Fermilab PIP-II Status and Strategy

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HB2016

3-8 July 2016

In partnership with:

DAE IIFC PIP-II

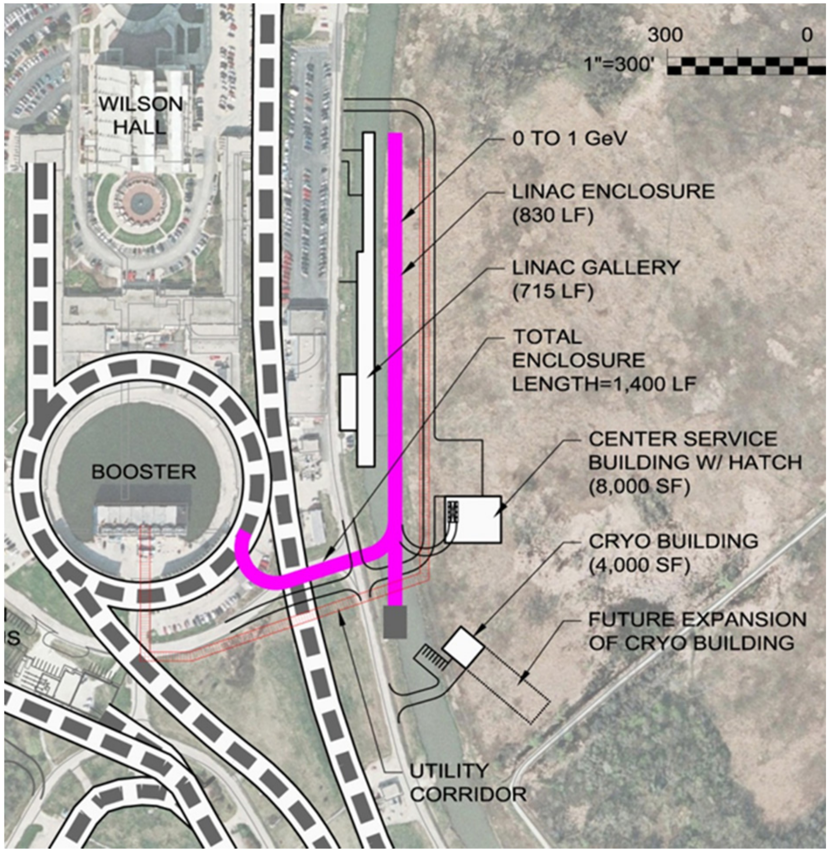
Fermilab

- The leadership of Particle Physics Energy Frontier has moved to CERN, Geneva, Switzerland.
- Fermilab is focusing on taking a world leadership in the Intensity Frontier High Energy Physics (2025)
  - Several Neutrino Physics Experiments
    - Flagship DEEP Underground Neutrino Experiment (DUNE)
      - Large mass Liquid Argon neutrino detector
      - Fine Grain Tracker Neutrino Detector
  - Muon Physics ($\mu \rightarrow e$)
- Accelerator technology development for Intensity Frontier Accelerator
  - Superconducting Linac with high efficiency
    - Proton Improvement Plan (PIP-II and PIP-III)

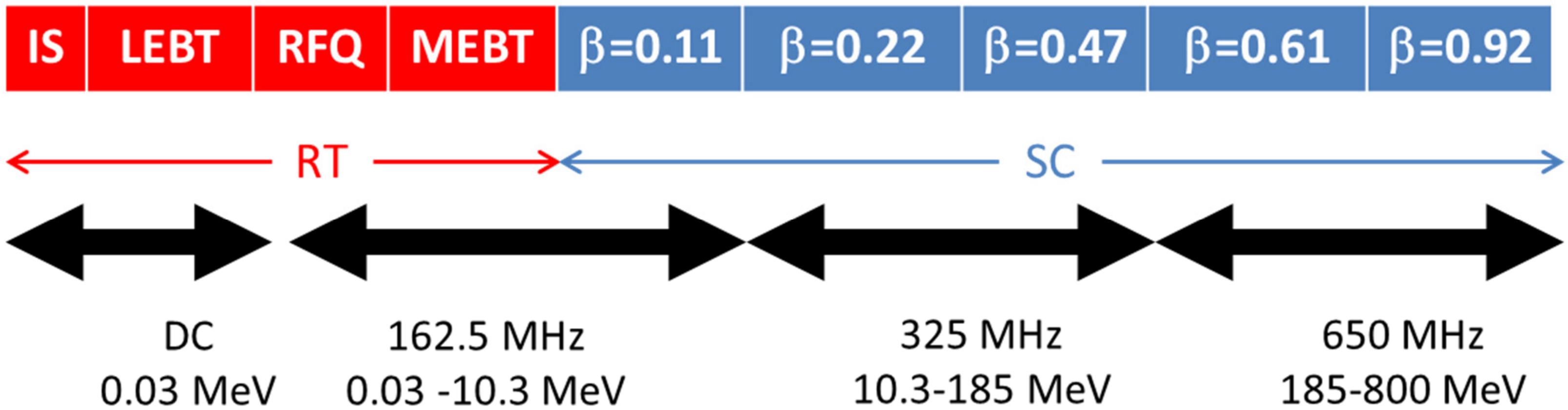
PIP-II (Proton Improvement Plan–II)

The PIP-II goal is to support long-term physics research goals by providing increased beam power to LBNF, while providing a platform for the future.

- Design Criteria
  - Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations
  - Support the current 8 GeV program including Mu2e, g-2, and short-baseline neutrinos
  - Provide an upgrade path for Mu2e
  - Provide a platform for extension of beam power to LBNF to >2 MW
  - Provide a platform for extension of capability to high duty factor/higher beam power operations
  - At an affordable cost to DOE
- Goal: Initiate operations in newly-configured complex in ~2025



PIP-II Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

PIP-II Project Status and Strategy

- PIP-II is now a recognized DOE project (CD-0)
  - Conceptual design phase
    - Goals established via Mission Need Statement (MNS) and P5 Report
  - Cost range upper end established at $650M
  - Project scheduled over 2016-2025, with 2020 start of construction
  - India collaboration was critical in achieving CD-0
  - Next up is CD-1: “Approve Alternative Selection and Cost Range”
- CD-1 deliverables:
  - Conceptual Design Report, including alternatives analysis
  - Updated cost estimate
  - Resource Loaded Schedule
  - Risk Management Plan
  - NEPA strategy
  - etc.
  - Goal: FY2017
    - Draft of CDR + Alternatives by July
    - Substantial progress on everything else by September

PIP-II Collaboration

- Organized as a “national project with international participation”
  - Fermilab as lead laboratory
- Collaboration MOUs for the development phase (through CD-2) :

National	IIFC
ANL	BARC/Mumbai
LBNL	IUAC/Delhi
SLAC	RRCAT/Indore
ORNL/SNS	VECC/Kolkata

- Major Collaboration with India
- Europe
  - Discussions have center around contribution of LB650 cavities and cryomodules
  - INFN, Cockcroft Institute, Saclay

India Collaboration

- India is major partner during both R&D and construction phases
  - Governed by Annex I to the U.S. DOE-India DAE Implementing Agreement, signed in January 2015
- Joint Project Document for the R&D Phase
  - Signed by DOE and DAE in August 2015
  - Establishes scope and dates for all R&D phase deliverables
    - Covers all technical aspects of the linac
  - Four DAE laboratories (BARC, IUAC, RRCAT, VECC)
  - Managed by Sub-project Managers/Coordinators at Fermilab and in Indian laboratories
  - Initial DOE/DAE review of progress in January 2016 (BARC, Mumbai)
- Seven Indian engineers arrived in fall 2015 for two-year residencies
  - Several 2-4 months visitors focused on specific project

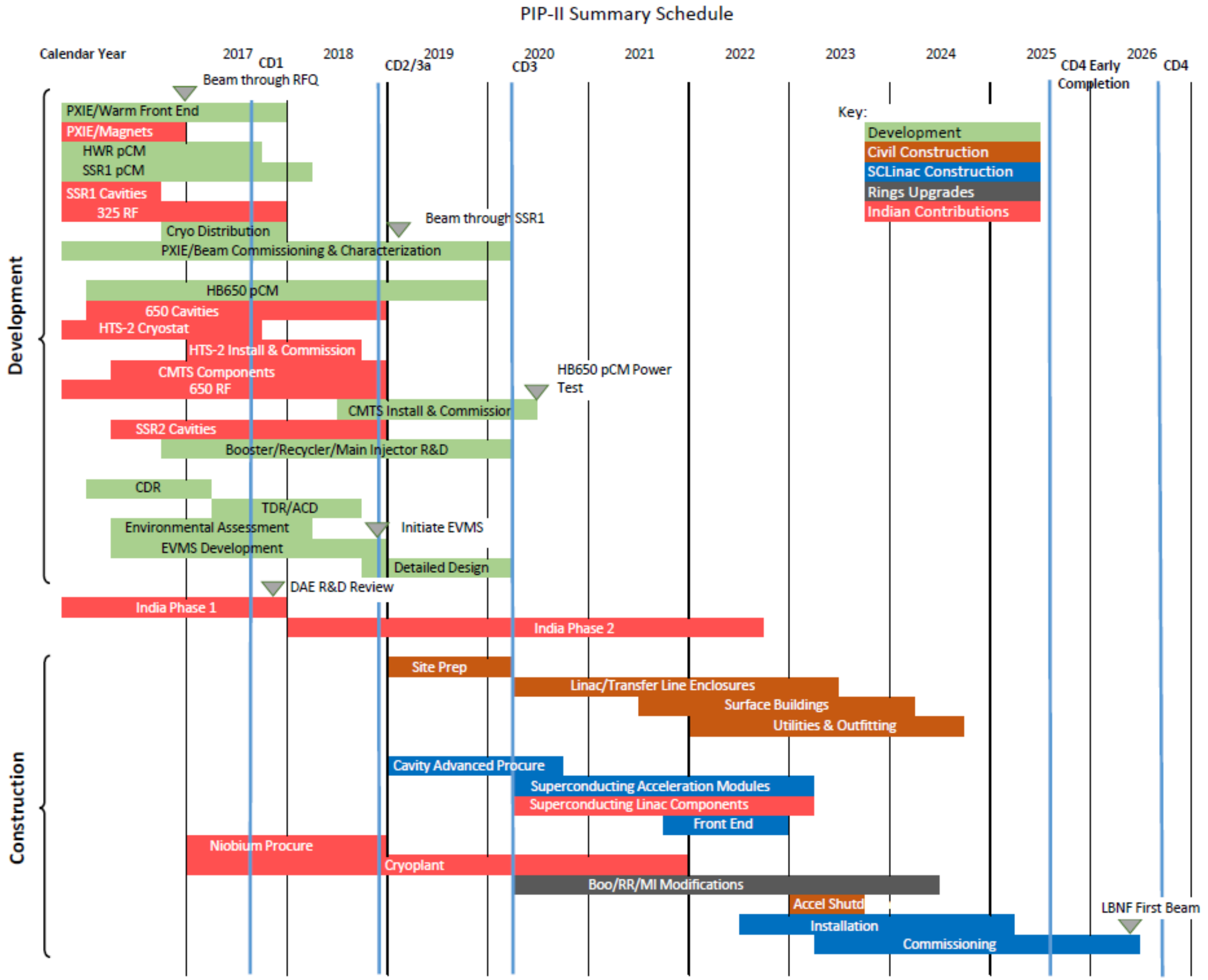
PIP-II R&D Program

- The goal is to mitigate risk: Technical/cost/schedule
- Technical Risks
  - Front End
    - Delivery of beam with required characteristics and reliability
  - Operate SC Linac in pulsed mode at low current
    - Primary issue is resonance control in cavities

