Cryogenics and Cryomodule for Large Scale Accelerators

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This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Cryogenic Systems Requirements
  - SRF technology based accelerators require "2 K" Cryo System (sub atmospheric) Apply Lessons learned from operating machines
  - Prototype and validate new technologies
- Integrated Cryogenic system design to support the Functional Requirements and Operational Parameters
- Successful examples of Large SRF Cryogenic systems in operation
  - JLab
    - » Cryogenics Commissioning "challenges" and new technologies developments
  - SNS
    - » Application of the lessons learned
    - » The beauty of the flexibility of the superconducting LINAC
    - » One unexpected result that testifies for the design
- FRIB
  - Accelerator scope and requirements
  - Cryogenic Distribution system and cryomodule validation tests

Dedicated to JLab's technical leadership in cryogenics, cryomodule engineering and systems integration

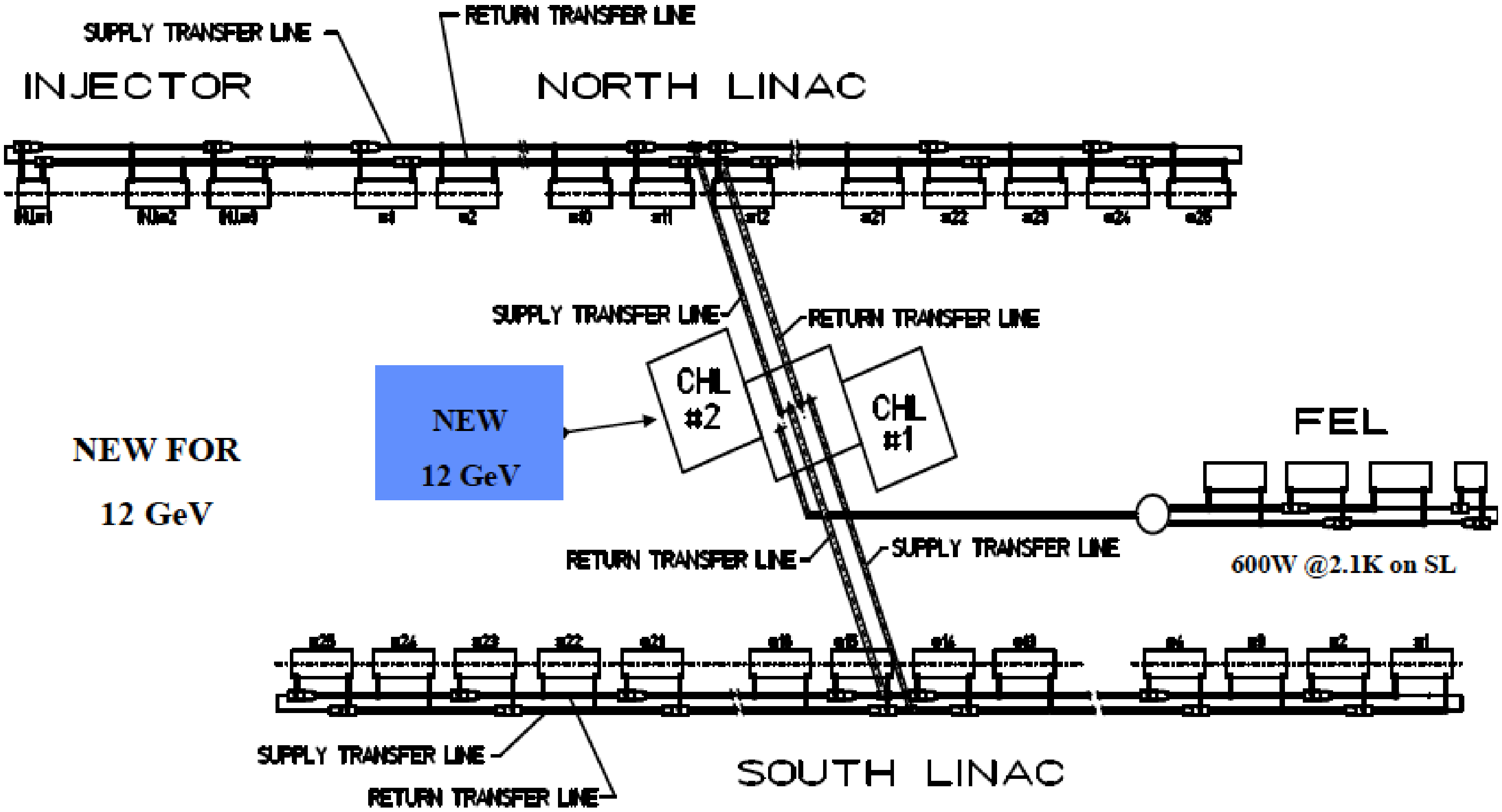
Cryogenic Systems Requirements

- Temperature levels and stability requirements
  - Bottom up requirements
  - Devices
  - Efficiencies at different levels
- Heat Loads definition
  - Bottoms up system requirements analysis with integrated load characteristics cryogenic plant and utility design
- Operating Parameters
  - CW, Pulsed
  - Heat Loads Implications, design consequences
- Operating modes Requirements
  - Impact on capacity margin
  - Impact on component matching
- Iterations and optimization processes

Integrated Cryogenic System Design to Support the Functional Requirements and Operational Parameters

- Availability, Reliability, Maintainability and Upgradability considerations
  - Repair strategy
- Cryogenic Distribution and Loads Segmentation
  - Warm up and cool down requirements
  - Safety Implications
- Vacuum Spaces Segmentation
  - Leak Checking
  - Vent lines location
  - Safety Implications
- Installation and Commissioning Strategy considerations
- Safety integrated with design
- Prototyping and design validation tests to minimize risks
- Iterations and optimization processes
  - Real estate and facility requirements

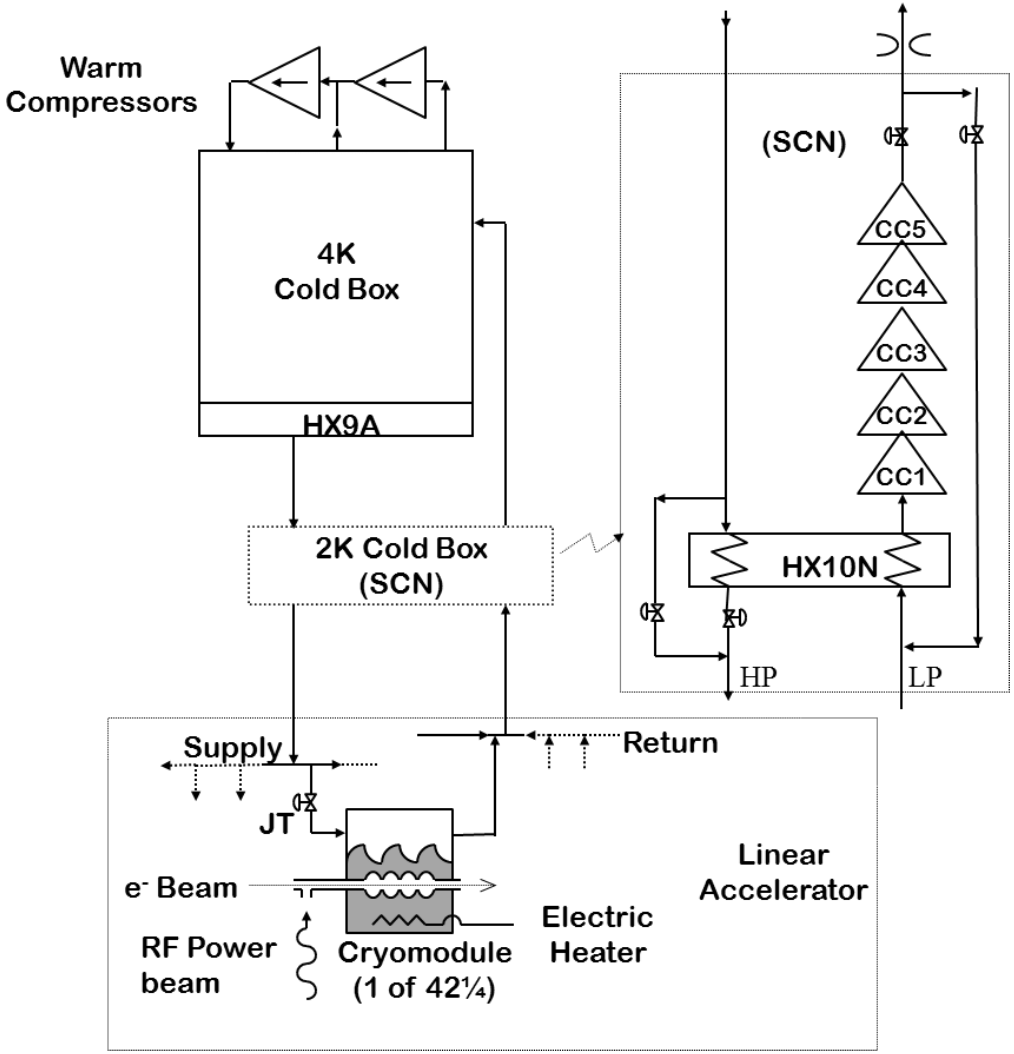
JLab Cryogenic Distribution Planning (1980s)



JLab Cryogenic System

- <u>Helium Refrigerator System</u>
- 4.6 kW @ 2.1 K
- 12kW @ 38/50 K
- 10g/s Liquefaction @ 4.5 K

- <u>Cryogenic Transfer Line System</u>
- 4.5 K & 38 K Helium Supply and 2.2 K & 50 K Helium Return

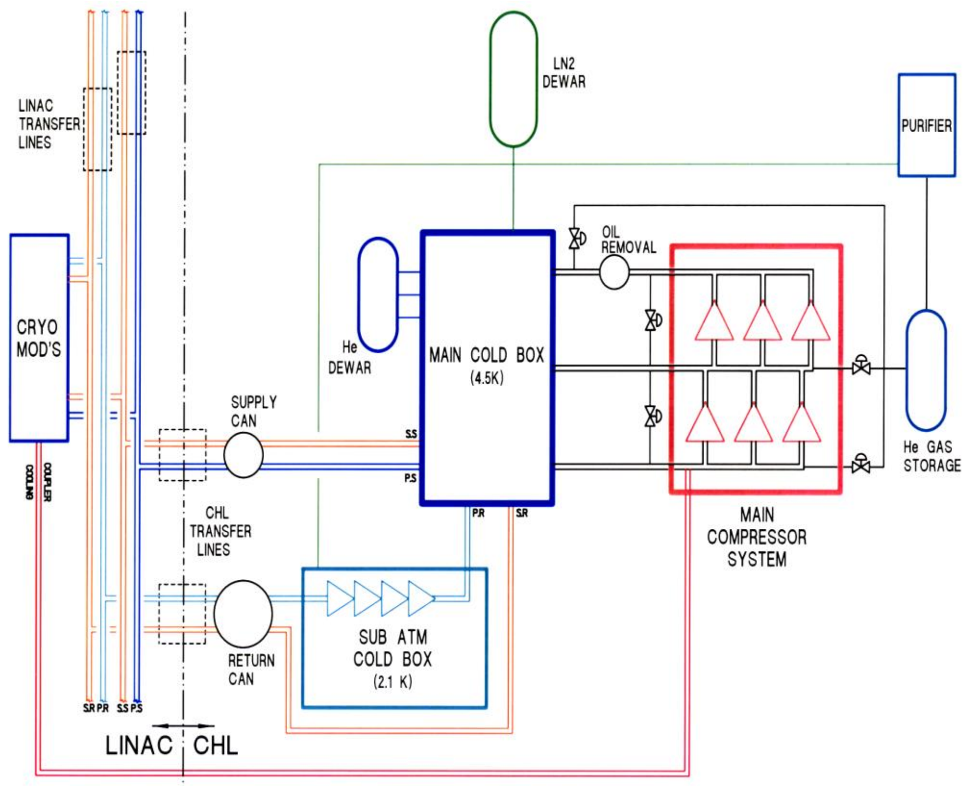


JLab Commissioning Lessons Learned

- After three years of unsuccessful attempts by the equipment suppliers, JLab took over and developed the pump down path to achieve the 2 K operating temperature
- Added new components (HXs, Cold Compressor, etc)
- Modified Design
- Improved thermal isolation and LN2 cooling
- Lessons Learned applied to new JLab 2 K Cold Boxes and SNS system

Process Block Diagram of the SNS Refrigerator System (~1/2 JLab's size). (2000's)

