FRIB

FRIB Cavity and Cryomodule Performance, Comparison with the Design and Lessons Learned

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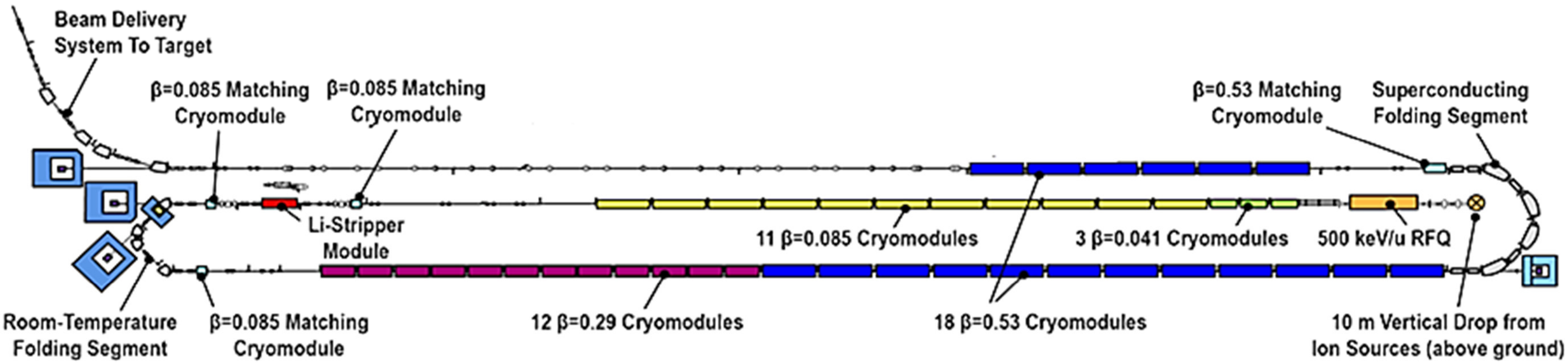
Outline

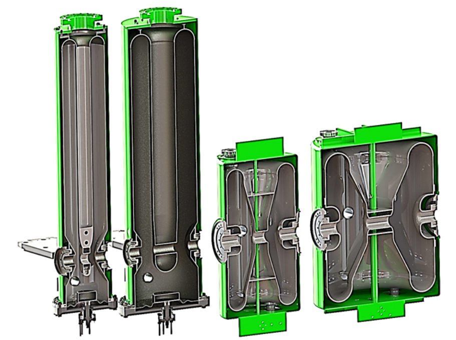
- FRIB beam commissioning has been performed on 15 cryomodules in the FRIB and validates the FRIB cryomodule bottom up assembly and alignment method
- This talk will focus on:
  - FRIB Cryomodule Design
  - FRIB Cryomodule Assembly
  - FRIB Cryomodule Performance
  - Lessons Learned
  - Summary & Path Forward

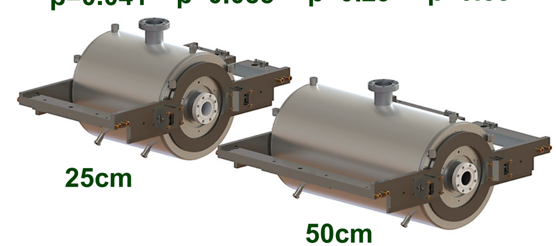
FRIB Superconducting Driver Linac

Six Cryomodule Designs, Four Superconducting Cavity Types, Two Superconducting Solenoid Types



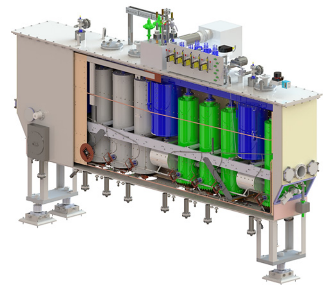
	β	Type	Component Counts (Baseline + Spare)		
			Cryomodules	Cavities	Solenoids
Quarter Wave Resonator	0.041	Accelerating	3+1	12+4	6+2
	0.085	Accelerating	11+1	88+8	33+3
		Matching	1+1	4+4	-
Half Wave Resonator	0.29	Accelerating	12	72	12
	0.53	Accelerating	18	144	18
		Matching	1	4	-
	Totals		46+3	324+16	69+5



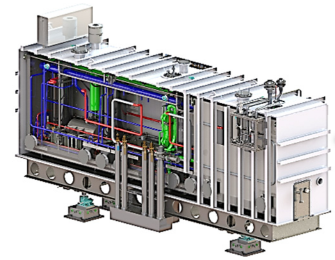


Cryomodule Design is Complete

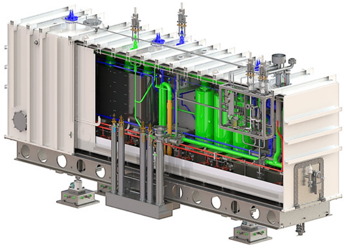
ETCM design complete 2013



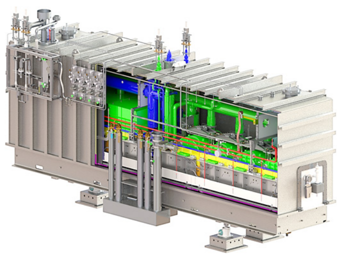
ReA3 β=0.085 QWR design complete 2013



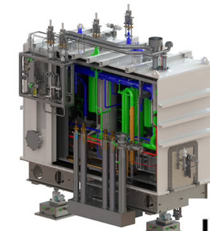
ReA6/FRIB β=0.085 QWR design complete 2014