  PIP2IT

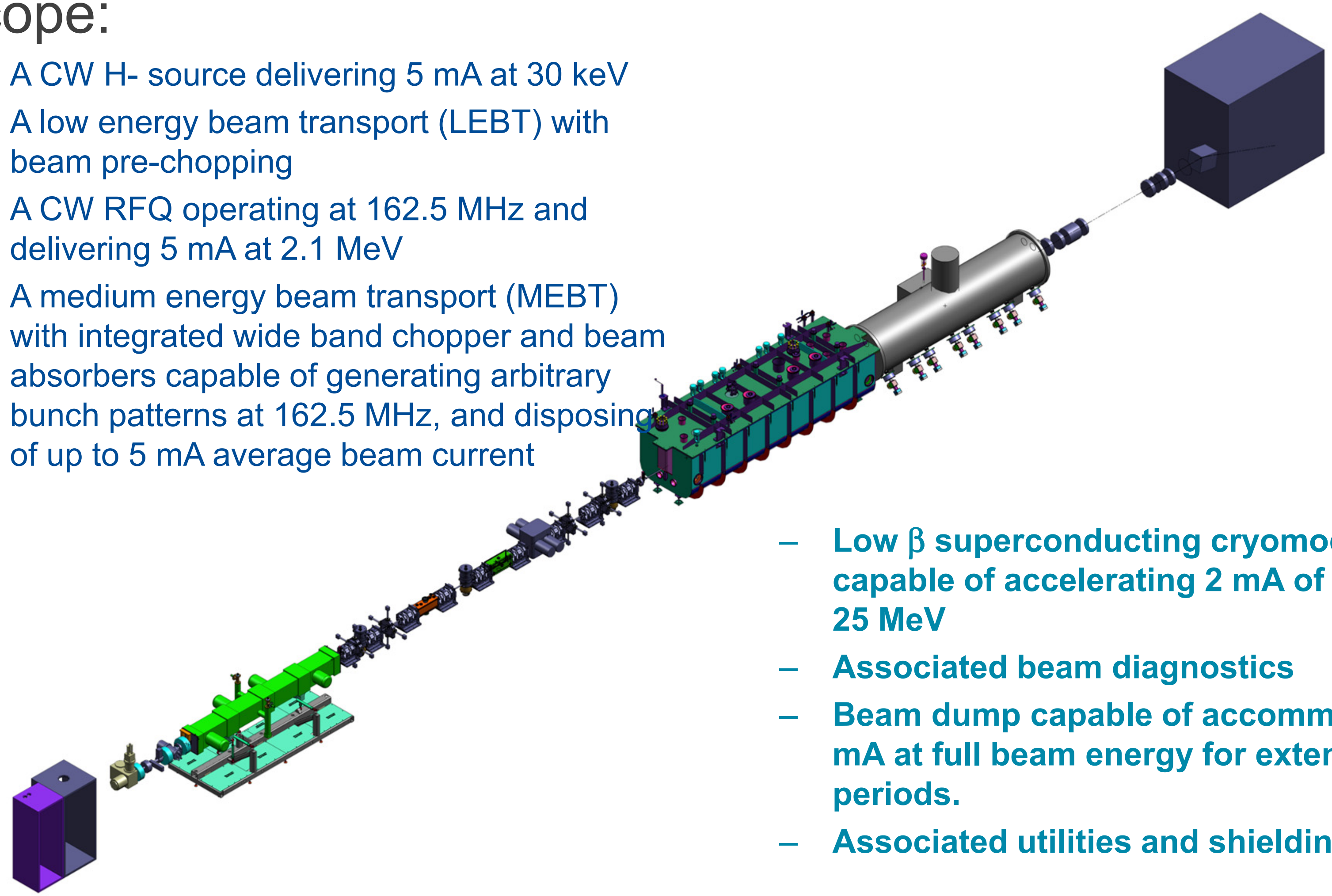
  - Booster/Recycler/Main Injector beam intensity
    - 50% per pulse intensity increase over current operations
    - Booster longitudinal emittance (slip-stacking)
    - Transition crossing
    - Beam loss/activation
  - Develop requisite capabilities of partners and vendors
- Cost/Schedule Risks
  - Superconducting RF
    - Cavities, cryomodules, RF sources
- Goal: Complete R&D program in 2019

PIP-II Status: Preliminary Schedule



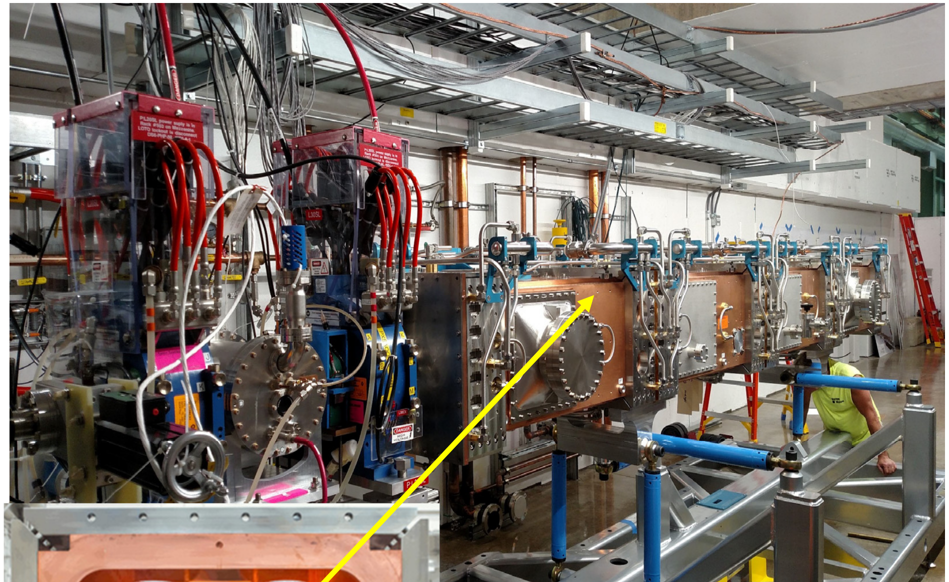
PIP-II Injector Test

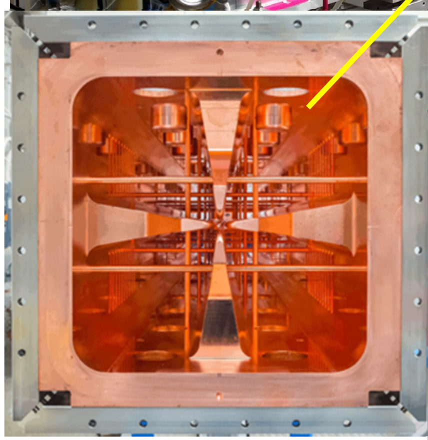
- Scope:
  - A CW H- source delivering 5 mA at 30 keV
  - A low energy beam transport (LEBT) with beam pre-chopping
  - A CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
  - A medium energy beam transport (MEBT) with integrated wide band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of up to 5 mA average beam current

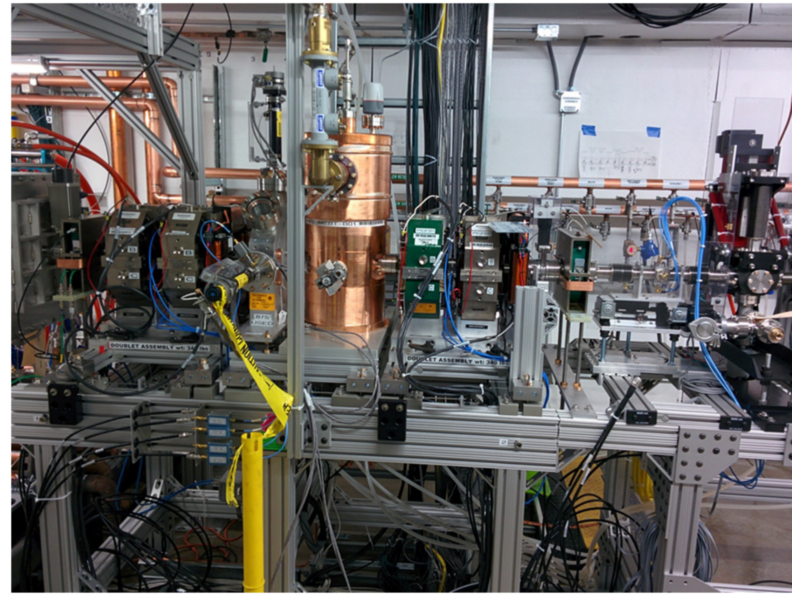


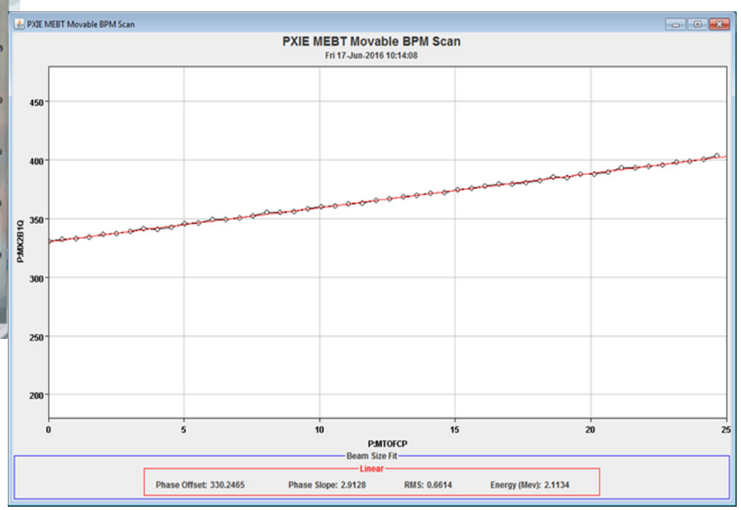
  - **Low β superconducting cryomodules capable of accelerating 2 mA of beam to 25 MeV**
  - **Associated beam diagnostics**
  - **Beam dump capable of accommodating 2 mA at full beam energy for extended periods.**
  - **Associated utilities and shielding**