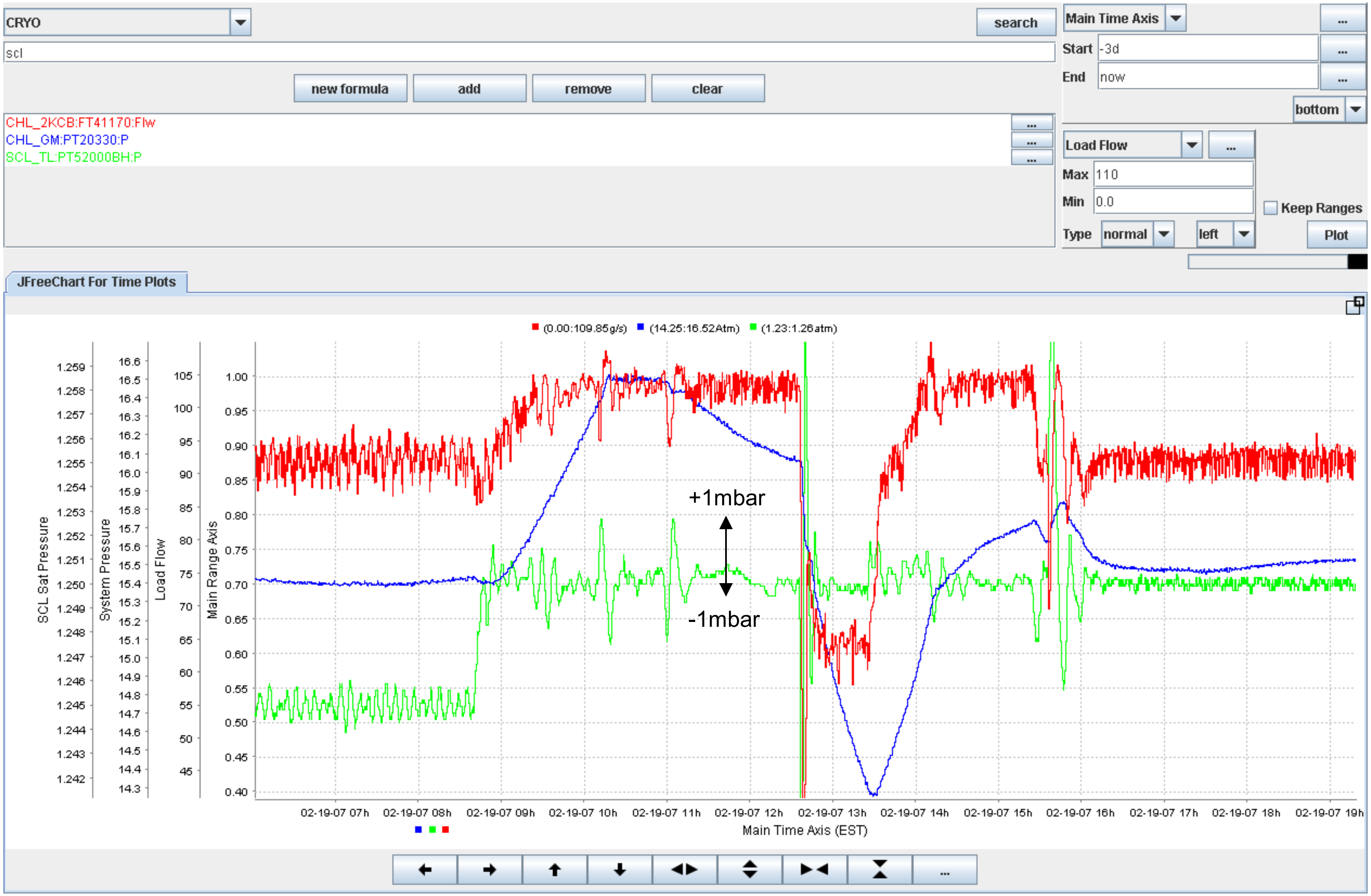
- Helium Refrigerator System
- 2400 W Capacity@ 2.1 K
- 8300 W Shield Load @ 38/50 K
- 15g/s Liquefaction at 4.5 K
- 80g/s Liquefaction Mode
- Cryogenic Transfer Line System
- 4.5 K & 38 K Helium Supply and 4.0 K & 50 K Helium Return



The first high-energy SC linac for protons, and the first pulsed operational machine at a relatively high duty.

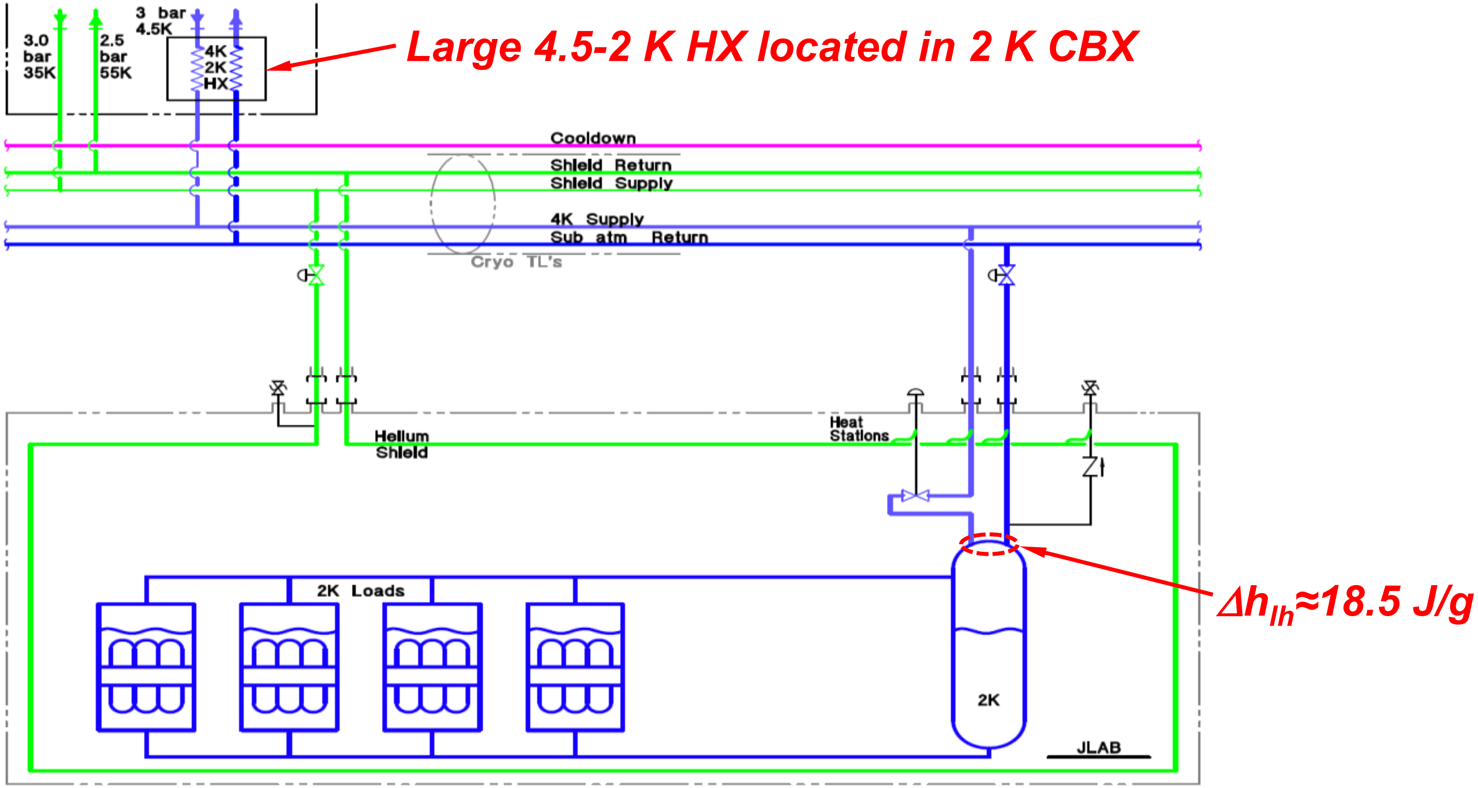
High reliability and availability, stable and flexible operations. Multiple components warm up and repair.

Unexpected Result: 1GeV@4.47 K
A tribute to the Design



CM Cryogenic Design Considerations [1]

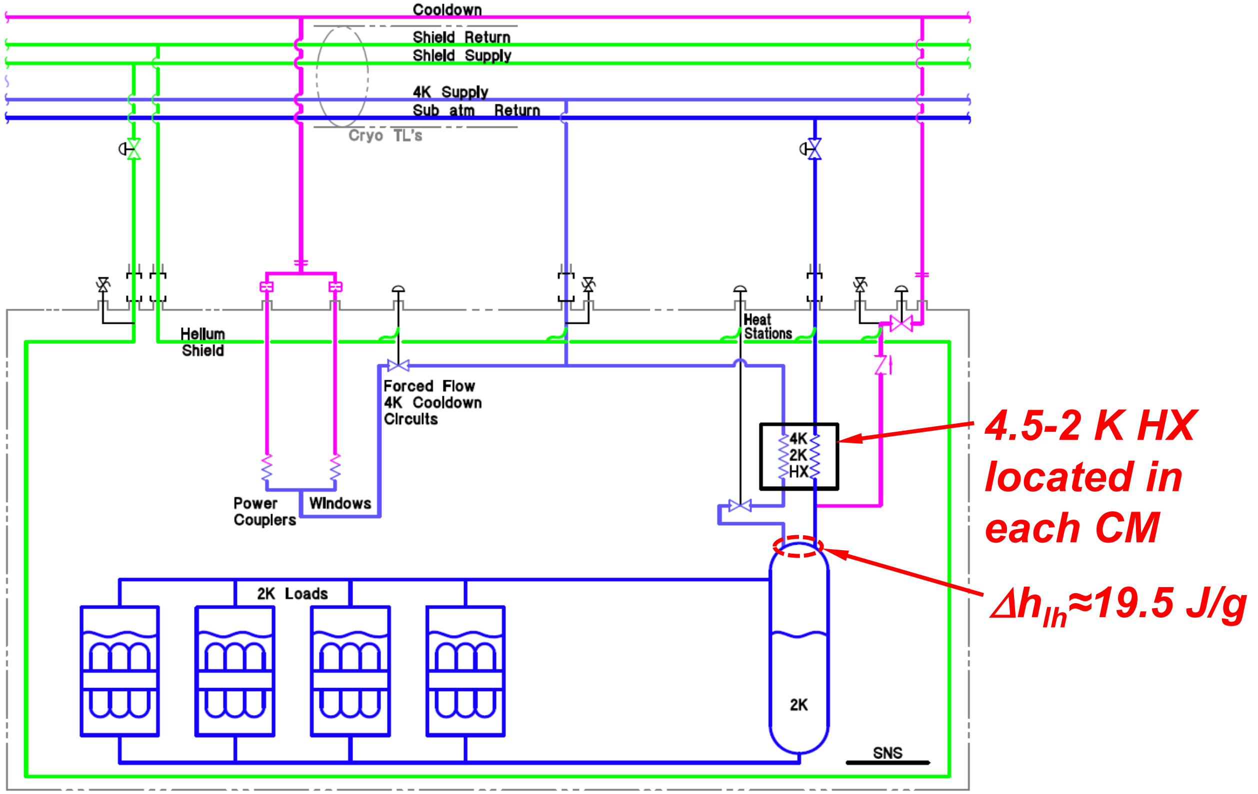
- JLab helium distribution system
  - CEBAF distribution system heat in leak of ~12W per CM + CM Static heat in leak of ~18W per CM is adsorbed at 2 K



V. Ganni, et al, "Helium Refrigeration Considerations for Cryomodule Design," Advances in Cryogenic Engineering 59, American Institute of Physics, New York (2014)

CM Cryogenic Design Considerations [2]

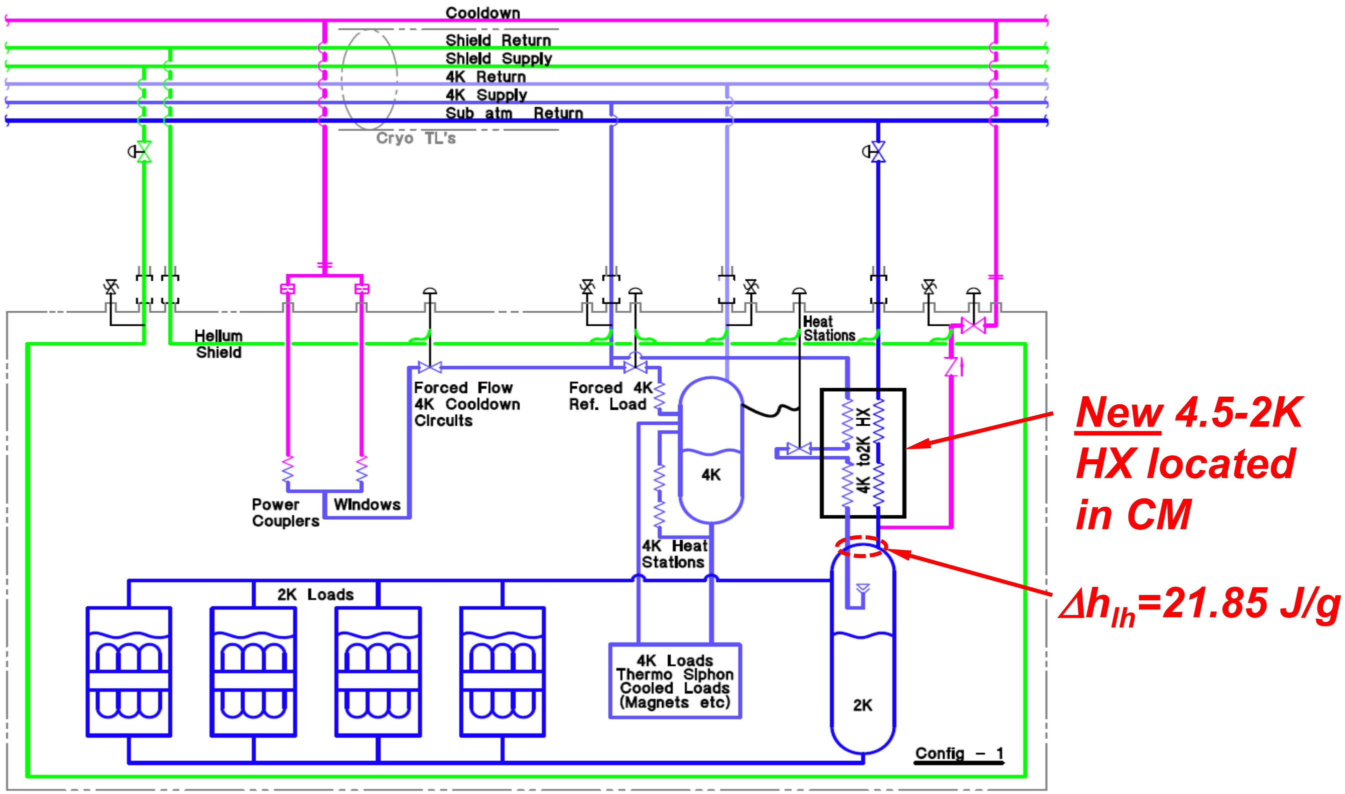
- SNS helium distribution system
  - SNS distribution system heat in leak ~10W per CM is adsorbed at ~4 K (which is equivalent to ~3W at 2 K)



