Cryomodule Production and First Cool Down Of FRIB Superconducting Linac

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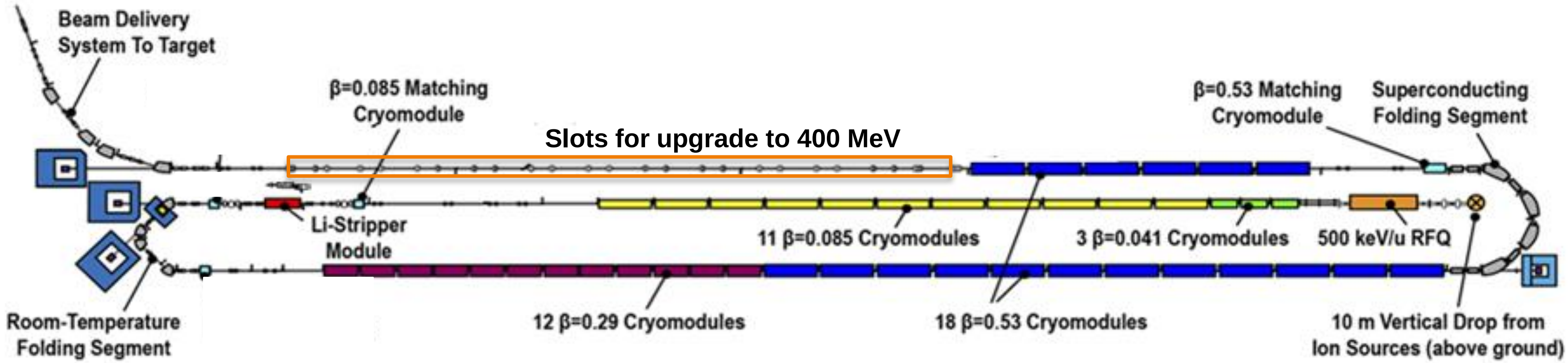
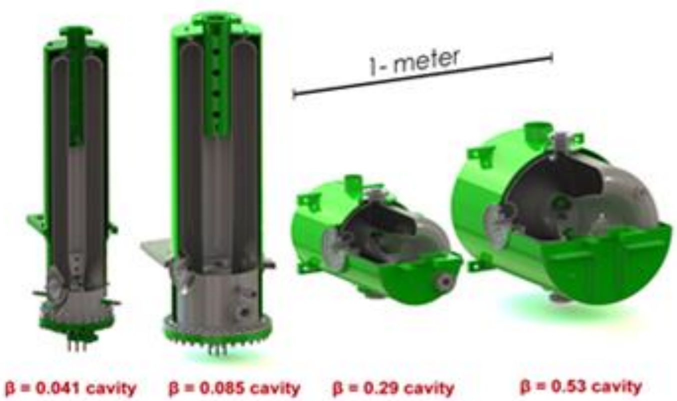
Outline

- Overview
- Cryomodule construction status
- Cool down and commissioning of first three cryomodule
- Summary

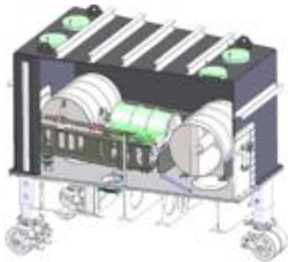
FRIB Superconducting Linac
Ion Species up to ^{238}U 200 MeV/u, 400 KW



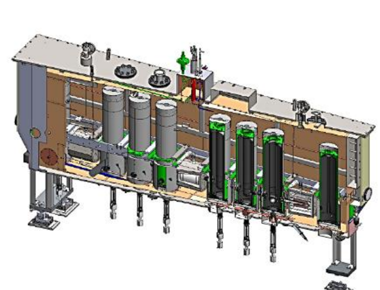


Quarter Wave Cryomodule				
β	***Type***	***Component Counts (baseline + spares)***		
		Cryomodules	***Cavities***	***Solenoids***
0.041	**accelerating**	**3 + 1**	**12 + 4**	**6 + 2**
0.085	**accelerating**	**11 + 1**	**88 + 8**	**33 + 3**
	matching	**1 + 1**	**4 + 4**	**-**
Half Wave Cryomodule				
0.29	**accelerating**	**12**	**72**	**12**
0.53	**accelerating**	**18**	**144**	**18**
	matching	**1**	**4**	**-**
TOTALS		**46 + 3**	**324 + 16**	**69 + 5**

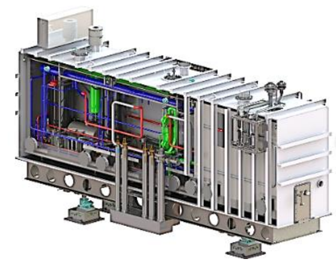
Cryomodule Design Is Completed
FRIB Cryomodule Development and Validation Path



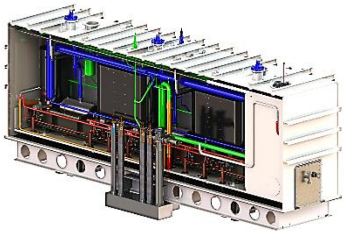
ETCM design complete 2013



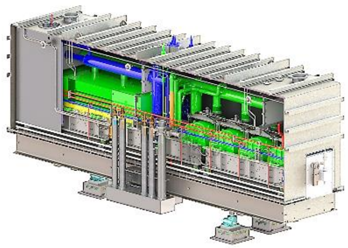
ReA3 design complete 2013



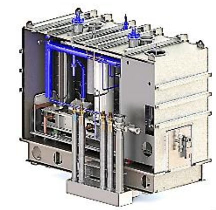
ReA6/FRIB QWR design complete 2014



FRIB QWR design complete 2015

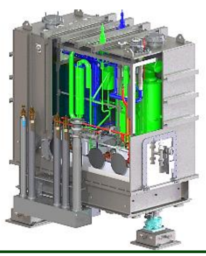


FRIB HWR design complete in 2016

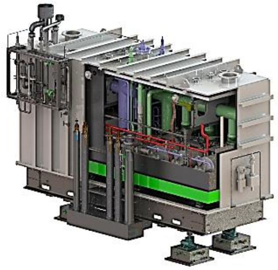


Jefferson Lab

FRIB β=0.041 QWR design complete in 2016

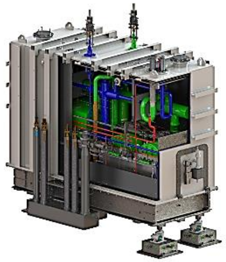


FRIB β=0.085 QWR Matching design complete in 2016



Jefferson Lab

FRIB β=0.29 HWR design complete in March 2017



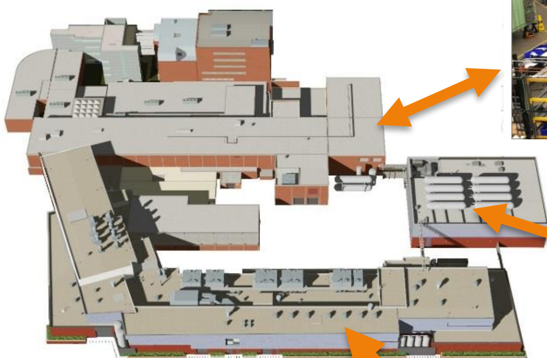
FRIB β=0.53 HWR Matching design complete June 2017

