Construction and Performance of FRIB Quarter Wave Prototype Cryomodule

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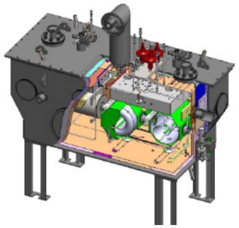
Outline

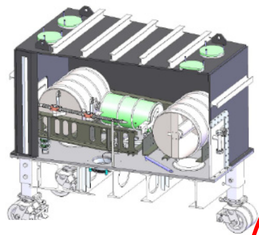
- FRIB has manufactured a prototype cryomodule that utilizes two superconducting quarter-wave resonators (QWR) and one superconducting solenoid, and is referred to as the ReA6 cryomodule. This talk will focus on:
  - ReA6 Cryomodule Design
  - ReA6 Assembly
  - ReA6 Test Setup
  - ReA6 Test Results
  - Production Implications
  - Summary & Path Forward

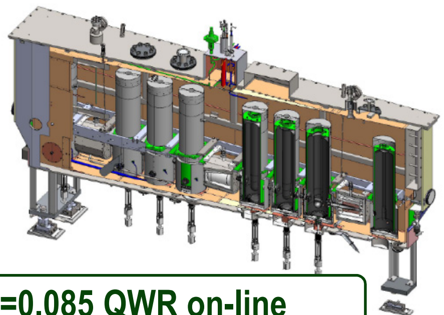
Cryomodule Prototyping Program Supports FRIB Construction

HWR TDCM, Decommissioned 2012



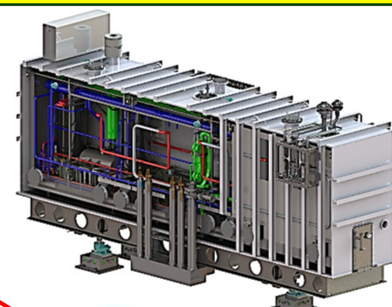
ETCM, Tests Completed in 2013



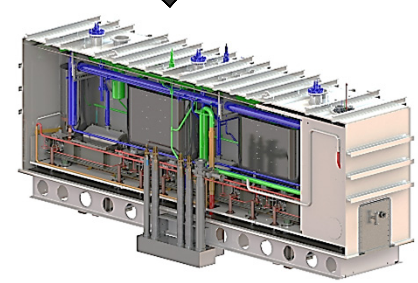


ReA3 β=0.085 QWR on-line

ReA6/FRIB, CM with 2 QWRs
Successfully tested



FRIB 8 HWR CM
Construction planned in 2016

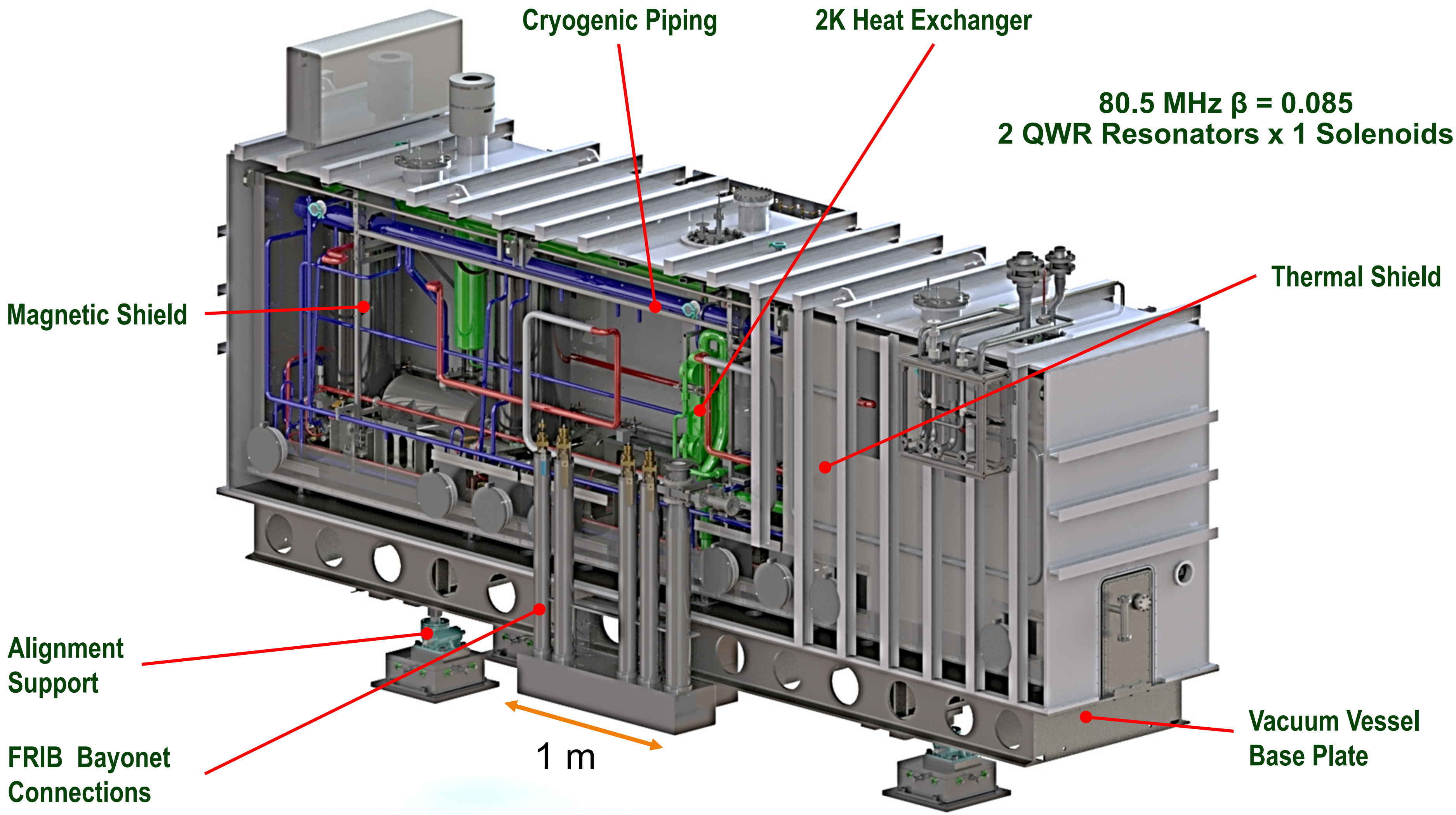


FRIB 8 QWR CM
Construction of components started in 2015

- Allowing to test
  - RF BW, He pressure stability, mechanical stability
  - Innovative CM design solutions
  - Integrated CM performance in operation conditions
- Scheduled to allow feedback to mass production

