Progress of FRIB SRF Production

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On behalf of the FRIB Project

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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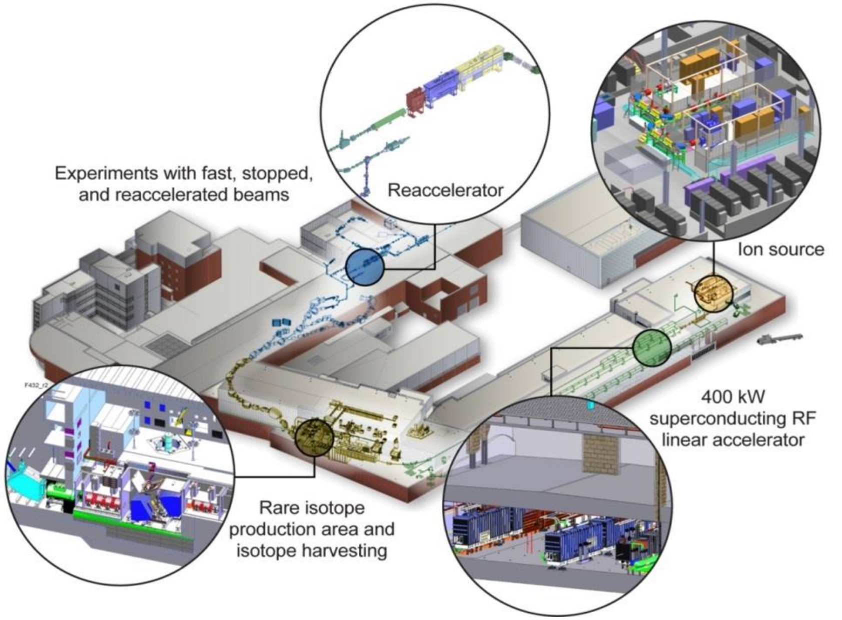
Outline

- FRIB Project Overview
- Superconducting Linac features
- SRF production progress
- Summary

Facility for Rare Isotope Beams (FRIB)

- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University
- Serving nearly 1,400 users
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u and provide beam power up to 400 kW
- Project timeline
  - CF construction (CD3-a) started in March 2014
  - Accelerator system construction(CD3-b) started October 2014
  - Early beam commissioning of the Front End 2017
  - Final completion (CD4) in 2022