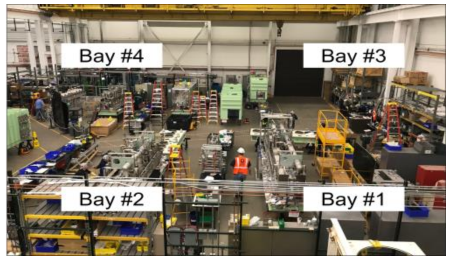
FRIB SRF Infrastructure

FRIB perform all processing assembling and testing on site

5 construction bays and 2 test bunkers

FRIB site at Michigan State University

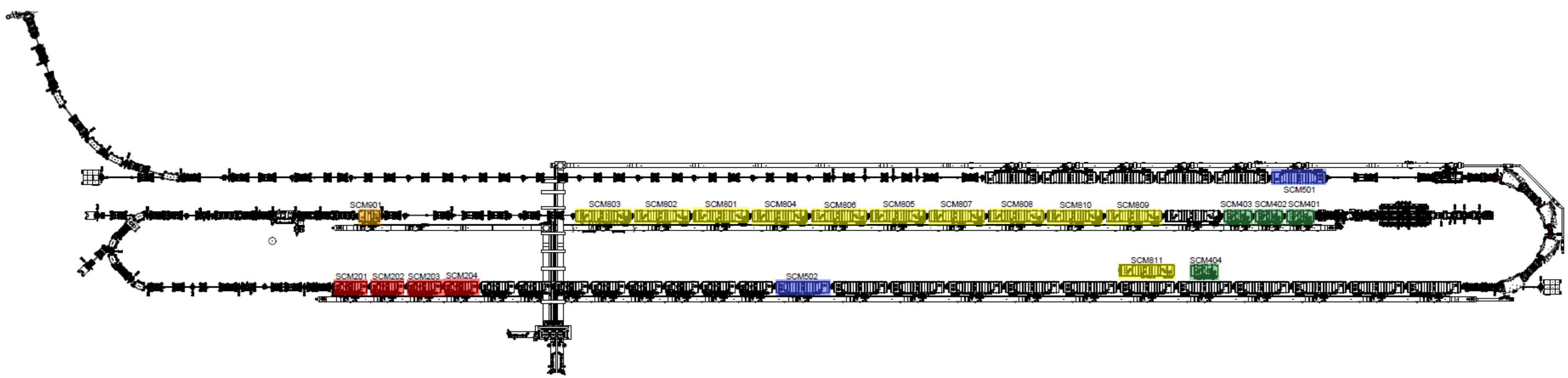




SRF Highbay built specifically for processing and testing FRIB SRF technology with dedicated cryoplant and an additional bunker

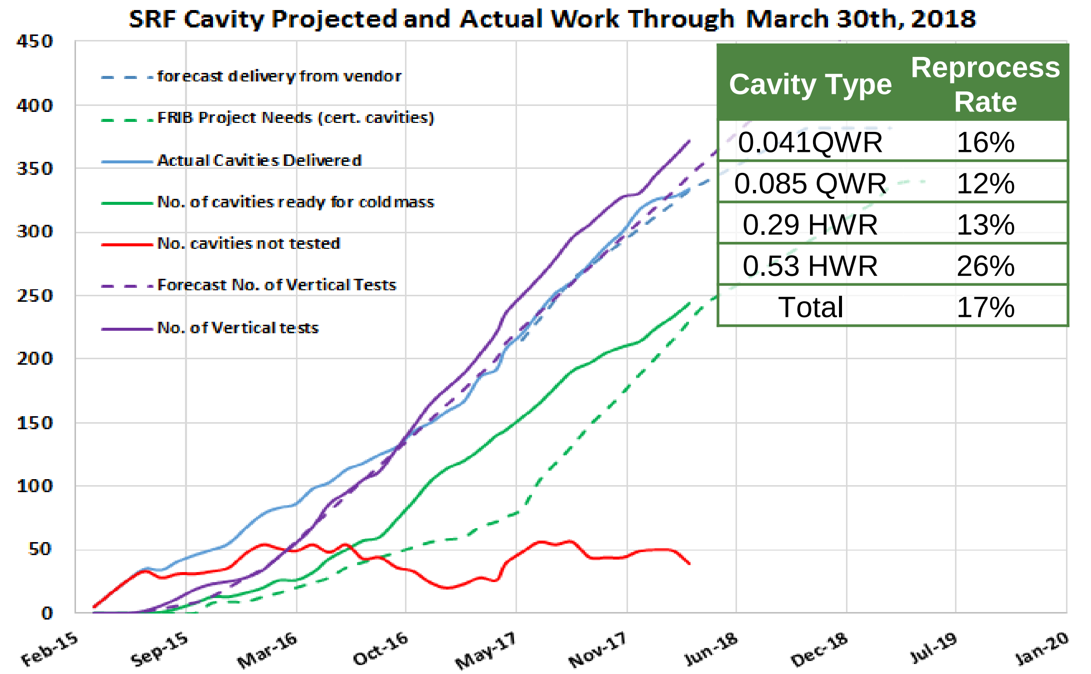
Cryomodule Production Status
Project to complete by end of 2019

Type	Coldmass completed	Cryomodule assembled	Cryomodule bunker tested	Cryomodule in tunnel	Cryomodule needed (T+P)
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 buncher	1	1	1	1	1+1
β=0.29	12	8	5	5	12
β=0.53	8	2	2	2	18
β=0.53 buncher	0	0	0	0	1
Total	35+1	25+1	22+1	22+1	46+3

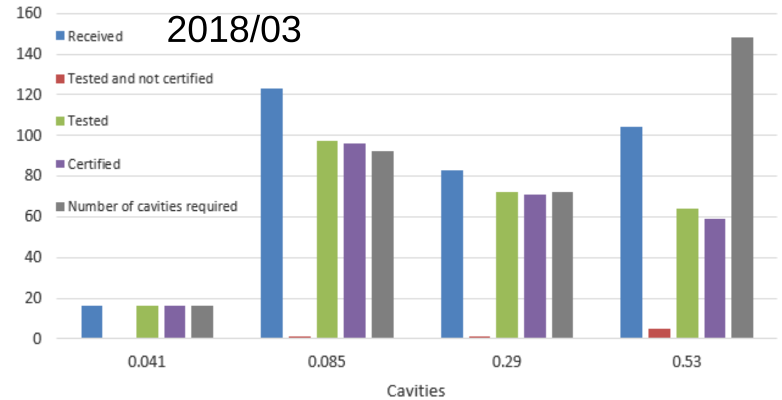


FRIB Cavity Status

- Over 290 cavities (90% of FRIB project baseline needs) have been received and accepted.
- More than 260 cavities have been certified and the rest are in the work flow