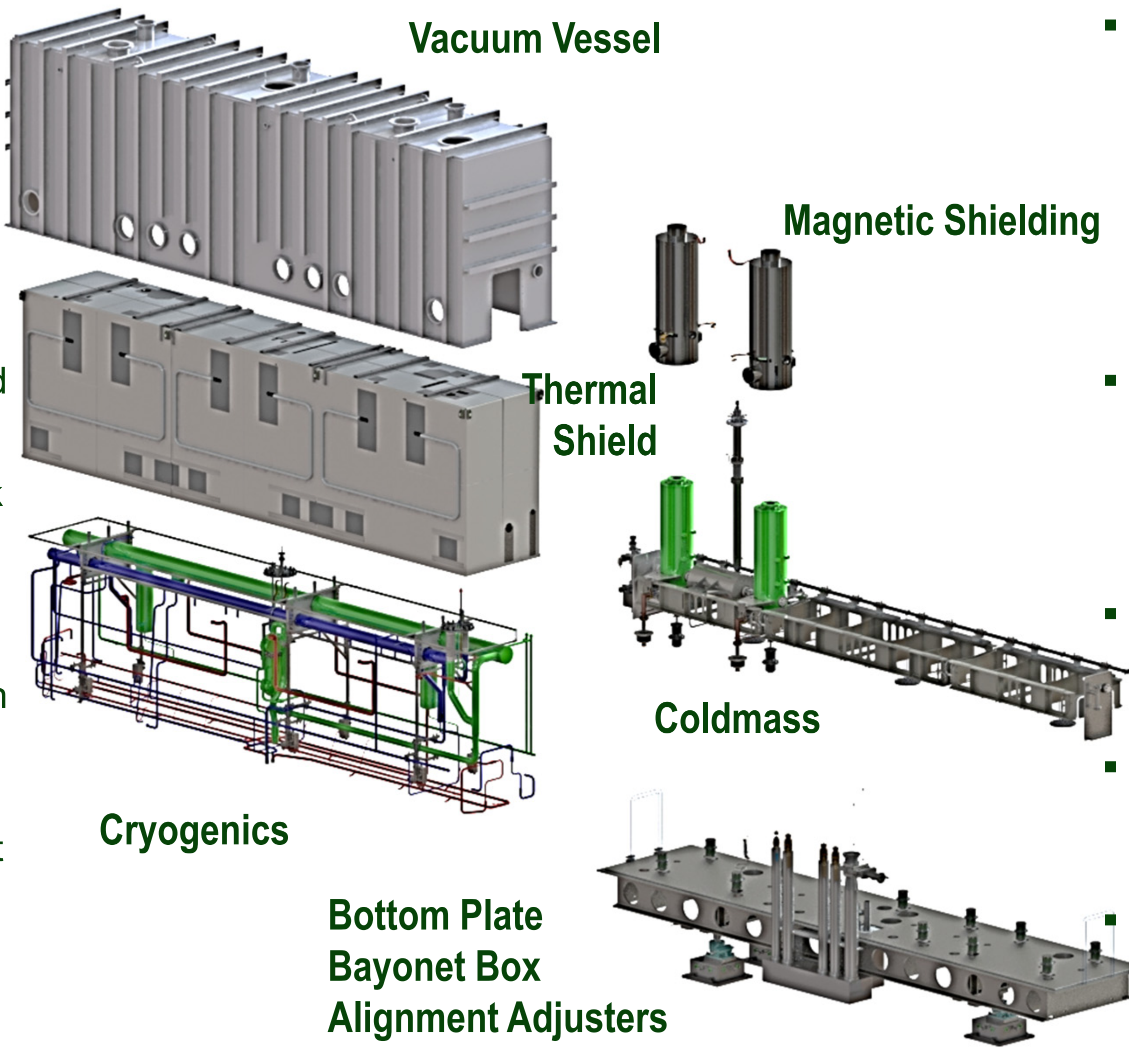
ReA6 Quarter Wave Cryomodule
Modular Design to be Used on All FRIB Cryomodule Types

80.5 MHz β = 0.085
2 QWR Resonators x 1 Solenoids



Cryomodule Main Components Allow Modular Procurement

- Simplify where possible and look toward production and design improvements
- Optimized for mass production with interchangeable parts and machined fits
- 3 piece strong back supports tighter alignment requirements to remove or reduce ‘cross-talk’ between resonator position during assembly
- Assembly is in front at waist level with nothing overhead improving visibility



- Fewer assembly fixtures – no upper assembly stand needed for building therefore multiple modules can be assembled at the same time
- Attachment of slot covers to thermal shield, nothing to restrict access and fewer slots
- Minimize the hanging of critical components during assembly
- MLI easier to manage and not hanging in the way
- Improved alignment and mass-production, better serviceability

FRIB Develops Technical Innovations For Low-beta Cryomodules

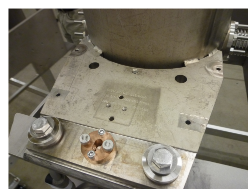
Rail & Baseplate Assembly Optimized For Mass Production

Self-Aligning Support Systems

Custom Alignment Rail Heat Treatment

Full Stress Relieve to Minimize Distortion During Cool-down

Reset To Austenitic State (Min. Permeability)



Cavity mount provides stress free thermal contraction with significant anti-rocking stiffness