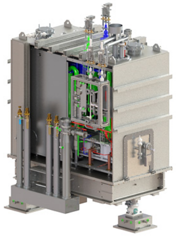
FRIB β=0.085 QWR design complete 2015



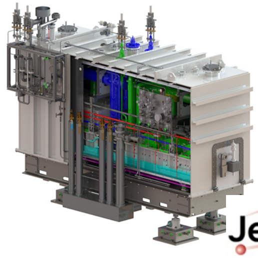
FRIB β=0.53 HWR design complete in 2016



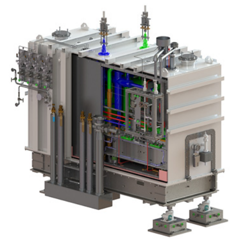
FRIB β=0.041 QWR design complete in 2016



FRIB β=0.085 QWR Matching design complete in 2016



FRIB β=0.29 HWR design complete in 2017

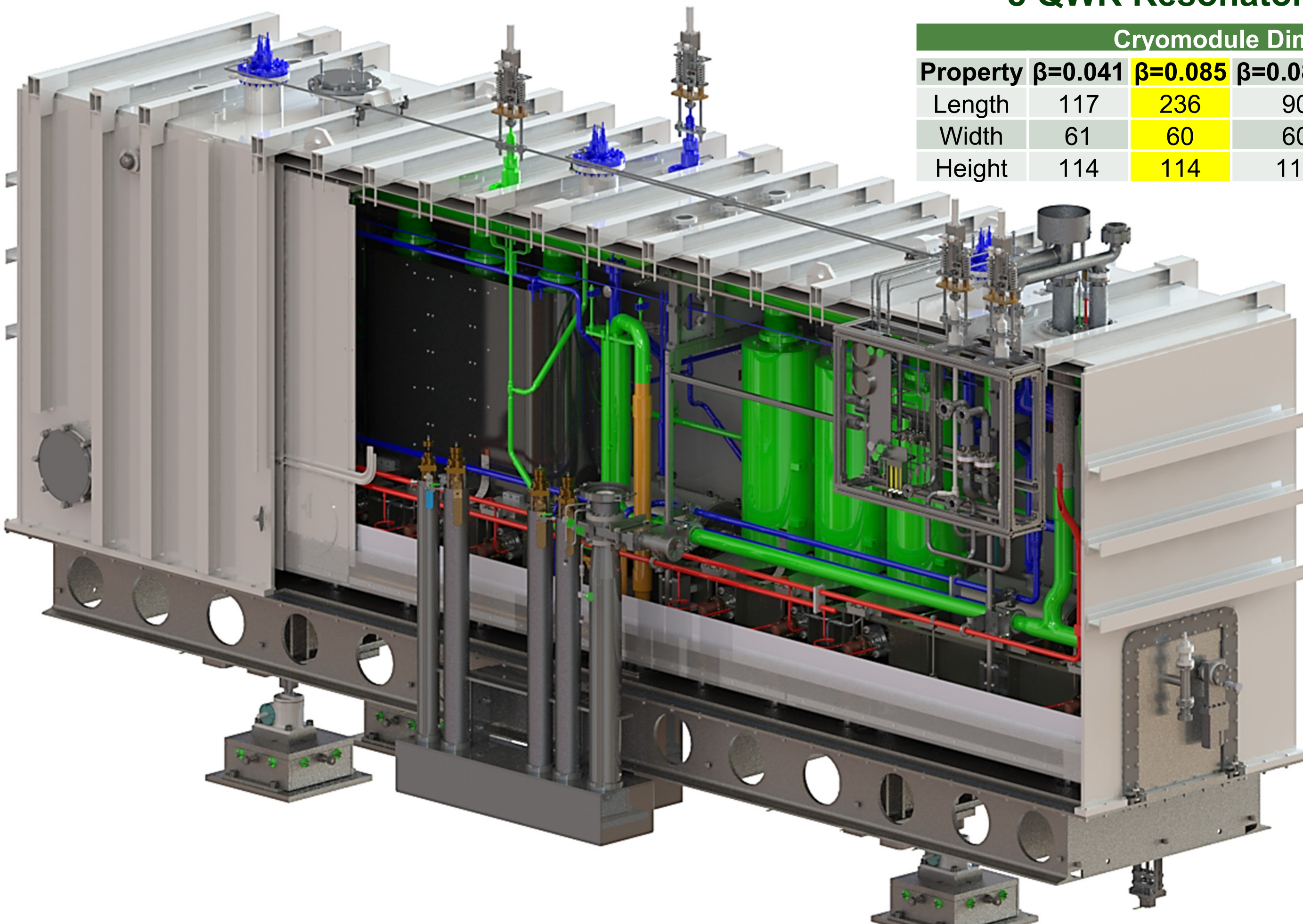