V. Ganni, et al, "Helium Refrigeration Considerations for Cryomodule Design," Advances in Cryogenic Engineering 59, American Institute of Physics, New York (2014)

CM Cryogenic Design Considerations [3]

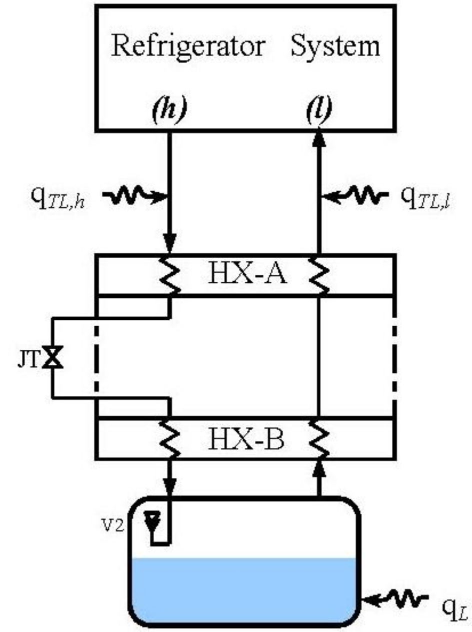
- Generalized distribution system
  - Enthalpy flux can improve ~9.3% for the same mass flow rate as compared to SNS



V. Ganni, et al, "Helium Refrigeration Considerations for Cryomodule Design," Advances in Cryogenic Engineering 59, American Institute of Physics, New York (2014)

2 K Heat Exchanger Design Benefit from JLab and SNS Successful Experiences

- JLab design (1980s)
  - Centralized heat exchanger in the cold box
    - » Transfer Line loads are at 2 K
- SNS design (2000s)
  - Distributed heat exchangers at the loads
    - » Transfer line loads are not at 2 K anymore
- JLab designed a 4 K/2 K Heat Exchanger to improve 2 K process
  - A prototype HX of ~5 g/s constructed at JLab
- Test cryostat with 4 K/2 K Heat exchanger designed by JLab and built by FRIB/MSU
  - Tested at JLab
- FRIB baseline incorporates SNS design but continues to support work on the Joule Thomson (JT) Valve in between two sections of the HX to Improve capacity for the same mass flow rate
- V. Ganni, et al, “Helium Refrigeration Considerations for Cryomodule Design,” Advances in Cryogenic Engineering 59, American Institute of Physics, New York (2014)



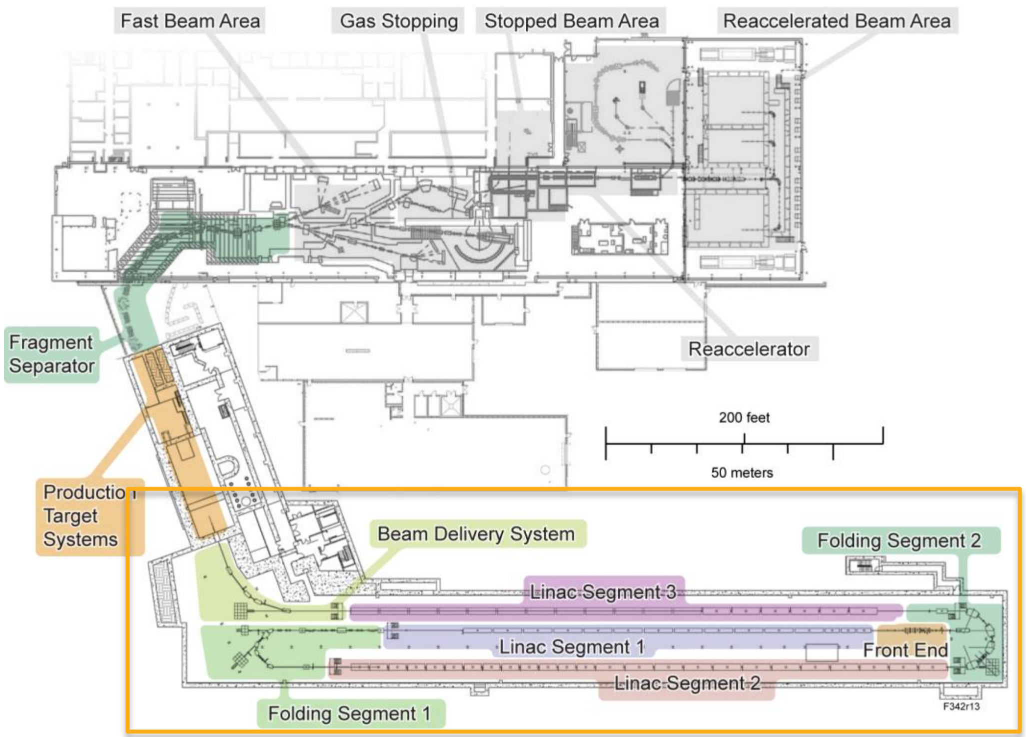
Jefferson Lab

OAK RIDGE National Laboratory

Cycle Improvements: The Ganni Cycle (Patent)

- System operates closed to optimum conditions for majority of operating modes by implementing the Ganni cycle: floating pressure, constant pressure ratio
- Minimum operating costs
- Minimum capital costs
- Minimum maintenance costs
- Maximum system capacity
- Maximum availability of the system

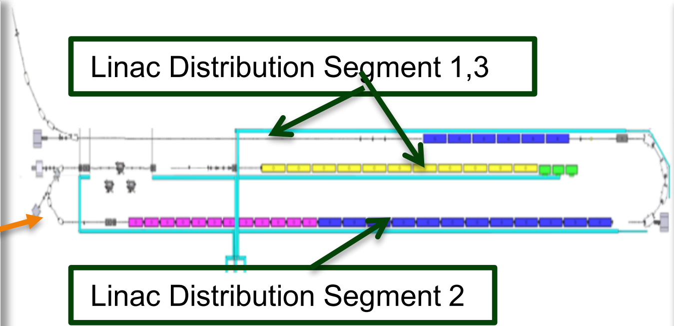
FRIB Scope & Requirements
High Reliability and Availability User Facility



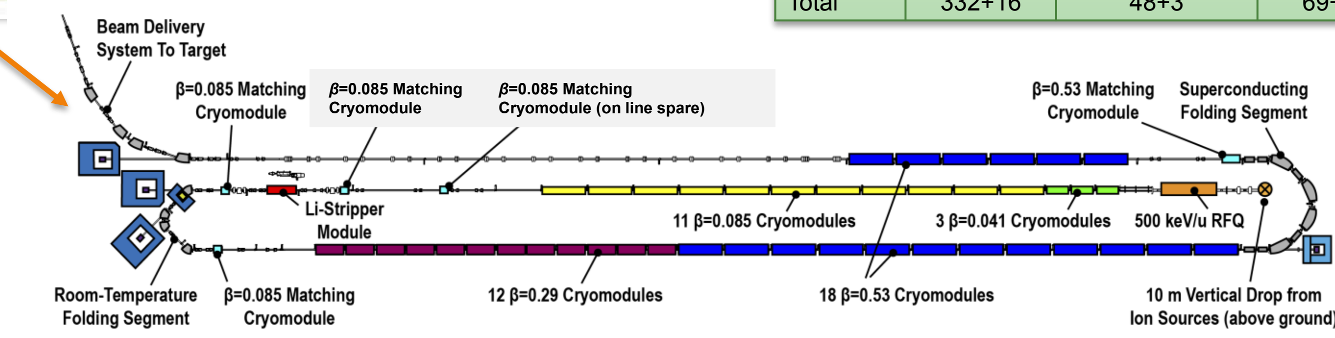
- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW
- Satisfy beam-on-target requirements

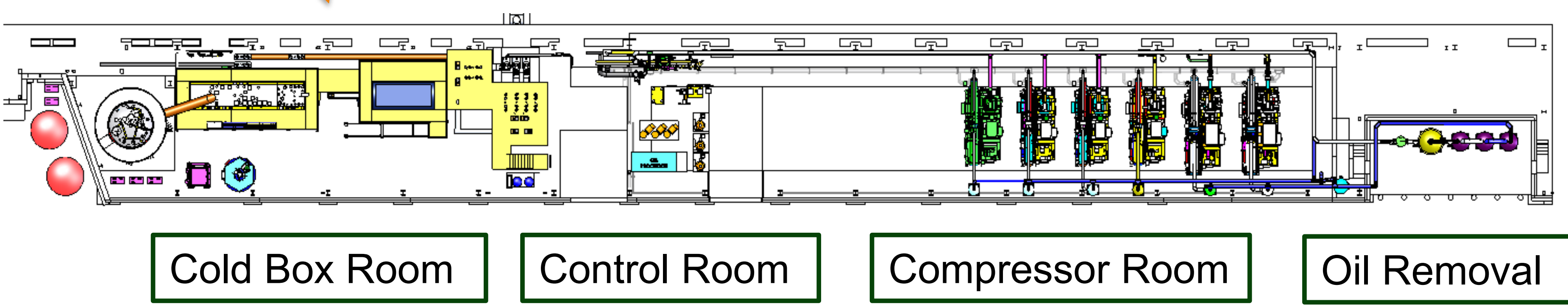
- Option for energy upgrade to >400 MeV/u by filling vacant slots with ~ 12 cryomodules
- Maintain Isotope Separation On-Line (ISOL) option
- Upgradable to multi-user simultaneous operation of light / heavy ions with addition of a light-ion injector

FRIB Cryogenic Systems and Cryomodules Layout



Cavity Type	Quantity of Cavities	Quantity of Modules	Quantity of Solenoids
β=0.041	12+4	3+1	6+2
β=0.085	88+8	11+1	33+3
β=0.29	72	12	12
β=0.53	144	18	18
Additional Matching Modules	12+4 4	3+1 (β=0.085) 1 (β=0.53)	n/a
Total	332+16	48+3	69+5





FRIB Cryogenic Heat Loads & Capacity

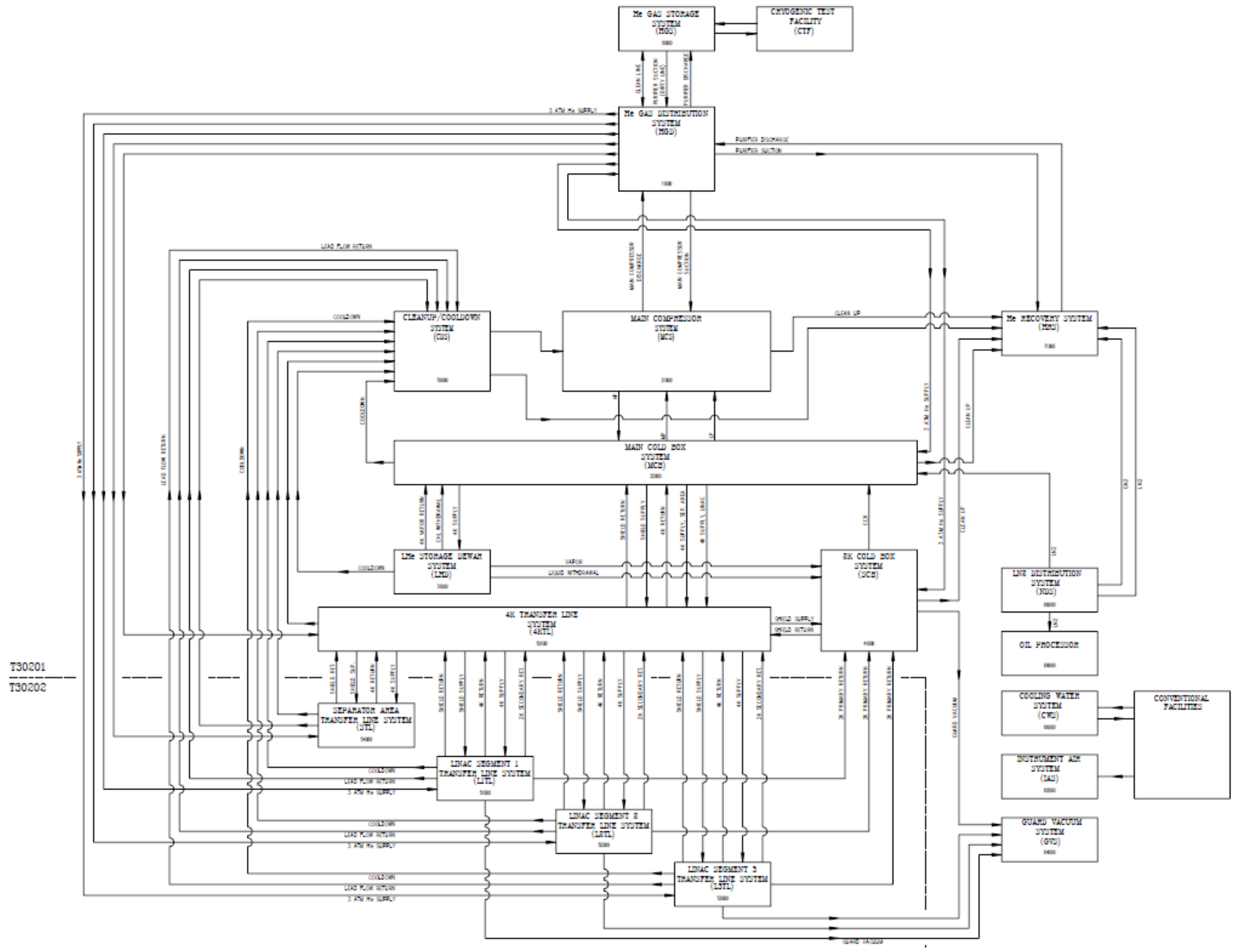
- Cryogenic heat loads T30200-TD-000244

Load (W)	2 K	4.5 K	38/55 K
Cryomodules	2349	1195	7331
Magnets	0	573 + 4 g/s	1640
Beam Loss	0	25	0
Distribution	514 @ 4.5 K	492	4787
Total	2349 + 514 @ 4 K	2285 + 4 g/s	13758

