Preliminary Design of FCC 800MHz Cryomodule at Fermilab

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FCC Week 2024

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In partnership with:

CERN

Outline

- Layout and preliminary design of the FCC 800 MHz cryomodule
- Leveraging the PIP-II SRF&Cryo experience for the FCC 800 MHz development
  - Fine segmented cryomodules design
  - Integration of elliptical 650 MHz cavities
  - International transportation of cryomodules
- Fermilab SRF&Cryo cryomodule capabilities
- Robot-assisted technology for critical assemblies

Introduction

- The fine segmentation is the current baseline configuration for the FCC 800 MHz cryomodule.
  - The insulating vacuum and the cryogenic circuits are confined within the individual cryomodule, with the only connection between modules being at the beam tube.
  - All external connections to the RF, vacuum, beamline, and instrumentation systems are made of removable junctions at the cryomodule itself.
  - The connections to cryogenics and relief lines are made through "jumpers", welded connections.

- Through collaborative efforts with colleagues at CERN, the current design aligns with the main defined functional, technical and interface requirements. K. Canderan
  - The FCC 800 MHz cryomodule shall fit within the transverse and longitudinal dimensional envelopes for the two different locations in the accelerator: collider and booster V. Parma

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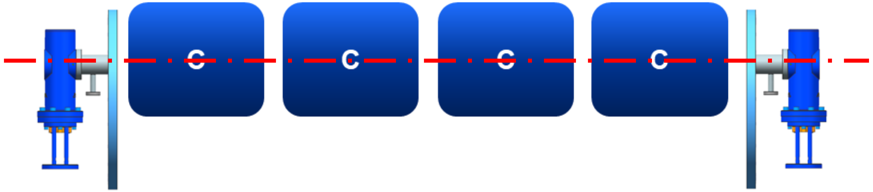
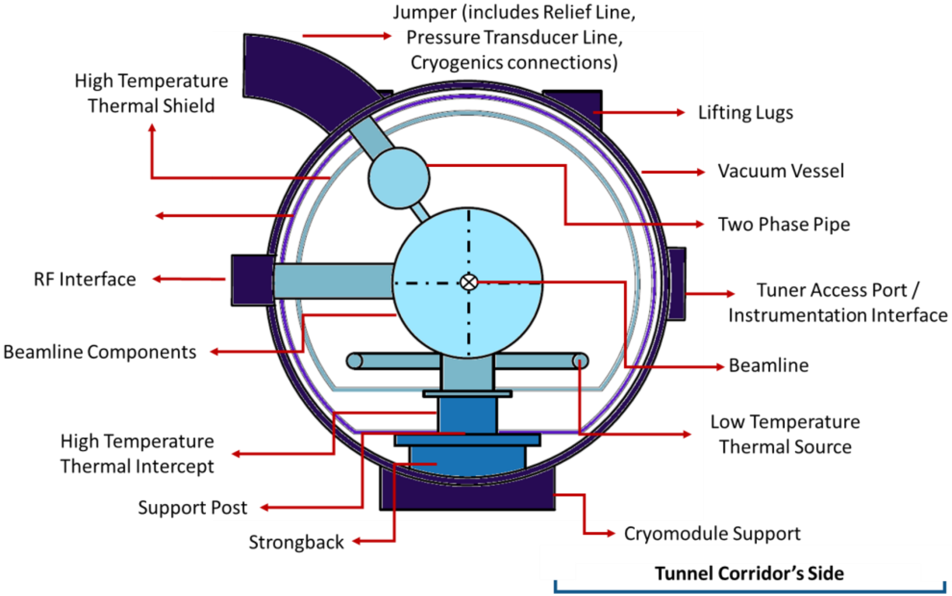
Layout of the FCC 800 MHz Cryomodule

The conceptual design houses four superconducting 800 MHz cavities. K. McGee

Each cavity bottom-supported on a room temperature strongback, which is a distinctive feature of Fermilab's cryomodule style that was developed for the PIP-II project.