FRIB β=0.53 HWR Matching design complete 2017

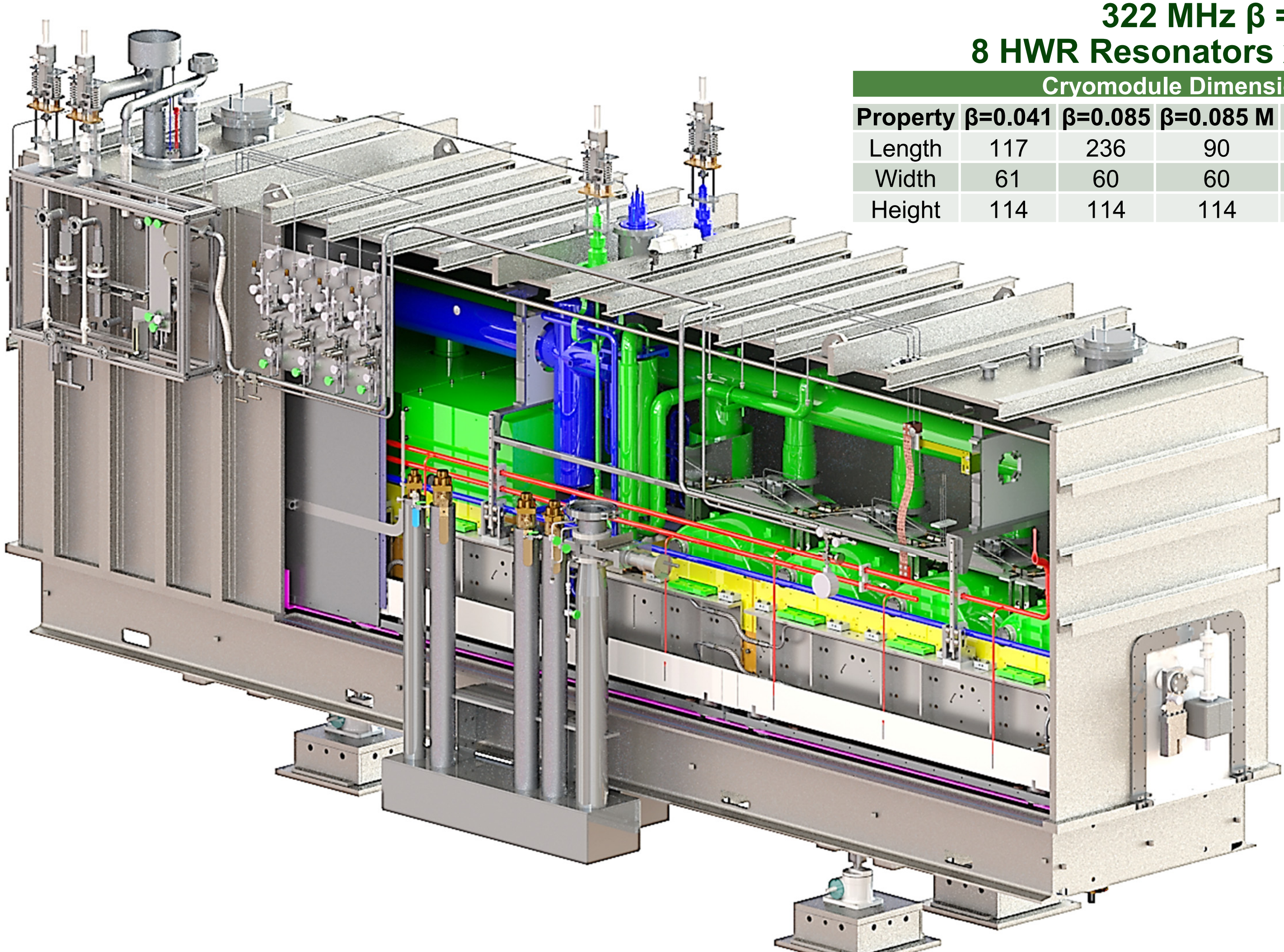
FRIB Quarter Wave Cryomodule
Modular Design to Used on All FRIB Cryomodule Types

80.5 MHz β = 0.085
8 QWR Resonators x 3 Solenoids

Cryomodule Dimensions (in)						
Property	β=0.041	β=0.085	β=0.085 M	β=0.29	β=0.53	β=0.53 M
Length	117	236	90	143	230	122
Width	61	60	60	60	60	60
Height	114	114	114	109	107	114