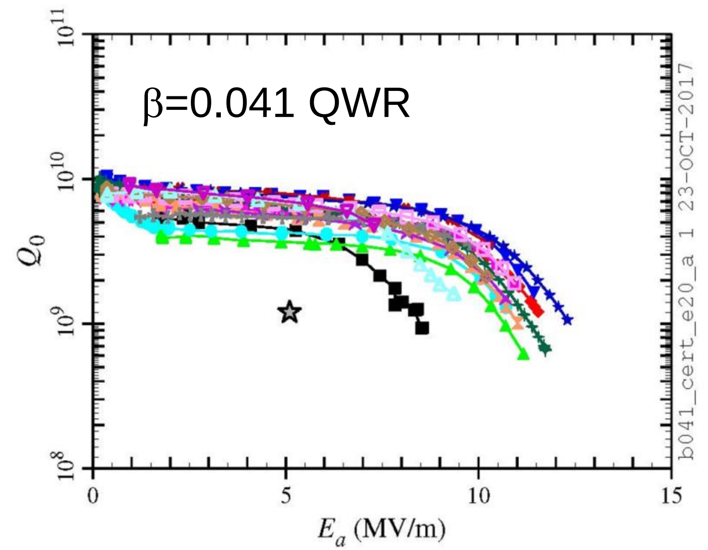


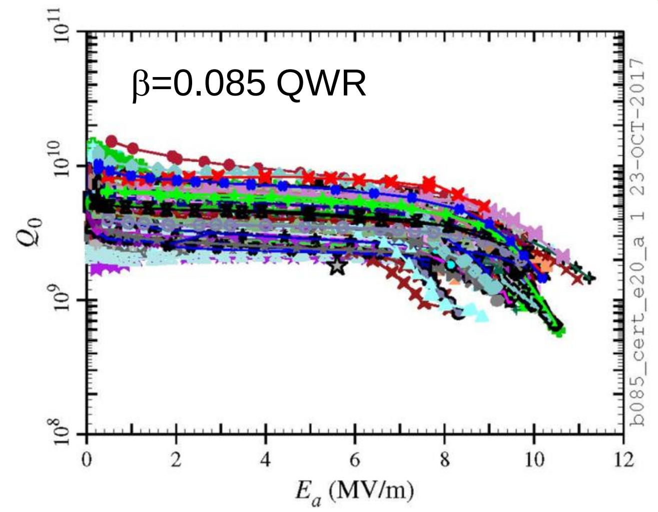
Cavity Type	Reprocess Rate
0.041QWR	16%
0.085 QWR	12%
0.29 HWR	13%
0.53 HWR	26%
Total	17%

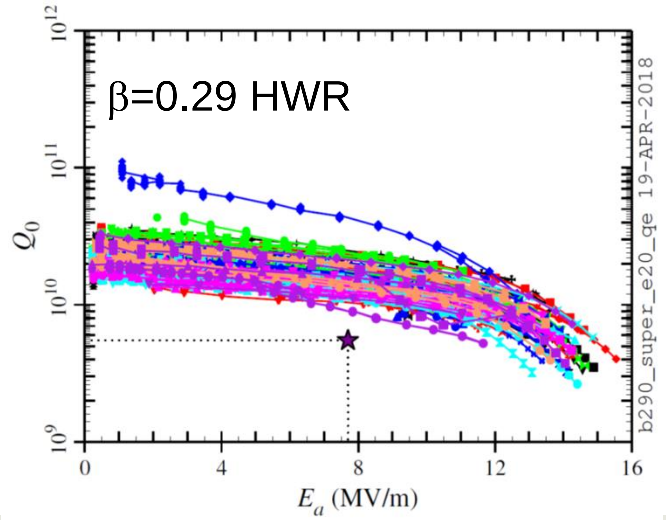


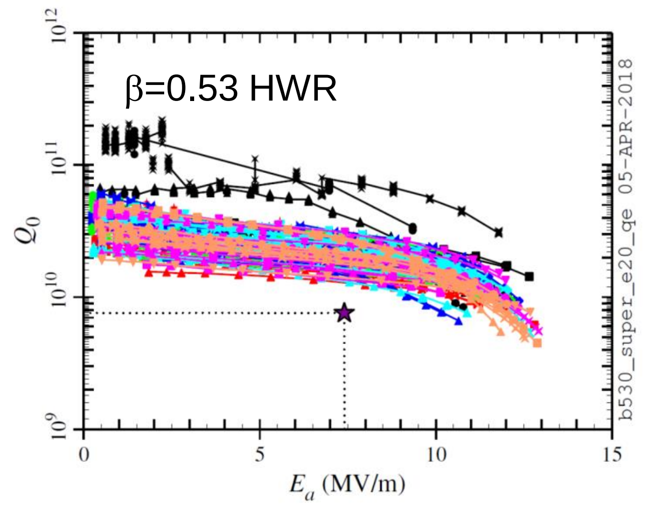
- VTA cold test through put more than 3 per week average and 1 per day at peak
- Reprocess rate is below 20% overall.

FRIB Cavity VTA Results



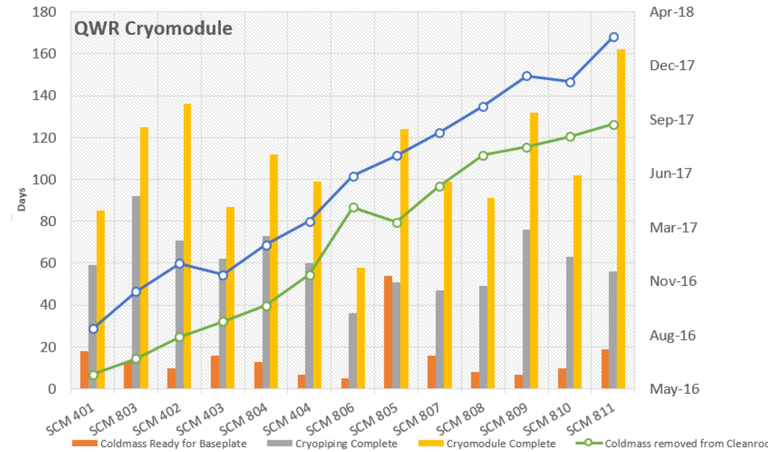


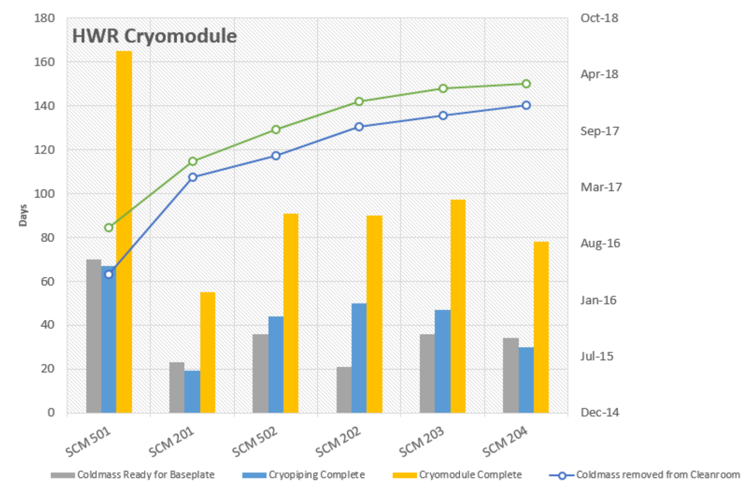




Cryomodule Production Status

- Coldmass (cleanroom assembly) production 1.5 per month
- Cryomodule assesmbly at 1 per month
- Cryomodule bunker test 1 per month