- Refrigeration System Design Capacity T30201-SP-000160

Mode	2 K	4.5 K	38/55 K
Max Capacity (W)	3600 (180 g/s) + > 514 @ 4 K	4200 + 14 g/s	20000

Process Block Diagram of the FRIB Refrigerator



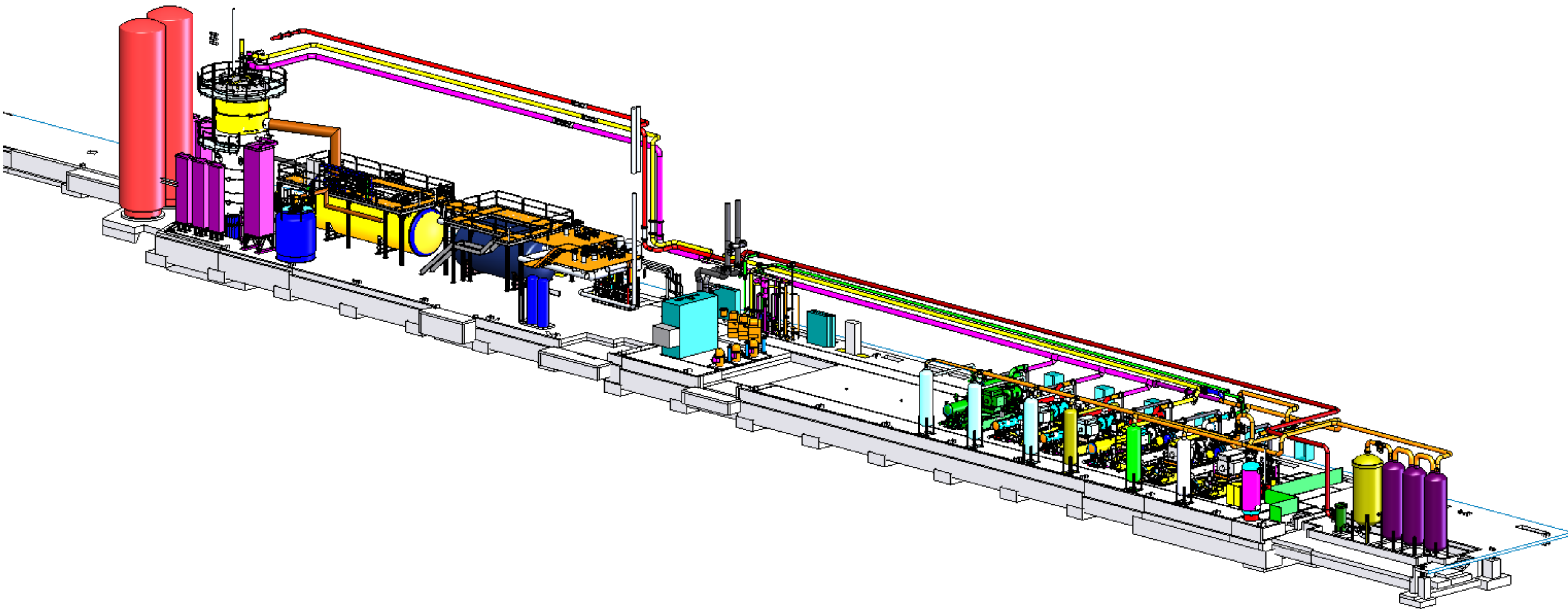
Integrated Cryogenics Extending the SNS Practice to FRIB

- Integrated design of the cryogenic refrigeration, distribution and cryomodule systems is key to efficient SRF operation
  - Ganni Cycle: floating pressure process that adapts efficiently to changing loads
  - Cryogenic Distribution systems are segmented to facilitate commissioning, operation and maintenance
  - Cryomodules connected with U-tubes for maintenance, availability and safety
  - 4 K-2 K Heat Exchangers housed inside the cryomodules to optimize efficiency
- Fundamental Design principles support user facility mission for:
  - ***Availability, Reliability, Maintainability and Upgradability***

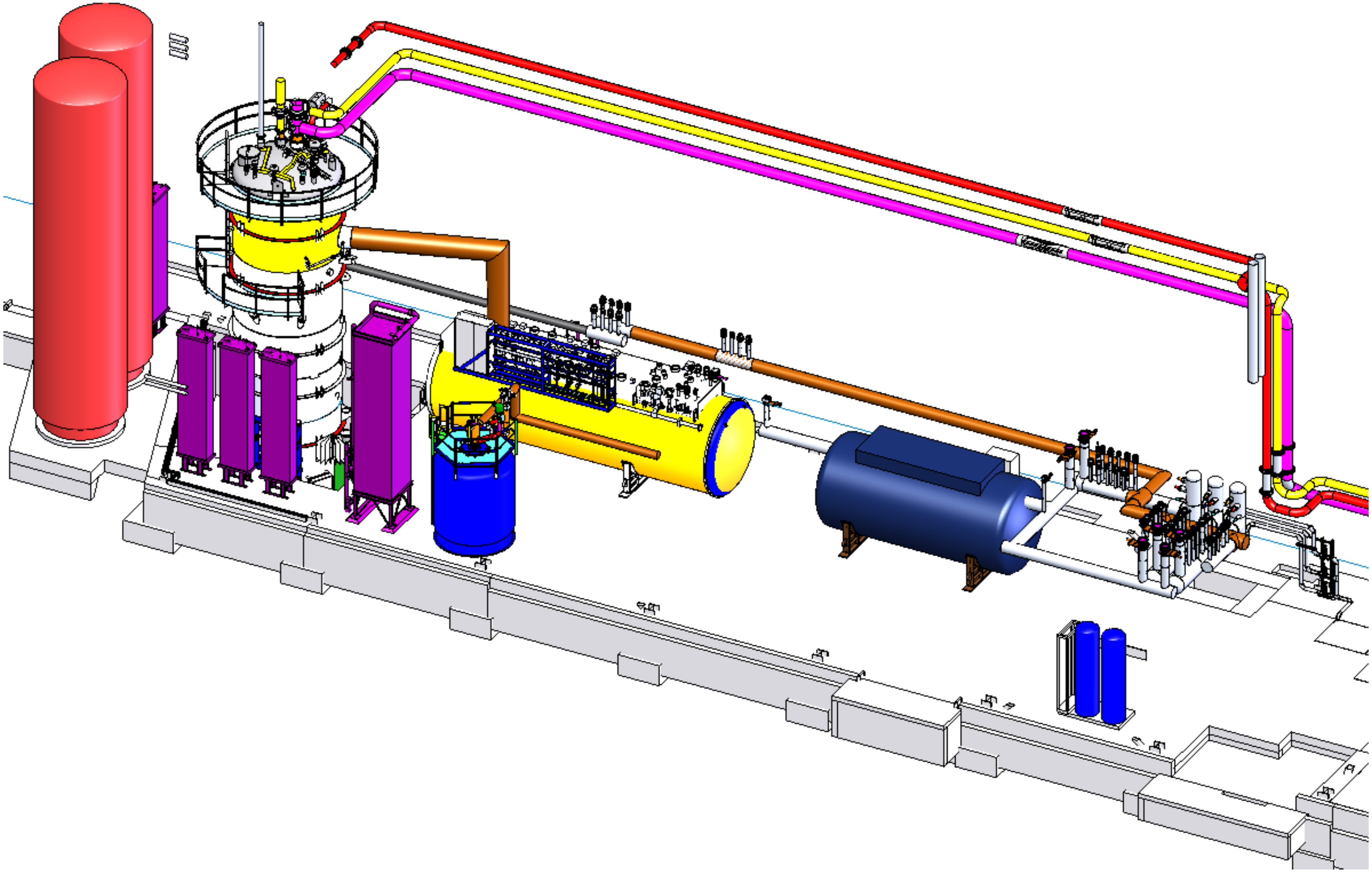
FRIB Cryogenic Systems Key Design Features

- Single refrigerator system with the capabilities needed to support the operations of superconducting cavities at sub atmospheric pressure and superconducting magnets
- The distribution system consists of three separate linac segment lines and one separator distribution line
- Each segment may be cooled down and warmed up independently
- U-tubes are utilized to optimize availability, operability and maintainability
- Supercritical helium supply(3atm-4.5 K) to the cryomodules and magnets in parallel
- 4 K / 2 K heat exchanger and JT Valves in the cryomodule
- Sub-atmospheric system using cold compressors
- The system shall also provide refrigeration loads at 4.5 K, liquefaction loads at 4.5 K for the magnet power leads, and shield loads between 38 K and 55 K
- A safety factor of 30-50% based on component knowledge and optimization
- Cryomodules and magnets will be allowed to be warmed up and/or cooled down independently