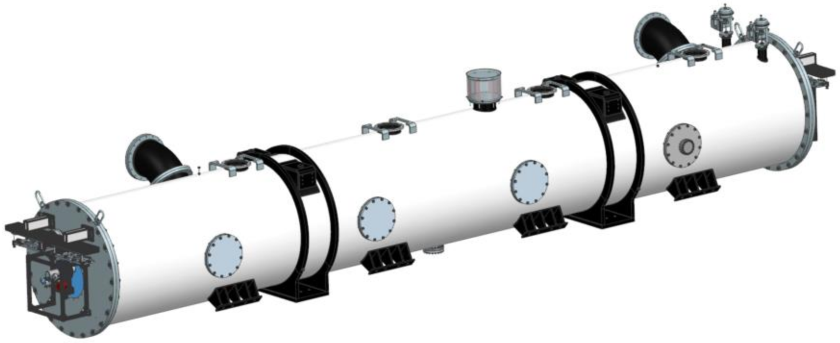
Longitudinal layout



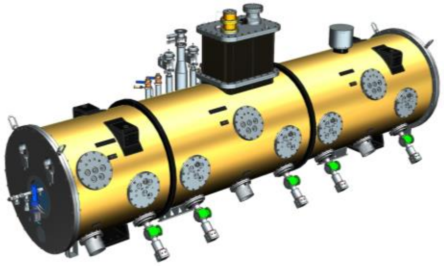
Cross section layout

Preliminary design of FCC 800MHz Cryomodule

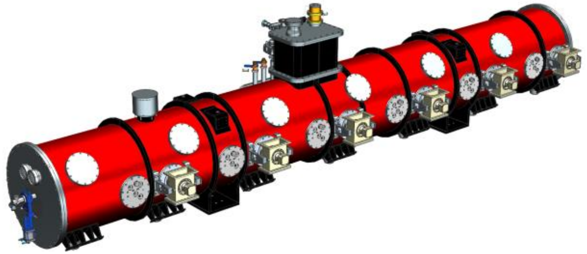
- The FCC 800 MHz CM design is based on SSR2 and HB650 PIP-II CMs with the following main differences:
  - Heat exchangers and valves are integrated into the Cryogenic Distribution System (CDS).
  - A “Jumper” will be used to interface with CDS through welded connection into the tunnel (no u-tubes).
  - Couplers are actively cooled with helium.



FCC 800 MHz cryomodule



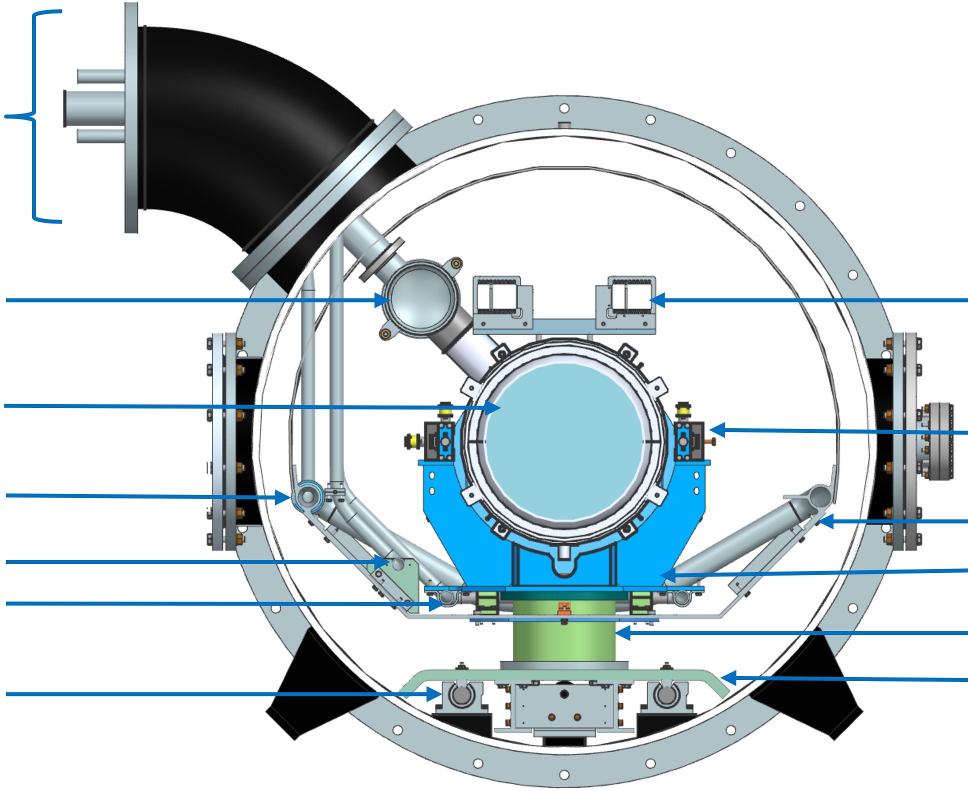
PIP-II SSR2 cryomodule



PIP-II HB650 cryomodule

“Final Design of the Pre-Production SSR2 Cryomodule for PIP-II Project at Fermilab”, V. Roger et al., Proceedings of LINAC 2022
“Design of the 650 MHz High Beta Prototype Cryomodule for PIP-II at Fermilab”, V. Roger et al., Proceedings of SRF 2021