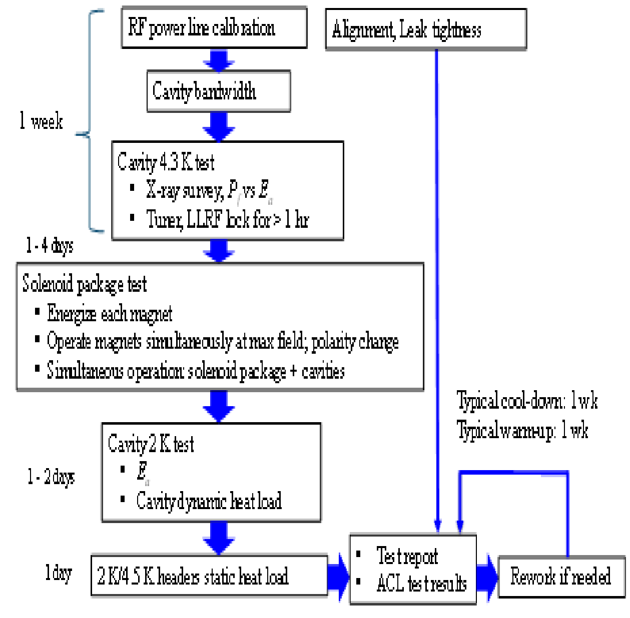


Cryomodule Testing Program

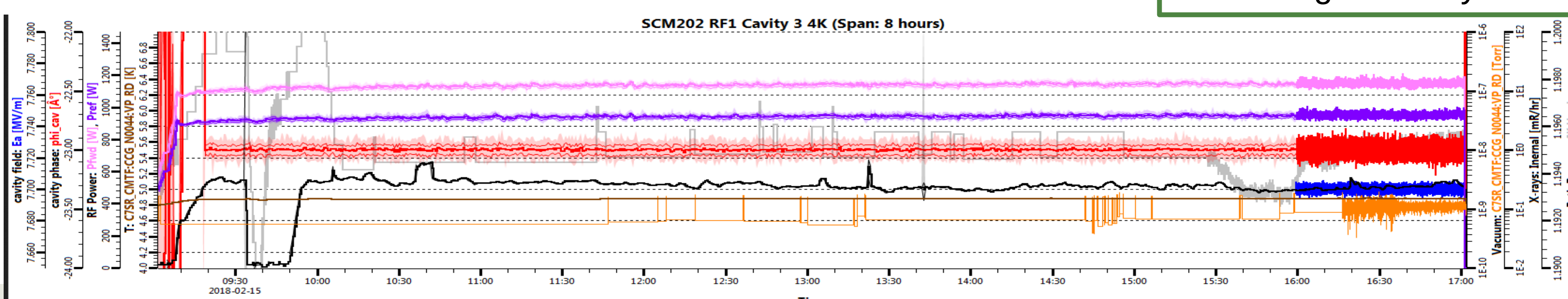
- FRIB Cryomodules are fully tested before installation in the FRIB tunnel. 23 cryomodules have been certified.
- We do calibration and check for Xrays, gradient, LLRF locking, heat load, magnet operation, tuning range
- Q_0 values measured in the cryomodules are above FRIB specification with comfortable margin

		4.5 K Static [W]		2K Static [W]		Q_0 in CM at 2K	
CM Type	CM Tested	Spec	Measured *	Spec	Measured*	Spec	Measured*
041 QWR	4	12.8	14.9	3	3.9	1.20E+09	2.70E+09
085 QWR	11	20.5	21.2	4	7.75	1.80E+09	3.30E+09
29 HWR	5	13.1	13.2	5.1	4.8	5.50E+09	1.30E+10
53 HWR	2	16.1	12.8	6.3	6.5	7.60E+09	1.80E+10

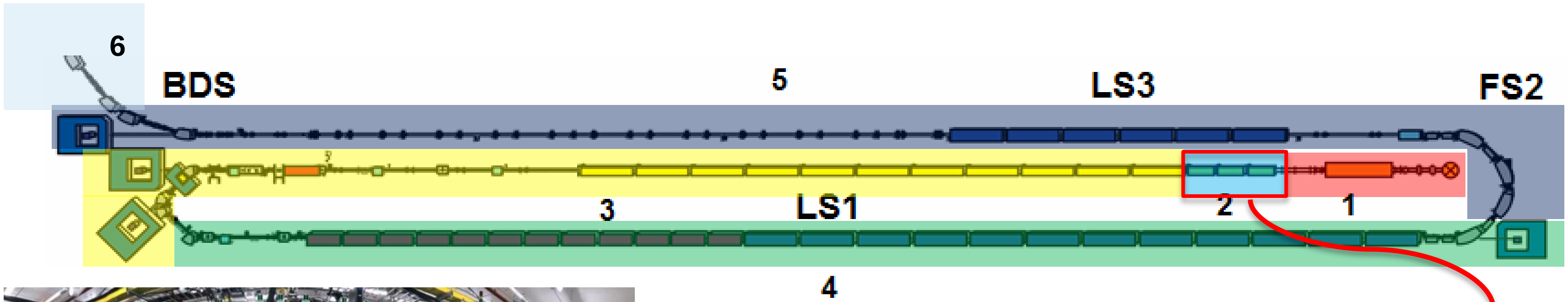
* Measurement is average for all the modules

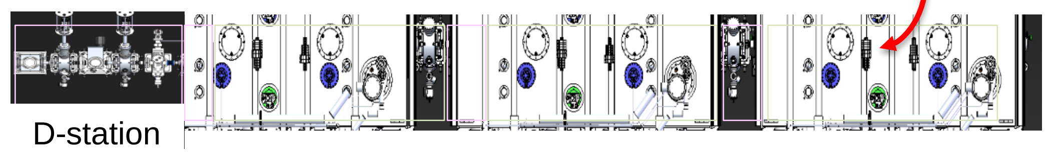


SCM202, Cavities 3 and 4: 8 hours locking to test system stability



FRIB Phased Beam Commissioning Plan





ARR	Area with beam	Status
1	Ion Source, Low Energy Beam Transport, RFQ, Medium Energy Beam Transport	Done, 07/2017
2	**Linac Segment (LS) 1 (β=0.041 cryomodules)**	**05/2018**
3	Remainder of LS1 and first 45 degree dipole of Folding Segment (FS) 1	02/2019
4	Remainder of FS1, LS2	04/2020
5	FS2, LS3	09/2020
6	Beam Delivery System, Target, Pre-Separator in Target Hall	TBD
Final	Prior post-start items, Pre-Separator outside Target Hall, reconfigured A1900, entire facility	Before 06/2022

- Accelerate heavy ion beams to energies < 2.4 MeV/u
  - First three cryomodules (β=0.041)
  - Warm Diagnostics Boxes between cryomodules
  - Commissioning Diagnostic Station (D-Station)