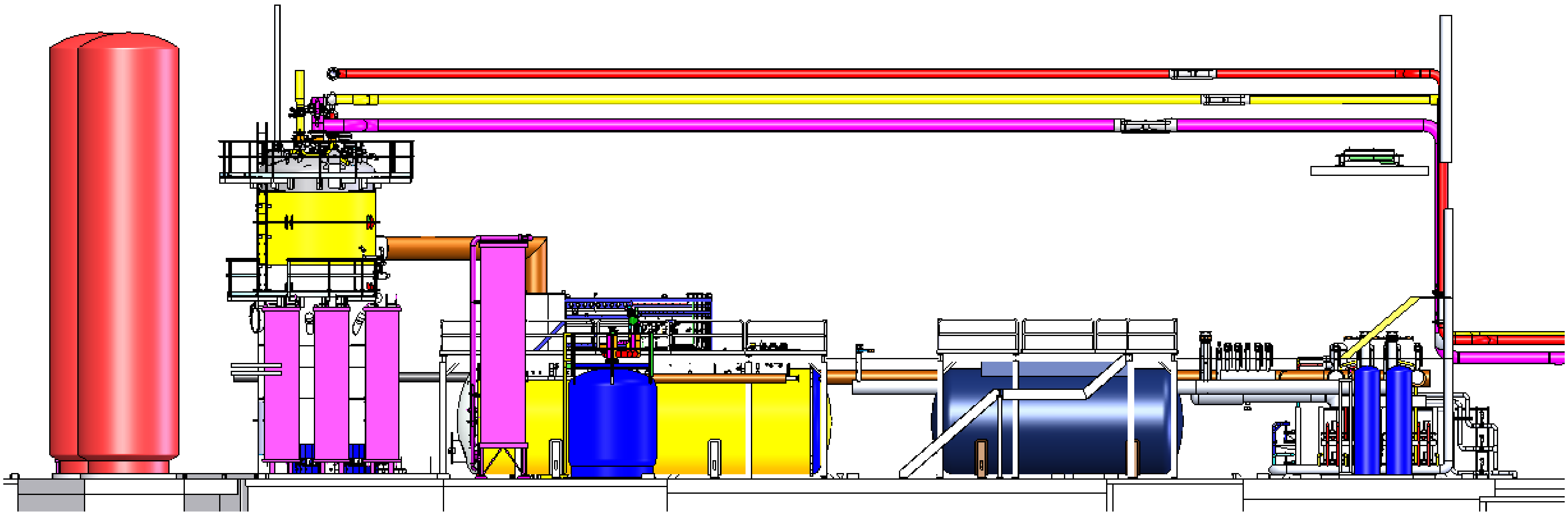
FRIB Cryogenic Plant



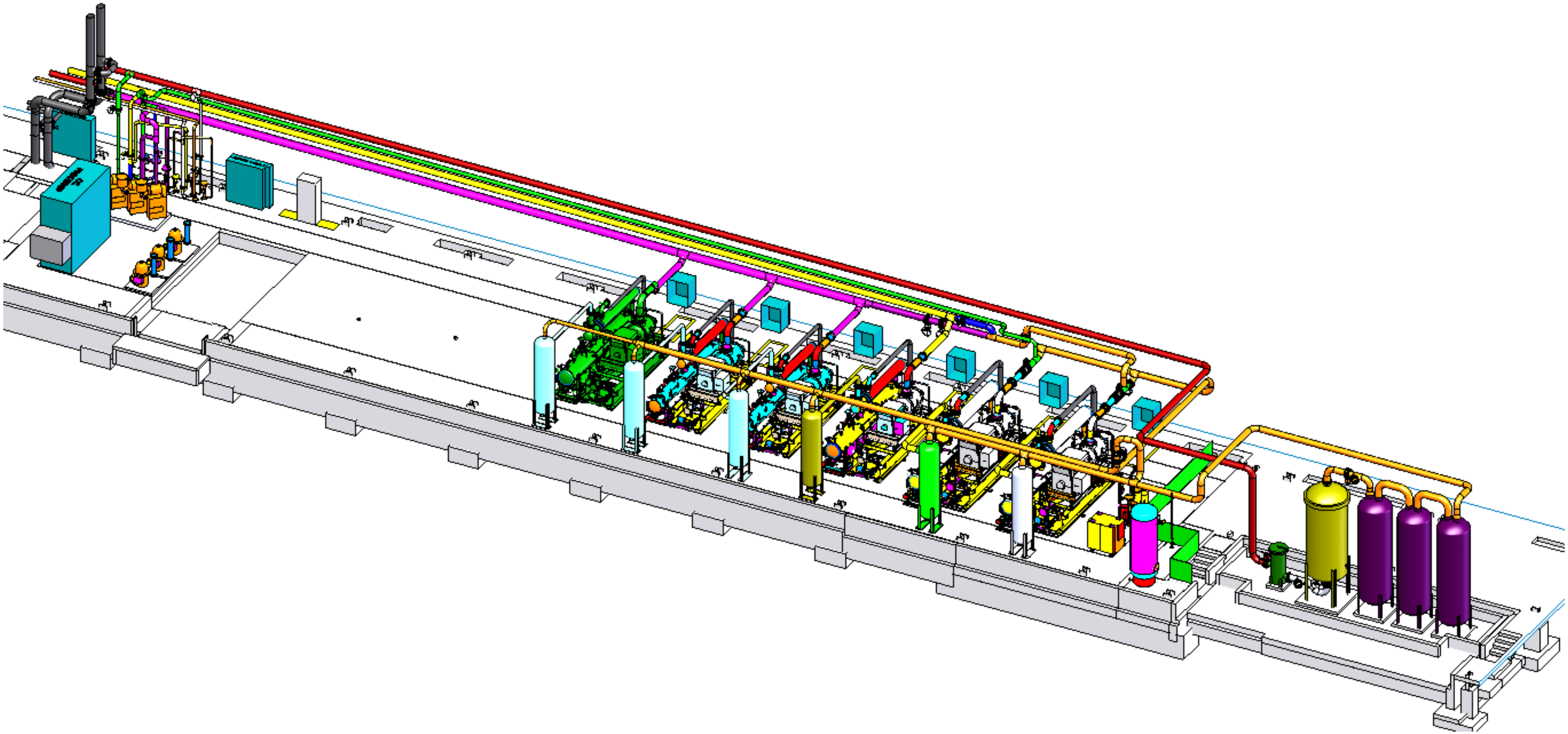
Cold Box Room Isometric View



Cold Box Room North Elevation

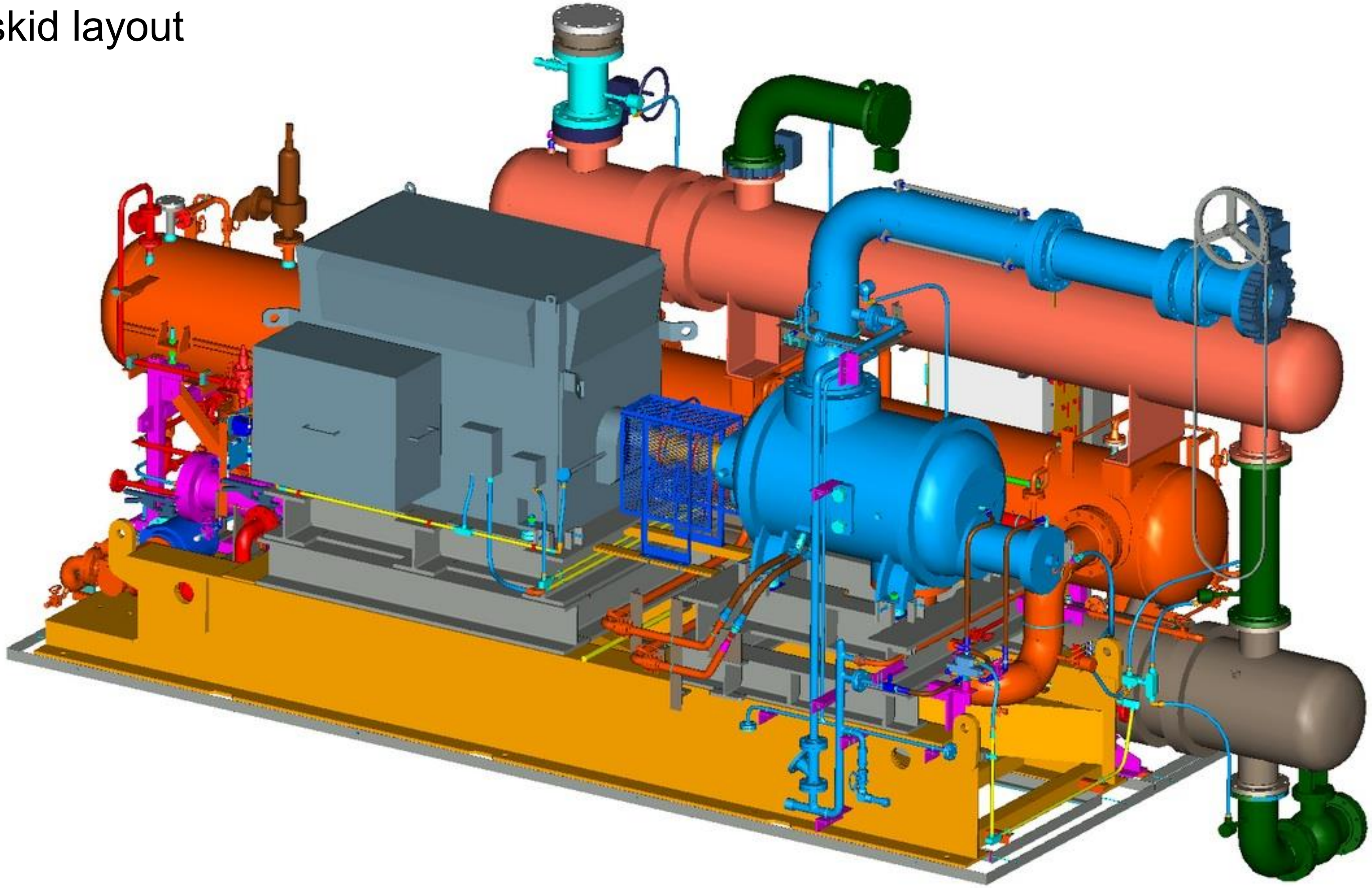


Compressor Room Isometric

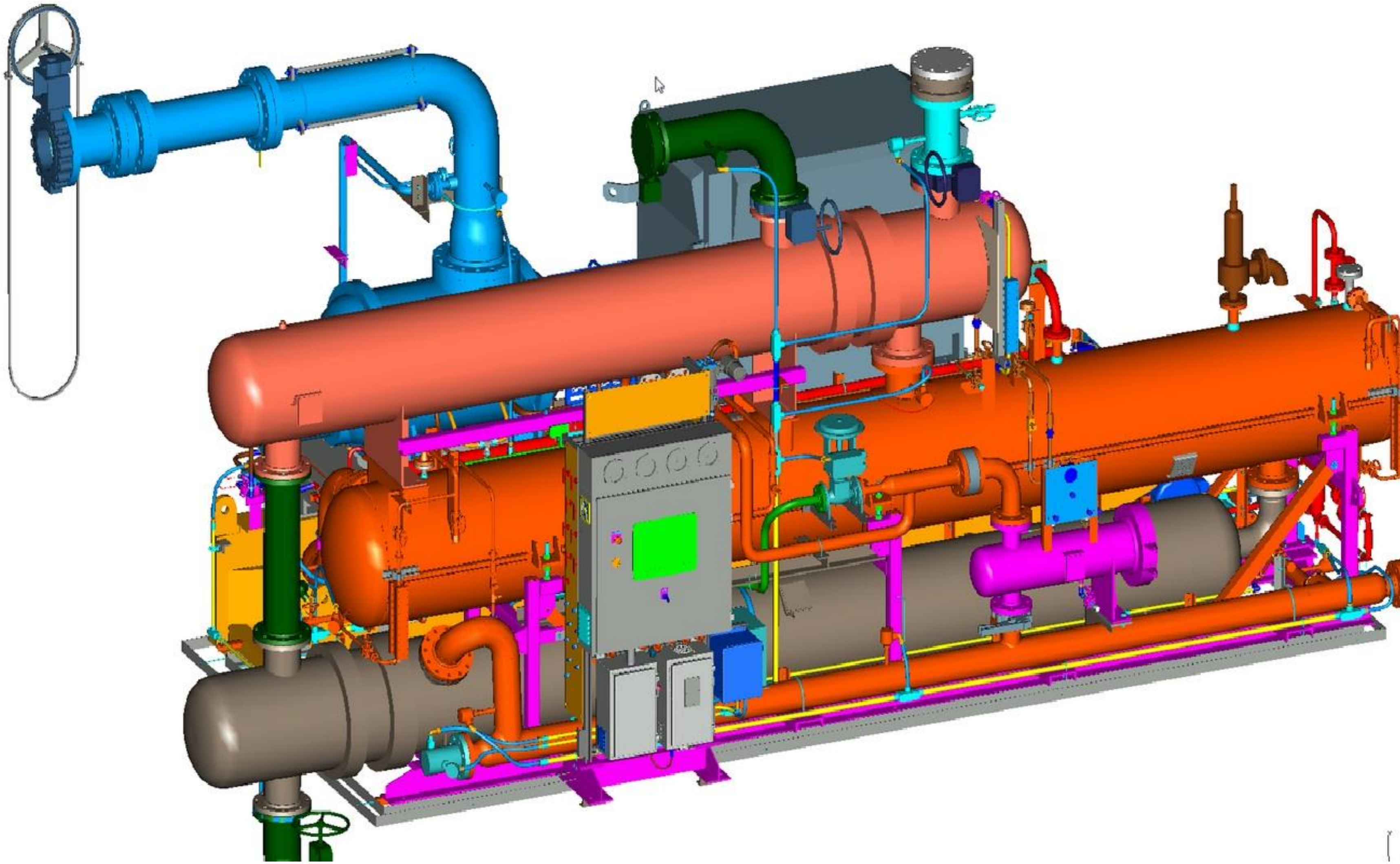


Warm Compressor Status

HP skid layout



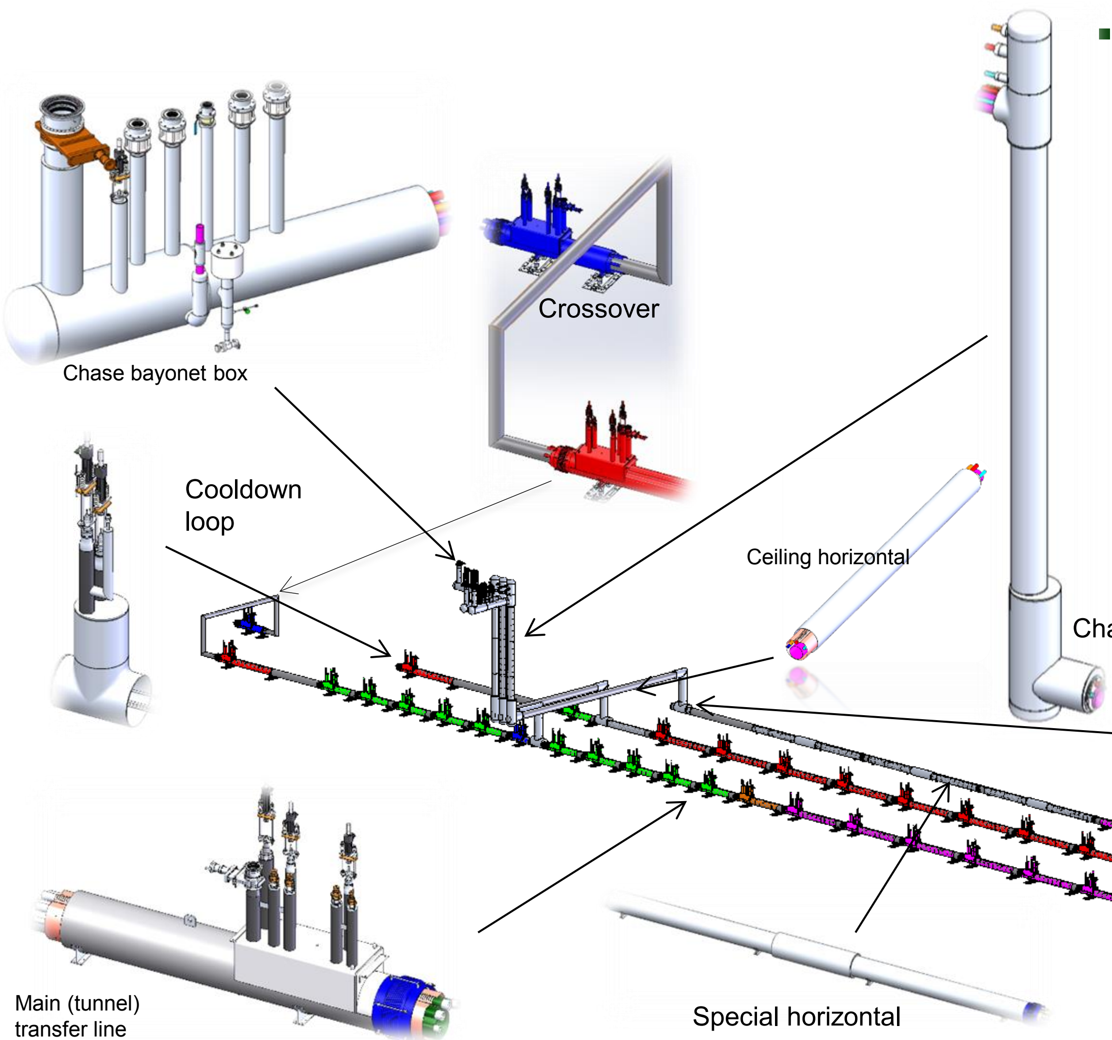
HP Skid Layout—Cooler Side

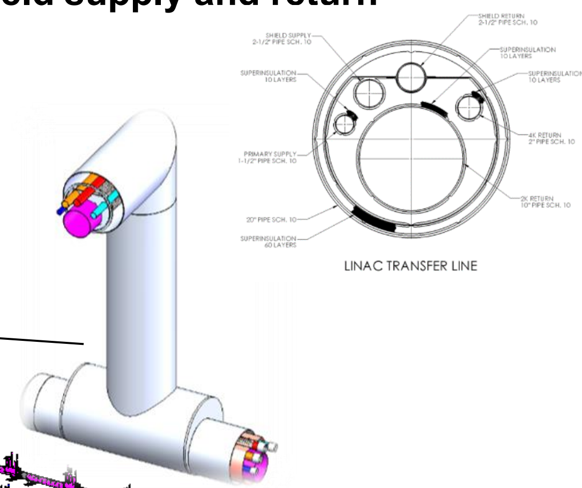


Linac Distribution Breakdown

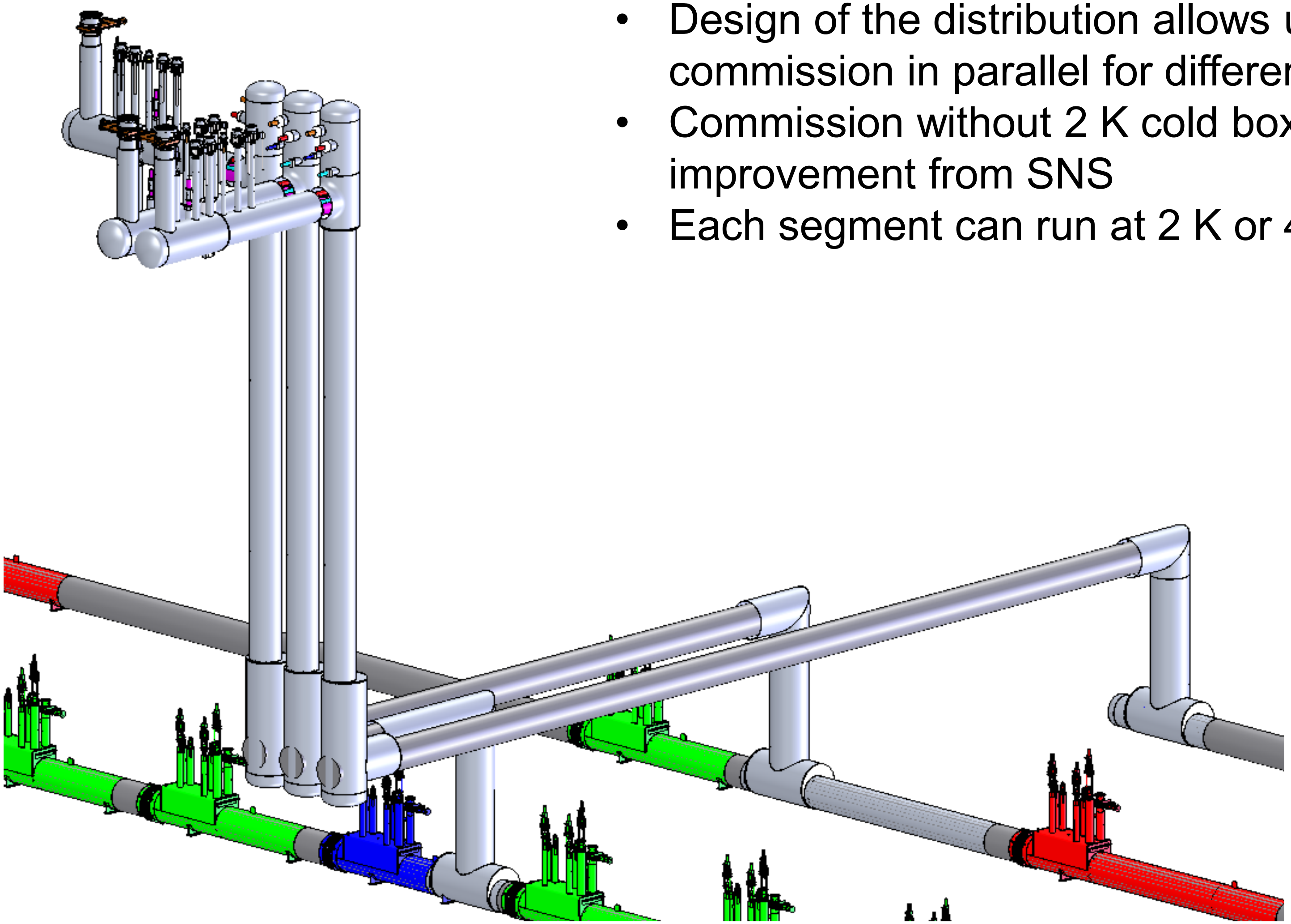
- **Independent transfer lines to each of the three linac segments to support**
  - **Staged commissioning**
  - **Maintenance**

Linac transfer line contains
- **2 K return**
- **4 K supply and return**
- **Shield supply and return**



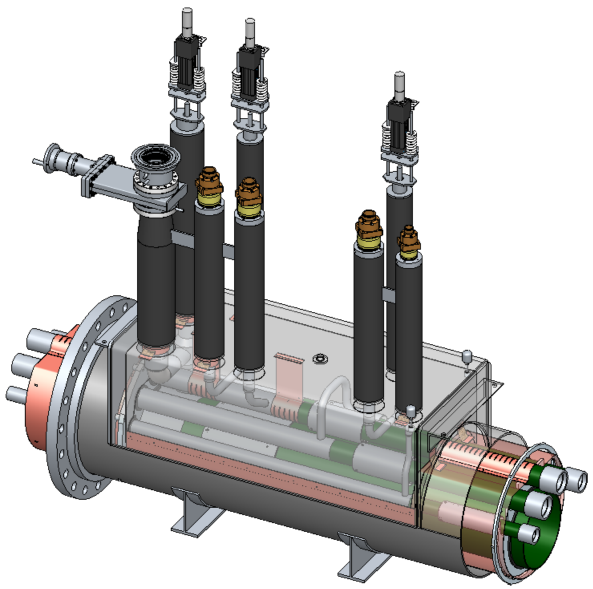


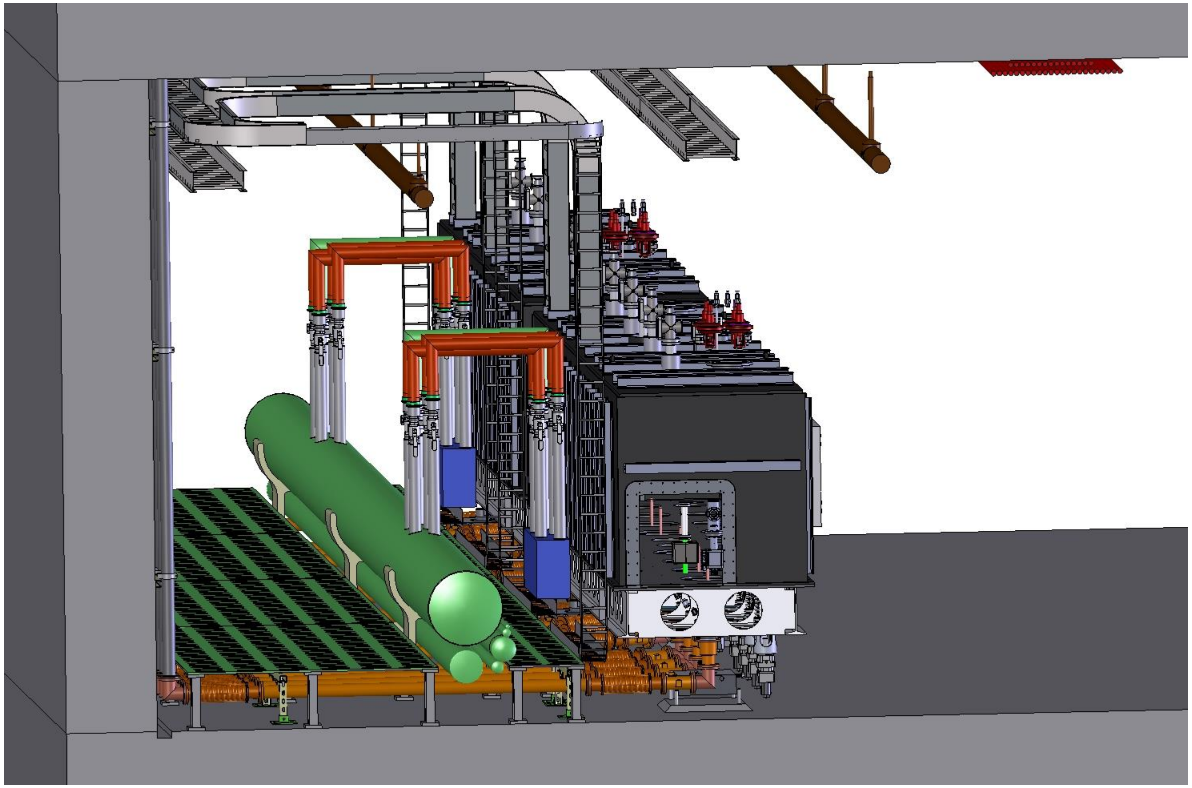
Cryogenic Distribution Designed to Optimize Installation, Commissioning and Operation



- Design of the distribution allows us to install and commission in parallel for different segments
- Commission without 2 K cold box which is an improvement from SNS
- Each segment can run at 2 K or 4 K independently

Cryomodules and Cryogenic Systems Design is Integrated and Optimized to Provide Availability and Maintainability Safety is Integrated with Design

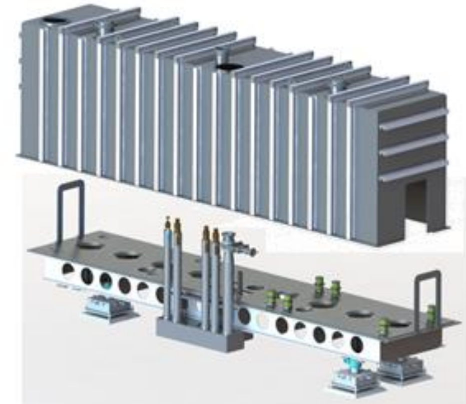


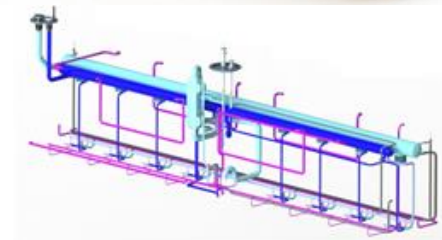


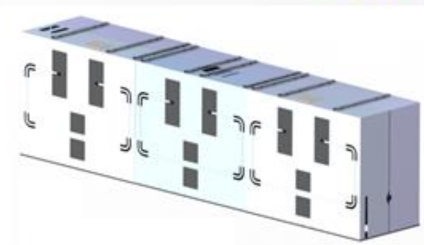
- Cryogenic Safety and Oxygen Deficiency Program T10401-AD-000168