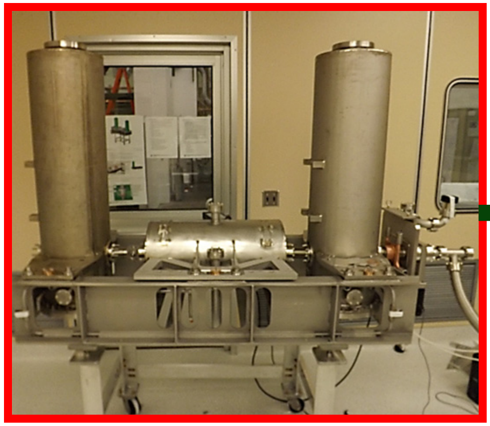
3 Way O-ring

Separated Cavity/Cryomodule Isolation Vacuum

Cryogenic Support System

Decouple Cryogenics from QWRs – Frequency & Phase Stability

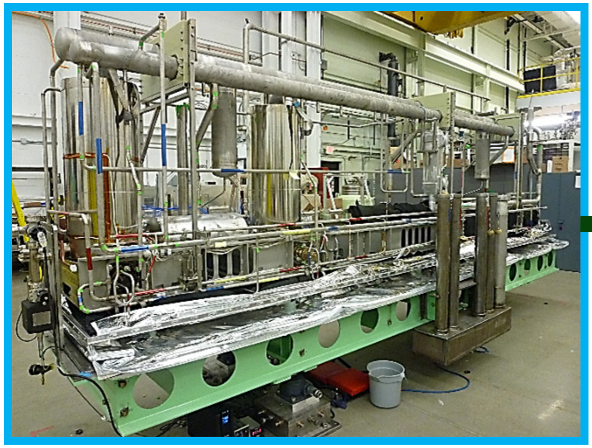
ReA6 Cryomodule Assembly Sequence



Cleanroom Assembly Prepared

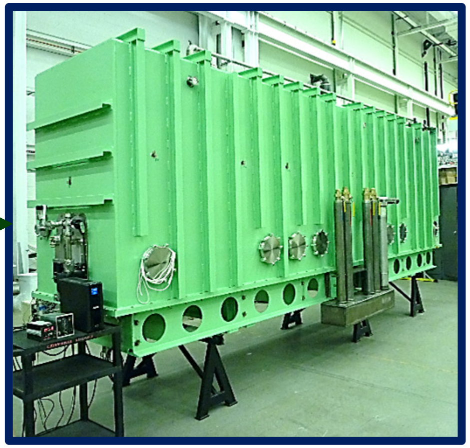
Baseplate Assembly Prepared

Coldmass Installed to Baseplate



Cryogenic Systems Installed

Thermal & MLI Installed



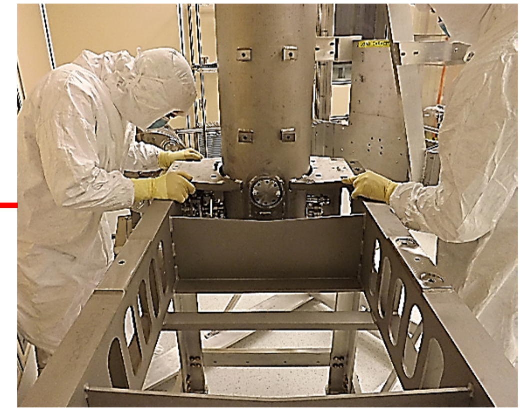
Vacuum Vessel Cover Installed

ReA6 Cryomodule Assembly Sequence – Coldmass and Baseplate Preparation

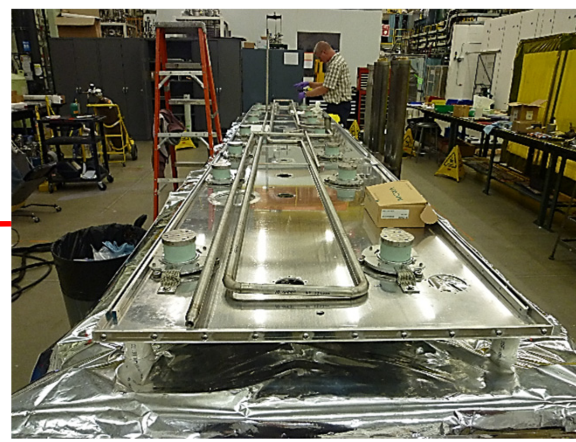
Cleanroom Assembly Prepared

Solenoid Installation

Resonator Installation



Baseplate Assembly Prepared



MLI, Lower Thermal Shield, and G-10 Post Installation

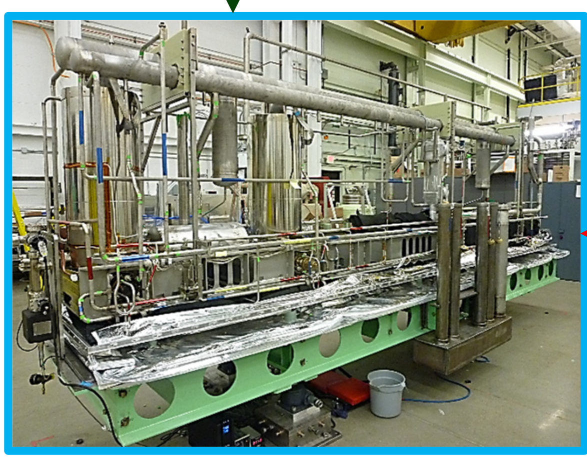
Bayonet Box Welded to Baseplate

ReA6 Cryomodule Assembly Sequence – Coldmass and Cryogenic Installation

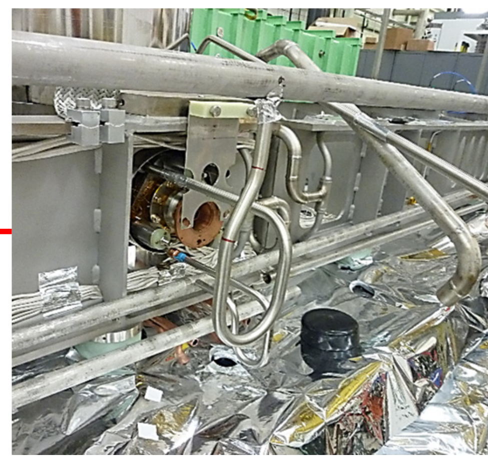
Coldmass Installed to Baseplate

Coldmass Lift onto Baseplate

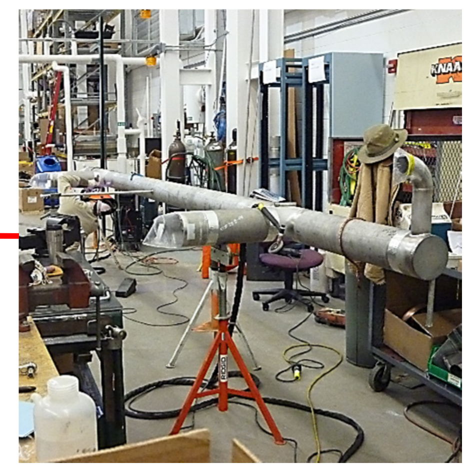
Installation of Lower Magnetic Shield and Tuner to Coldmass



Cryogenic Systems Installed



Fabrication of Cooling Intercepts



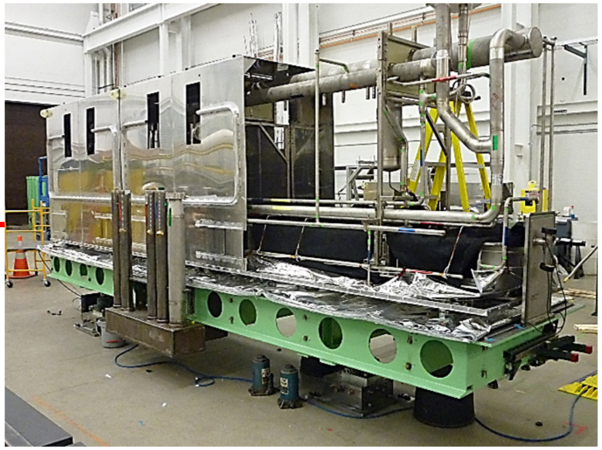
Fabrication of 2 K Header

ReA6 Cryomodule Assembly Sequence – Thermal Shield and Vacuum Vessel Installation