Beam Line Devices Installed and Aligned

- Beam line devices installed and pumped down to $< 5 \times 10^{-9}$ Torr

CA02

CA01

CA03

Warm box

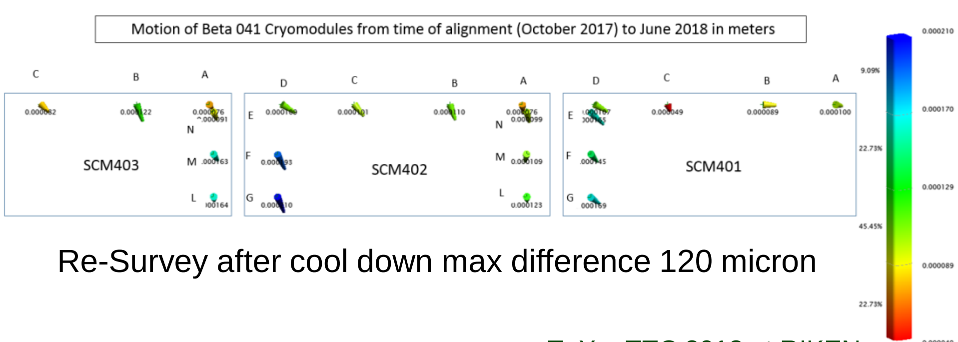
D-station

- Aligned all three cryomodules in tunnel to specification (< 1 mm)
  - Maximum misalignment of
    Cavities, Δx : 0.39 mm, Δy : 0.42 mm, Δz : 0.73 mm
    Solenoids, Δx : 0.20 mm, Δy : 0.05 mm, Δz : 0.36 mm

Name	Pitch_R1_Deg	Roll_R2_Deg	Yaw_R3_Deg	Horz_Off_Meters	Vert_Off_Meters	Longitudinal Off _Meters
SCM401 (CA01)						
LS1_CA01_CAV1_D1127	0.0339	-0.0026	0.0234	0.000399 BR	0.000179 DN	0.000175 US
LS1_CA01_CAV2_D1136	0.0250	-0.0230	0.0179	0.000126 BR	0.000128 DN	0.000170 DS
LS1_CA01_CAV3_D1142	0.0957	0.0039	0.0008	0.000081 BR	0.000323 DN	0.000119 DS
LS1_CA01_CAV4_D1150	0.0747	0.0084	-0.0310	0.000138 BL	0.000040 UP	0.000280 DS
LS1_CA01_SOL1_D1132	0.0083	-0.0379	-0.0980	0.000117 BR	0.000002 DN	0.000027 US
LS1_CA01_SOL2_D1146	0.0307	0.0248	-0.0911	0.000202 BL	0.000037 UP	0.000243 US
SCM402 (CA02)						
LS1_CA02_CAV1_D1161	-0.0087	-0.0036	-0.0024	0.000239 BL	0.000049 DN	0.000564 DS
LS1_CA02_CAV2_D1169	-0.0105	-0.0395	0.0061	0.000186 BL	0.000074 DN	0.000735 DS
LS1_CA02_CAV3_D1176	-0.0363	-0.0274	-0.0283	0.000194 BL	0.000037 DN	0.000723 DS
LS1_CA02_CAV4_D1184	0.0438	-0.0878	-0.0262	0.000173 BR	0.000205 UP	0.000609 DS
LS1_CA02_SOL1_D1165	0.0244	0.0256	-0.0734	0.000114 BL	0.000001 DN	0.000095 US
LS1_CA02_SOL2_D1180	-0.0054	-0.0546	-0.0321	0.000010 BL	0.000028 UP	0.000360 DS
SCM403 (CA03)						
LS1_CA03_CAV1_D1195	0.0710	0.0311	-0.0546	0.000001 BR	0.000213 UP	0.000417 DS
LS1_CA03_CAV2_D1203	0.0061	0.0356	0.0239	0.000139 BL	0.000186 UP	0.000333 DS
LS1_CA03_CAV3_D1209	0.0526	-0.0256	-0.0107	0.000092 BR	0.000418 UP	0.000301 DS
LS1_CA03_CAV4_D1218	-0.0310	-0.0363	-0.0326	0.000096 BL	0.000006 UP	0.000351 DS
LS1_CA03_SOL1_D1199	0.0220	0.0364	-0.0112	0.000100 BL	0.000034 UP	0.000046 US
LS1_CA03_SOL2_D1214	0.0007	-0.0416	0.0058	0.000073 BR	0.000052 UP	0.000138 DS

BPM (< 0.4 mm)

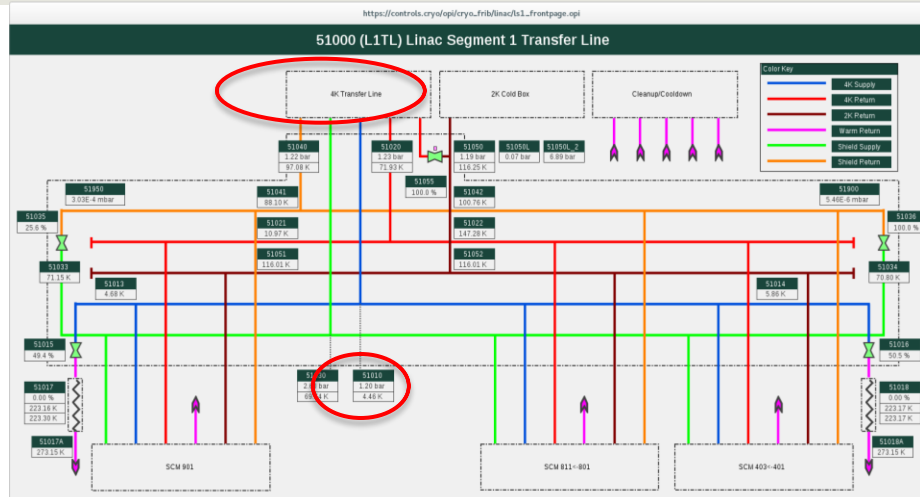
Lattice Slot	Beam UP/DOWN	Beam LEFT/RIGHT
LS1_CA01:BPM_D1129	0.000097 UP	0.000254 BL
LS1_CA01:BPM_D1144	0.000616 UP	0.000288 BL
LS1_CA02:BPM_D1163	0.000044 DN	0.00094 BL
LS1_CA02:BPM_D1177	0.000222 DN	0.000236 BL
LS1_CA03:BPM_D1196	0.000337 UP	0.000296 BL
LS1_CA03:BPM_D1211	0.00009 DN	0.000045 BR



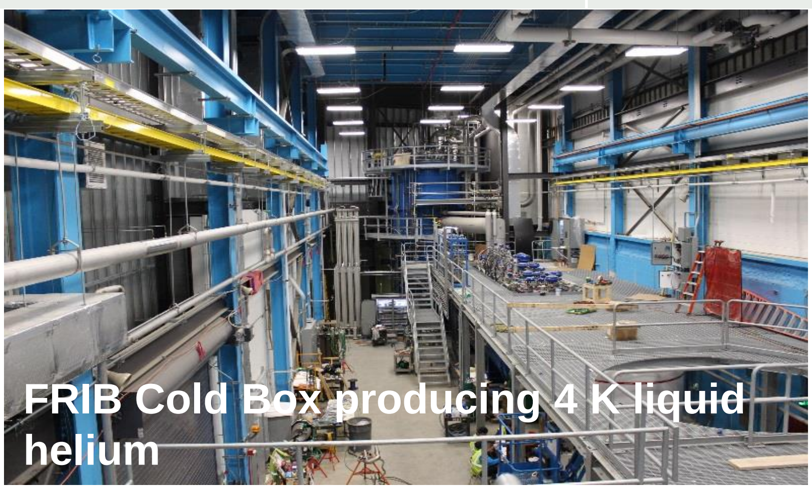
Re-Survey after cool down max difference 120 micron