Radio Frequency Quadrupole (LBNL) and MEBT









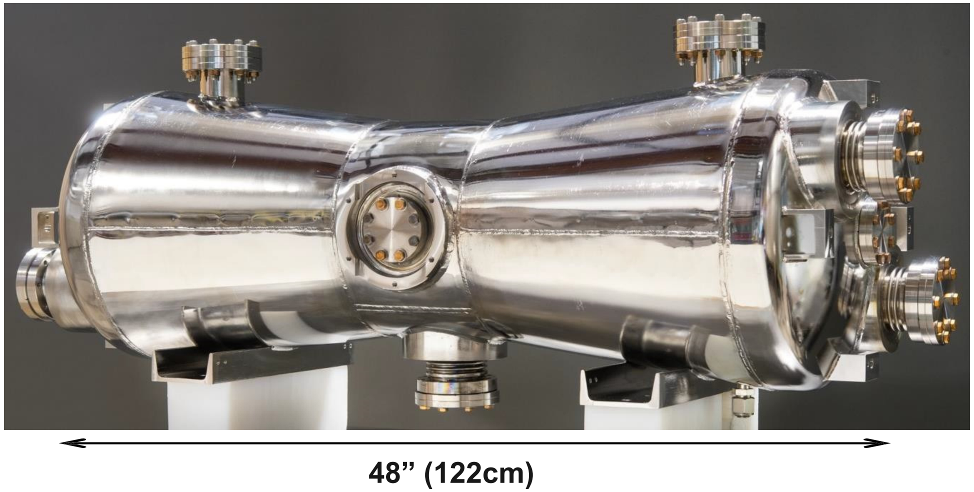
Energy Measurement:

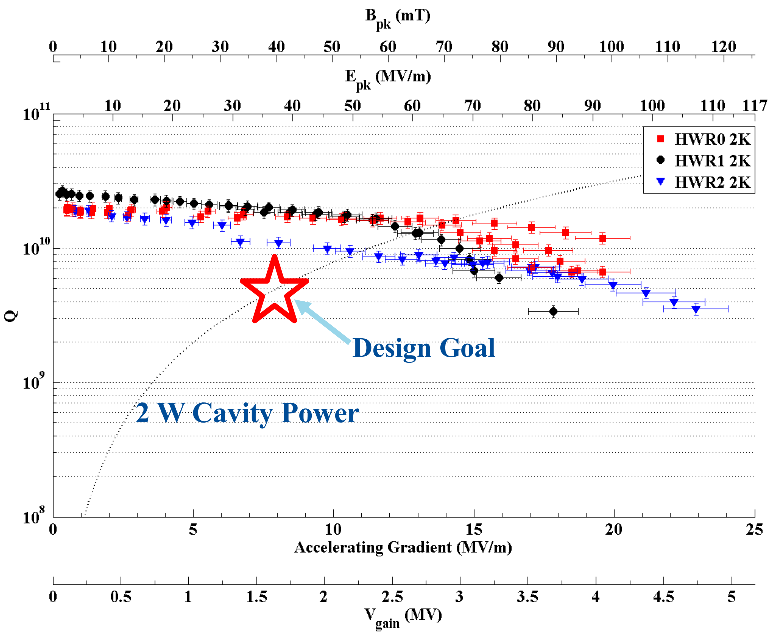
- Time of Flight BPM
- 2.12 MeV ± 0.5%

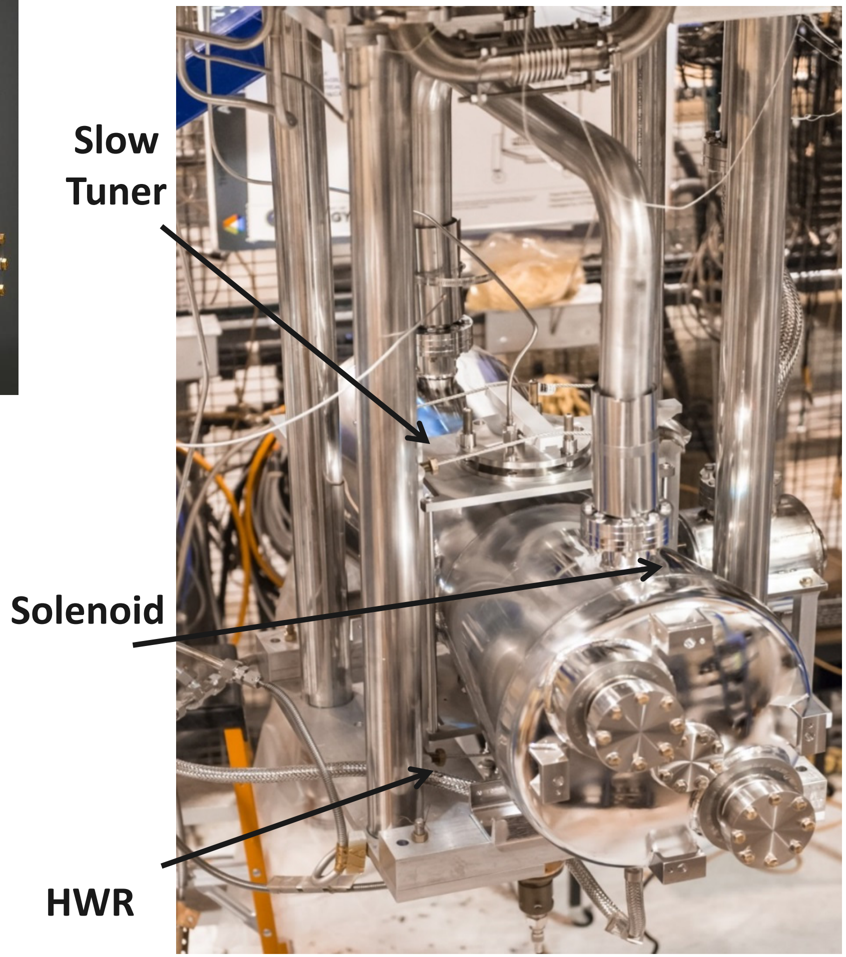
With quadrupoles and dipole correctors tuned, practically the entire beam goes into the Faraday Cup at the end of the beam line at the nominal current of 5 mA.

– Less than a week of commissioning.

Half Wave Resonator Cryomodule (ANL)

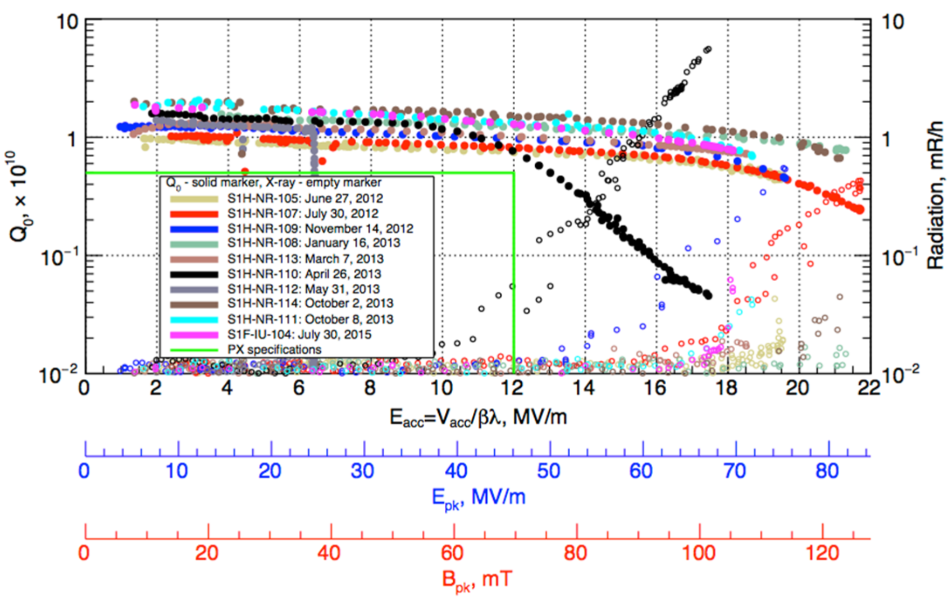


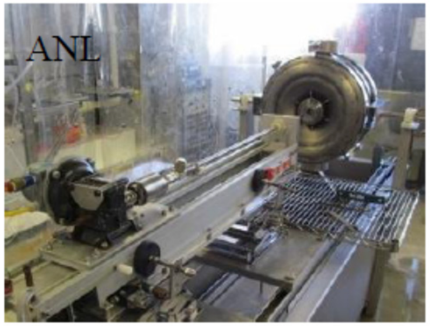




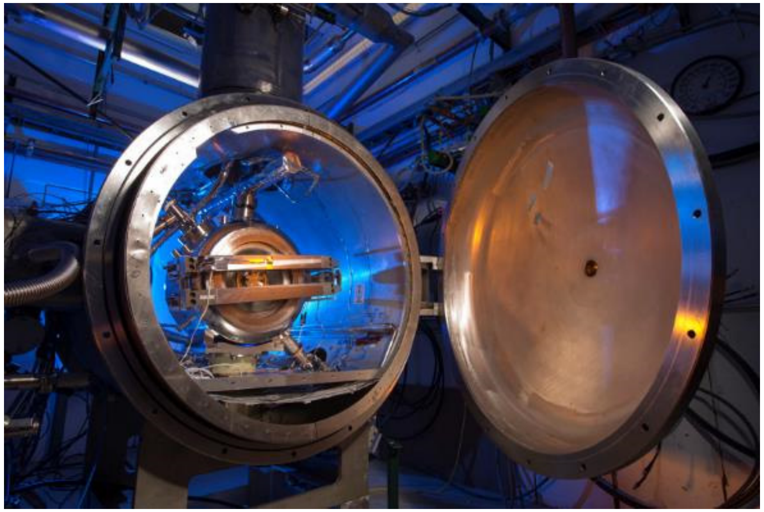
SSR1 β = 0.22 R&D

- Twelve SSR1 cavities have been fabricated for PIP-II.
  - In addition 2 SSR1 cavities have been fabricated under IIFC
- Chemically processed at ANL and cold-tested at Fermilab
  - Cavities meet the PIP-II specifications
- Cavities are being dressed and high RF power tested Fermilab