FRIB Half Wave Cryomodule
Modular Design to Used on All FRIB Cryomodule Types

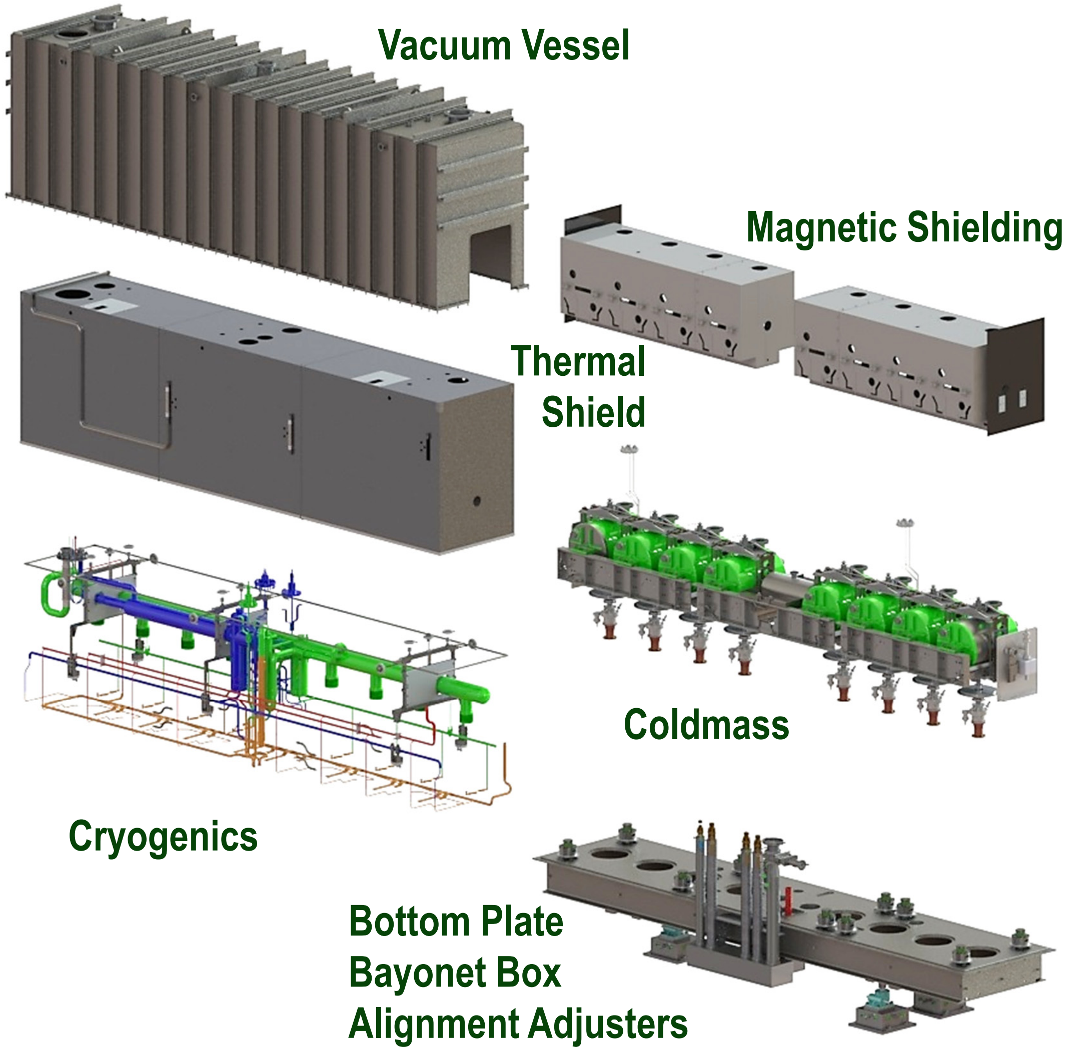


322 MHz β = 0.53
8 HWR Resonators x 1 Solenoids

Cryomodule Dimensions (in)						
Property	**β=0.041**	**β=0.085**	**β=0.085 M**	**β=0.29**	**β=0.53**	**β=0.53 M**
Length	117	236	90	143	230	122
Width	61	60	60	60	60	60
Height	114	114	114	109	107	114

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

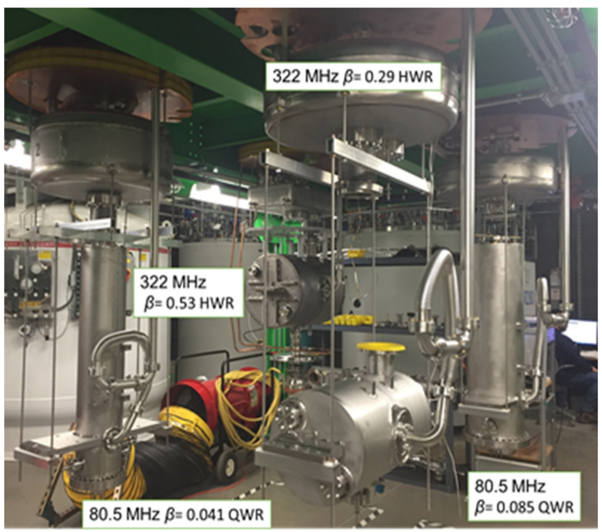
Cryomodule Production Overview

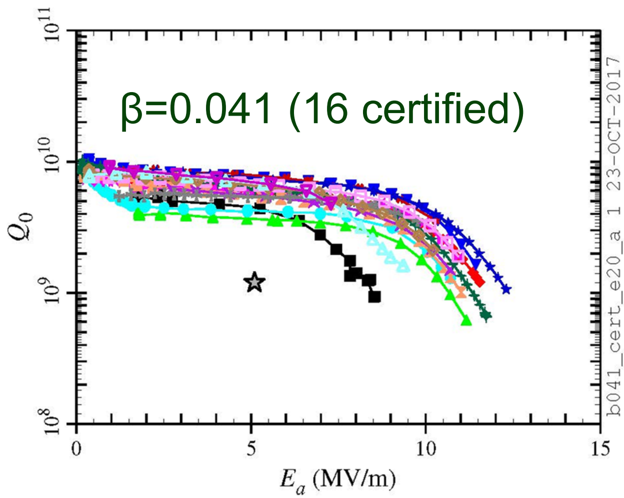
- All QWR cryomodules (Linac Segment 1 and Folding Segment 2) production is complete and installed into the tunnel
- Linac Segment 2 β=0.29 cryomodule production is completed and installed into the tunnel
- Coldmass and Module production peaked and started to ramp down CY2019
- On track to complete coldmass production by the end of CY2019

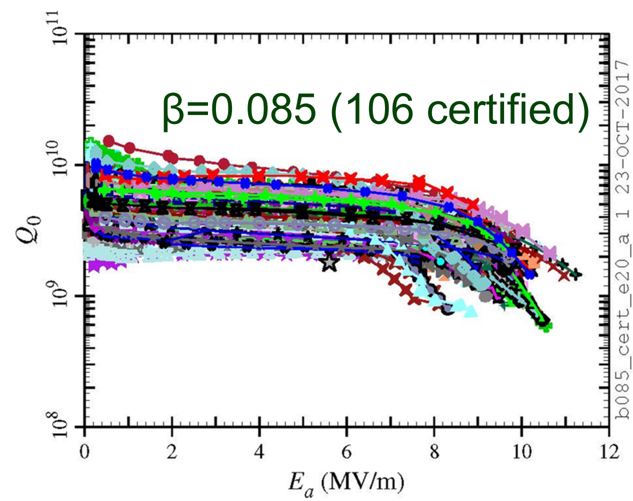
Type	Coldmass completed	Cryomodule assembled	Cryomodule bunker tested	Cryomodule in tunnel	Cryomodule needed
β=0.041	3+1	3+1	3+1	3+1	3+1
β=0.085	11	11	11	11	11+1
β=0.085 Matching	1+1	1	1	1	1+1
β=0.29	12	12	12	12	12
β=0.53	15	13	6	6	18
β=0.53 Matching	1	0	0	0	1
Total	43+2	40+1	34+1	33+1	46+3