Thermal & MLI Installed

Coldmass MLI Installed

Test Fit of Thermal Shield



Vacuum Vessel Cover Installed

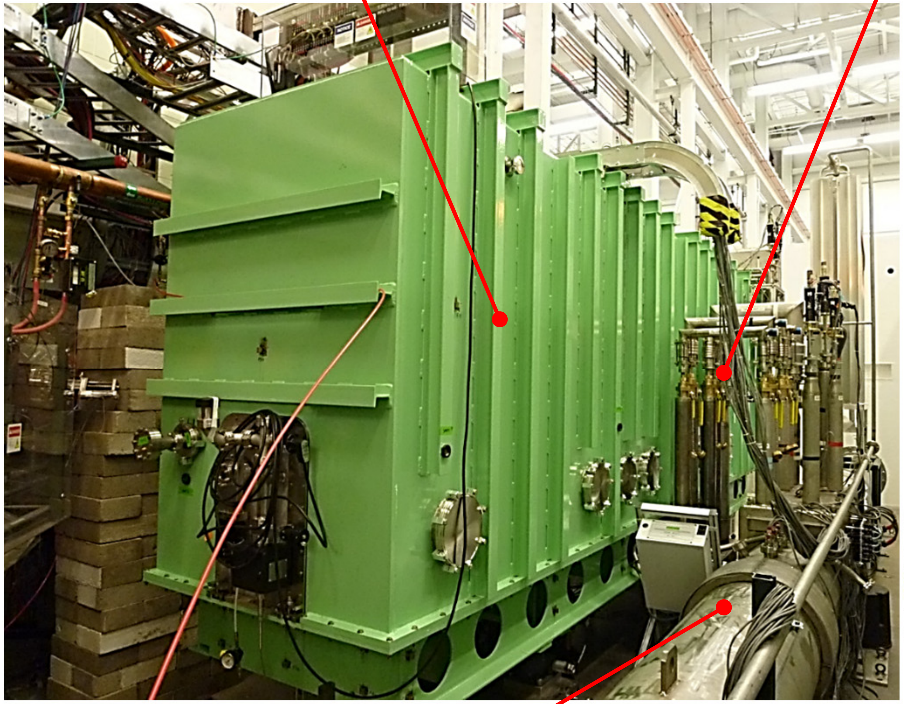
Vacuum Vessel Lift onto Baseplate

Thermal Shield MLI Installed

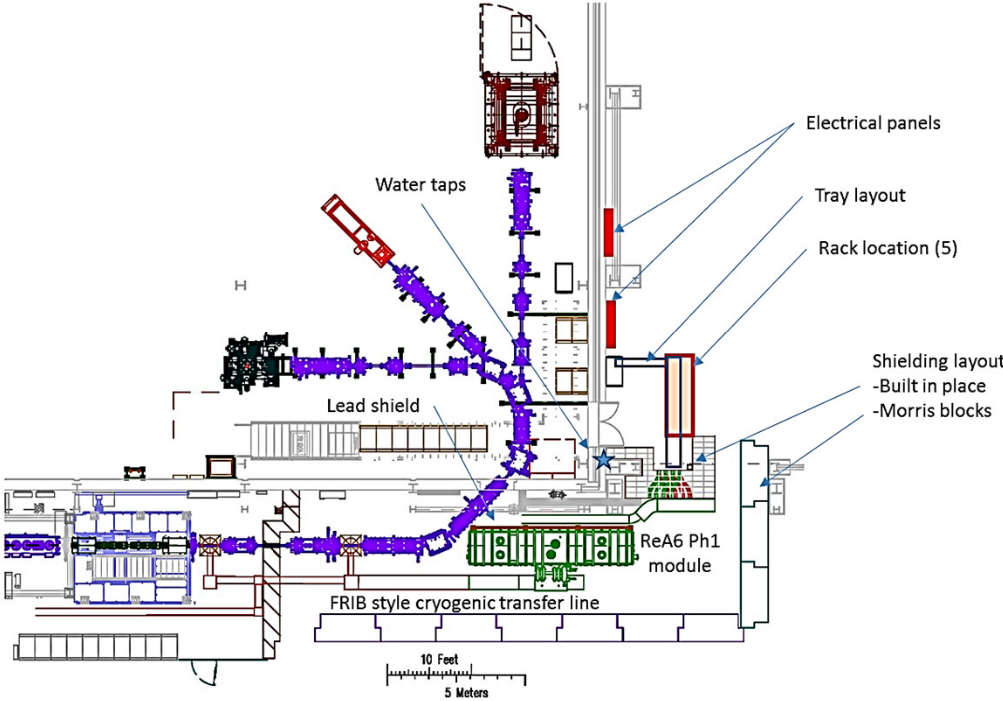
ReA6 Installation Layout is a Representative Cross Section of the FRIB Tunnel

ReA6 Cryomodule

U-Tube Cryogenic Connections



FRIB Transfer Line and Bayonet Box



Test Bunker Constructed Using Existing Facility

FRIB β=0.085 Prototype Cryomodule Tested
Bottom-up Design Validated and Mature for FRIB Production

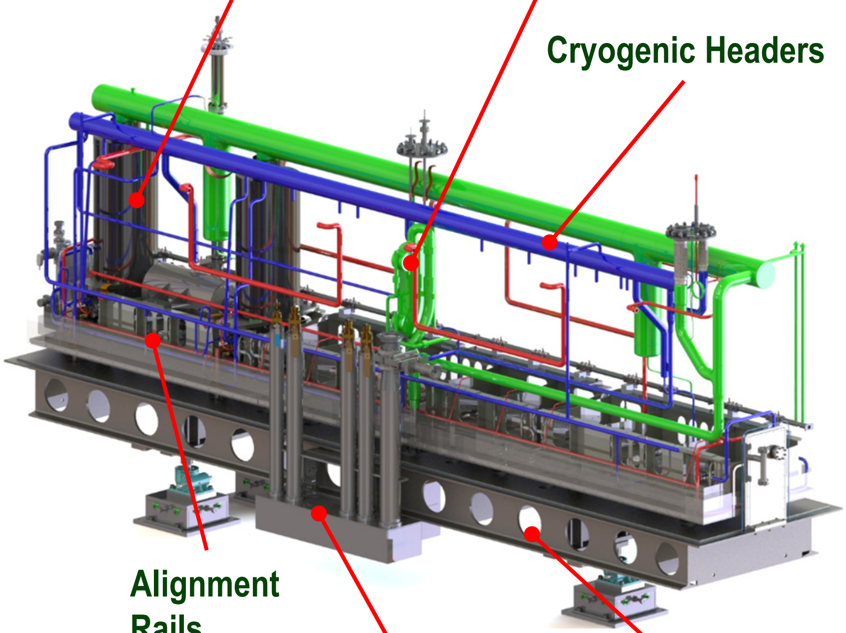
Objective Measures	Date
Quarter Wave Resonator (QWR) certified	Done, 06/2014
Integrated QWR test with ANL coupler	Done, 06/2014
Coldmass assembled on baseplate	Done, 10/2014
Alignment survey complete	Done, 11/2014
Cryomodule assembly complete and test start	Done, 03/2015
Alignment verification	Done, 04/2015
Cavity 24-hour lock and vibration control verification	Done, 05/2015
Cryomodule test completion	Done, 06/2015