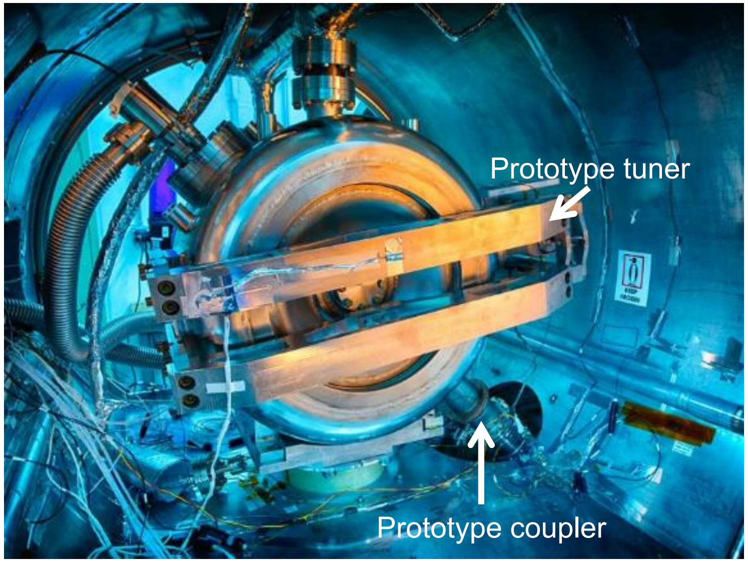


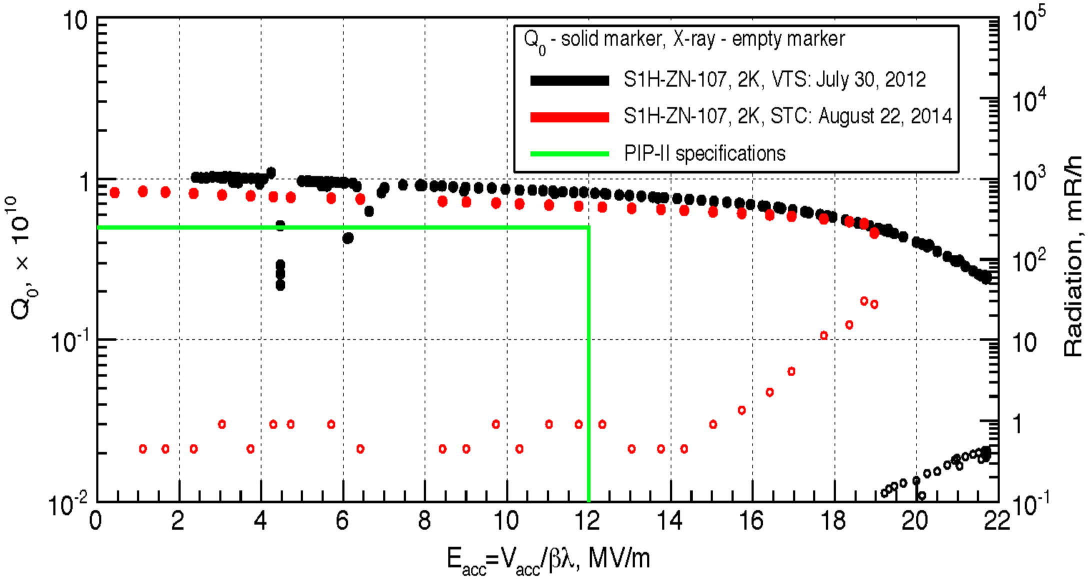


S107 "Ice Breaker" Fully-Integrated Tests in STC



- First jacketed cavity was tested in the STC cryostat
- Prototype coupler and prototype tuner installed
- Performance of cavity, coupler and tuner were confirmed with a total of 3 tests, latest Jan 2016



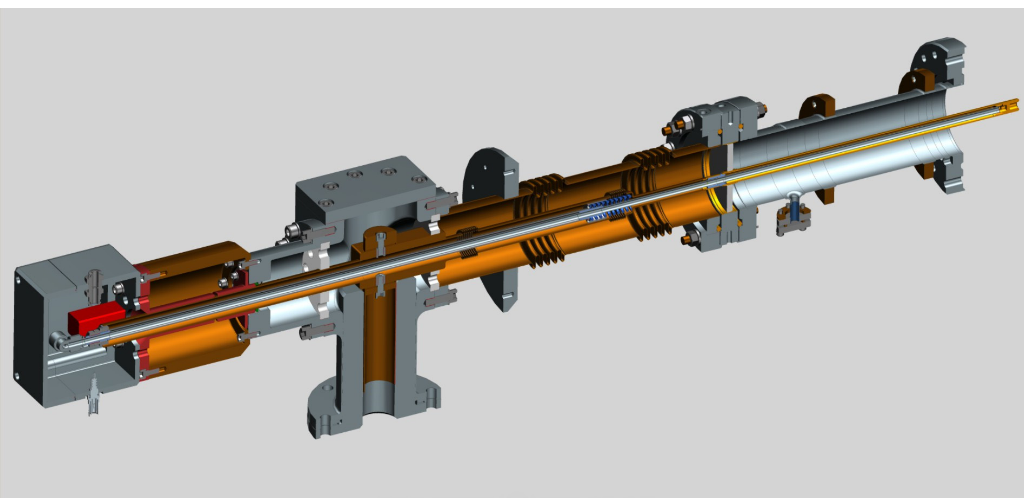


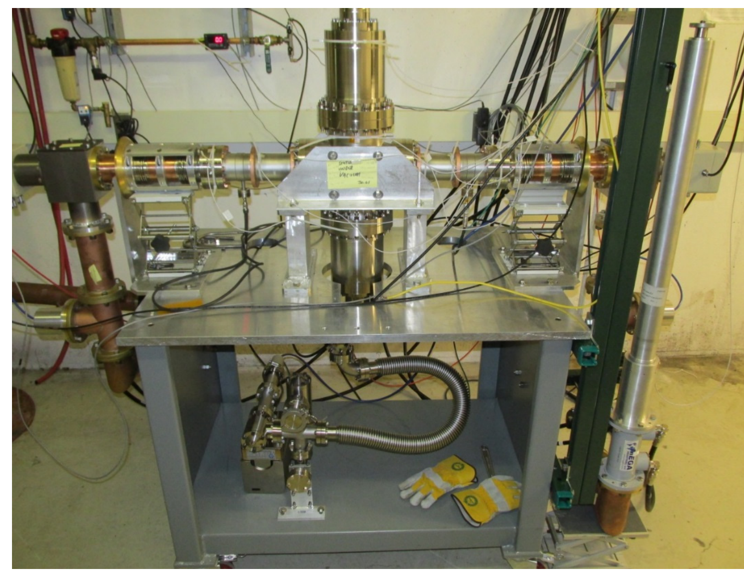
No Q0 degradation found in comparison of performance of cavity S107 in VTS (black) and STC (red). Mild FE present in STC consistently through each test.

Original Result of Cold Tests of the Fermilab SSR1 Cavities, A. Sukhanov et al., Proceedings of LINAC2014, Geneva, Switzerland

325 MHz coupler

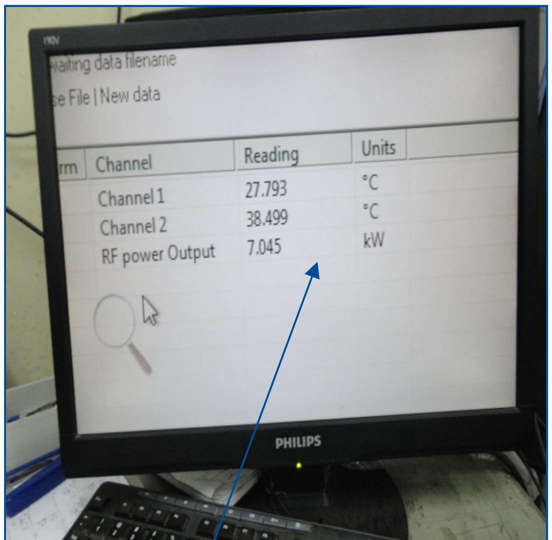
- Three prototype couplers were fabricated.
  - Two couplers were successfully tested up to 30 kW, CW, full reflection
  - Couplers were tested to failure. One coupler was destroyed at power level ~ 47 kW, CW, full reflection
  - Third coupler is used routinely in STC with SSR-I cavity at power level ~ 10 kW, CW, full reflection.
- 10 couplers are under production in Mega Industries, LLC





7 kW, 325 MHz SSRFPA (BARC)

Display of Calorimetric measurement of RF Power

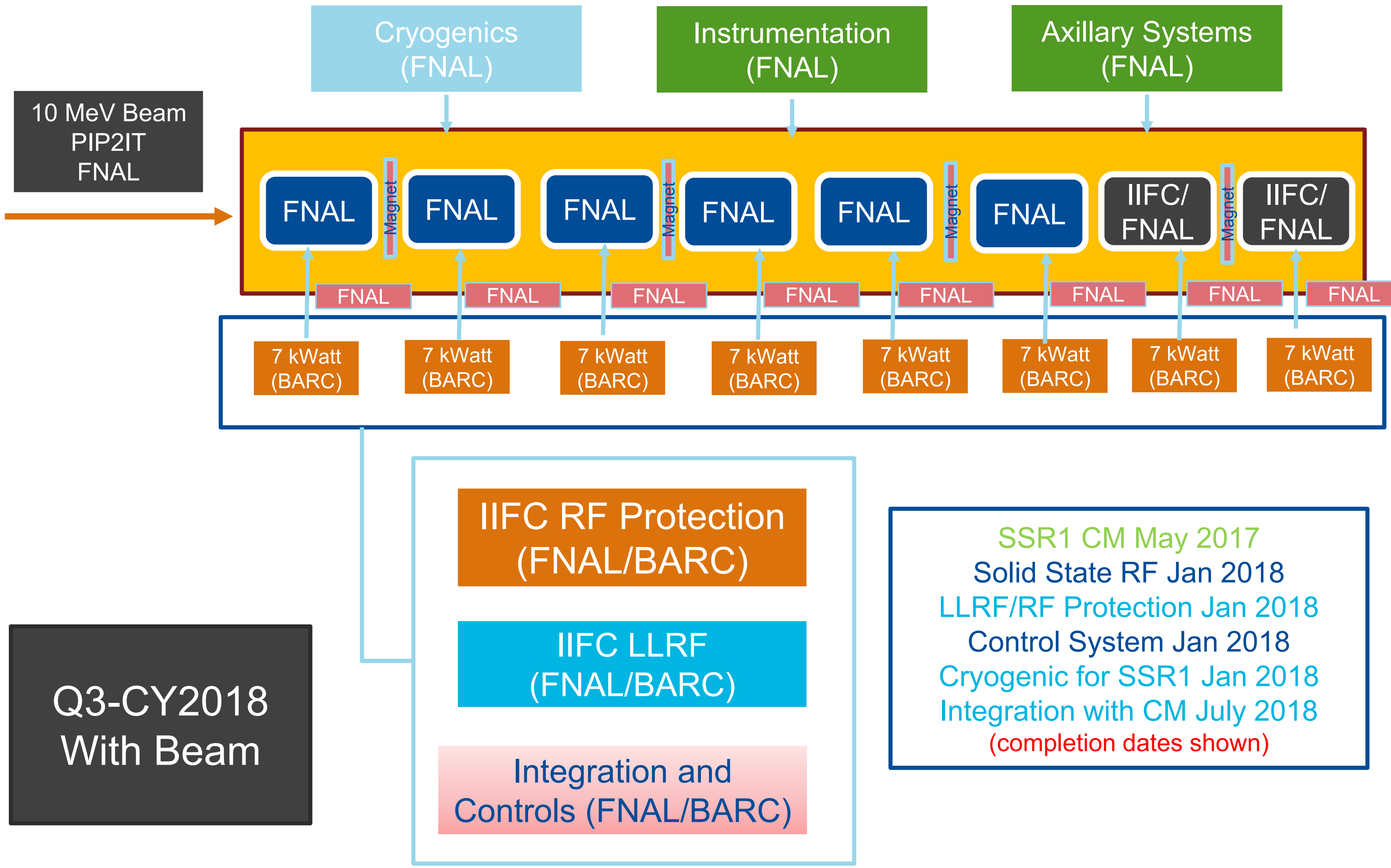


Sensor data of Calorimetric measurement of RF Power

RF Power Waveform at 7 kW on spectrum analyzer

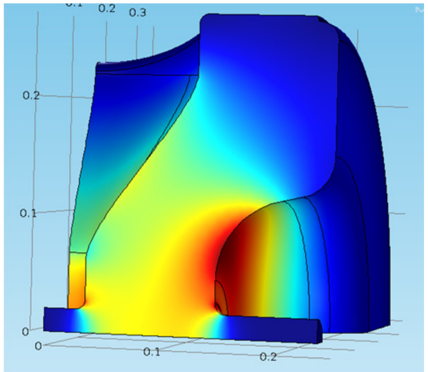
Meets the Design Specifications

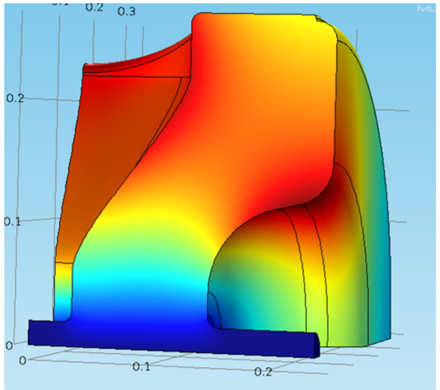
System Test of SSR1 CM & RF Power with Beam