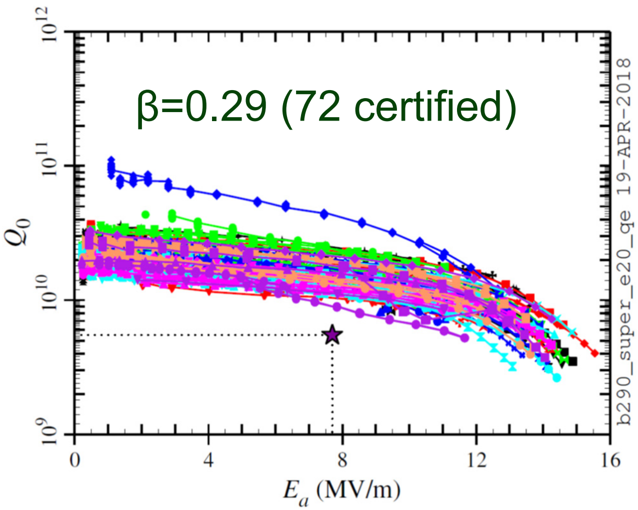
SRF Vertical Test Area

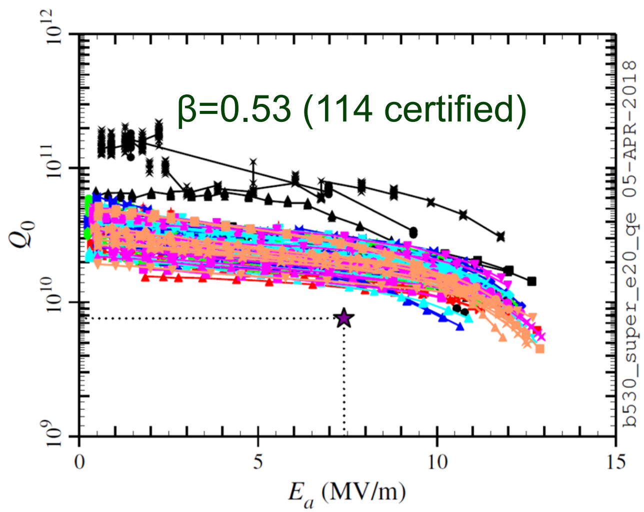
Certified FRIB Cavities with Comfortable Margin











Coldmass Production Will Complete in 2019

4 β = 0.041: 4 QWRs x 2 Solenoids

11 β = 0.085: 8 QWRs x 3 Solenoids

1 β = 0.085M: 4 QWRs

12 β = 0.29: 6 HWRs x 1 Solenoids

18 β = 0.53: 8 HWRs x 1 Solenoids

1 β = 0.53M: 4 HWRs

Cryomodule Assembly Sequence – Baseplate Installation

Coldmass Assembly Prepared

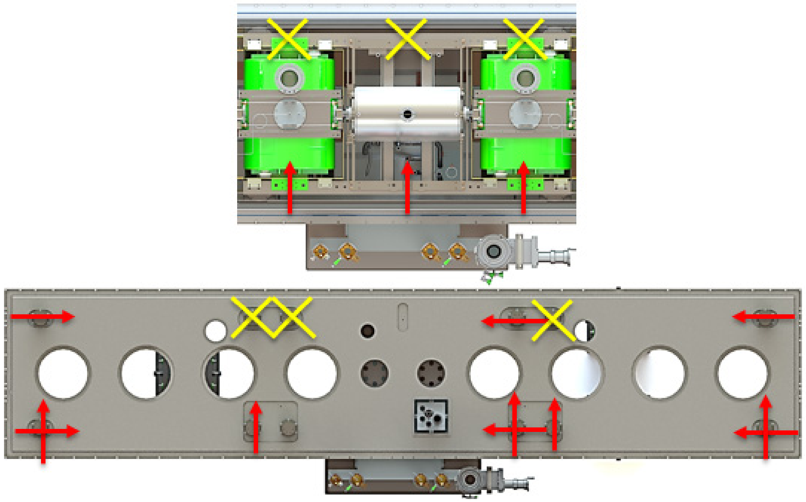
Cryomodule Baseplate Prepared

Coldmass Assembly Lifted to Baseplate

Coldmass Assembly Installed to Baseplate

FRIB Cryomodule Alignment

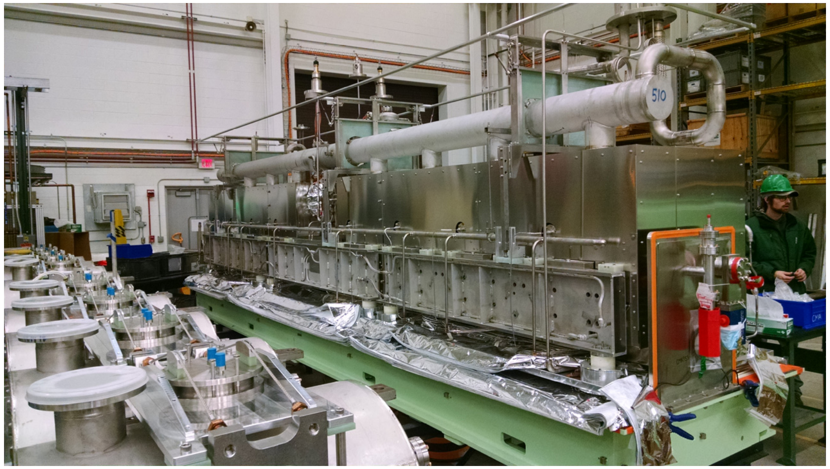
- Cryomodule alignment control:
  - Manufacturing and assembly steps to produce an accurate cold mass assembly with meaningful and reliable external fiducials for installation
    - » The baseplate machined accuracy goals were reached and the baseplate can be reliably and repeatedly supported for cold mass assembly
    - » The master-side hole alignment goal on the rails was reached on transverse component placement
  - Control and verification of the warm-to-cold offset movements during cool-down
  - Installation and placement accuracy of the cryomodule assembly in the tunnel
    - » 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
- Alignment group performs survey of the coldmass elements after installation to baseplate
  - Solenoids that have a trajectory error greater than 200 μm can be correct by yaw adjustment
  - Shim components as needed to correct pitch error
- Three days is required to perform and approve results of survey data
- Survey results are within alignment budget (+/- 1mm)



Cryomodule	Resonator		Solenoid	
	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)
β=0.041 (4)	0.12/0.26	0.19/0.52	0.12/0.26	0.05/0.13
β=0.085 (11)	0.26/0.79	0.24/0.72	0.13/0.37	0.11/0.43
β=0.085M (1)	0.07/0.15	0.07/0.13	-	-
β=0.29 (12)	0.32/0.89	0.26/0.	0/0	0/0
β=0.53 (12*)	0.28/0.71	0.56/0.89	0/0	0/0
β=0.053M (1)	0.11/0.157	0.11/0.26	-	-