- ReA6 Major Development
  - Realistic FRIB conditions
  - Confirmed QWR subsystems performance
  - Validated integrated cryomodule performance in operation
  - Validated bottom-up cryomodule design
  - Assembly flow and work instructions
    - » Developed tooling and fixture needed for assembly work

- Production Implications for FRIB First Cryomodule
  - Process and piping design simplification
  - Value engineering for major components
  - Improve the design to be assembly friendly and modular

FRIB Cryomodule Design Validation: ReA6 tested in FRIB Operation Conditions

- ReA6, 2-QWRs CM tested for final design validation of FRIB cryomodule and its subsystems
- Installed on a FRIB-type cryogenic distribution box
- QWR operation test at 4 K, in more demanding conditions than in FRIB due to larger pressure fluctuations and at 2 K
- Test of all parameters and simulation of FRIB operation:
  - Cool-down & warmup, repeated
    - » Alignment, vacuum, instrumentation
    - » Cryogenic losses
    - » Cryogenic operation
  - SRF testing
    - » SRF subsystems performance (QWRs, tuners, RF couplers, LLRF, HLRF)
  - Superconducting Solenoids testing
  - Long term cryomodule locked operation in FRIB conditions
    - » Steady state parameters measurements (cryogenics, SRF, amp-phase errors and detuning distributions, and mechanical vibrations)



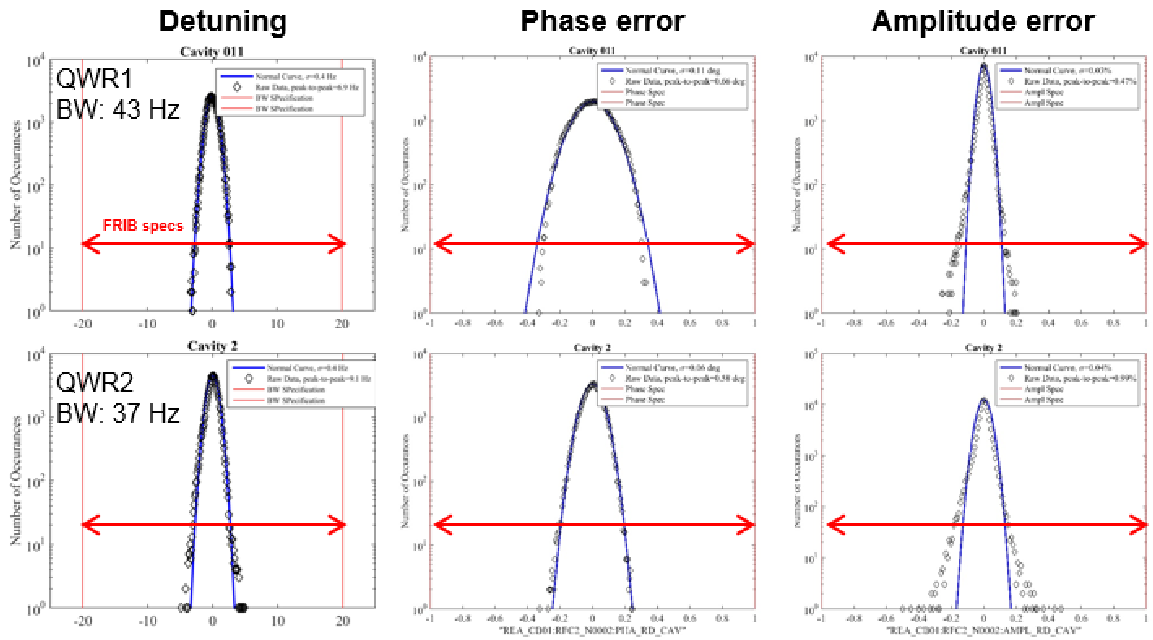
ReA6 Testing Highlights

- The cryomodule systems performance was reliable and within specifications
- The QWR performance was very good with no field emission and a large margin in EQWR performance very good, no x rays, large margin in E_a
- The resonator and cryomodule mechanical stability were well controlled
- The resonators phase and amplitude lock by FRIB low level radio frequency (LLRF) controllers were reliable and with small errors
- The total helium heat load at 2 K was 4.1 W/QWR at 6.2 MV/m where the FRIB budget is 4.5 W/QWR at 5.6 MV/m
- The stepper motors driving the tuners were able to track the cavity frequency without the aid of the piezoelectric actuators
- The FPC during operation maintained a stable temperature with no multipacting
- Verified cryomodule alignment requirements, repeatability and predictability
- Cooled down and warmed up transfer lines and cryomodule multiple times (4) with different shield configurations
- Cryomodule cool-down time is less than 3 days
- Verified U-tubes operations to support different configurations

Quarter-wave Resonator Performance All FRIB Specifications Fulfilled – 4.3 K

	Gradient	Detuning		Phase		Amplitude	
Test	E_a (MV/m)	σ (Hz)	pk-pk (Hz)	σ (deg)	pk-pk (deg)	σ (%)	pk-pk (%)
Measured QWR 1 – 4.3 K	6.2	0.4	6.9	0.11	0.66	0.03	0.47
Measured QWR 2 – 4.3 K	6.2	0.4	9.1	0.06	0.58	0.04	0.99
Measured QWR 1 – 2 K	6.2	0.4	6.8	0.19	1.04	0.06	0.43
Measured QWR 2 – 2 K	6.2	0.8	11.0	0.23	1.60	0.09	1.05
FRIB goal 2K	5.6	<2.25	<20	<0.25	<2	<0.25	<2

- 4.3 K Test
  - 24 hours lock,no trips
  - 2 FRIB QWRs
    - » 6.2 MV/m
    - » ~ 40 Hz bandwidth
    - » ~ 800 W RF power
  - Steady operation conditions
  - Detuning, phase and amplitude errors well within specifications