- FRIB Cryoplant Oxygen Deficiency Hazard Analysis T30200-CA-000056
- FRIB Linac Tunnel Oxygen Deficiency Hazard Analysis T30200-CA-000041
- FRIB Policy on Pressure Design T10500-PO-000009

FRIB Cryomodules Design Approach

- Resonators operate at 2 K and magnets at 4.5 K and are both supported from the bottom to facilitate alignment
- Cryogenic headers are suspended from the top for vibration isolation
- Use common cryomodule designs principles for all seven cryomodule types
  - Support rails, cryogenic circuit, thermal shield, vacuum vessel
- Build and test 0.085 prototype cryomodule (ReA6) to validate fundamental FRIB cryomodules design
- Build and test a full preproduction 0.085 cryomodule to launch 0.85 production
- Build and test a preproduction 0.53 cryomodule
- In parallel to completing the design and test of 0.085 preproduction cryomodule start and complete design at JLab of 0.041cryomodule
- While completing the design and test of 0.53 preproduction cryomodule complete the design at JLab of 0.29 cryomodule
- Downsize the full size cryomodule designs to two types of matching cryomodules

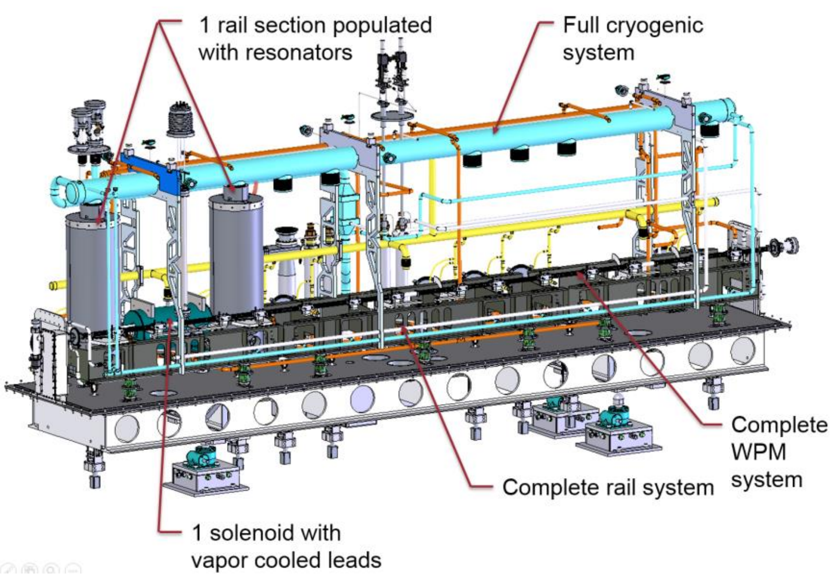




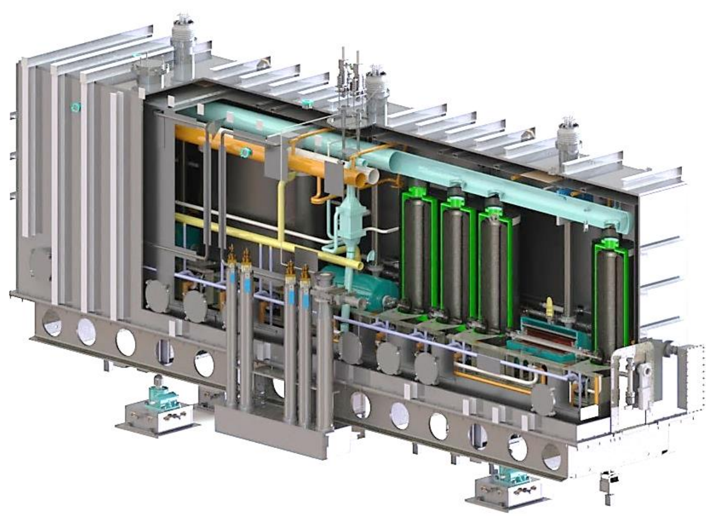


FRIB Cryomodule Design Validation

- β=0.085 prototype cryomodule (ReA6) allows testing and design validation of FRIB cryomodule fundamental design and its subsystems
  - CM with 1 complete rail (2 QWRs and 1 solenoid) installed in ReA linac for full testing