The * indicates one outlier that was removed from the data set which was a pre-production module

Cryomodule Assembly Sequence – Cryogenics, Thermal Shield, and Vacuum Vessel Installed



Cryogenics and Magnetic Shield Installed

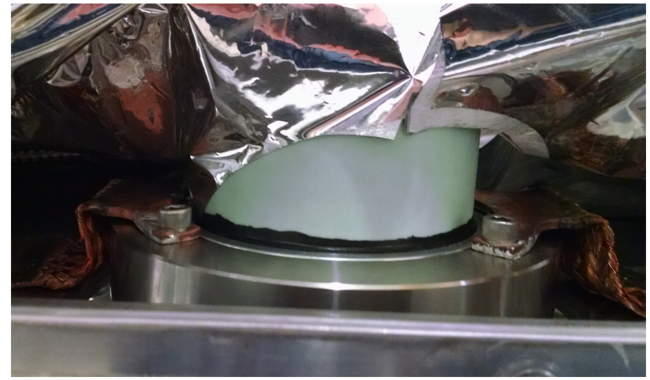
Coldmass Wrapped in MLI

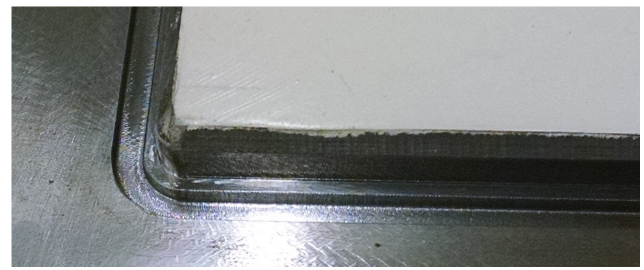
Thermal Shield Installed

Vacuum Vessel Installed

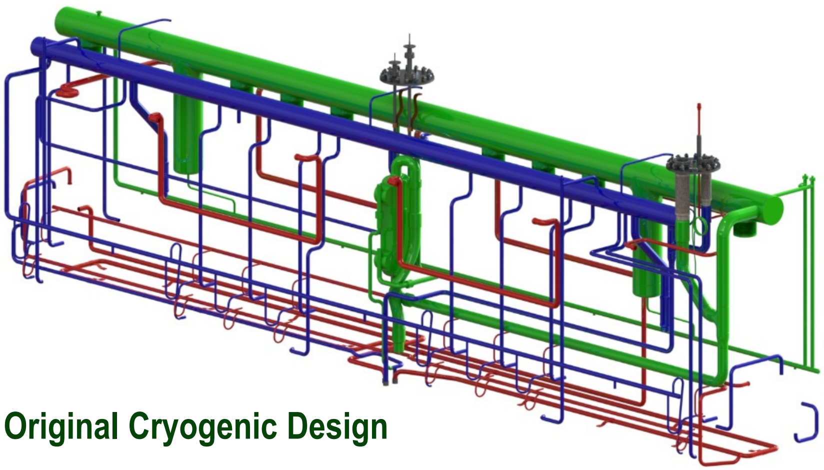
Build Lessons Learned

- Build floor improvements documented and tracked by engineering
  - Corrective actions (ECO and/or work instructions update) implemented successfully before next build
- Alignment Rail/G-10 Posts
  - Mounting pads need be wider
  - G10 post intercept straps were difficult to mount
- Baseplate
  - Bottom plate O-ring groove surface finish not to print
- Magnetic Shields
  - Magnetic Shield tops can be assembled earlier in the assembly sequence
- Thermal Shield
  - Thermal Shield cover plates for flexline needed to be slotted to opened up for clearance
  - Pincher bars for the thermal shield are too thick

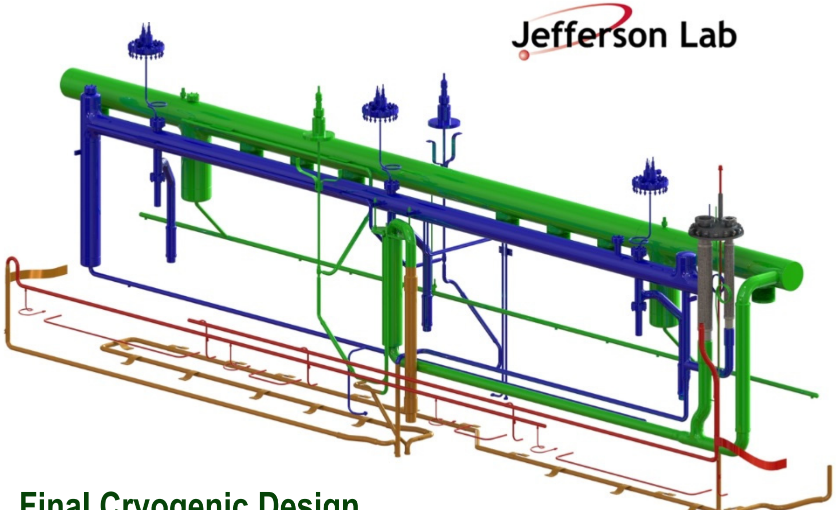




Production Implications: Cryogenic System Value Engineering



Original Cryogenic Design

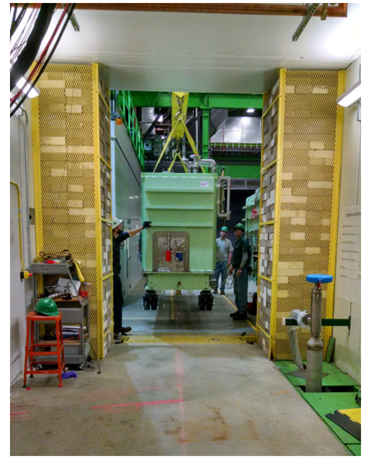


Final Cryogenic Design

- 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
- 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