2012 FRIB Construction Site

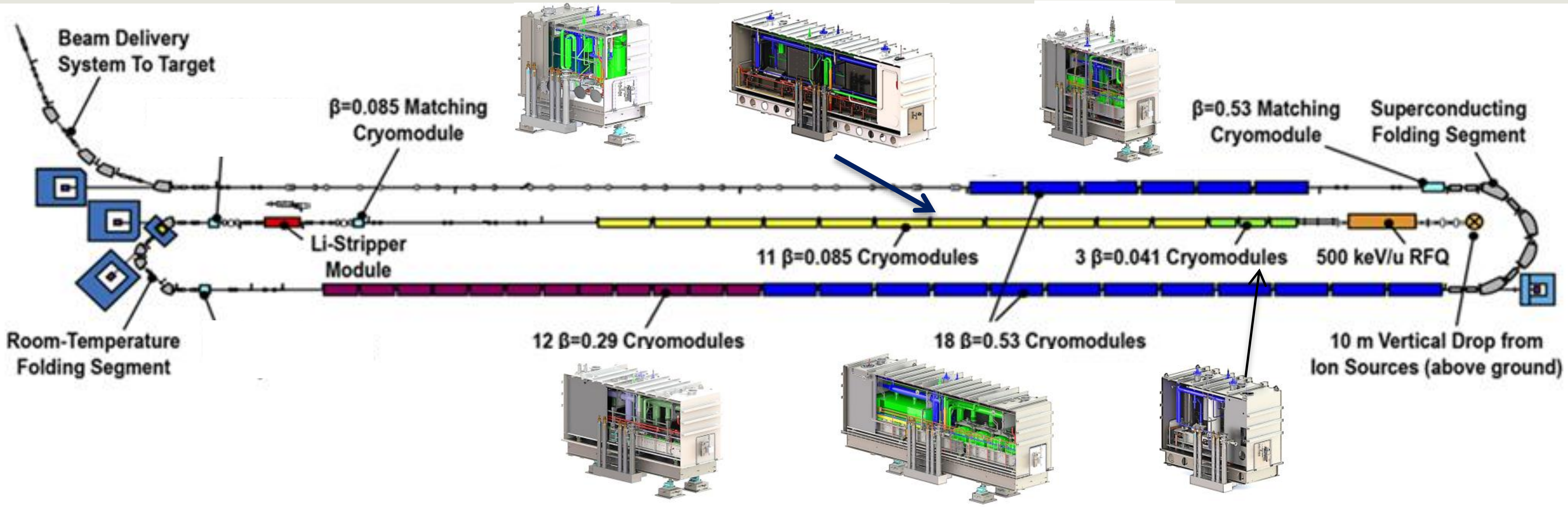

2014 FRIB SRF Highbay

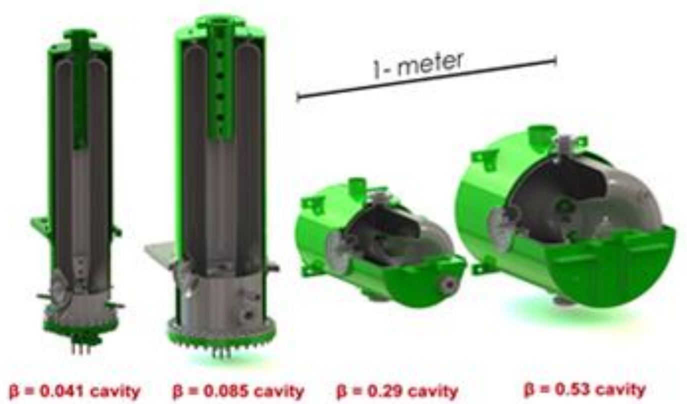

2016 FRIB Overlook


2017 FRIB Tunnel

FRIB Superconducting Driver Linac Scope

324 SRF cavities from β=0.041 to 0.53, six type cryomodules, one cavity - one RF source (semiconductor amp.), high gradient CW operation at 2K



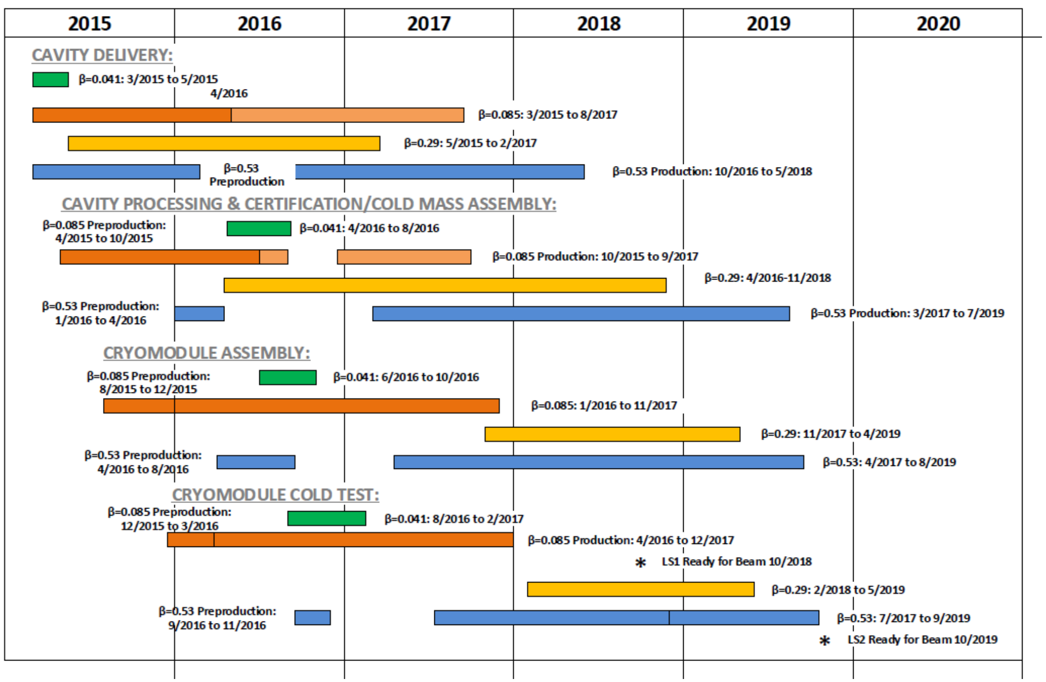


Quarter Wave Cryomodule				
β	Type	*Component Counts (baseline + spares)*		
		Cryomodules	*Cavities*	*Solenoids*
0.041	accelerating	3 + 1	12 + 4	6 + 2
0.085	accelerating	11 + 1	88 + 8	33 + 3
	matching	1 + 1	4 + 4	-
Half Wave Cryomodule				
0.29	accelerating	12	72	12
0.53	accelerating	18	144	18
	matching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