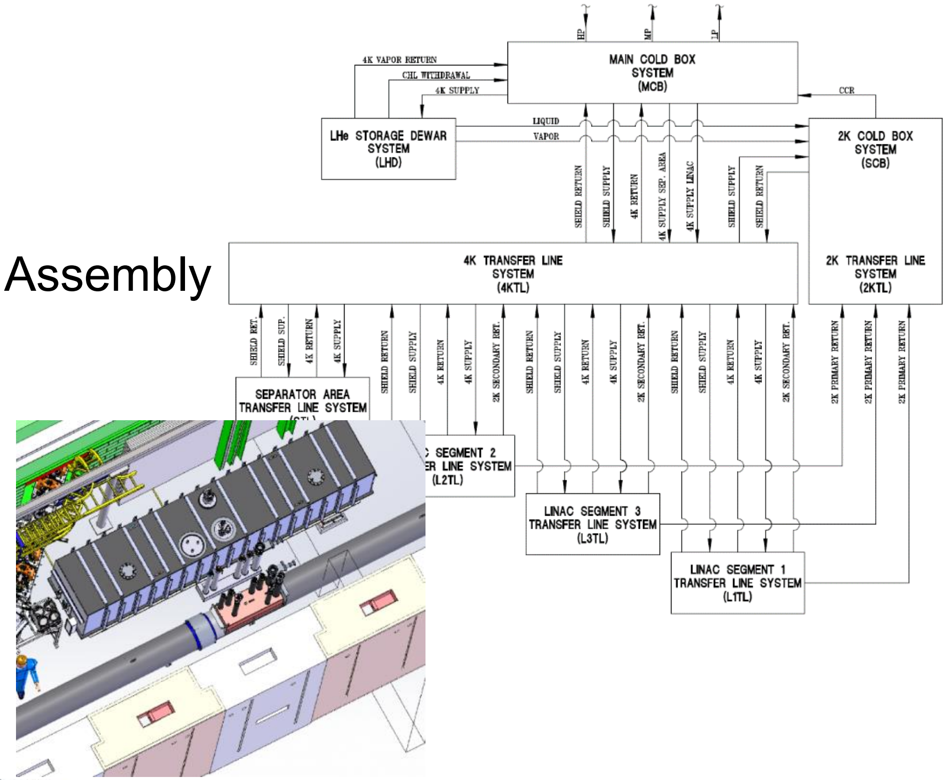
Scheduled to complete in March 2015

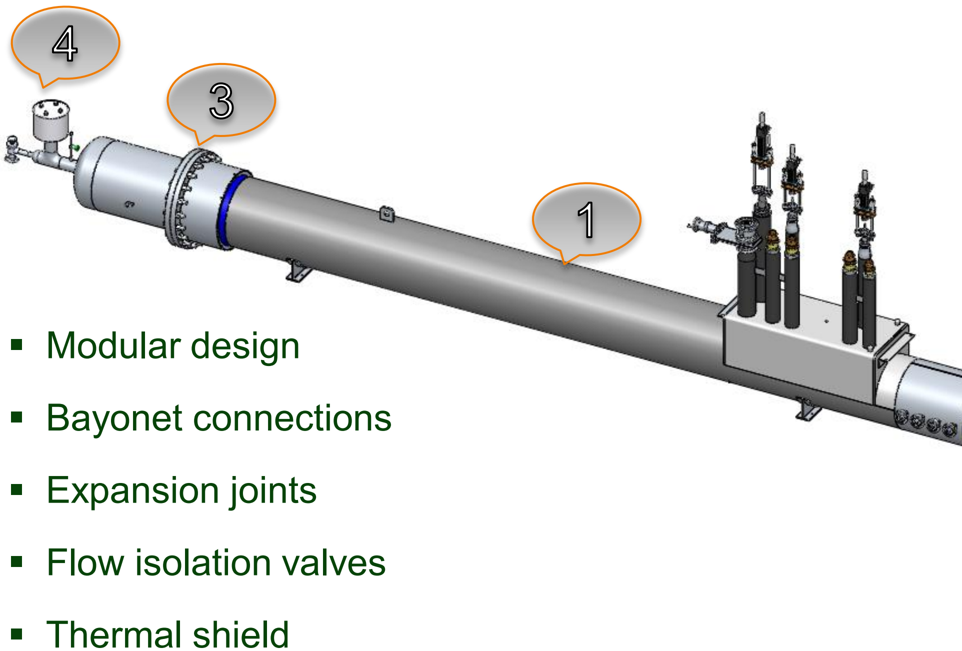


Design, Assemble and Test FRIB CM0.085 preproduction in 2015

FRIB Cryogenic Distribution Prototype Installed for β=0.085 Prototype Cryomodule Validation Project

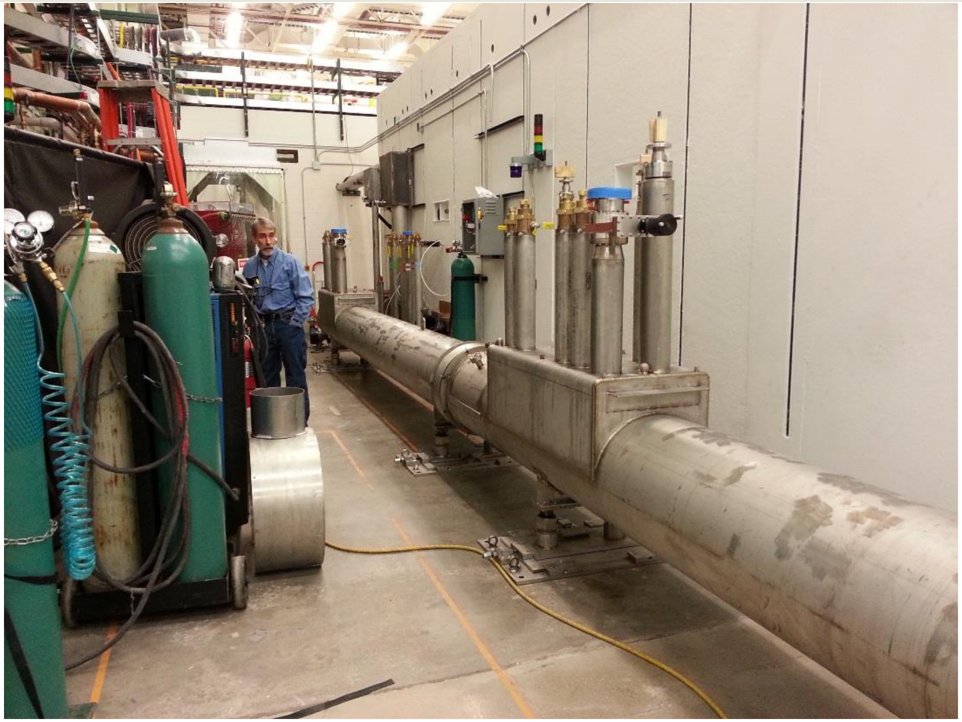
- FRIB Transfer Line Test Assembly
  1. 1st TL section
  2. 2nd TL section
  3. Loop End Assembly
  4. Relief End Cap & Parallel Plate Relief Assembly





- Modular design
- Bayonet connections
- Expansion joints
- Flow isolation valves
- Thermal shield

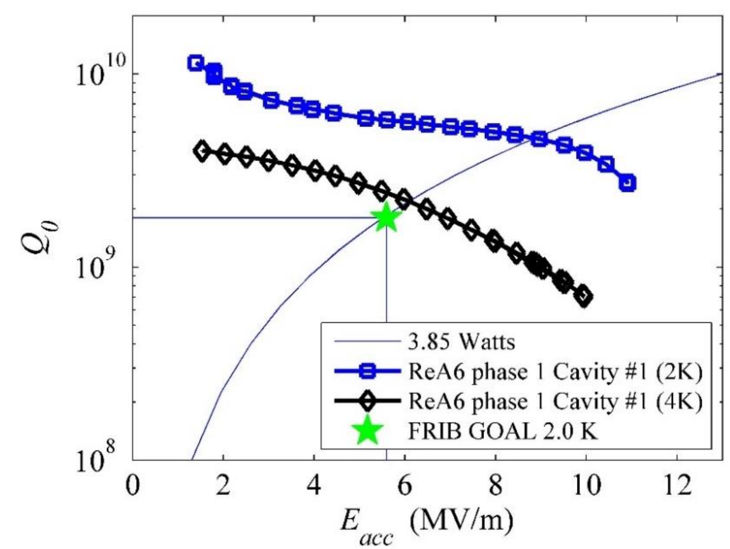
FRIB Cryogenic Distribution Prototype Installed for ReA6 Cryomodule Validation Project



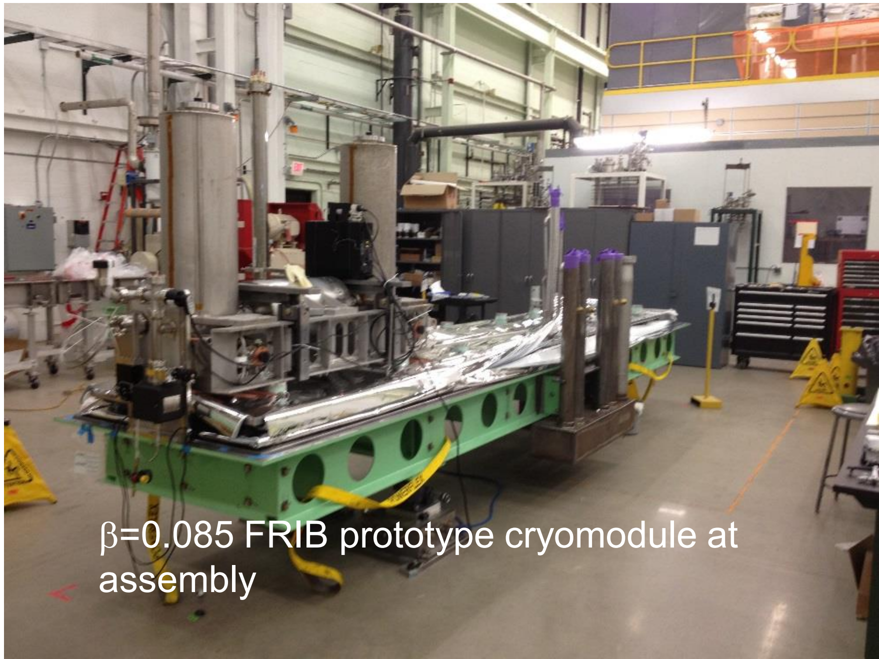
- TL Prototypes: Modular design, bayonet connections, expansion joints, flow isolation valves, thermal shield
  - 1^{st} unit shipped – June 2014
  - 2^{nd} unit delivery – August 2014
  - Testing – March 2015

β=0.085 Prototype Cryomodule Assembly and Installation to be Followed by Preproduction β=0.085 Cryomodule

- Alignment survey demonstrated the alignment tolerance can be met by 6 point supports during assembly
- Major aspects to be confirmed:
  - Alignment upon cool down to confirm previous Engineering Test Cryomodule results
  - Frequency locking in vibrational environment
- Lessons learned:
  - Delays due to vendor and fabrication error, sophisticated cryogenic piping and supports, staff inexperience and resource inefficiency
  - Knowledge will lead to a better design for FRIB production cryomodule



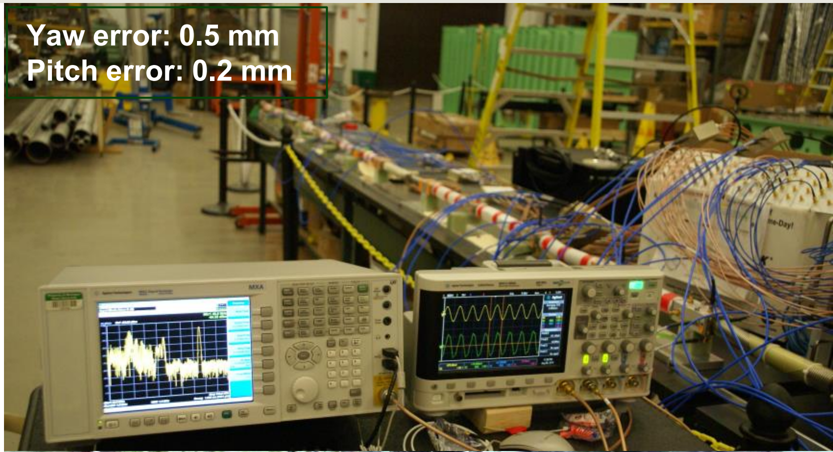
Milestone	Date
QWR certified	Done, 6/2014
Integrated QWR test with ANL coupler	Done, 6/2014
Coldmass assembled on baseplate	Done, 10/2014
Alignment survey complete	Done, 11/2014
Cryomodule assembly complete	2/2015
Cryomodule cool down and test	3/2015



FRIB β=0.085 Prototype Cryomodule @4 K, RF locked at FRIB specs. Alignment verified after multiple cool downs. Thermal loads verified. Very stable conditions. Test program ongoing

- Major results
  - Welding construction conforms to ASME B31.3 piping codes and pressure vessel codes
  - Design debugged; work flow, work instructions, tooling and fixture needs developed
- Major aspects to be confirmed
  - Alignment upon cool down to confirm previous Engineering Test Cryomodule results
  - Frequency locking in vibrational environment
- Lessons learned and improvements
  - Process and piping design simplification
  - Value engineering for major components

Objective Measures	Date
Quarter Wave Resonator (QWR) certified	Done, 06/2014
Integrated QWR test with ANL coupler	Done, 06/2014
Coldmass assembled on baseplate	Done, 10/2014
Alignment survey complete	Done, 11/2014
Cryomodule assembly complete	Done, 03/2015
Cryomodule cooled down and RF locked at FRIB specs. Alignment reproducibility confirmed. Heat Loads confirmed per design. Tests program on going	**Start cool down on April 22th. Authorized for RF on April 28th**




β=0.085 FRIB prototype cryomodule upon assembly completion

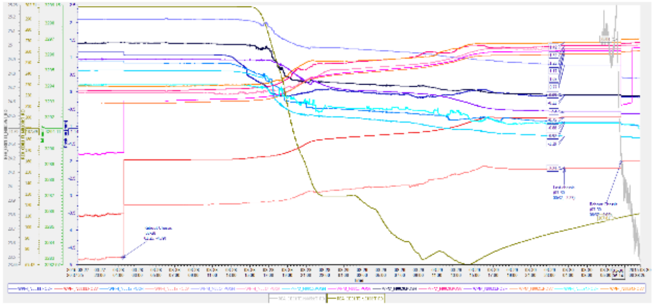
ReA6 Cryomodule Alignment Factors & Results

