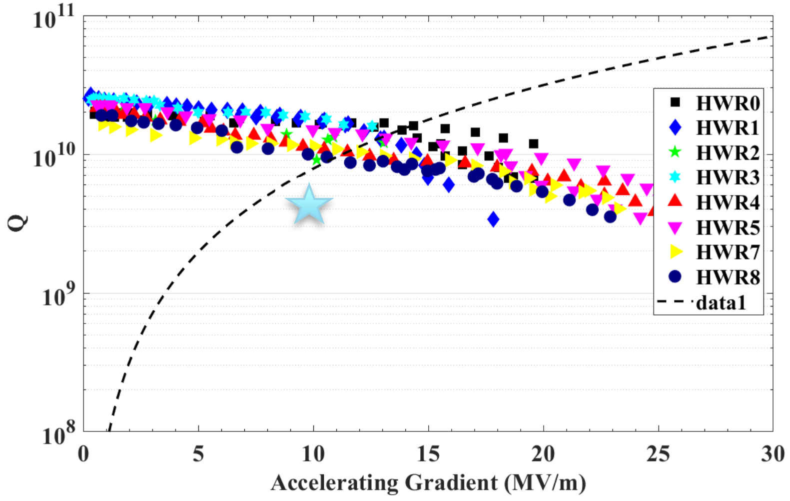


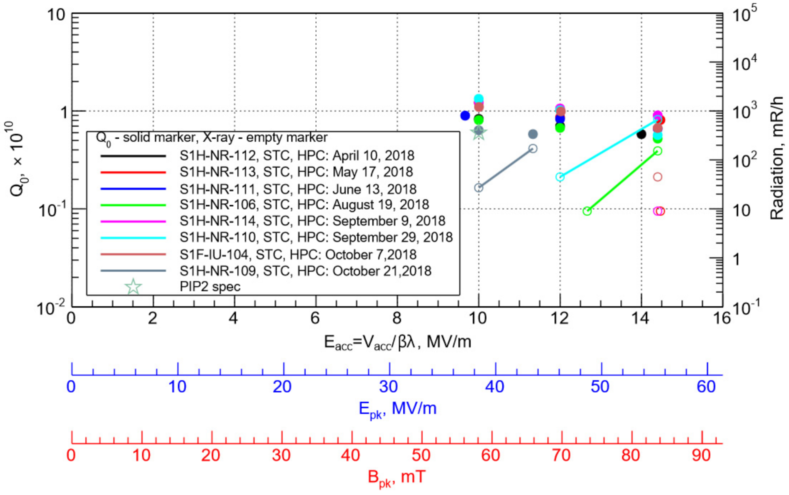
**S. Kazakov et al., MOP080**



PIP-II

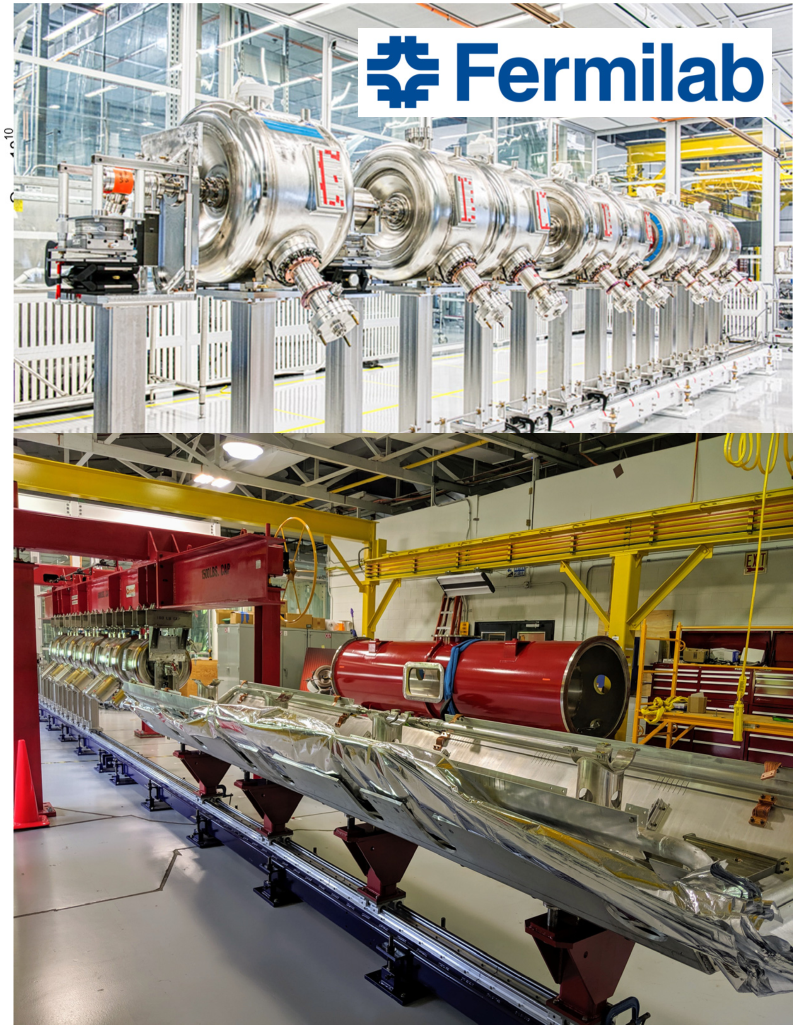
# Recent Progress – Cryomodules



# Recent Progress – Cryomodules


HWR cryomodule cold mass assembly




SSR1 cryomodule cold mass assembly

**MOP101, MOP102, TUP095, THP090, THP091**

# Lessons Learned

- Lessons Learned from other Projects
  - Transportation by design
  - Comprehensive fastener torque specification
  - Studying microphonics early
  - Attention to magnetic field trapping during cryomodule test
  - Quality Engineer assigned to SRF Systems

- Lessons Learned within PIP-II
  - Improvement of assembly traveler
    - Spoke cavity S104 had a near-miss of uncontrolled pump down

**D. Passarelli et al., TUP095**

# Summary

- PIP-II SRF development is pushing the state of art to meet the needs of intensity frontier program at Fermilab.
  - PIP-II is the highest energy CW SRF proton linac in the world
  - PIP-II has attracted interest from Partner labs for in-kind contributions.
- Cryomodule development plan allows sufficient prototyping to feedback to production.
- Technical risks and challenges are mostly understood
- Lessons learned from other projects benefits PIP-II
- Significant progress has been made on all fronts
  - First two cryomodules nearing completion – RF testing in the fall.
- We thank all the partner labs for their contributions !

Thanks for your attention.

Questions ?

# Why a new Accelerator?

3 Nobels in last 30 years:
1988: discovery of muon neutrino
1992: discovery of neutrino
2002: cosmic neutrinos

- Neutrinos: most ubiquitous matter particle in the universe, yet the least understood
  - Elementary particles with smallest mass of known particles
    - < one millionth that of the electron
  - 'neutrino' - electrically neutral and so small (mass)
  - typically pass through matter unimpeded & undetected
  - come in three flavors: electron, muon, tau
  - neutrinos *oscillate* between different flavors in flight
  - parameters of the oscillations still not completely understood
    - could unlock our understanding of the universe!
  - been a focus of physics at Fermilab since the beginning

  - Current focus on the oscillations: short baseline (detectors on site) and long baseline (detectors in Minnesota and South Dakota)