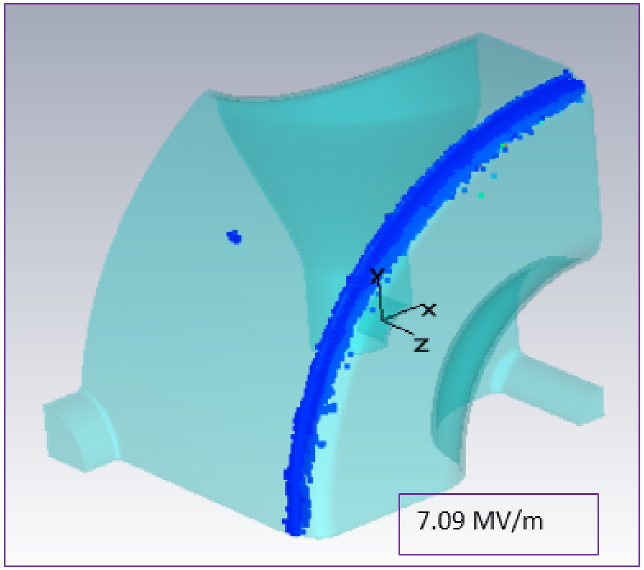


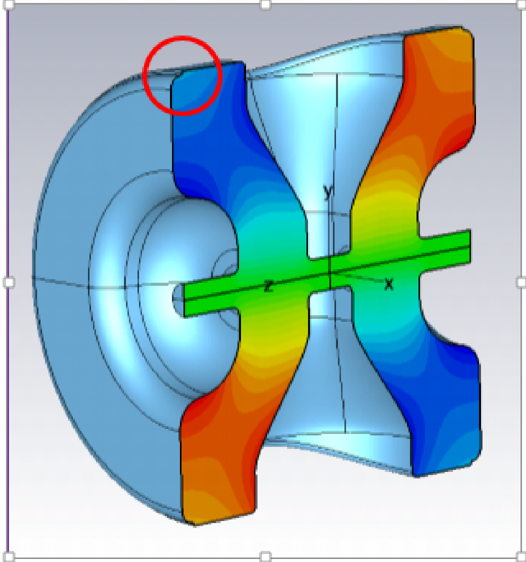
SSR2 $\beta = 0.47$ Cavity

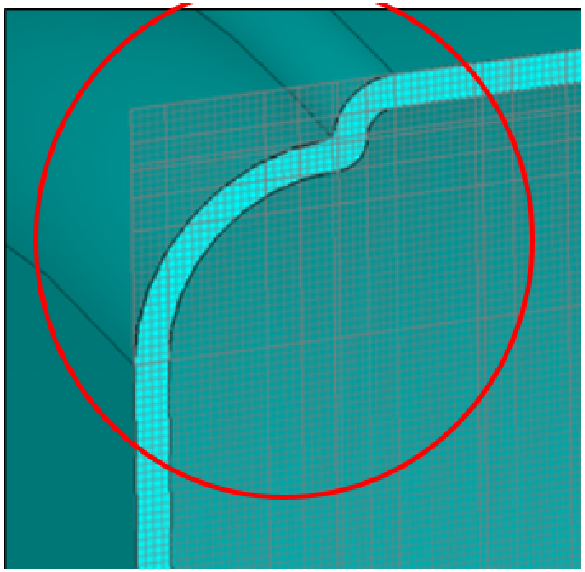
- Fermilab has finalized the SSR2 RF Design.
- BARC will proceed with this RF design and finalize the SSR2 Mechanical Design for manufacturing.
  - BARC will fabricate 1st prototype.
- Investigating details of cavity design, fabrication, including e-beam facility







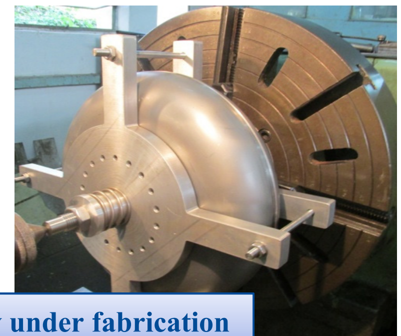


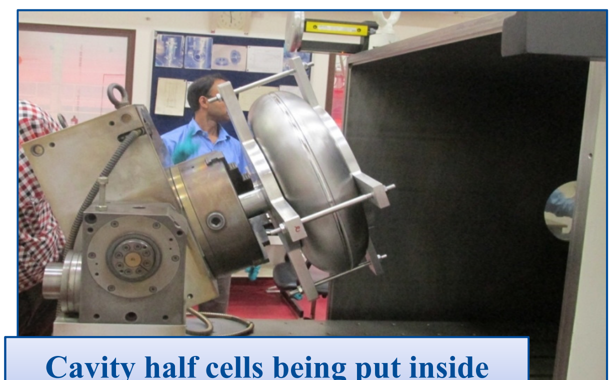


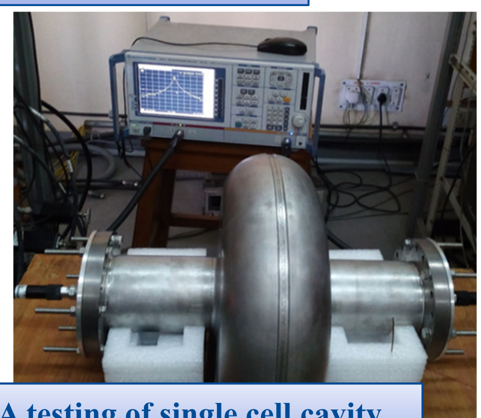
Development of β = 0.61 (VECC)

- VECC has fabricated one β = 0.61, 1-cell Nb cavity in collaboration with IUAC. (Dec 2015)
- Processing and testing at Fermilab (4-7/2016)


Half cells after cleaning


1-cell cavity under fabrication

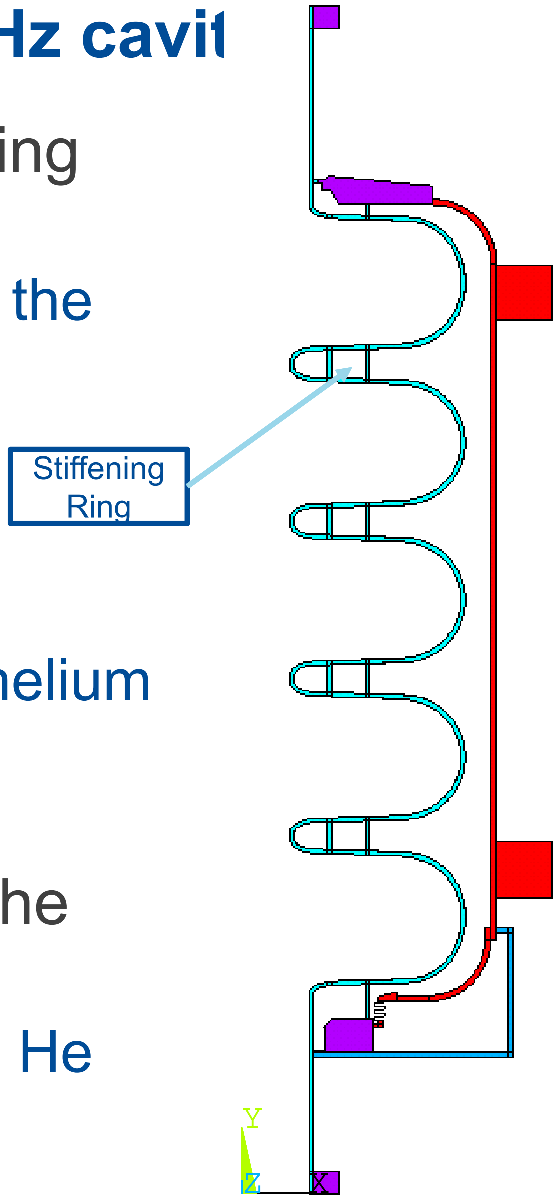

Cavity half cells being put inside EBW machine for Equator welding


VNA testing of single cell cavity


Vacuum leak rate checking of single cell cavity at LN_2 temperature

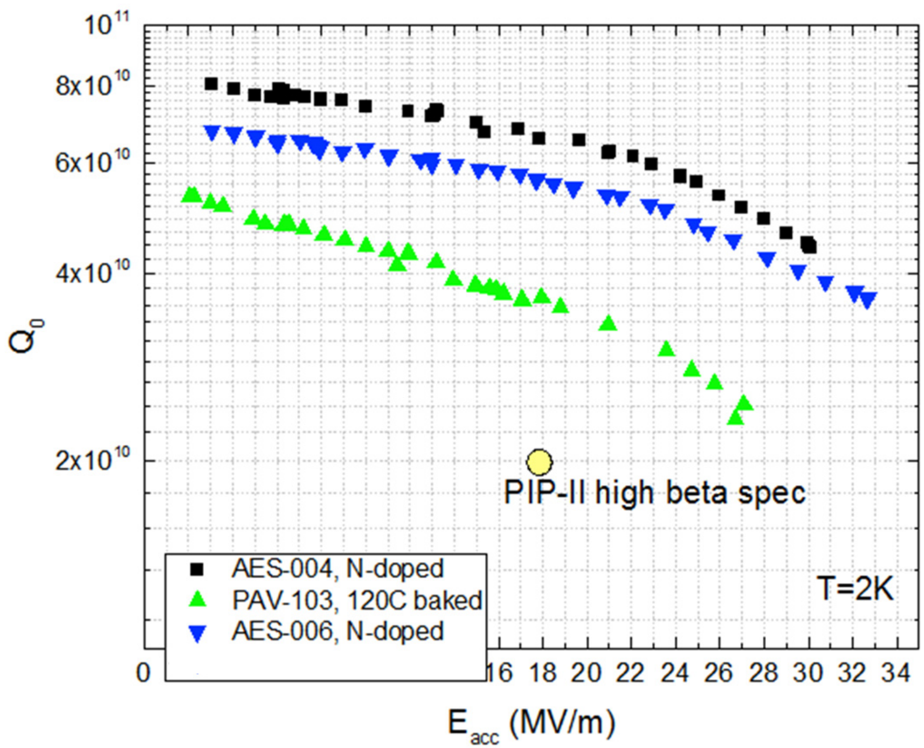
Design Development of β = 0.61, 650 MHz cavit