- Alignment control broken into three main areas
  1. Manufacturing and assembly steps to produce an accurate cold mass assembly with meaningful and reliable external fuducials for installation
  2. Control and verification of the warm-to-cold offset movements during cool-down
  3. Installation and placement accuracy of the cryomodule assembly in the tunnel

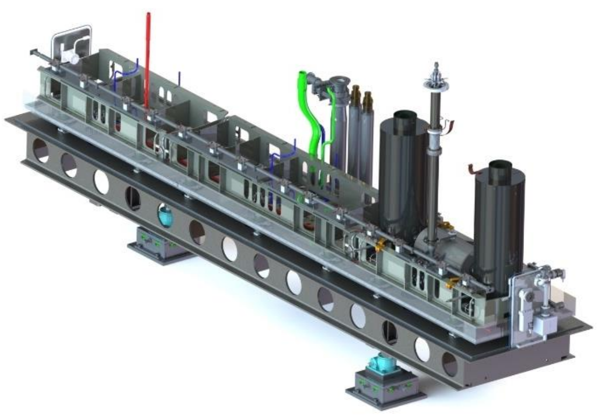
- Alignment Results through ReA6 testing
  - Alignment of coldmass components on baseplate during assembly within ± 0.4mm
    - » Laser Tracking during Assembly
  - Alignment of coldmass components during cooldown within ± 0.25 mm of predicted
    - » Indicated by WPM and direct measurement on cavity tuners
  - Alignment within ± 0.65mm
  - Specification: ± 1mm

Best-Fit Line Frame (Through US & DS Component Centers) No Cover, 6pt Support (meters)			
	Long	Transverse	Vertical
Cavity1 US	-	-0.000050	0.000505
Cavity1 Center	-	-0.000143	0.000192
Cavity1 DS	-	-0.000237	-0.000122
Solenoid US	-	0.000362	-0.000349
Solenoid Center	-	0.000113	-0.000464
Solenoid DS	-	-0.000135	-0.000580
Cavity2 US	-	0.000128	0.000141
Cavity2 Center		0.000030	0.000273
Cavity2 DS	-	-0.000068	0.000404

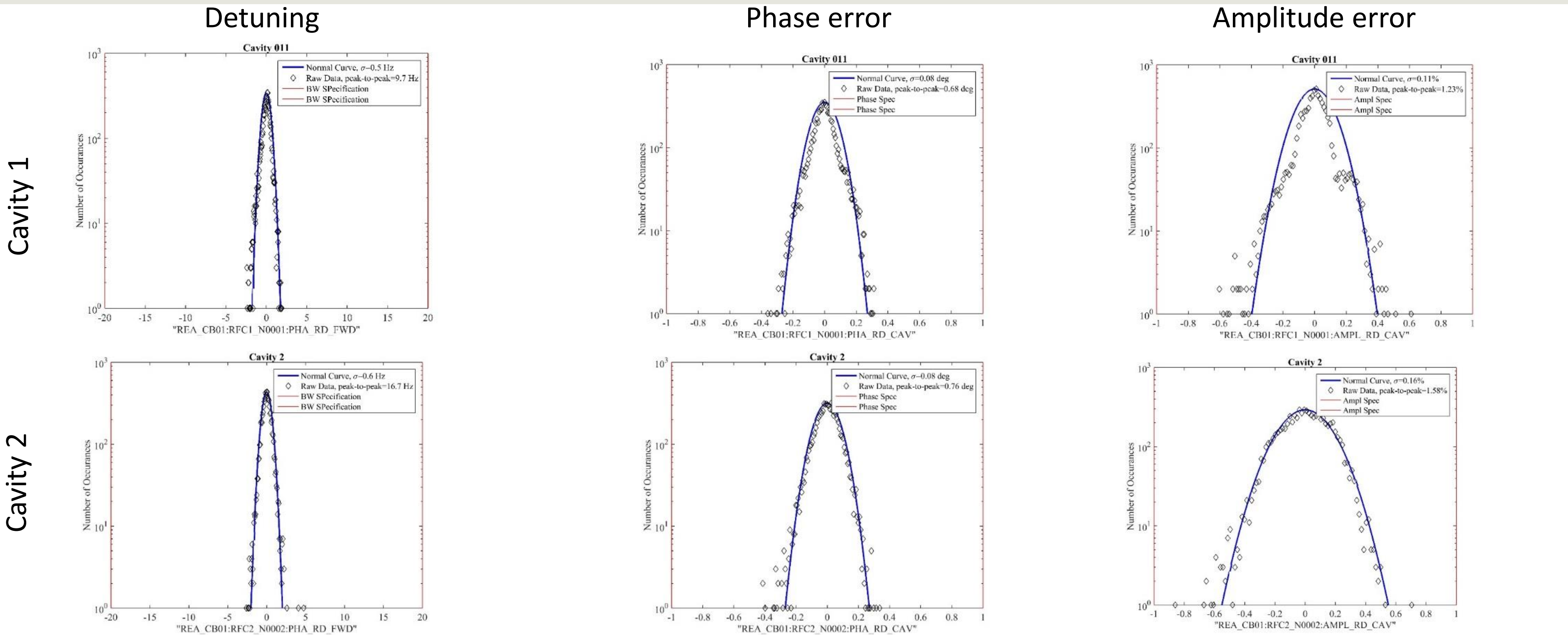
Coldmass Alignment on Baseplate



WPM Data During Cooldown



β=0.085 Prototype Cryomodule @4.3 K. Phase and Amplitude Processed RF Data Supports FRIB Specs and RF bandwidth, earthquake certified (Sat May 2nd , 12:30pm magnitude 4.2 earthquake, 2nd largest ever in West MI, the state's strongest recorded event was in August 1947, a 4.6 magnitude in almost the exact same location). Both cavities are locked to 80.4905 MHz, E_a=5.7 MV/m (two hours data)



	Gradient	Detuning		Phase		Amplitude	
4.3K test	E_a (MV/m)	σ (Hz)	pk-pk (Hz)	σ (deg)	pk-pk (deg)	σ (%)	pk-pk (%)
Measured QWR 1	5.7	0.5	9.7	0.08	0.68	0.11	1.23
Measured QWR 2	5.7	0.6	16.7	0.08	0.76	0.16	1.58
FRIB goal 2 K	5.7	<2.25	<20	<0.25	<2	<0.25	<2

FRIB β=0.085 Prototype Cryomodule Outside the Experimental Vault

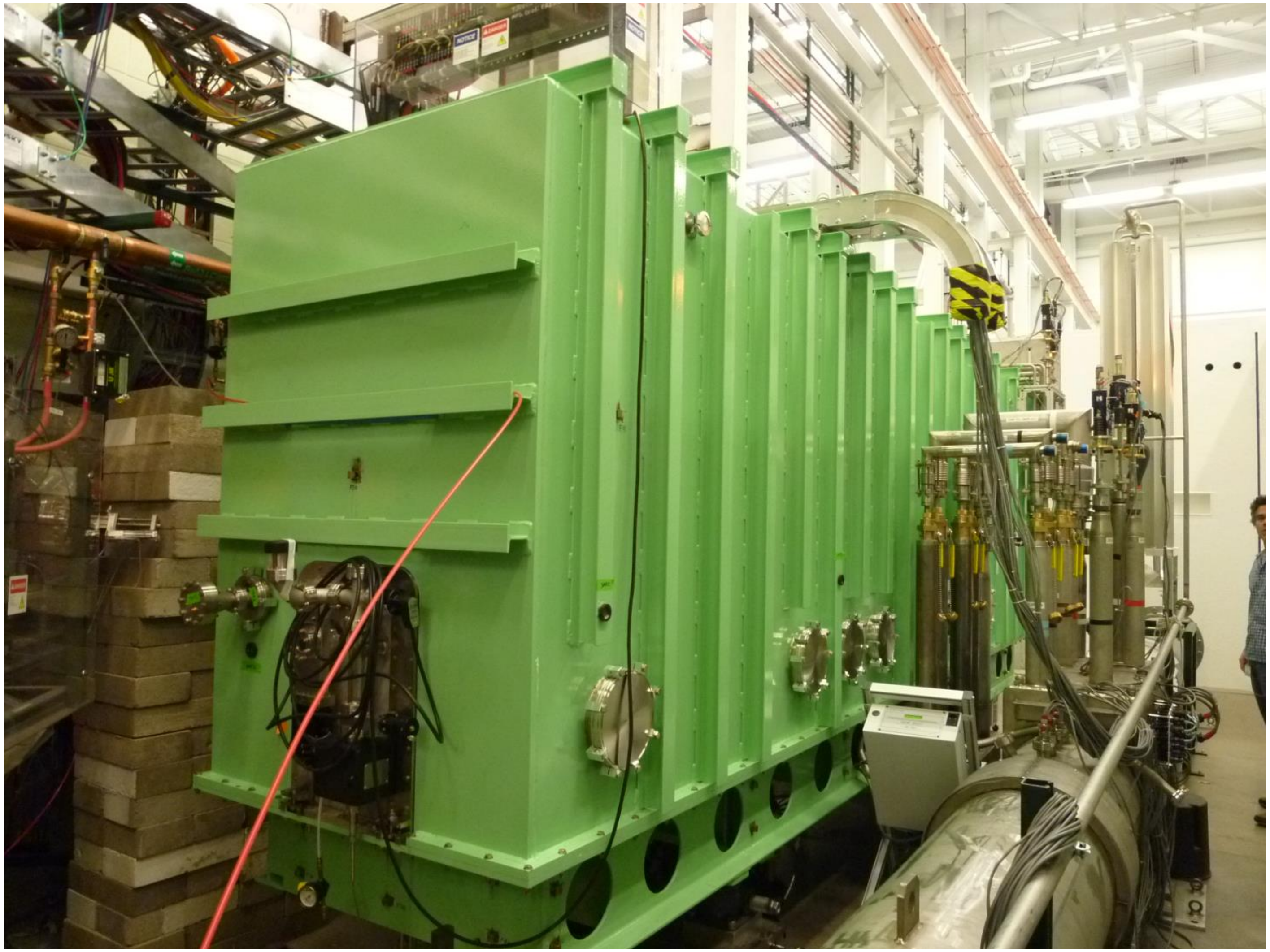
FRIB β=0.085 Prototype Cryomodule View of the Gate to the Experimental Vault

FRIB β=0.085 Prototype Cryomodule Inside the Experimental Vault

FRIB β=0.085 Prototype Cryomodule FRIB Transfer Line and Cryomodule View

FRIB β=0.085 Prototype Cryomodule U-tubes Connections to the Cryomodule, Electrical Valve Actuators. 2 K Return

FRIB β=0.085 Prototype Cryomodule



FRIB β=0.085 Prototype Cryomodule Cool Down Return and Lead Flow Return

FRIB β=0.085 Prototype Cryomodule U-tubes Connections

FRIB β=0.085 Prototype Cryomodule RF Lines, Controls and Instrumentation

Continue to Leverage Collaborations
New WFO Contracts Signed with JLab and ANL

- ANL
  - Liquid lithium stripper
  - Beam dynamics verification; β=0.29 HWR design; SRF tuner validation
- BNL
  - Plasma window & charge stripper, physics modeling, database
- FNAL
  - Diagnostics, SRF processing
- JLab
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler **
  - HWR processing & certification*
  - QWR and HWR cryomodule design
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass design; beam dynamics**
- ORNL
  - Diagnostics, controls
- SLAC**
  - Cryogenics**, SRF multipacting**, physics modeling
- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling **
  - SRF, QWR etching*
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets*
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ
- ESS
  - AP*
- DTRA
  - RFQ power supply**

* Under discussion or in preparation

** Completed

Red: Active/actively planned WFO contract

Summary

- FRIB Cryomodule and Cryogenic System design are integrated and optimized to assure safety, maximum efficiency, availability, installation and commissioning optimization and enhanced maintenance capabilities
- β=0.085 prototype (ReA6) cryomodule is a very important milestone to validate FRIB cryomodule design. Tests are ongoing
- The fabrication, installation and testing of the FRIB prototype cryogenic transfer line in the framework of the β=0.085 prototype cryomodule validation project is an important FRIB technical milestone
- JLab's collaboration and leadership in cryogenics and cryomodule engineering is a fundamental technical partnership toward FRIB completion and success

Cryogenic Plant Building Equipment Integrated into Conventional Facility and Compatible with Commissioning and Operation Requirements

- FRIB cryoplant building meets system requirements
  - Cold box room: 4484 sq. ft.; compressor room: 7828 sq. ft. (~twice JLab CHL#2 building size)
- Ventilation
  - Cold Box Room: 18,300 cfm design
    - Supplied high at north wall and low at south wall
    - Returned high at east wall
    - Min Required Flows
      - » 18,300 cfm for Oxygen Deficiency Hazard (ODH)
      - » 16,000 cfm for equipment cooling
  - Compressor Room: 120,000 cfm design
    - Supplied near ceiling at west wall
    - Returned at lower level at east end
    - Min Required Flows
      - » 27,500 cfm for ODH
      - » 120,000 cfm for equipment cooling (5.25 MW @ 15)
- Adequate reserve in water, compressed air, and power
  - Uninterrupted power supply (UPS) backup for controls (lasts about 20 seconds)
  - ~10 seconds after outage: two 750 kW diesel generators turn on
  - Within 30 minutes of the outage: gas turbine generator at MSU power station provides 4 MW to FRIB/NSCL

ReA6 2Cavity CM Testing and Validation

- The FRIB cryomodules have some unique characteristics and mechanical solutions which have never been used before in this category of devices, namely
  - Bottom up construction
  - Cavity alignment system with sliding supports
  - Operation at 2 K with low-β resonators

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