Preliminary design of FCC 800MHz Cryomodule - Cross section



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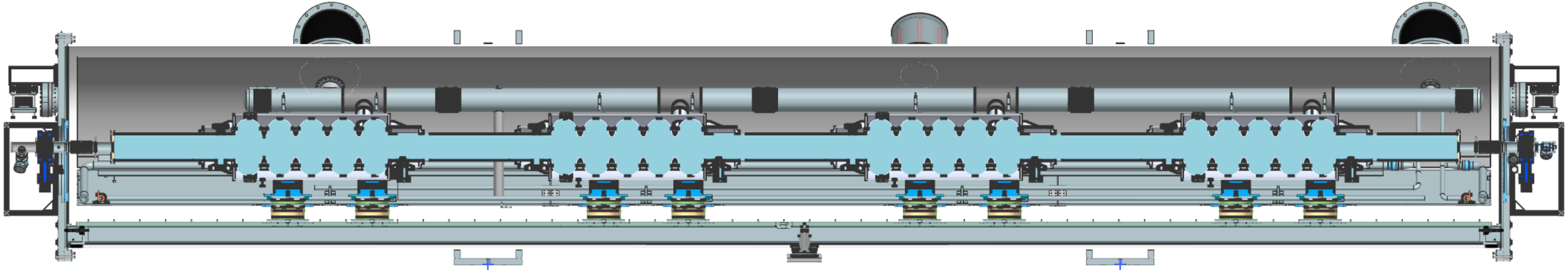
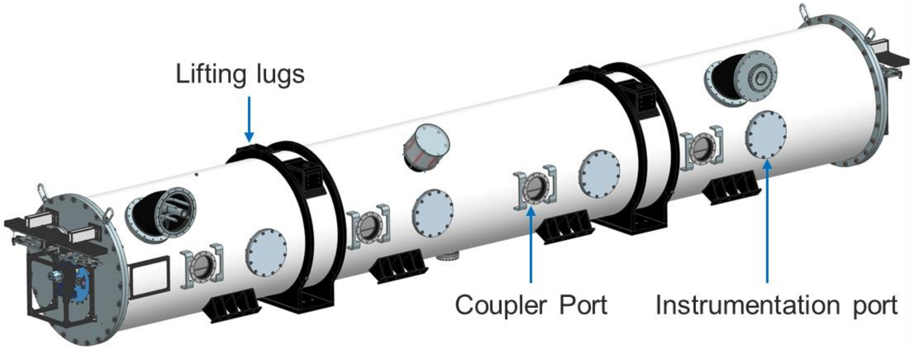
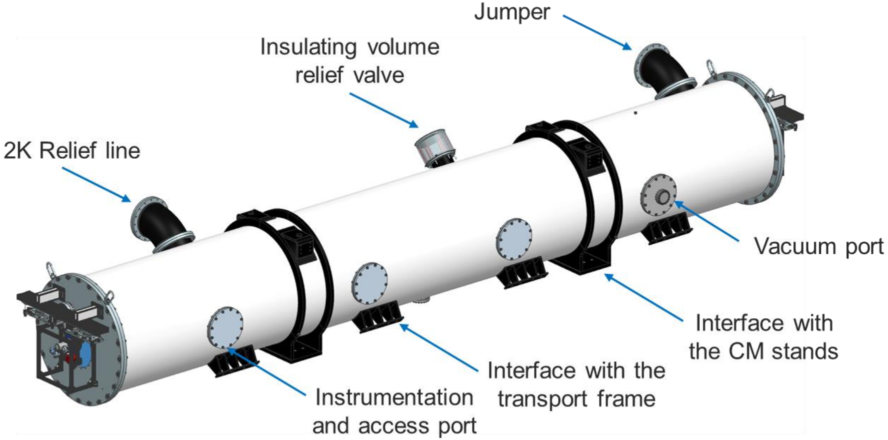
Preliminary design of FCC 800MHz Cryomodule