Cryomodule Production Status
LS1 Completion by End of 2017

- All QWR cryomodules (LS1 &FS1) production is on track to be completed by end of 2017
- HWR Cryomodule production started after β=0.53 HWR preproduction module validated
- FRIB will receive all production cavities by the middle of 2018
- On track to complete all cryomodules by end of 2019

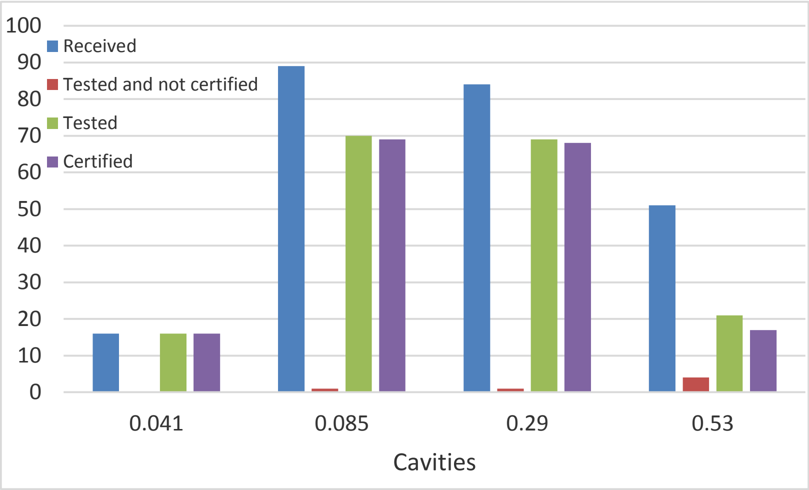
Type	Coldmass completed	Cryomodule assembled	Cryomodule bunker tested	Cryomodule placed in tunnel	Cryomodule Scope (T + P)
β = 0.041	4	4	3	3	3+1
β = 0.085	7	5	4	4	11+1
β = 0.085 Matching	1	1	1		1+1
β = 0.29	2	1			12
β = 0.53	2	1	1	1	18
β = 0.53 Maching	0				1
Total	16	12	9	8	46+3




β=0.041 cryomodules are all installed in tunnel

Cavity Processing and Test Status

- Over 230 cavities have been received and accepted
- 170 cavities have been certified and the rest are in the work flow
- Overall in-house rework rate is less than 20%
  - β=0.085 QWR rework rate is expected to continue to decrease as performance issues are resolved
  - β=0.53 HWR rework rate is expected to decrease to planned rate as processing issues are resolved



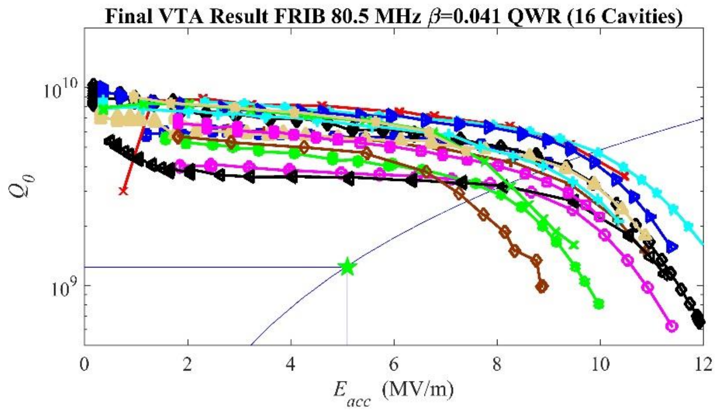
Cavities in the hold area

Cavity being prepared for chemical etching

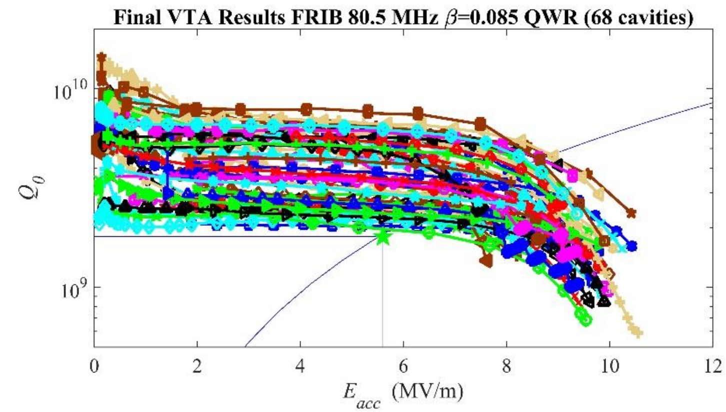
FRIB cavities in the vertical test area prep mezzanine