Cryomodule Bunker Testing Program

- Total of 34 cryomodules bunker tests are complete and met all FRIB specifications
  - 34/49, 69% planned modules certified
- Production cryomodule testing has demonstrated test rate of one cryomodule per month
  - Includes installation and removal
- One cryomodule had to be retested after rework (microphonics issue)
- All results are documented in document control center (DCC)
- Nonconforming test results and reworks are documented and approved
- Test bunker installation layout is a representative cross section of the FRIB tunnel



Issues, Lessons Learned from Bunker Testing

Issue	Notes
Multipacting in HWR (322 MHz) coaxial coupler	Added bias to the inner conductor, all HWR module certified with bias
QWR (80.5 MHz) Warm window overheating in bunker test	PLC trip was reset by cryomodule test personnel (retrain) Warm window still had desiccant from shipping (rework all modules)
LLRF development issues	Debugging on LLRF done in bunker testing program
Instant Trips: Bug or real	There are rare trip events that do not seem real, still building tools to check them
Production Bias Tee Certification	Production test overheating (OK for 3kW). Working with Vendor to reduce inner conductor temperature
Mismatch on RF patch / LLRF	Add attenuation to pad standing waves (as done in bunker tests), mismatch explains RF calibration mismatch with beam
Pneumatic tuner valve calibration	Can be done in situ during cryomodule test (saves one day per bunker test)
CCG / SHV cable troubles	Bad cable looks like good vacuum
Firmware / Software Management (LLRF)	Use bunker testing to check LLRF firmware upgrades and find bugs
Pneumatic tuner helium line ice block	During cooldown, a valve on tuner manifold leaked air into line and made ice. Tuning range checked during warm up
Microphonics Issue in SCM404	Cavities 1 & 4 could not lock, we warmed up, did some reworks and recertified

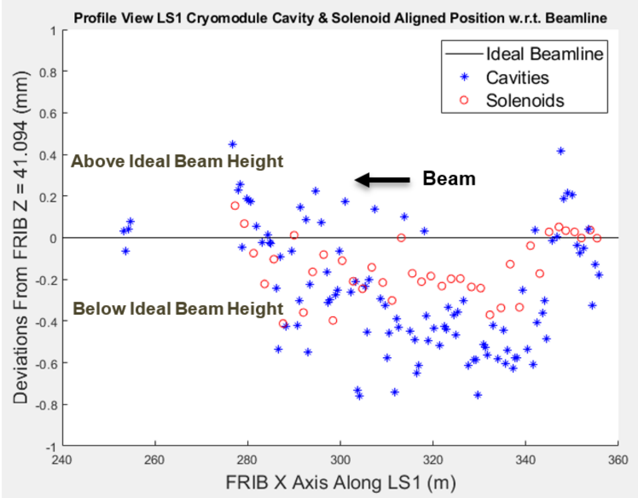
Cryomodule Transportation and Installation

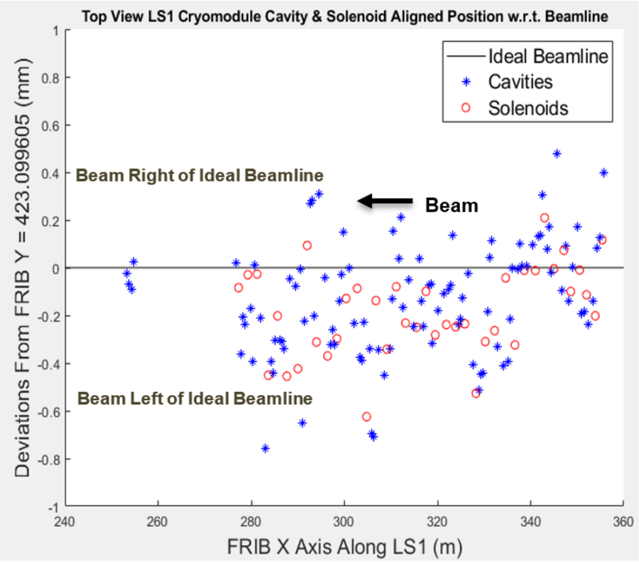
- Total of 33 cryomodules have been transported to tunnel
- Linac Segment 1 and Folding Segment 1 QWR (β=0.041 and β=0.085) cryomodules are installed and aligned
  - Fully integrated into FRIB linac and commissioned
- Linac Segment 2 β=0.29 cryomodules are installed into the tunnel and alignment is underway
  - Preparation for linac commissioning
- Linac Segment 2&3 are being populated with β=0.53 cryomodules as they complete bunker testing

Cryomodule Alignment in Linac Segment 1

- Alignment complete on Linac Segment 1 cryomodules which includes β=0.041 and β=0.085 cryomodules
- Alignment was tested and quantified during beam commissioning
  - Required 25% of available corrective dipole current to steer the beam on-axis within +/- 1mm
- Calculation of cavity and solenoid positions accounts for:
  - Solenoid mapping magnetic offset data
  - Cavity and solenoid fiducialization data
  - Assembly measurements relating cavity and solenoid fiducials to cryomodule baseplate fiducials
  - Offset corrections for thermal effects of cool down
  - Baseplate distortion between assembly and vacuum jacket installation and transport
  - As-aligned baseplate fiducial measurements
- Solenoids were prioritized in the alignment process

Statistic (mm)	Resonator	Solenoid
Maximum Offset	0.878	0.671
Average Offset	0.423	0.287
Sample Std from Average Offset	0.199	0.163