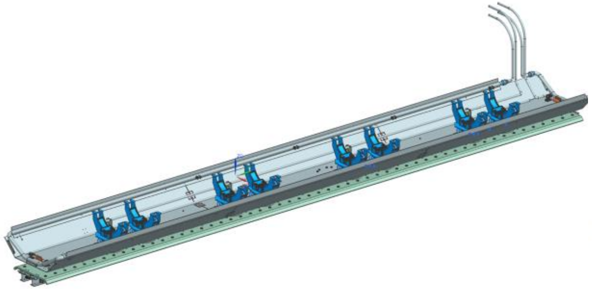




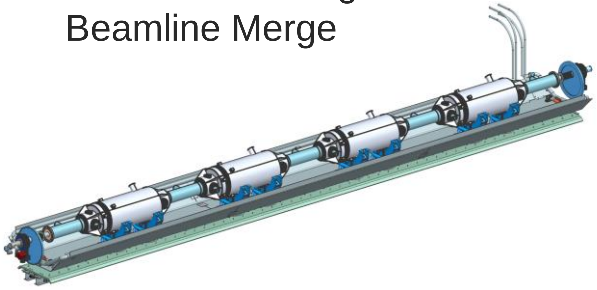
FCC 800MHz cryomodule assembly phases

Phase 1a: Beamline assembly in the cleanroom

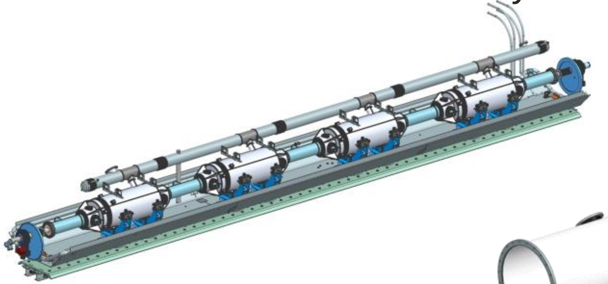
Phase 1b: Strongback Assembly



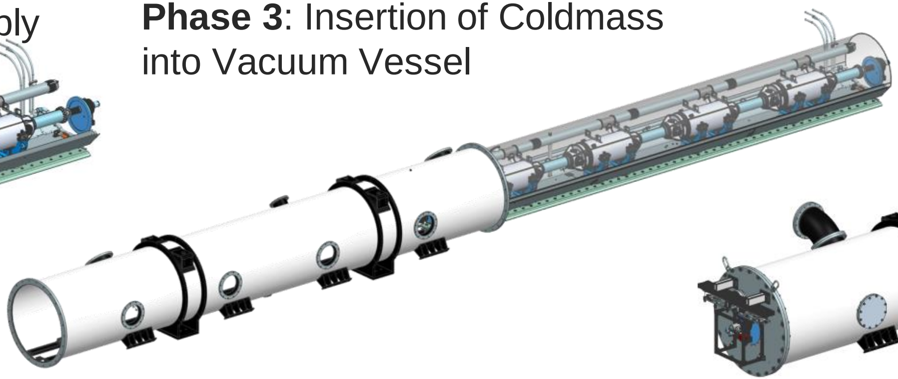
Phase 1c: Strongback and Beamline Merge



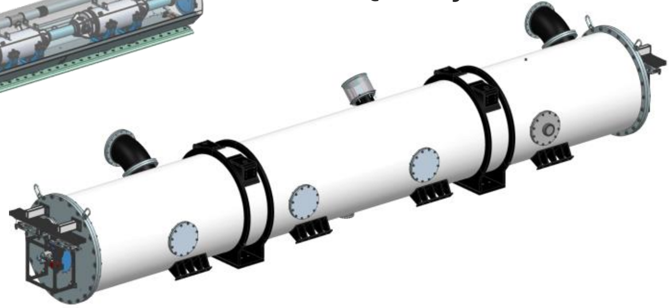
Phase 2: Coldmass Assembly



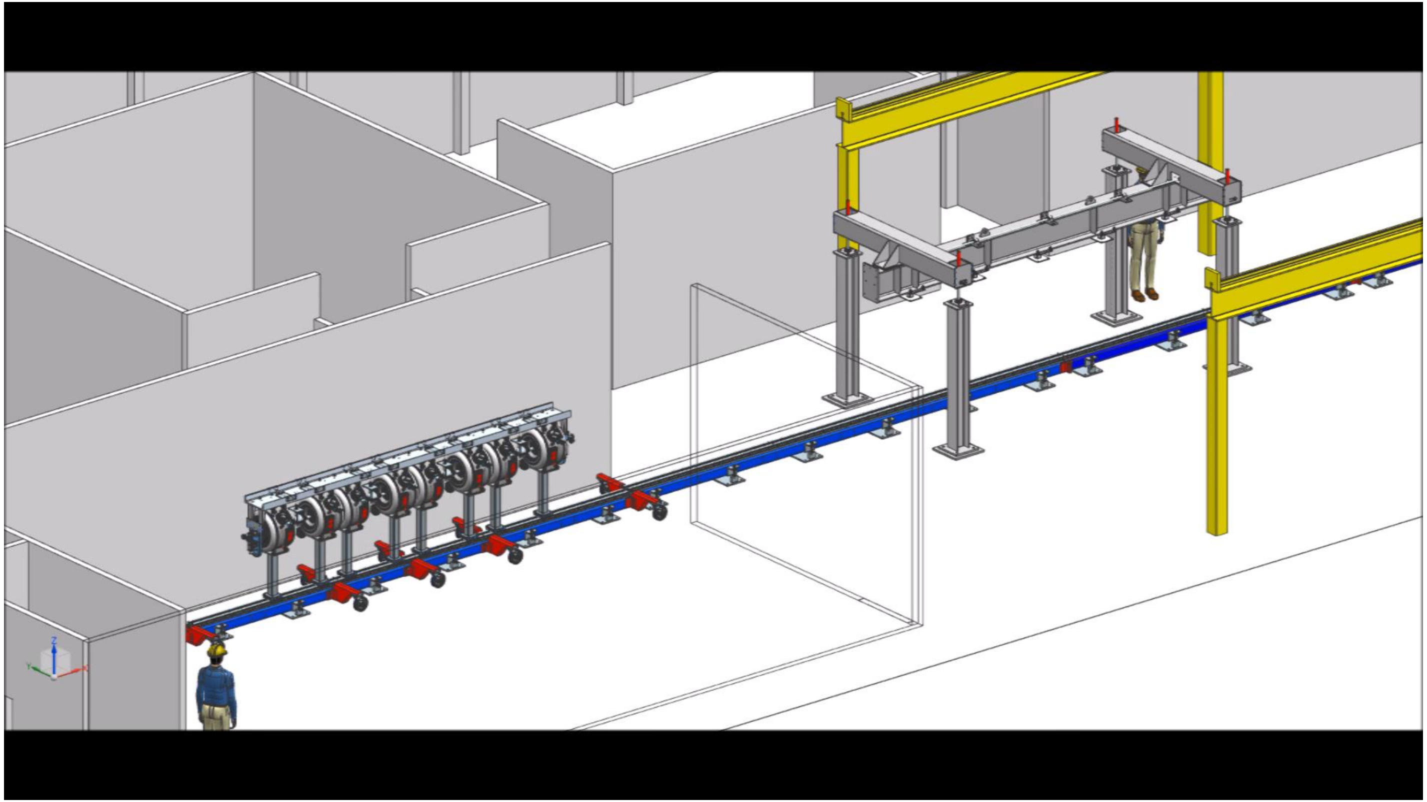
Phase 3: Insertion of Coldmass into Vacuum Vessel