Quarter-wave Resonator Performance All FRIB Specifications Fulfilled – 2 K

	Gradient	Detuning		Phase		Amplitude	
Test	**E_a (MV/m)**	**σ (Hz)**	**pk-pk (Hz)**	**σ (deg)**	**pk-pk (deg)**	**σ (%)**	**pk-pk (%)**
Measured QWR 1 – 4.3 K	6.2	0.4	6.9	0.11	0.66	0.03	0.47
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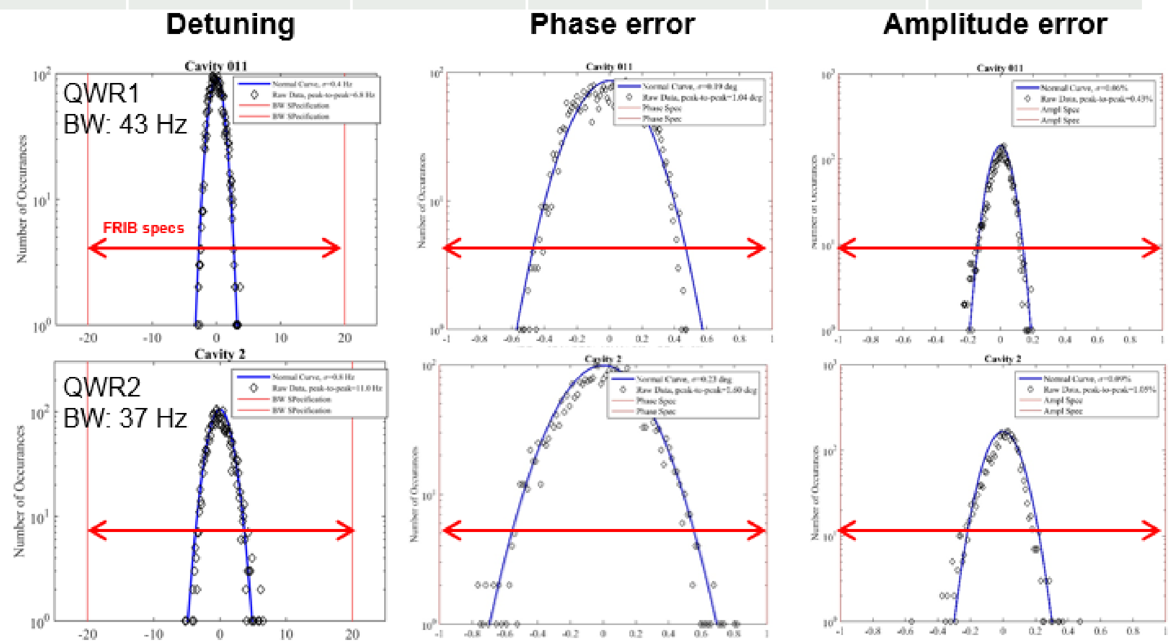
FRIB goal 2K	5.6	<2.25	<20	<0.25	<2	<0.25	<2

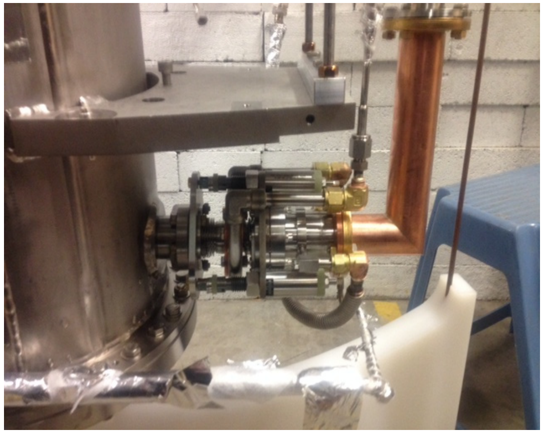
- 2 K Test
  - Limited testing time
  - Steady operation as in the 24 hour test at 4 K, same LLRF settings
  - 1 hour test, reliable lock, no trips
  - Detuning, Phase and Amplitude errors larger than at 4 K, but well within specifications



Tuners and FPC Meeting Design Goals

- Tuner:
  - In the preparatory phase of the ReA6 test it was found that the initial setting for the tuner control current was too low, causing critical reduction of tuner force, reduced tuning range and sporadic resonator unlock
  - Once restored to the proper settings, the tuner performed at specification; however, the dedicated chip in the LLRF controller required extra air cooling
  - A major tuner validation achievement was realized as the stepper motors driving the tuners were able to track the cavity frequency without the aid of the piezoelectric actuators
    - » This may eliminate the need for the costly piezoelectric actuators as a fine tuning element as the speed, force and resolution of the present tuner fulfill the FRIB specifications

- FPC:
  - The FPC during operation maintained a stable temperature with no multipacting
  - The power coupler operated up to 800 W
  - Precise bandwidth of the FPC was also achieved