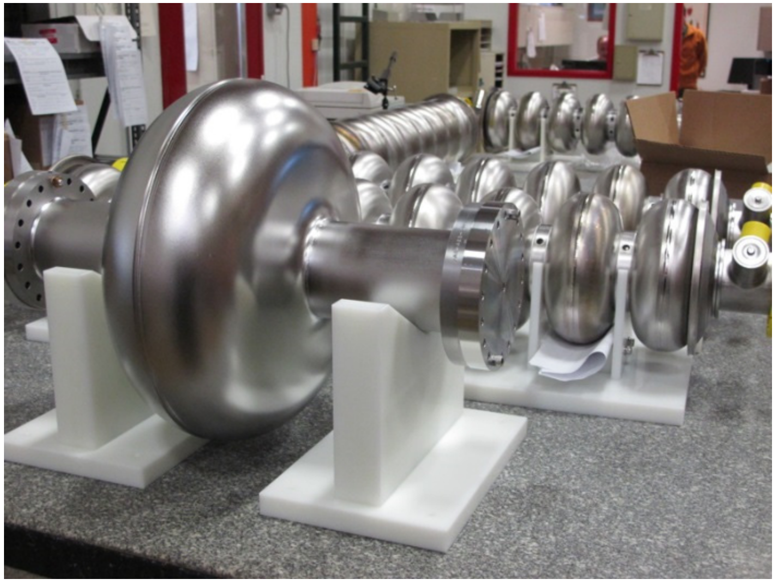
- 5-cell LB650 cavity design carried out, using new FRS.
  - The necessary parameters are well within the prescribed limits .
- The design studies includes
  - 3D Multipacting
  - Lorentz Force Detuning (LFD)
  - Pressure sensitivity under external liquid helium pressure
  - Structural analysis with Stiffener Rings
- Further study is in progress for finalizing the design.
  - It will include the Fermilab End Group and He Vessel design.



650 MHz High Beta Single-Cell Q0 R&D

- Results – highlights – 120C bake versus N doping
  Q~ 7e10 at 2K, 17 MV/m – world record at this frequency!
- Applying N doping to 650 MHz (beta=0.9) leads to double Q compared to 120C bake (standard surface treatment ILC/XFEL)



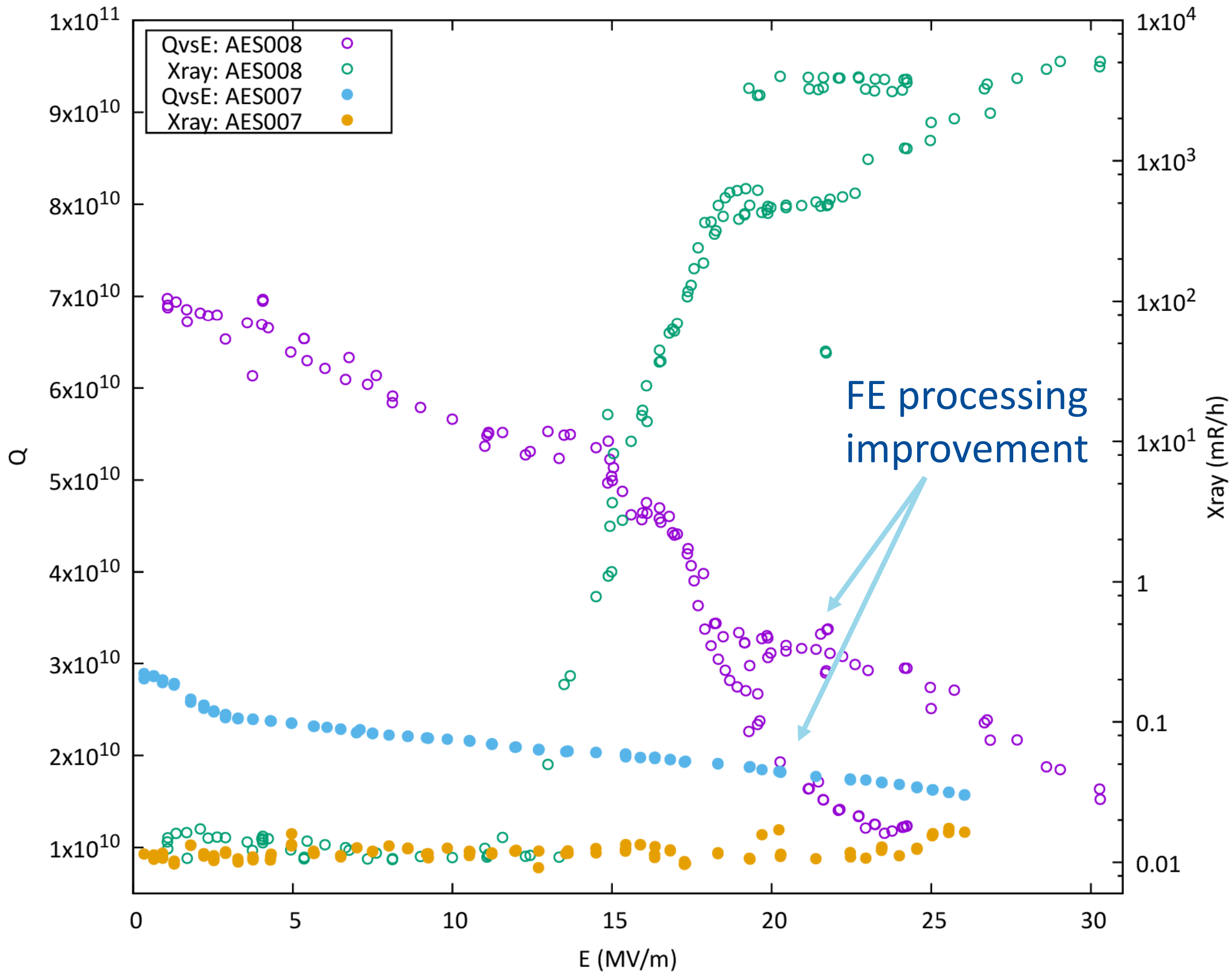


FNAL—Grassellino, Melnychuk, Merio, Rowe, Sergatskov, et al.

650 MHz High Beta Multi-cell Results

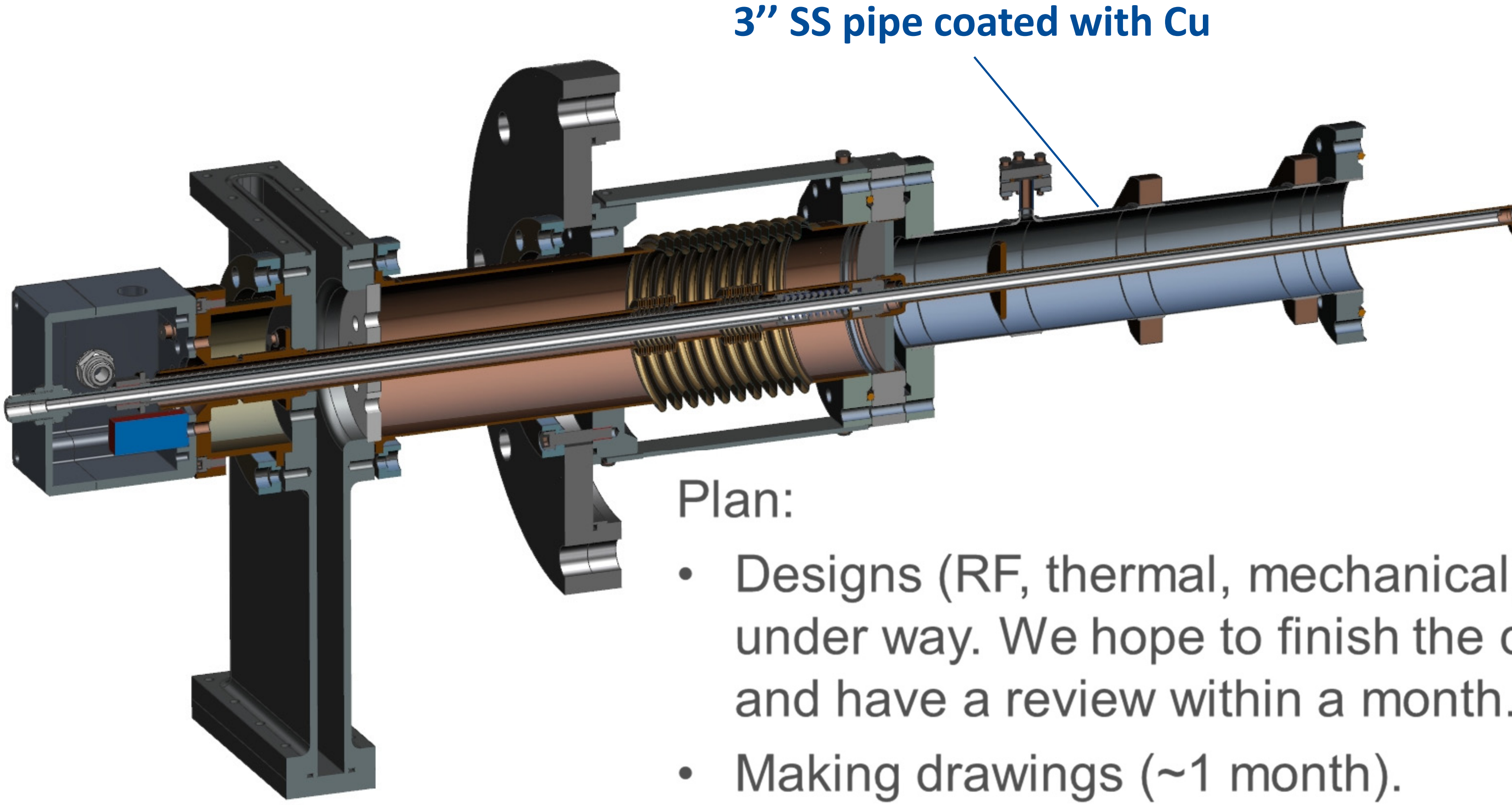
AES008
- Excellent Q0 +gradient
- Multi-pacting
- High FE
- No Quench
- Aggressive re-cleaning
- Re-rinsed
- 2nd Test FE persisted

AES007
- Moderate Q0
- Over-doped
- Quench @ 27 MV/m
- No FE
- Minimal multipacting
- More EP needed



FNAL—Sergatskov, Grassellino, Melnychuk, Merio, Rowe, et al.