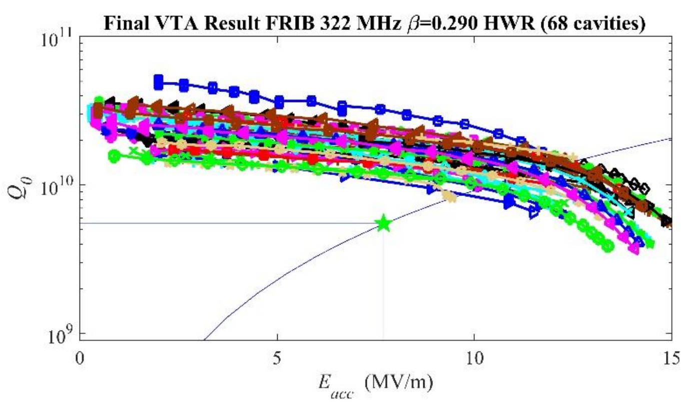
VTA Performance Certified FRIB Cavities

Meeting FRIB Specification with Comfortable Margin

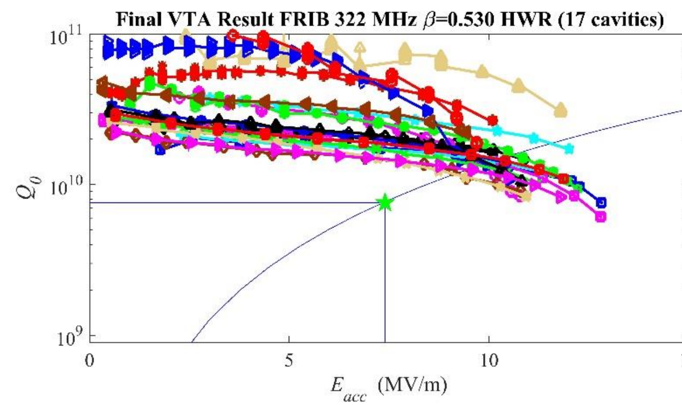


β_0 = 0.041 β_0 = 0.085
Quarter-Wave Resonators
80.5 MHz





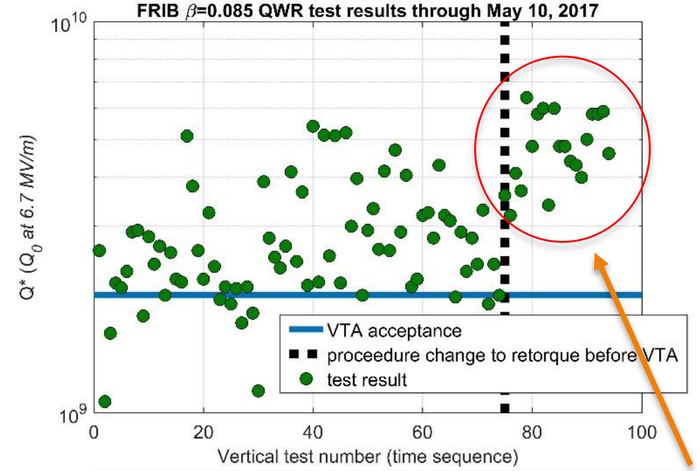
β_0 = 0.29 β_0 = 0.53
Half-Wave Resonators
322 MHz



THYA01

Cavity Processing and Certification Program

- β=0.085 performance issue: progress made
  - Additional loss associated with inconsistent RF joint at indium
  - VTA results confirmed no degradation after thermal cycles
- β=0.29 cavity certification near completion. Virtual welding and plastic deformation techniques developed
  during processing and after testing to mechanically tune
  cavity
- β=0.53 production cavities: issues and mitigation
  - Issues: higher frequency shift rate at chemistry caused insufficient bulk BCP; blind spots during HPWR
  - Mitigations: change frequency goal at vendor; optimize HPWR
    programming and nozzle