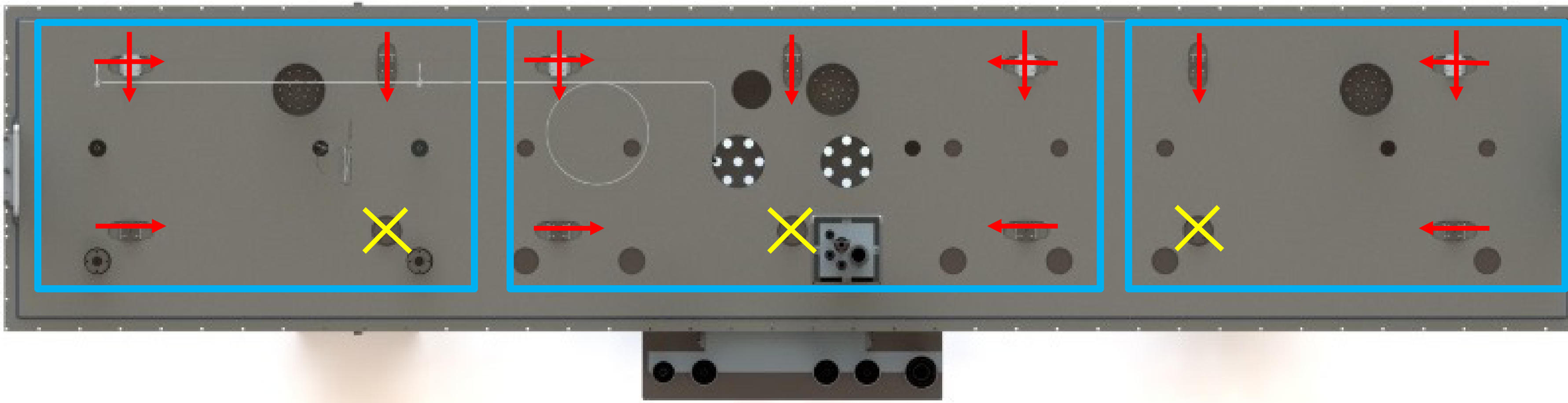


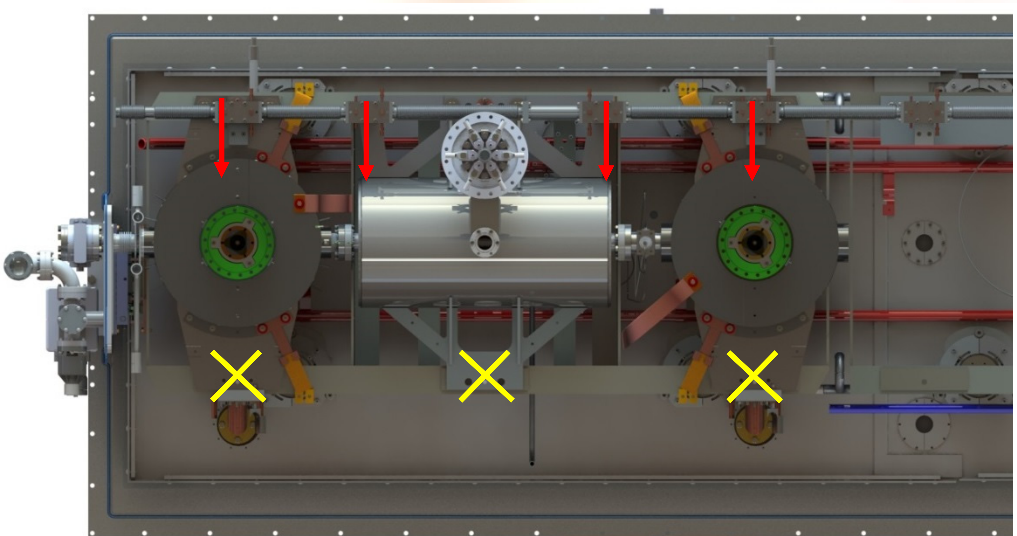
Total Heat Load Within Specifications

Test temperature		Static (W/CM)	Dynamic (W/QWR)	Total (W/QWR)	Cavity Q
4.2 K	*(2 QWRs @ 6.2 MV/m)*	5.2	4	6.6	1.6E9
2 K	*(2 QWRs @ 6.2 MV/m)*	5.2	1.5	4.1	>5E9
2 K FRIB	*(8 QWRs @ 5.6 MV/m)*	≤4	≤4	≤4.5	≥1.8E9

- Level vs. time static and dynamic load measurements performed (with thermal shield cooled with LN). Thermal load calibrated by means of heaters
- Measured Static Load of Header with 2 QWRs: 5.2 W (*>4 W, FRIB specs.*)
  - Same result at 4 K and 2 K, linked to limited measurement sensitivity
  - Calculated contribution from couplers: 0.15 W/FPC
- Dynamic loads match vertical tests: clean cold mass assembly achieved
- FRIB total heat load budget for 8-QWR cryomodules: 36 W
- Total heat load extrapolated from ReA6 test: ≤32.8 W, within FRIB budget

Cryomodule Alignment Factors





- Manufacturing and assembly steps produce an accurate cold mass assembly with meaningful and reliable external fiducials for installation
- Control and verify the warm-to-cold offset movements during cryomodule cool-down
- Install and accurately place the cryomodule assembly in the FRIB tunnel

Summary of Overall Cryomodule Component Alignment

Stage (± mm)	Resonator		Solenoid	
	Transverse	Vertical	Transverse	Vertical
Assembly	0.237	0.505	0.362	0.580
Cool-down	0.254	0.327	0.181	0.102
Overall	0.491	0.832	0.543	0.682
Budget	1	1	1	1

Yaw Error: 0.497 mm
Pitch Error: 0.231 mm

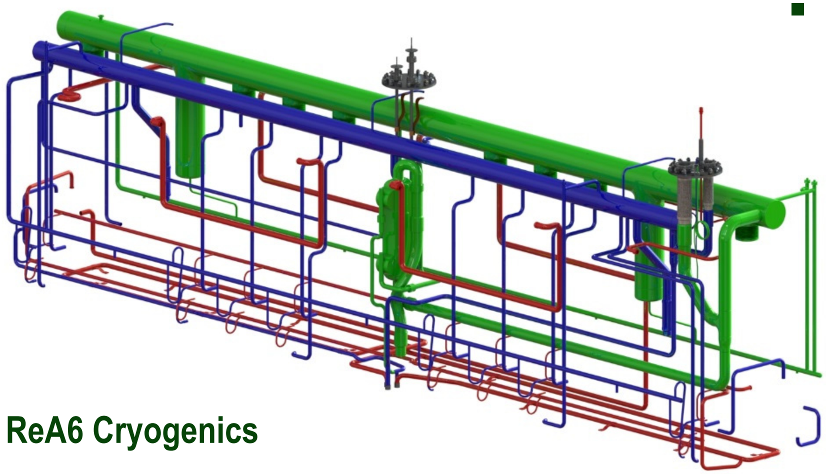
- The baseplate machined accuracy goals were reached and the baseplate can be reliably and repeatedly supported for cold mass assembly
- The master-side hole alignment goal on the rails was reached on transverse component placement
- The baseplate and vacuum vessel bolted assembly does actually perform as a rigid assembly when the adjuster mounts are manipulated and can be treated as a rigid assembly during installation
- The more stringent requirement for solenoid pitch and yaw error (< 0.3 mm common axis within the cryomodule) will required a new adjustment feature to be incorporated into the mount for CM production
- Alignment of the cavities and solenoids is repeatable from two measured cool-downs

Production Implications: ReA6 Build Lessons Learned Examples

- Baseplate
  - Bottom plates beams identified incorrectly (labeled as S12 x 31.8)
    - » Model updated with 1 configuration, descriptions corrected (S12 x 50)
    - » Vendor concerns about machining: items not rigid enough
  - Installation of the slide bearing/riser and G10 post is not feasible as currently designed
    - » Elongate bearing slots to facilitate bearing install/removal
  - Add inspection areas on machine surfaces that remain accessible after coldmass installation