Phase 4: Finalization and Quality controls



PIP-II cryomodules assembly phases



The cryomodule assembly process is composed of the following phases:

Phase 1a: Beam line assembly in the cleanroom

Phase 1b: Strongback Assembly

Phase 1c: Strongback and Beamline Merger

Phase 2: Coldmass Assembly

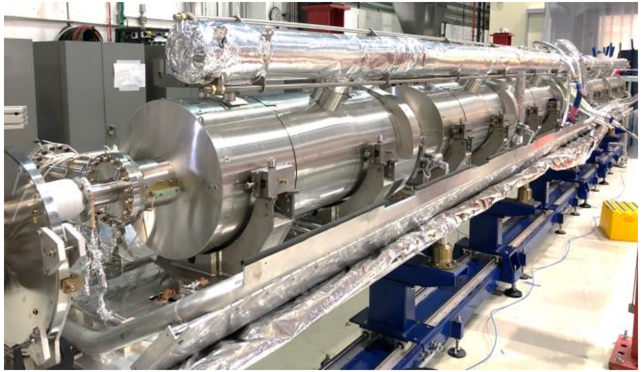
Phase 3: Insertion of Coldmass into Vacuum Vessel

Phase 4: Finalization and Quality controls

Prototype HB650 Cryomodule – Assembly phases

The pCM HB650 was fully designed, assembled and tested at Fermilab.