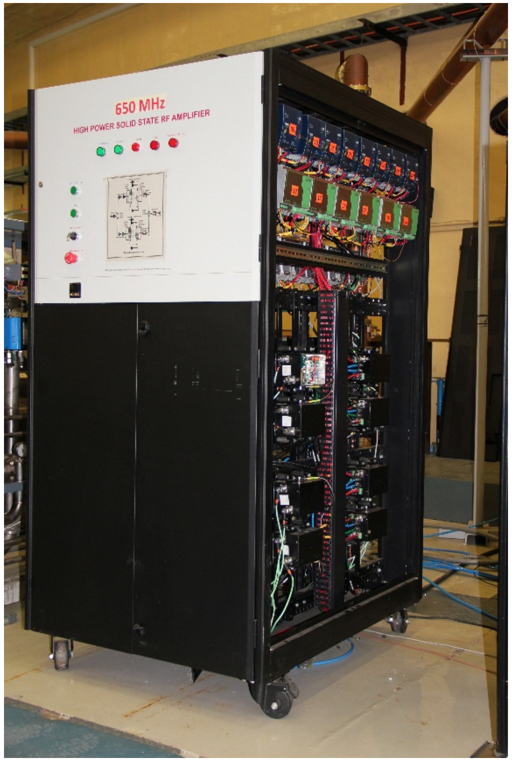
650 MHz coupler



Plan:

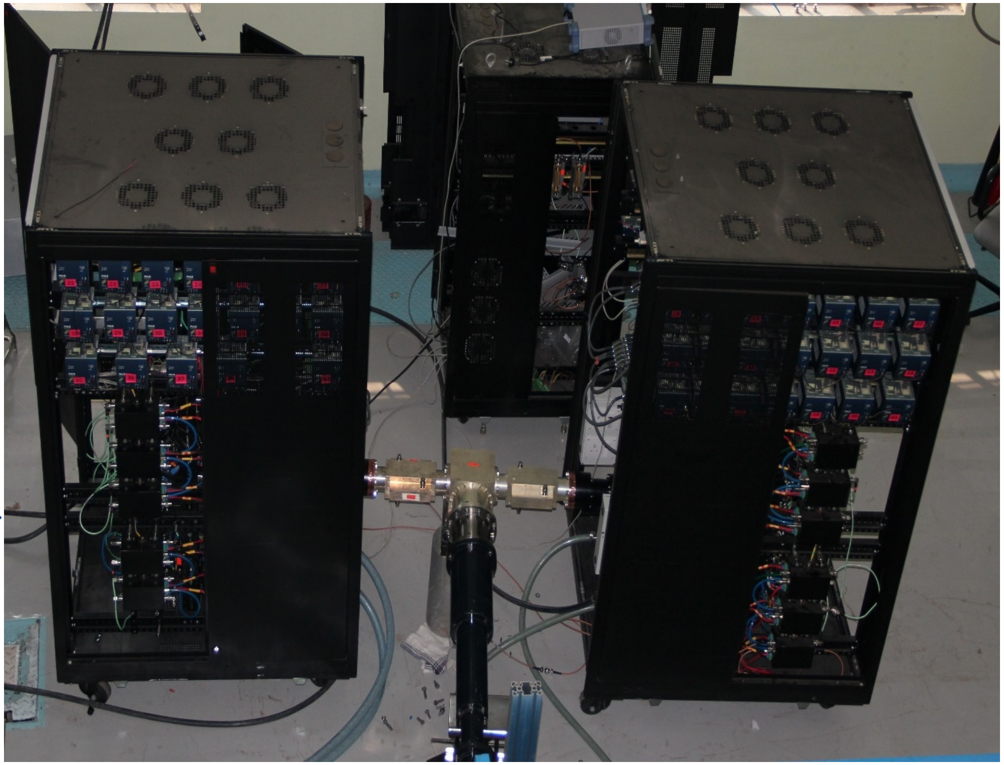
- Designs (RF, thermal, mechanical) are under way. We hope to finish the designs and have a review within a month.
- Making drawings (~1 month).
- Procurement 2.5 couplers (~1.5 month)
- Fabrication (~6 month)

650 MHz SSRFA (RRCAT)



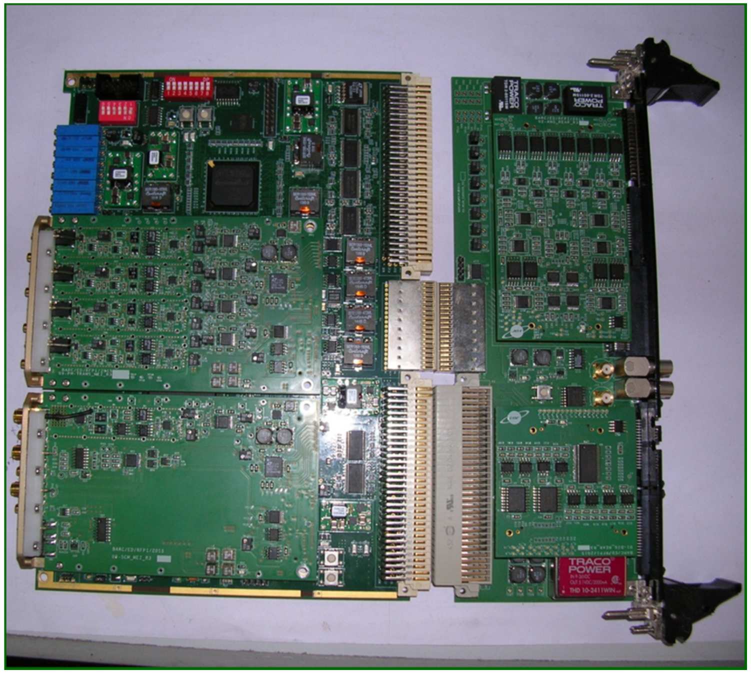
- Assembled 15 kW Amplifier of size (1m*1.2m*2m)

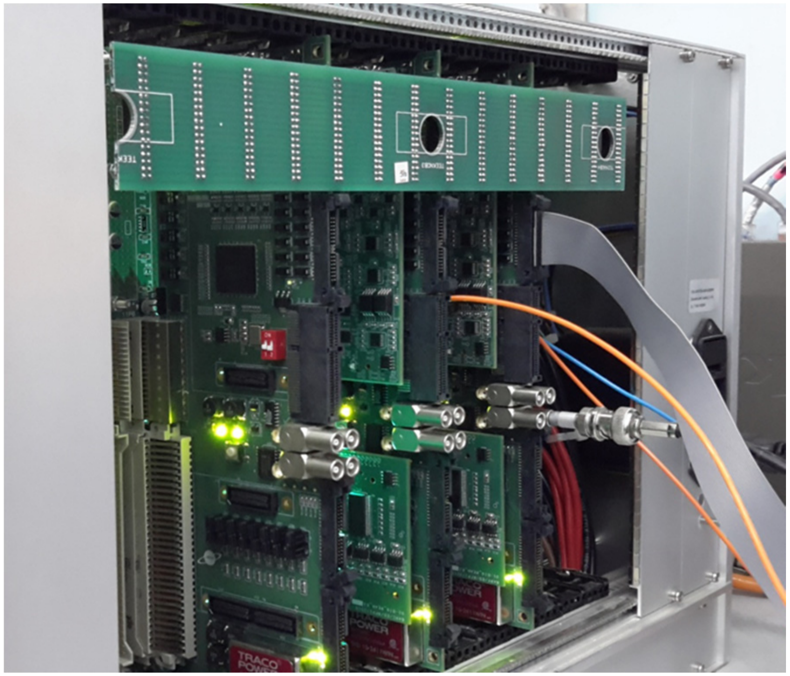
- Testing of 30 kW amplifier with dummy load



RF Protection and Interlock System

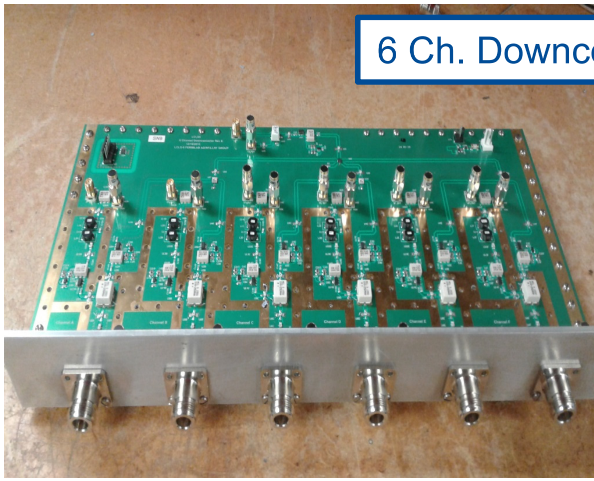
- A complete redesign of the Fermilab RF Protection Interlock system has been done in collaboration with BARC.
- BARC has completed detail test
  - It will be tested at Fermilab at a High Power Test Stand this summer.



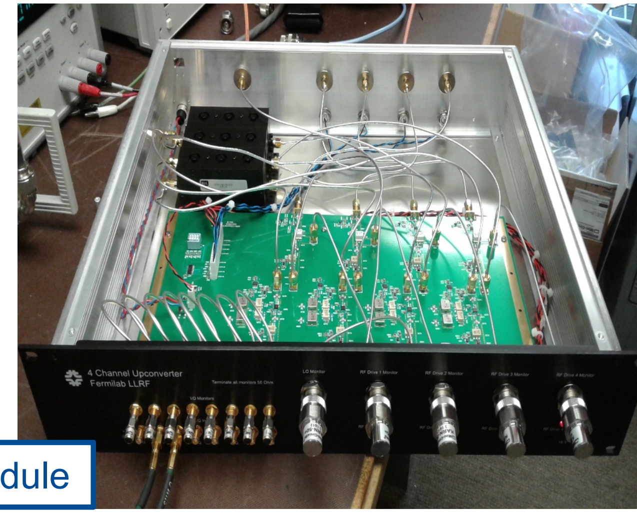


Low Level RF System

- Fermilab and BARC are jointly working on the design of an upgraded Low Level RF System for PIP-II