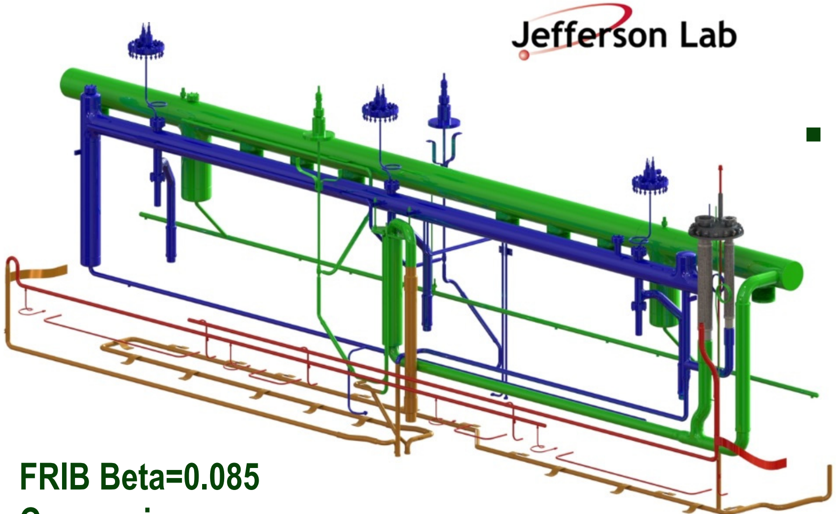
- Feedthrus
  - ReA6 first time cool down experienced a cold leak
  - 4 helium level probes leaked during cool down while all five hundred welding joints were fine
  - Improper choice of feedthrough was not spotted during design review and cold shock test was not performed on the assembly floor
  - Switch to proper cold feedthrough
  - All bimetal joints and cold instrumentation feedthrough will be cold shocked in the future as ACL steps

Production Implications: Cryogenic System Value Engineering



ReA6 Cryogenics

Jefferson Lab

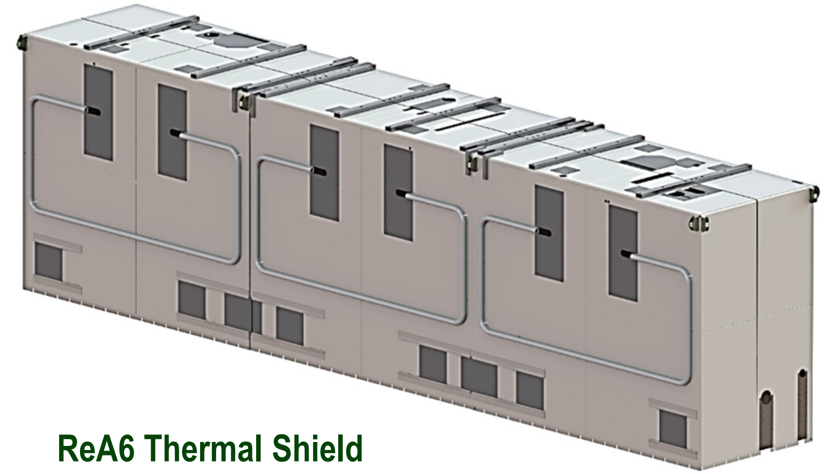


FRIB Beta=0.085 Cryogenics

- ReA6
  - Manufacturing approach which relied on vendors to deliver completed sub-assemblies
    - » Relied heavily on bent piping to minimize the number weld joints
    - » Difficult to find a qualified supplier for pipe bending
  - Actively thermally intercept the tuner drives and beamlines
    - » Fabrication of these actively cooled lines proved to be problematic due welding requirements and spatial constraints
    - » The benefits of active cooling were not great enough to outweigh the fabrication simplicity of passive cooling
- FRIB β=0.085 Cryomodule
  - Fittings shall be used throughout the welded assemblies and the sub-assemblies are broken down so that individual vendors may fabricate them
    - » The final welds will be handled at FRIB to bring the systems together
  - Thermal intercepts have been updated to a passive design

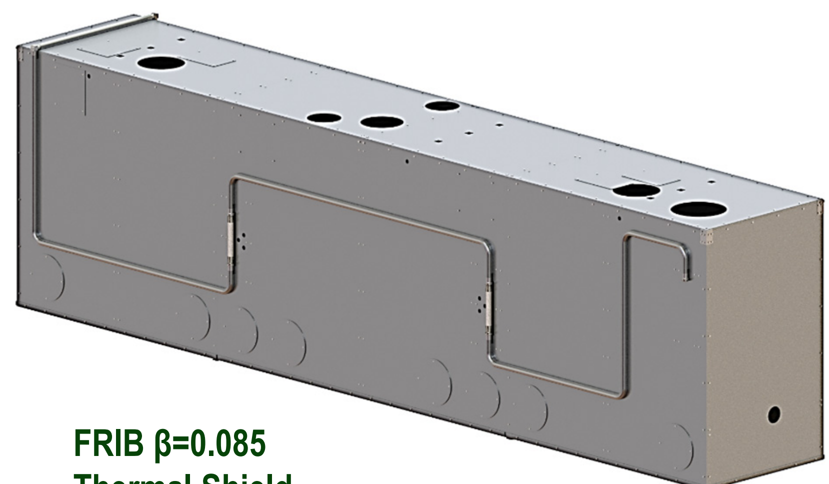
Production Implications: Magnetic and Thermal Shield Value Engineering

- ReA6
  - Complex sheet metal forming and many of the panels were difficult to manufacture as designed
  - The thin material extensions made the assembly difficult
  - Panel sizes on the magnetic and thermal shields were not optimized for material sheet sizes and required extensive continuous welding to join the material
  - Utilized pop rivets which impart a significant vibratory shock during installation and would require the rivets to be drilled out during disassembly



ReA6 Thermal Shield

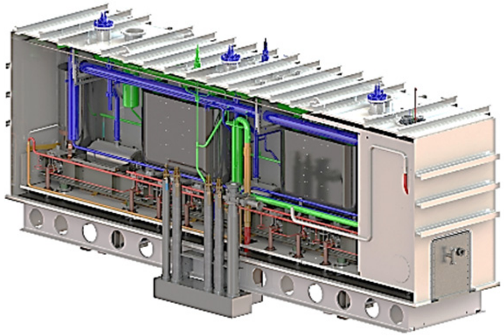
- FRIB β=0.085 Cryomodule
  - Panelized design which utilizes simplified geometry and eases installation
  - The panels are now matched to commercially available material sheet sizes which eliminates excess welding and wasted material
  - Fastening has been updated from rivets to self-broaching nuts that are welded to the panels which will ease assembly and disassembly



FRIB β=0.085
Thermal Shield

Summary and Path Forward

- The ReA6 cryomodule was successfully tested under FRIB conditions and achieved its design goals
- The testing validated the QWR subsystems and system level performance in the cryomodule
- Alignment requirements during assembly and cool-down were also verified
- The completion of the ReA6 build also validated the FRIB bottom-up design method
- β=0.085 Pre-Production Cryomodule
  - Design complete in August 2015
  - Fabrication and assembly complete by end of 2015
    - » Set up work flow needed to launch mass production
- β=0.53 Pre-Production Cryomodule
  - Design complete early 2016
- β=0.041 Cryomodule
  - Design complete by end of 2015 – Design by Jefferson Lab



FRIB 8 QWR CM
Construction of components started in 2015