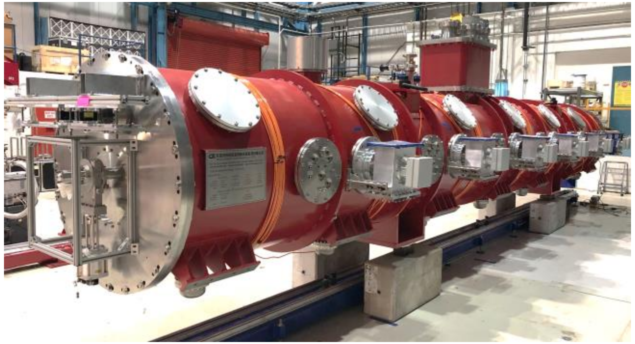
Cavity String rolled out from cleanroom



Integrated with strongback, 2K piping

Thermal shield and MLI

Insertion into vacuum vessel



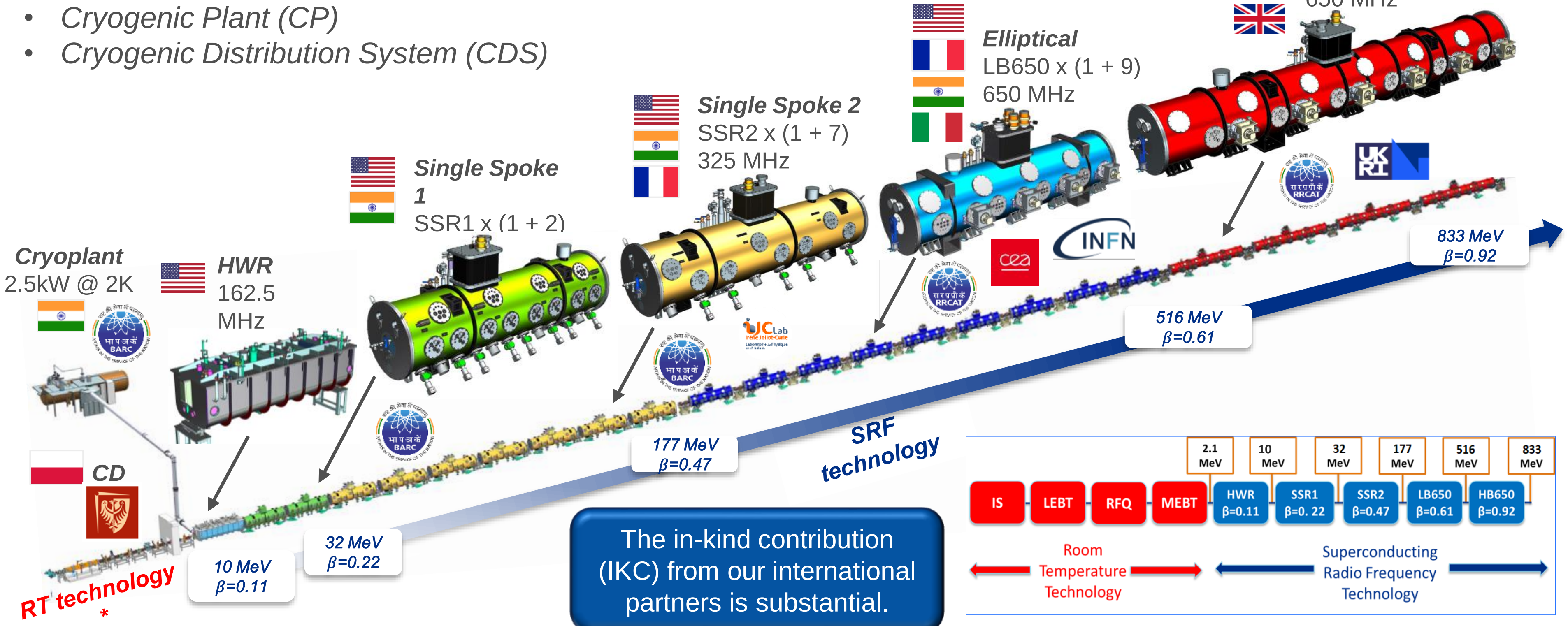
Completed cryomodule

Transport to PIP2IT test facility

PIP-II SRF-Cryo at Fermilab

Management, design, procurement, fabrication, and testing of:

- *Superconducting Radio Frequency (SRF) cryomodules*
- *Cryogenic Plant (CP)*
- *Cryogenic Distribution System (CDS)*



PIP-II technology map

Prototype HB650 CM – Cold test results

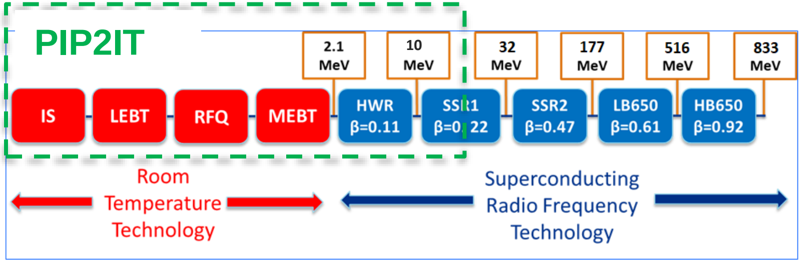
- **The prototype HB650 cryomodule was cold tested**

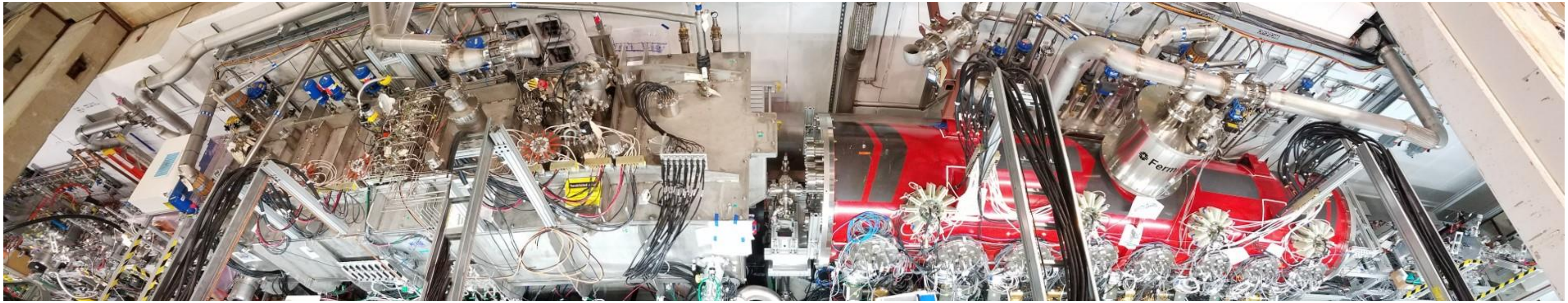
- Cavities were successfully cooled down to 2K
  - **Stable 2K operation** was maintained for several weeks
  - **Q preservation** through maintenance of **low background magnetic fields** (<5mG) and **fast cooldown**
- The **thermal shield** was successfully cooled to design value
- **Alignment** of cavities within specifications
- **Local** and **global magnetic** shielding successfully achieved <5mG in the CM
- Integrity of **insulating** and **beamline vacuums,** exceeding requirements in all operating conditions.
- Resonance frequency and Q_L measurements of **cavities** at RT, 4K, 2K.
  - Results are within the expected ranges.
- All eight **tuners** fully met acceptance criteria
  - All cavities were tuned to 650.000 MHz at 2K, except two cavities (as expected).
  - Background microphonics was within the specification
- All six **couplers** reliably worked to process multipacting barriers, and to increase cavities fields (Maximum power: 35kW)
  - The temperature of **single ceramic window** was maintained into the range $283K \leq T \leq 310K$ using the air flow and heaters