FRIB First cool down of Superconducting Linac

Objective Measures	Date
System utilities in place	Done, 6/2017
Cryogenic plant ODH system complete	Done, 8/2017
Warm compressor commissioning	Done, 9/2017
Tunnel ODH system complete	Done, 11/2017
Cryogenic plant 4 K operational	Done, 12/2017
Cryogenics ready for LS1 cryomodules, 4 K	Done, 4/2018
Cryogenic transfer line cooled down to 4 K	Done, 5/2018
Cryomodule cavity and solenoid cooled down to 4 K	Done, 5/2018



May 10, 2018, cryo transfer line LS1 at 4 K



FRIB Cold Box producing 4 K liquid helium

May 11, 2018, 1st cryomodule cooled down to 4 K in FRIB tunnel

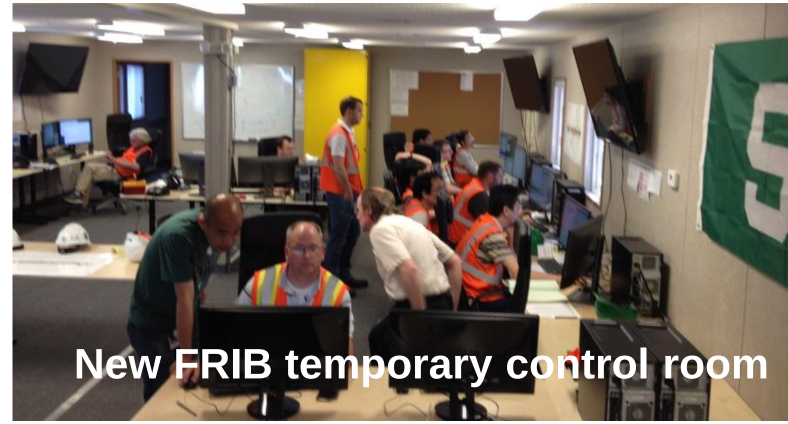
Cryomodule Commissioning without Beam

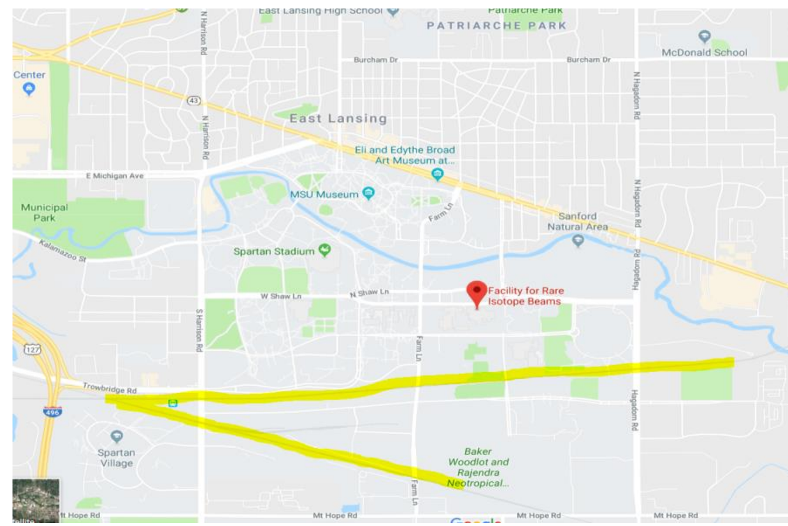
- Cryomodule commission goals
  - Bandwidth
  - Tuning range
  - Cavity to FRIB spec field (5.1 MV/m)
  - Magnet to FRIB specific field (8 T)
  - Conditioning cavity MP barriers
  - Tune the llrf control parameter settings to achieve the best control for amplitude and phase
  - Develop the automatic turn-on program to prepare for operators
  - Establish operation envelope for each cavity and magnet based on the commissioning test results
- Establish baseline performance of cryomodules at 4 K

Task list	
Interlock test after cooldown	Controls
4 K calibration	Cryomodule
RF line connection	RF systems
Secured tunnel by Access Control System (ACS)	Accelerator operations
Individual cavity testing [Tunnel secured]	Cryomodule
Full module cavity operation check (all cavities) [Tunnel secured]	Cryomodule
Magnet testing	Cryomodule
Full module operations check (all cavities and magnets) [Tunnel secured]	Cryomodule

CA RF Commissioning: β=0.041 cryomodules

- RF Commissioning started May 29th
- Most RF commissioning work was done in the second shift (3pm-11pm) to not interrupt installation work in the tunnel.
- We observed some disturbance from 3pm-11pm when there was heavy construction work
- No sign of impact from the freight train railway nearby the compus
- Both solenoid header and cavity header bath pressure are regulated very steady (Delta<0.005atm)

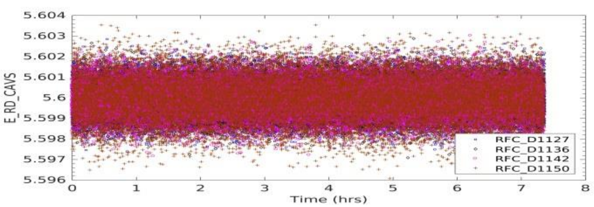

New FRIB temporary control room

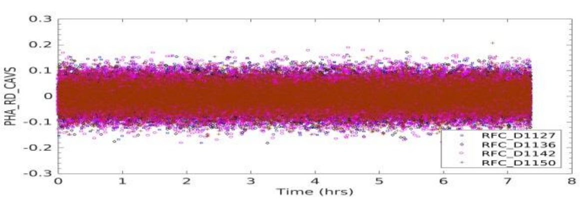


Yellow highlight are the railways

RF commissioning status: Cryomodule is ready for Beam

- 12 cavities SEL model scan to 5.6 MV/m and no FE. Conditioned MP barriers
- All cavities can reach reference freq within the tuner working range
- 11/12 locked at 10% higher gradient than the specification (5.1 MV/m Eacc –FRIB 2K specification)
- Cavity#8 can lock at 4.2 MV/m and work in progress to FRIB spec