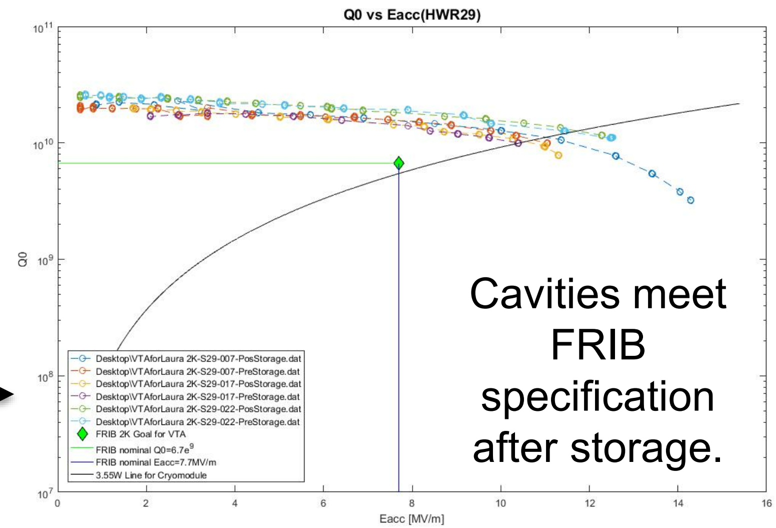


VTA results after retighten bottom flange

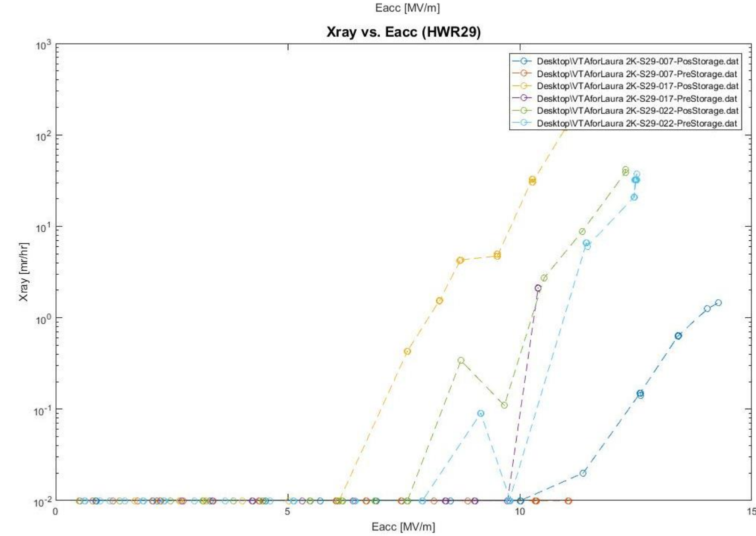
Storage of certified β=0.29 HWR

Certified Cavity Storage Procedure Verified

- Certified β=0.29 cavities bagged in clean room and placed in wooden crates
- 40 certified cavities in SRF rack storage; 18 stored in clean room
- 3 cavities stored in SRF High Bay rack for > 1 month and then retested



Cavities meet FRIB specification after storage.