? Higher static heat loads than the design values were observed

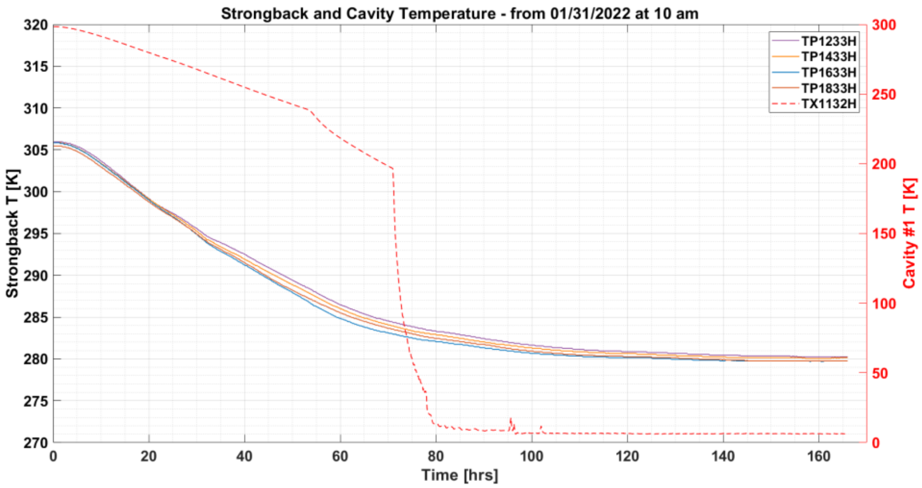
HWR and SSR1 at PIP2IT

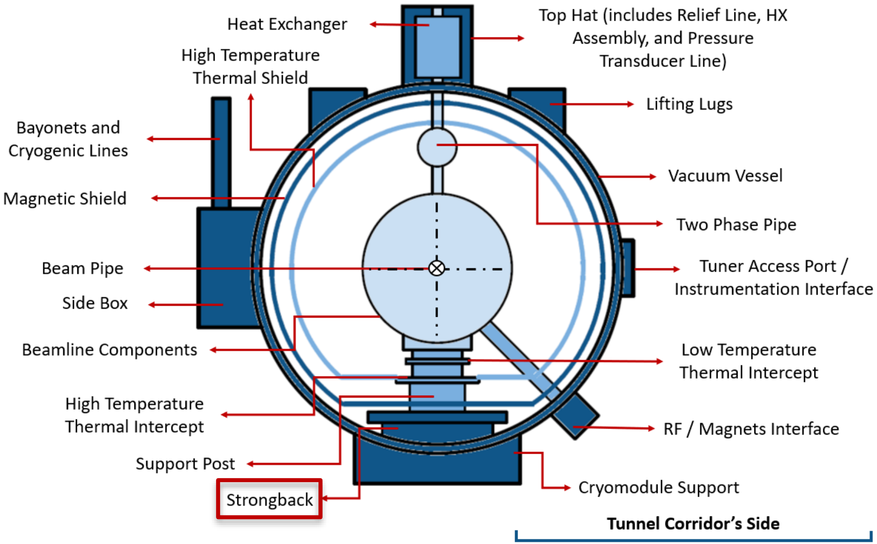
- HWR and SSR1 installed in PIP2IT: Feb - Jul 2020
- Individual CMs testing: Jul - Dec 2020
- CMs commissioned with beam Jan - Apr 2021





Strongback – the coldmass foundation



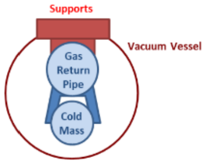


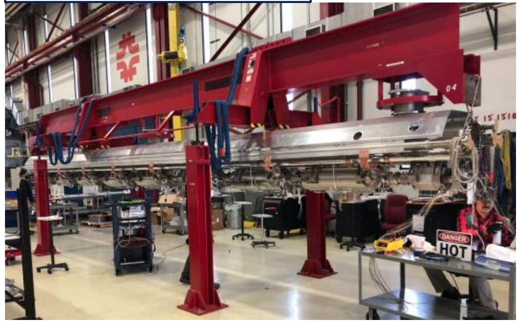
- The measured temperature is $281K \leq T_m \leq 310K$ with a thermal gradient never exceeding 1K. ✓
- The **thermal and structural performance** of the **SSR1 and HB650 strongback** during assembly, transportation, cooldown/warmup **validates the concept of the room temperature strongback** serving as the coldmass foundation. ✓