CA01: all 4 cavities at 5.6 MV/m

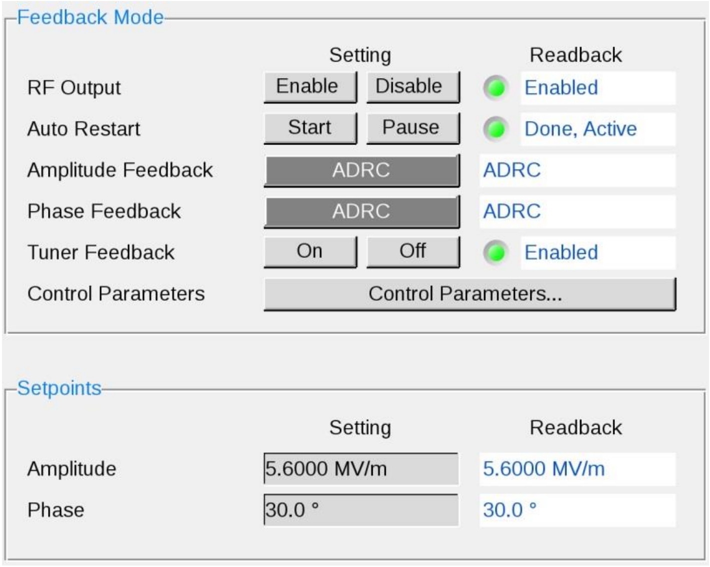
Cavity #	Eacc	Amplitude Stability (%)		Phase Stability (degree)		RF Power use (W)	
	(MV/m)	Pk-Pk	RMS	Pk-Pk	RMS	Average	Peak
1	5.6	0.13	0.01	0.37	0.04	274	335
2	5.6	0.13	0.01	0.35	0.04	284	307
3	5.6	0.13	0.01	0.37	0.04	213	281
4	5.6	0.13	0.01	0.37	0.04	227	302
5	5.6	0.23	0.01	0.97	0.06	309	483
6	5.6	0.15	0.01	0.48	0.05	225	350
7	5.6	0.09	0.01	0.47	0.07	232	265
8	4.2	1.9	0.07	1.7	0.10	156	950
9	5.6	0.1	0.01	0.37	0.04	321	381
10	5.6	0.1	0.01	0.37	0.04	306	502
11	5.6	0.1	0.01	0.37	0.04	270	443
12	5.6	0.1	0.01	0.37	0.04	261	306

LLRF Auto Turn On

- Start assistant
  - Cavity turn on procedure was identified and automated with Start Assistant on the Input/Output Controller (IOC) level to improve operation efficiency.
  - For example, Quarter Wave Resonator (QWR) turn on goes through 6 stages automatically, checks for critical interlocks (cavity low, frequency error, etc.), with wait time before ramping to final set-point.

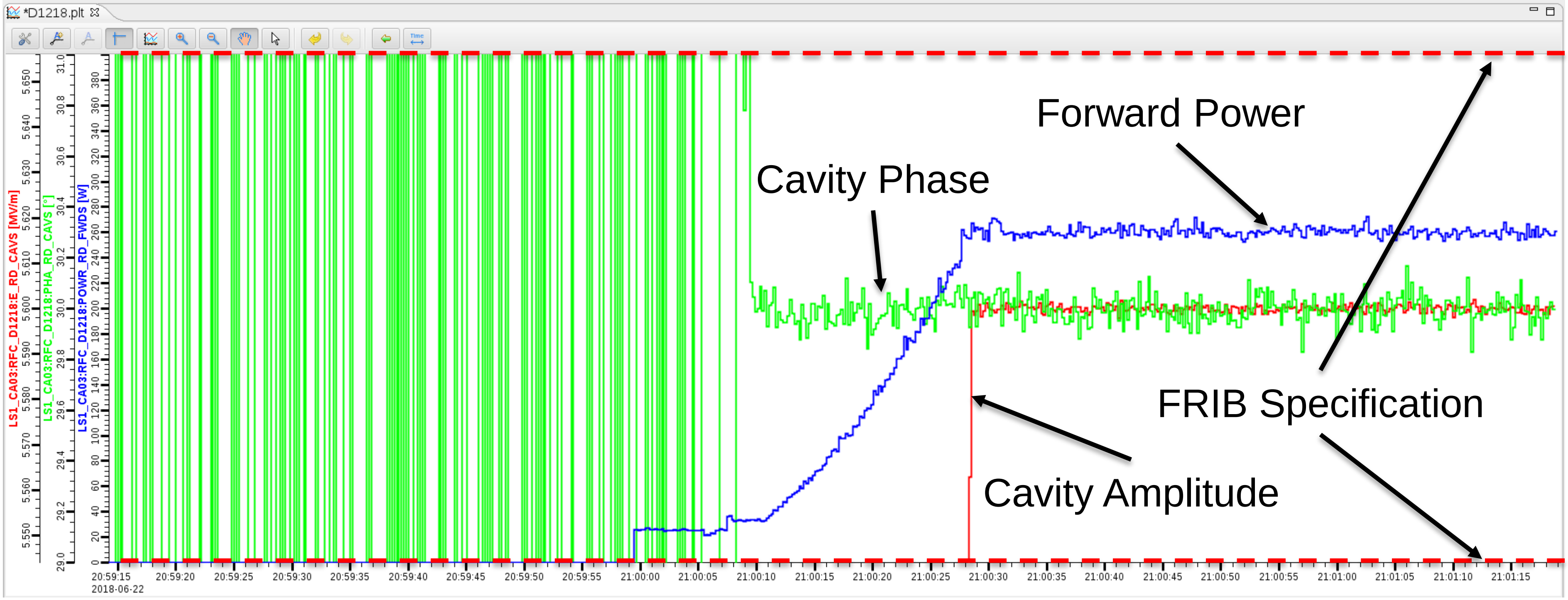
QWR Turn On Sequence

	RF	Amplitude	Amplitude Set-point	Phase	Tuner
	OFF	Open	Initial	Open	OFF
Stage 1	**ON**	Open	Initial	SEL	OFF
Stage 2	ON	Open	Initial	SEL	**ON**
Stage 3	ON	Open	Initial	**Open**	ON
Stage 4	ON	**Close**	Initial	Open	ON
Stage 5	ON	Close	Initial	**Close**	ON
Stage 6	ON	Close	**Final**	Close	ON



Example: LS1_CA03:RFC_D1218

- Example
  - The last cavity in CA03 (D1218) was turned on automatically and locked at the final set-point (5.6 MV/m) within 30 seconds.



Superconducting Magnets

- 2 Superconducting magnet packages per β= 0.041 cryomodule
- Each solenoid package come with vertical and horizontal dipole correctors
- Solenoid field and integrated strength (8T, 13.6 T^2/m)
- Mag shield design is local shield
- SC Magnet initial turn on sequence
  - Interlock check
  - Low current test and ramp to zero test
  - High current thermal imaging at the terminals
  - Polarity verification
  - Vapor cool leads control tuning

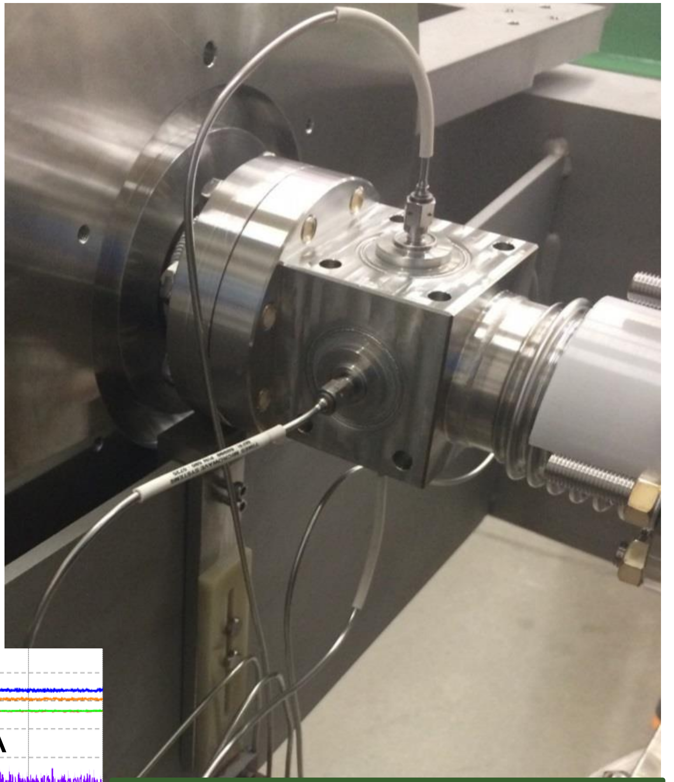
Table 2: Specification for the 25 cm solenoid package.