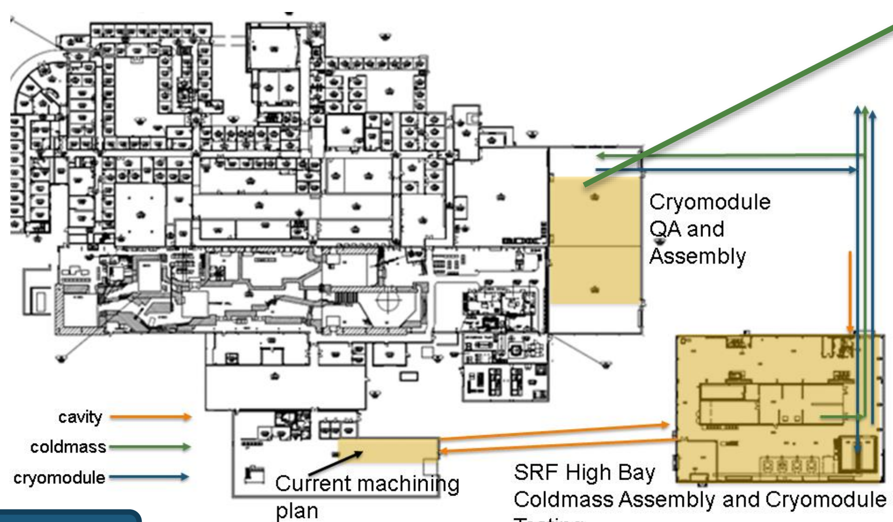



Bagged certified cavities


Certified cavities in SRF rack

FRIB Tailored Infrastructure to Support SRF Processing and Cryomodule Production

- Infrastructure setup for full in-house production:
  - All critical SRF tasks performed at MSU
  - Over 40,000 sq. ft. of cold mass and cryomodule assembly area established on site
  - Space for cold mass receiving, inspection, processing, testing, assembly and storage
  - SRF component inspection and degassing capabilities
  - Three vertical test area (VTA) Dewar and two test bunkers (one at East highbay and one at SRF highbay) and five CM assemble bays

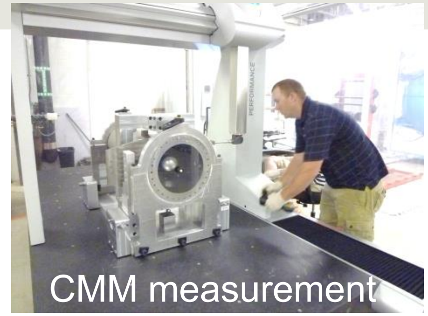


Two test bunkers in different area and supported by independent cryogenic refrigerators

THYA01

Dedicated SRF Facility Fully Operational Since 10/2016

- Functionalities of the SRF Highbay
  - Acceptance inspection
    - Dimensional inspection by CMM
    - Cold shock test, Leak check
  - Cavity processing and assembly
    - Large cleanroom
    - Cavity etching (BCP) system
    - Robotic high pressure rinsing system
    - Ultrapure water system
    - Hydrogen degassing furnace
  - Demagnetizing SRF compone**nts**
  - Cavity vertical test system,
    - 3 Dewars and 7 cold inserts
  - FPC RF conditioning
  - Cold mass assembly
  - Cryogenic system (Dedicated 900W helium refrigerator, helium purification and 2K system)