Fermilab SRF&Cryo cryomodule capabilities

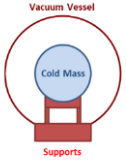
- FNAL has world-leading expertise in SRF cryomodule design, cleanroom and cryomodule assembly, as well as expertise in cryomodule transportation, and cold testing.
- Experience in 2 types of cold mass assemblies
  - Upper supported Coldmass Design – top supported cavities, used on FLASH, ILC, LCLS-II, and LCLS-II HE cryomodules
  - Strongback Design – bottom supported cavities, used on PIP-II cryomodules

Upper supported coldmass
"XFEL, ILC, LCLS-II projects"





Bottom supported coldmass
"Fermilab-style Cryomodule" PIP-II



Cryomodule Assembly Team at Fermilab

- Experienced teams with nearly 40 cryomodules built to date engaging in both prototype and production units type of scope

1.3 GHz LCLS-II Module

3.9 GHz LCLS-II Module

650MHz PIP-II Module

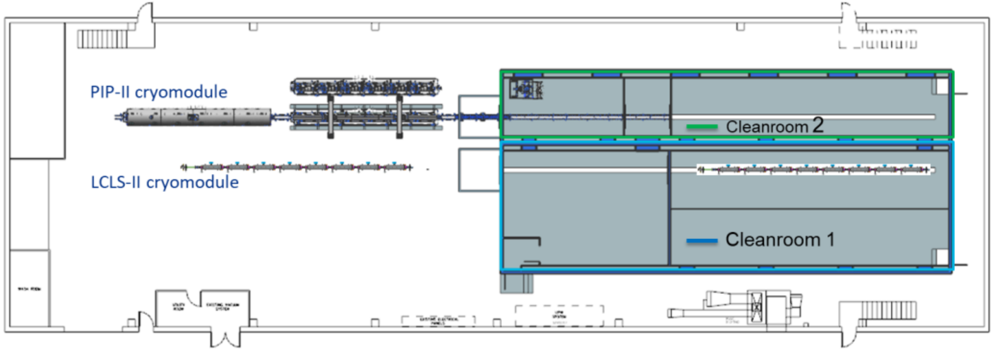
3.9 GHz FLASH Module

1.3 GHz ILC Type Module

325MHz PIP-II SSR1 Module

Cleanroom Assembly Facilities

Two independent string assembly class 10 cleanroom (ISO 4) lines are currently available at Fermilab. Currently, one is used for the LCLS-II project and the other for the PIP-II project.



Production rate:

- One string assembly per month has been achieved in LCLS-II production using a single production line, limited by cavity availability.
- With the second production line, two string assemblies per month can be achieved.
- Optimizing resources and processes, one FCC 800MHz string assembly per week could be assembled.

Robot-assisted technology for SRF assemblies

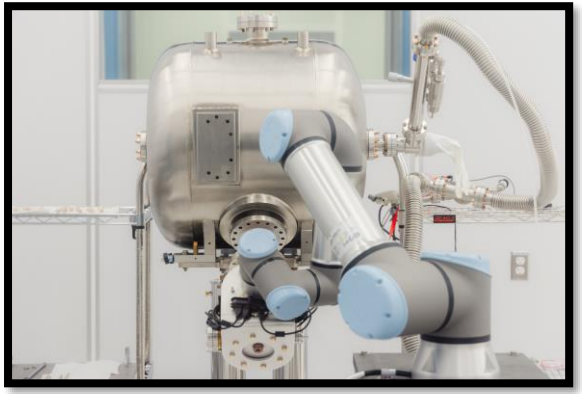
- A robotic arm has been successfully used to install couplers on the PIP-II SSR2 cavity.
- Should the use of robot-assisted technology be expanded for FCC particle-free assemblies?

Manual assembly in cleanroom

- Performance highly depend on operator ability, experience and commitment
- Operators are among the main sources of contamination

Robot-assisted assembly

- The assembly process is more efficient, systematic, and repeatable over time.
- Reduce the risk of chemical and particulate contamination during critical assembly steps



Conclusion

- We extend our thanks to our CERN colleagues for the opportunity to collaborate on this ambitious project.
- The teamwork and collaboration between our groups have been outstanding so far.
- Significant technical progress has already been made thanks to our joint efforts on the design of 800 MHz cryomodule (and cavity).
- The experience gained in designing, assembling, and testing PIP-II cryomodules has substantially expedited the design phase of the 800 MHz cryomodule.
- At Fermilab, we are committed to continuing our engagement and collaboration on this scope.

800 MHz cryomodule

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