FRIB 25 cm Solenoid Parameters		
Parameter	**Units**	**Value**
Operation temperature	K	4.5 +0.5/-0.0
Operation pressure	bar	1.3 +0.7/-0.0
I_{nom}, solenoid nominal current	A	≦ 90.9
$\int B_z^2\, dz$ at I_{nom}	T^2m	≧ 13.6
Peak solenoid field on beam axis[2] at I_{nom} (reference value)	T	≧ 8.0
$\int B_z^2\, dz$ uniformity at < $2R_O$ = 0.8 × cold bore inner diameter (full width)	%	≦ 2
Solenoid coil length (reference value)	cm	25
Cold bore inner diameter	cm	≧ 4.0
Minimum ramping rate using a 10 V power supply	A/s	≧ 0. 5% I_{nom}/s
Deviation of field center from mechanical center	mm	≦ 0.3
Steering Dipole Coil Parameters for 25 cm Solenoid Package		
$\int B_x$dz , $\int B_y$dz, integrated field strength	Tm	≧ 0.03
$\int B_x$dz , $\int B_y$dz uniformity within 15mm from the beam axis	%	≦ 5%
Mixing between $\int B_x$dz and $\int B_y$dz (x, y field mixing or cross talk)	%	≦ 2%
Perpendicularity tolerance between the X and Y dipoles	Degrees	≦ 1
Maximum current (see Section 1.5.9)	A	Option 1: ≦ 19.0

Polarity verification during the SC magnets commissioning test

Cryomodule Cold BPM systems

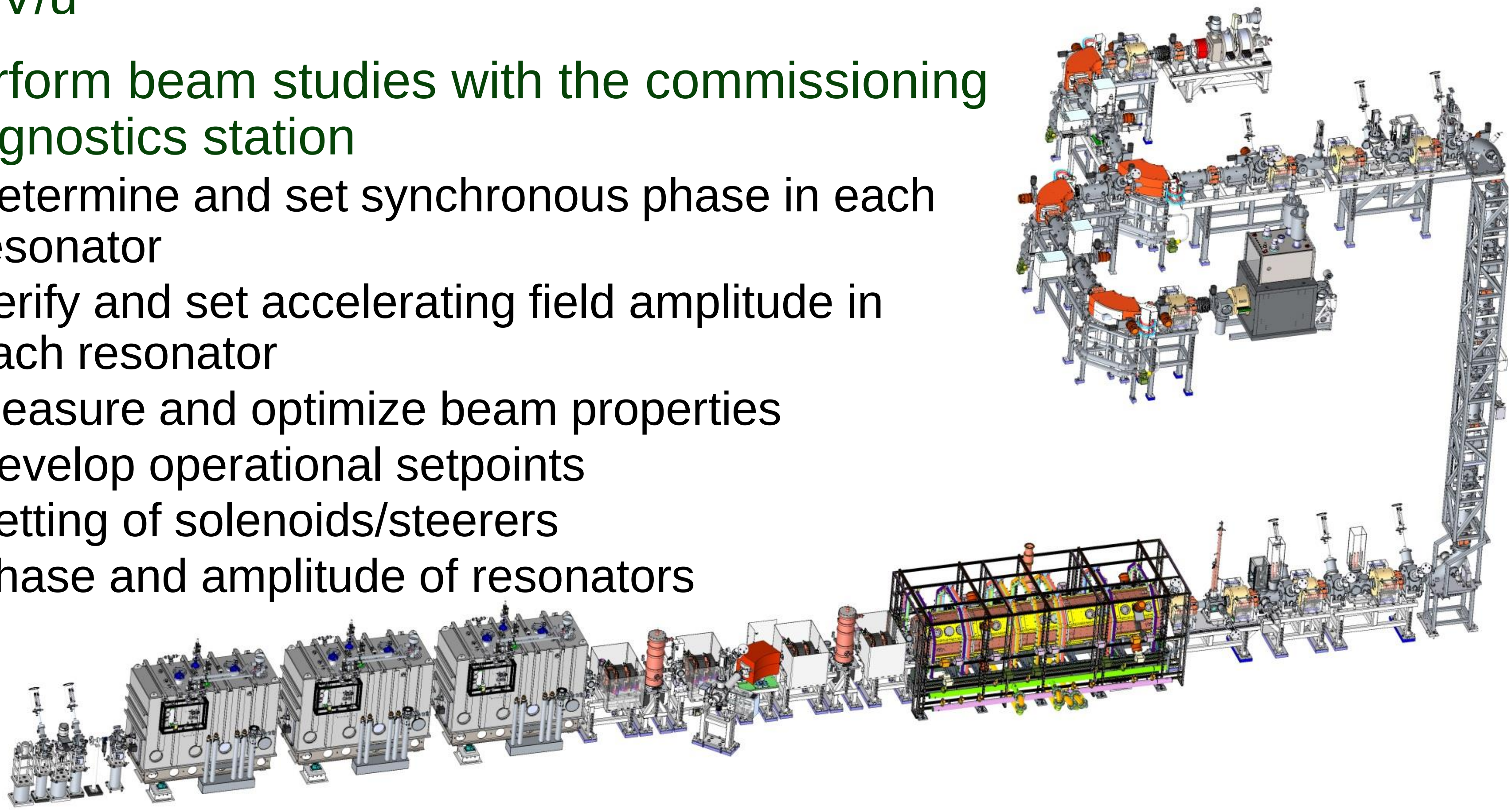
- Each 0.041 cryomodule has 2 button-type BPMs incorporated with the cold mass.
- Tuned to 2nd RF harmonic (161 MHz) with narrow bandwidth receiver.
- Position and intensity nonlinearities due to geometry and low-beta effects are compensated in software
- Sensitivity of BPMs ~100 um (position), 10's nA (intensity)
- Measured RF crosstalk equivalent beam current <10 nA
- Nominal beam current 100 nA – 1 mA



- 41 mm aperture
- 20 mm diameter button
- 0.090 inch mineral insulated, steel jacketed cold cable

Next Step of Commissionging

- Accelerate $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ beam to 1.46 MeV/u
- Perform beam studies with the commissioning diagnostics station
  - Determine and set synchronous phase in each resonator
  - Verify and set accelerating field amplitude in each resonator
  - Measure and optimize beam properties
  - Develop operational setpoints
  - Setting of solenoids/steerers
  - Phase and amplitude of resonators



Summary

- FRIB Cryomodule production is on-going and project to be completed by 2019
- First stage superconducting Linac cool down successfully
- Cryomodule performance meet the beam commissioning requirement
- β=0.041 cryomodules are ready for beam commissioning