CMM measurement


Large cleanroom


BCP facility


Cavity assembly


HPR system

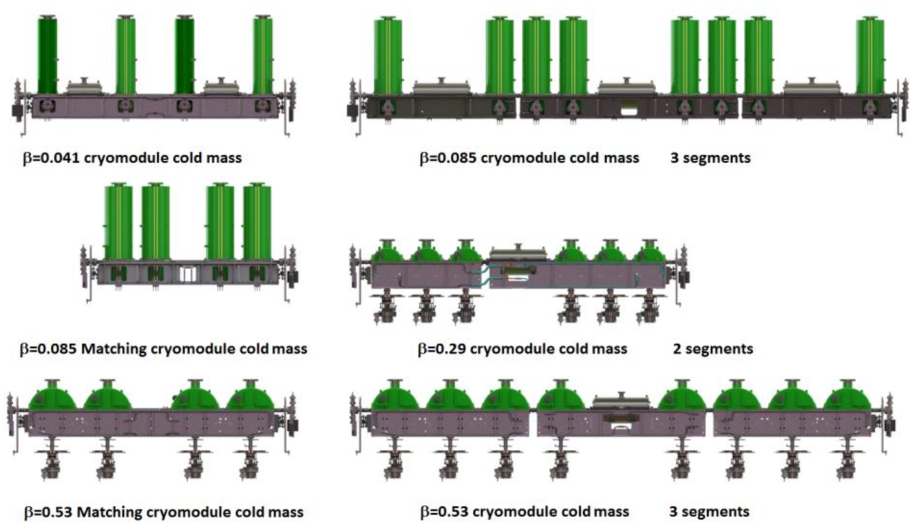

Vacuum furnace

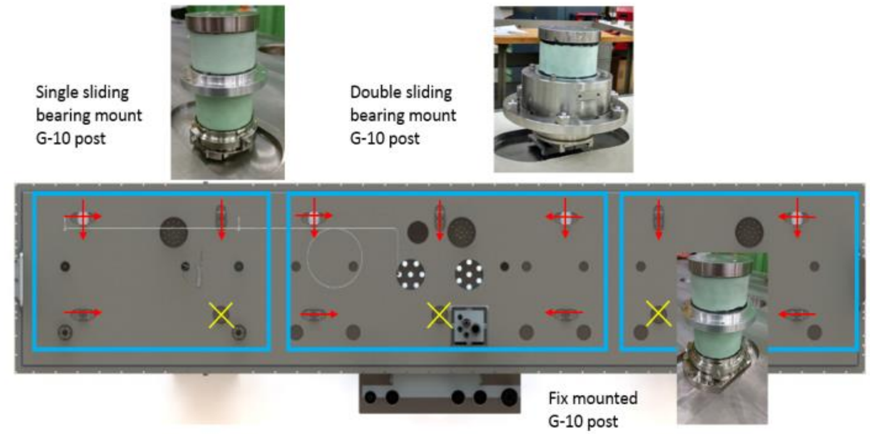

Cold box and 5000L Dewar


Vertical test area

FRIB Cryomodule Alignment

- Rigid baseplate provide stable and reliable platform for the cold mass
- Alignment of cold string is achieved by control stack tolerance of cold mass and baseplate.
- Average time spent on alignment is 3 days
- Using solenoid adjustment feature to reduce the alignment error to < 0.5 mm max
- Max measured errors are within the alignment budget





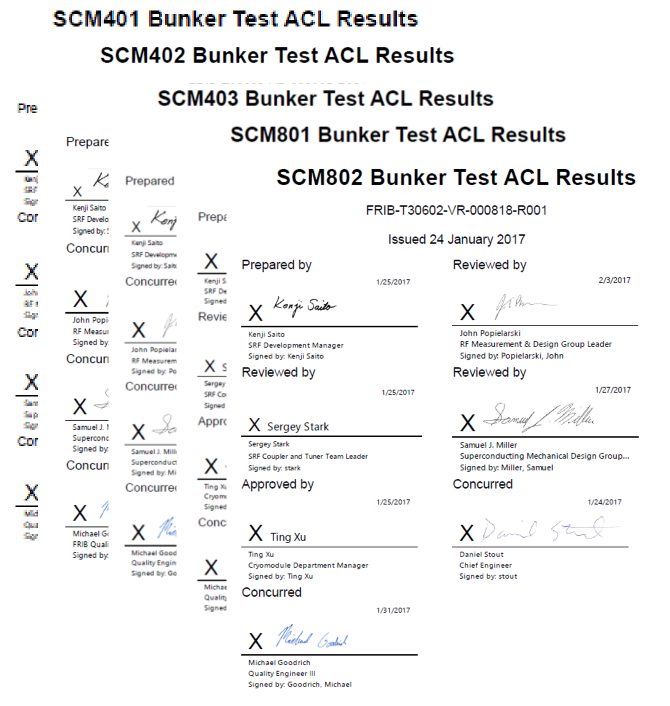
Cryomodule Alignment Survey Results.

Module	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 (6)	0.23/0.53	0.25/0.72	0.16/0.37	0.15/0.43
β=0.29 (1)	0.10/0.17	0.09/0.16	0.19/0.19	0.05/0.05
β=0.53 (1)	0.27/0.81	0.32/0.71	0.18/0.18	0.26/0.26
M β=0.085 (1)	0.07/0.15	0.07/0.13	-	-

* Cool down error is projected to be <0.33 mm

Cryomodule Testing Program

- Total of 9 cryomodules (56 cavities/19 magnets) have been tested and certified
- One cavity (SCM803/#7) could not lock due to RF transmission line problem; rework done
- Streamline production cryomodule testing and demonstrate rate of one per month (including installation and removal) on latest couple tests
- Update projection of cryomodules heat load based on actual data
  - Current projection within 10% of FRIB Spec (2349 W at T = 2 K, 1195 W at T = 4 K)
- Reworks after testing tracked by rework form and recorded in ACL results
  - RF bandwidth
  - Frequency (QWR)
  - Gate valves
  - Valve actuators/JT valve stem
  - Instrumentation wiring


SCM401 Bunker Test ACL Results

SCM402 Bunker Test ACL Results

SCM403 Bunker Test ACL Results

SCM801 Bunker Test ACL Results

SCM802 Bunker Test ACL Results

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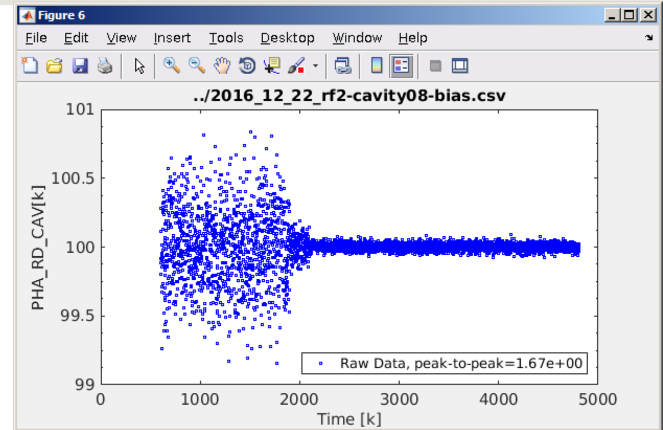
1/31/2017 X Michael Goodrich, Quality Engineer III, Signed by: Goodrich, Michael