6 Ch. Downconverter module

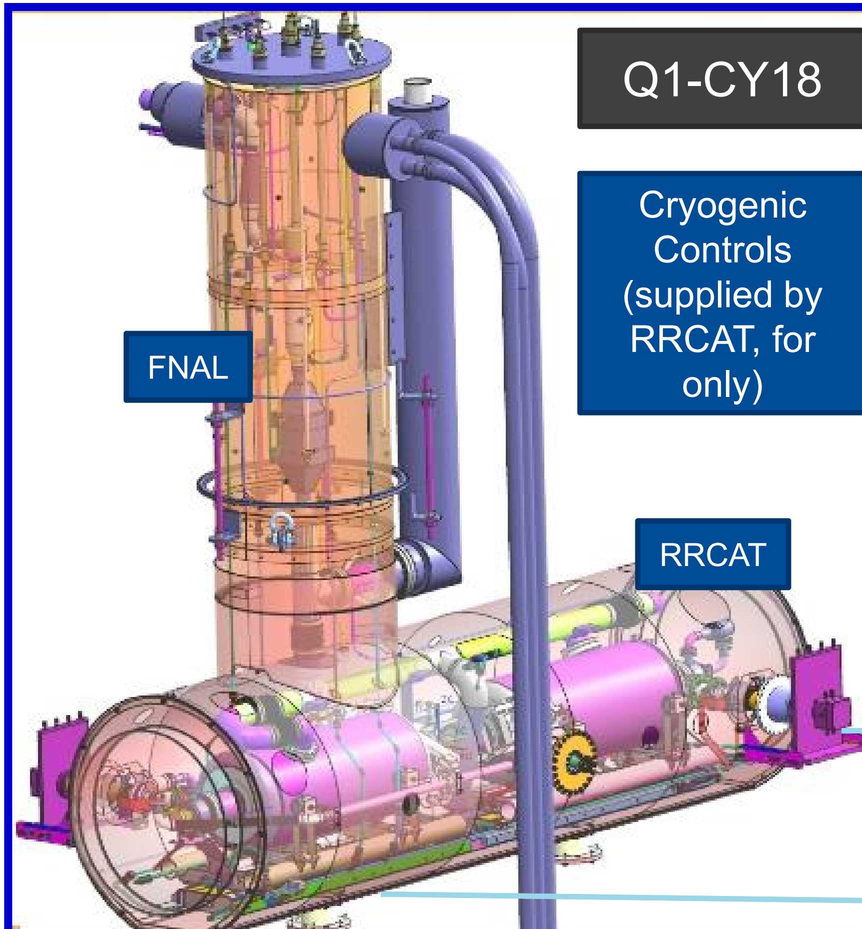


4 Ch. Up-converter module

Resonance Controller

- Digitizer board
- Digital LLLRF board
- RF Reference distribution System
- Support System:
  - Power Supply
  - Temperature Control
  - Rack Interconnect

650 MHz Dressed Cavity Horizontal Test Stand



Two 40 kWatt Units (RRCAT)

FNAL

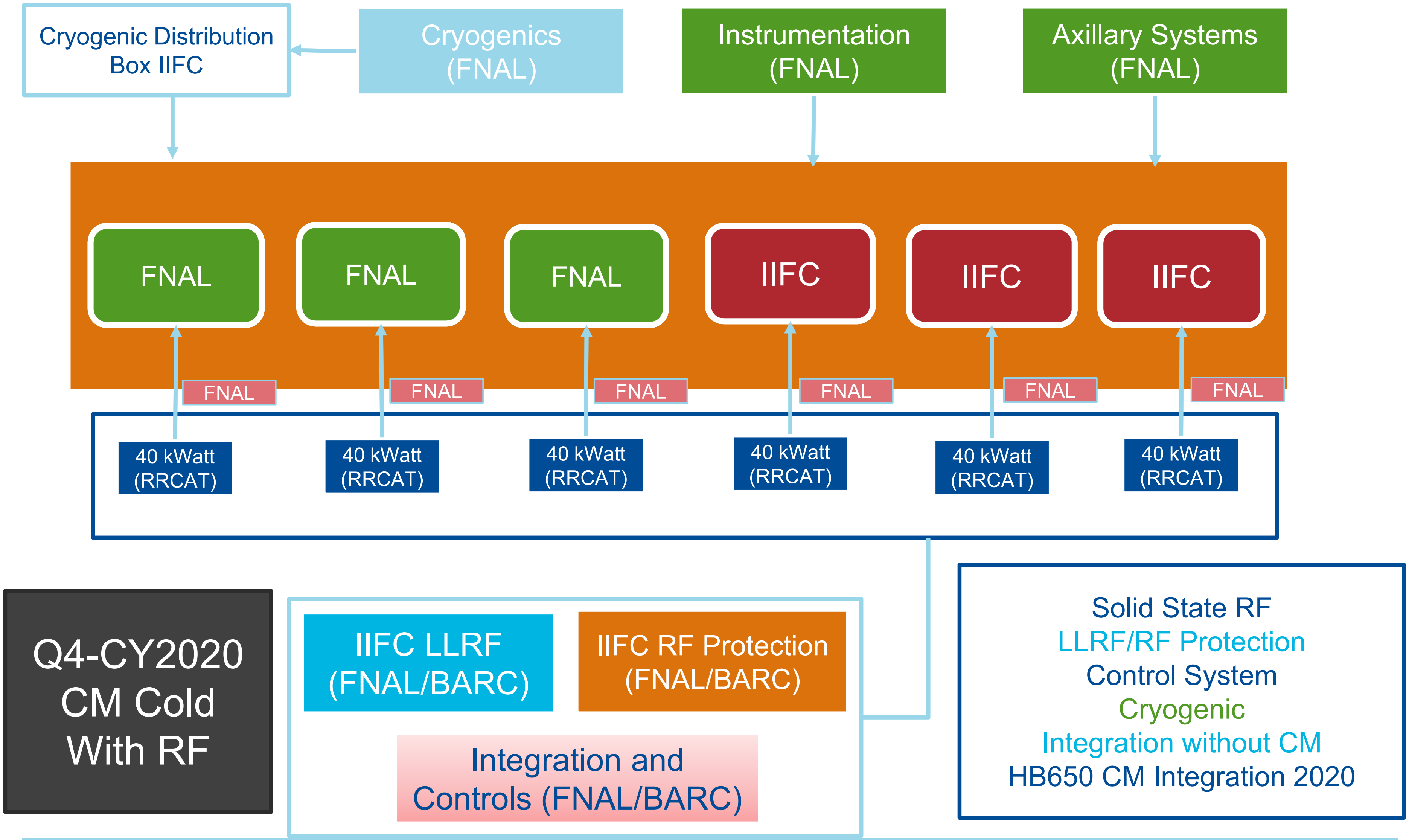
FNAL

Cryogenics for HTS July 2017 (RRCAT)
Two 40kWatt RF Oct 2017 (RRCAT)
LLRF/RF Protection April 2017 (BARC)
Control System May 2017 (BARC/RRCAT)
Integration with cryostat May 2018 (RRCAT)
Test of 1st Dressed Cavity May 2018 (RRCAT)
Cryostat at Fermilab 2019

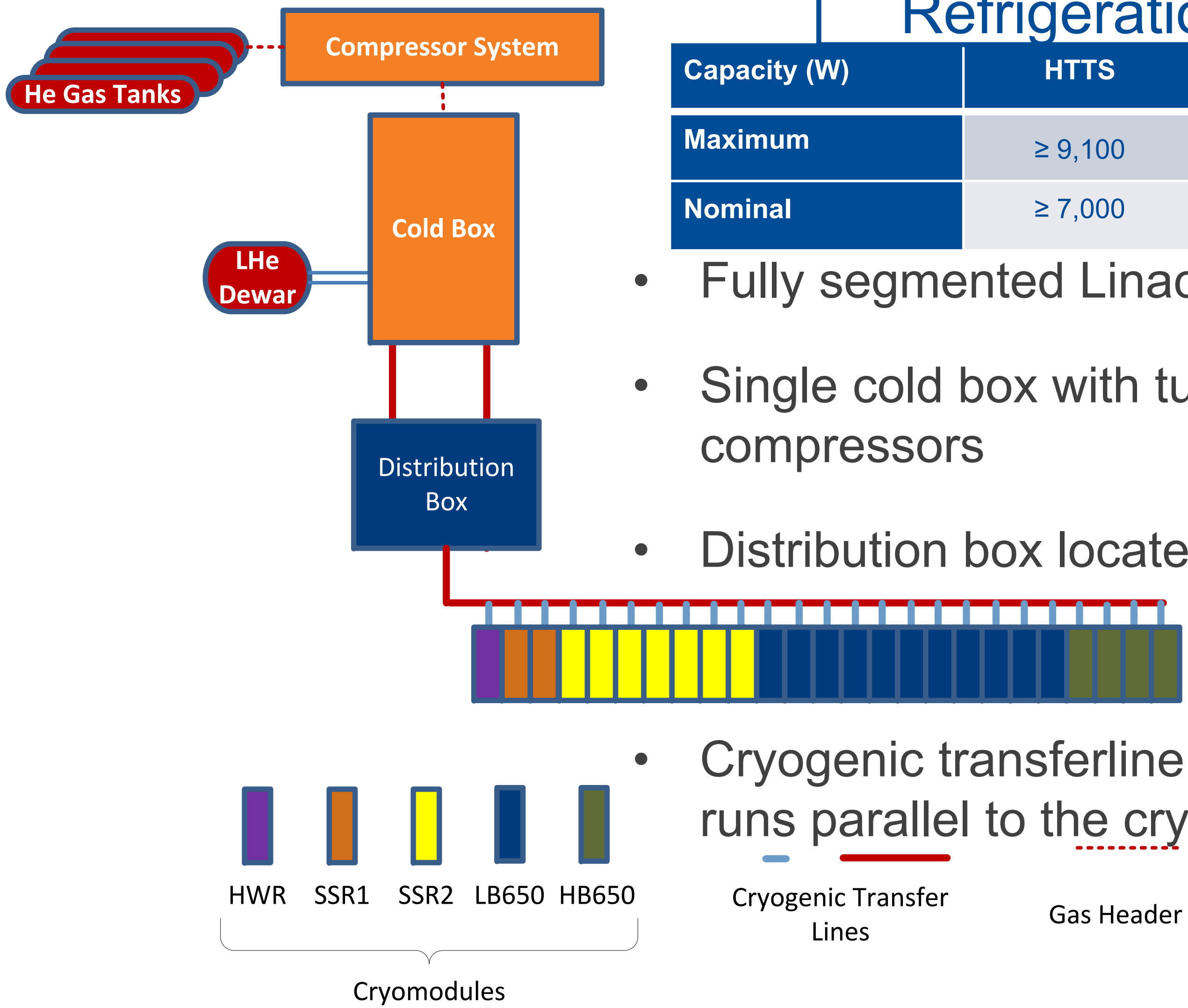
IIFC RF Protection (FNAL/BARC)	LLRF (FNAL/BARC)	Integration and Controls (FNAL/BARC/RRCAT)

IIFC PIP-II

Integrated Test of HB650 Cryomodule Test



PIP-II Cryogenic Plant: System architecture



Refrigeration Load

Capacity (W)	HTTS	LTTS	2 K
Maximum	≥ 9,100	≥ 1,500	≥ 1,900
Nominal	≥ 7,000	≥ 1,150	≥ 1,750

- Fully segmented Linac
- Single cold box with turbines and cold compressors
- Distribution box located in a refrigerator room
- Cryogenic transferline with bayonet cans that runs parallel to the cryomodules

Summary

- PIP-II represents a first step in the realization of the full potential of the Fermilab complex
  - Complete concept outlined in the Reference Design Report
  - Initial goal is to establish LBNF as the leading long-baseline program in the world, with >1 MW at startup
  - Platform for subsequent development of the accelerator complex
    - LBNF >2 MW
    - Mu2e sensitivity $\times 10$
    - MW-class, high duty factor beams for future experiments
- R&D program aligned with the requirements outlined in the RDR
  - Organized to support a 2019 construction start
  - India is a major partner in the R&D program that would lead to construction deliverables.
- CD-0 has been received and we are working towards CD-1
  - Conceptual Design Report
  - Alternatives analysis