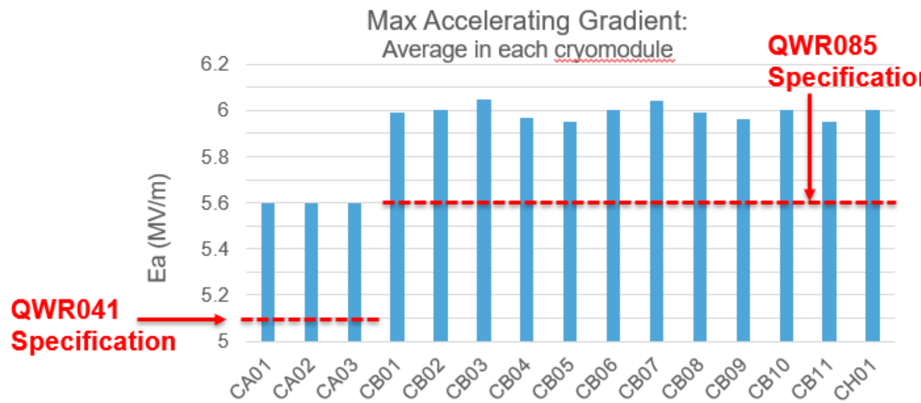


All QWRs for FRIB Driver Linac Have Been Commissioned

- Beam commissioning use all 15 QWR cryomodules in Linac Segment 1
  - 12 β=0.041 QWRs and 92 β=0.085 QWRs
  - High-power radio frequency run at 4.5 K
    - » The baseline design is 2 K and all Linac Segment 1 cryomodules have been tested at 2 K in linac
- Maximum gradient in Linac
  - All 104 cavities in Linac Segment 1 met the specification with 10-20% margins

Design Parameters

Accelrating Module Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.29	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.78	2.09	3.70
E_{acc} [MV/m]	5.1	5.6	7.7	7.4
Epk (MV/m)	30.8	33.4	33.3	26.5
Bpk (mT)	54.6	68.9	59.6	63.2
Q0 (VTA)	1.4E9	2.0E9	6.7E9	9.2E9
Number of cavities per cryomodule	4	8	6	8
Total Dynamic load to cryoplant **(2K)**	7.3	34.8	22.8	65.2
Control bandwith (Hz)	40	40	52	30
Maximum RF Power (W)	672	2469	2812	4974
Total # of Cryomodules Needed (# Cavities)	**3 (12)**	**12 (92)**	**12 (72)**	**18 (148)**

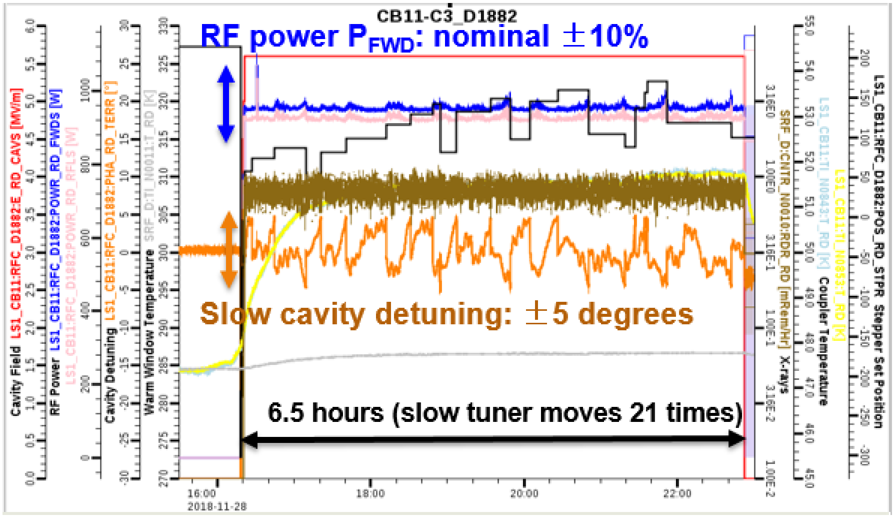


Issue and Resolution

Issue	Cause	Resolution
RF trip due to tuner slip: 12 CB cavities	The small stepper motor cannot provide enough torque to stably hold the tuner especially when changing direction	The next-size stepper can provide a high enough torque. 4 cavities: replaced the stepper motor and confirmed the issue was **resolved**. 8 cavities: plan to replace
Cavity low-field multipacting (MP) barrier	1) Leakage RF from LLRF to amplifier excites MP between amp-on and RF-on. 2) Field emission from neighboring cavities makes MP stronger	1) LLRF firmware was changed to eliminate undesired leakage RF, 2) A special sequence of cavity turn-on was used. This issue has been **resolved**
RF Amplifier trips on water flow	Maintenance work about RF rack cooling water flow was carried out	A maintenance procedure has been established by RF: **resolved**
Solenoid power supply and RF amplifier trips on water flow	Work on LS2 cooling water was carried out during beam commissioning, which caused 15% drop of LS1 water flow. Multiple magnet power supplies and RF amplifiers were tripped	Any work which may impact on the machine especially during commissioning is strictly controlled by WCP system: **resolved**
Unexpected immediate turn-off of all LS1 cavities	Misoperation regarding to MPS	Additional training for OIC has been performed, operation control screen has been improved: **resolved**

Lesson Learned: Linac Segment 1 Cavities Operated at 4.5 K

- All Linac Segment 1 cavities stably ran at 4.5 K during SRF commissioning; 4.5 K for beam commissioning
  - More conservative condition than the baseline 2 K from the standpoint of microphonics
  - Cavity slow and fast detuning is small enough even at 4.5 K
- Linac Segment 1 commissioning shows that 4.5 K operation is a feasible option
  - Could be more efficient than 2 K since the estimated heat load of Linac Segment 1 is 780 W at 4.5 K, 300 W at 2.0 K at the design gradients
  - Will continue to check stability at 4.5 K as Linac Segment 2 and 3 cryomodules are integrated



Summary and Path Forward

- FRIB cromodule design has been completed and validated
- Cryomodule bunker testing has validated cryomodule subsystems and system level performance in the cryomodule
- Linac Segment 1 cryomodules with 104 QWRs have been commissioned
  - Achieved the design gradient, amplitude and phase stability
  - Provided stable SRF operation for beam commissioning
  - The alignment of the cryomodules is well established and repeatable