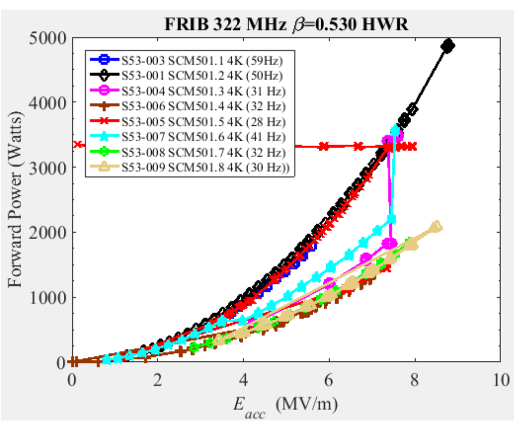
Installation of cryomodule into test bunkers

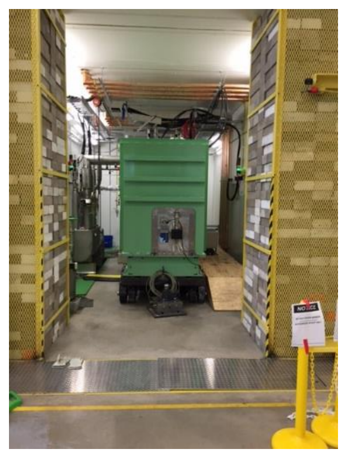
β=0.53 HWR Preproduction CM Validated!
RF Control Bandwidth: Well Within Design Specification

- All cavities locked with 30 Hz RF BW, 4 K within amplitude and phase specification: (<2° pk-pk phase stability, < 2% pk-pk amplitude stability)
- All cavities locked at voltage > design value (5.6% higher overall for the cryomodule)
- Total dynamic load of all the cavities is 33 W, hence we have 30 W margin relative to design goal of 63 W
- Magnet integration test successful
- Static heat load within design goal
- Cavity performance has no degradation after degaussing and thermal cycle (validates degaussing procedure!)

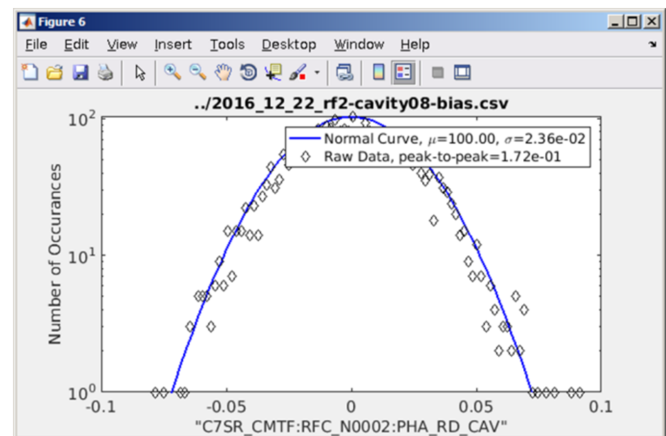


Optimized phase control





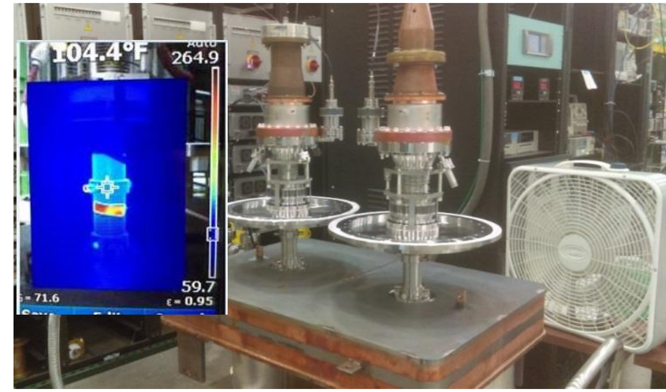
1st β=0.53 HWR cryomodule in test bunker

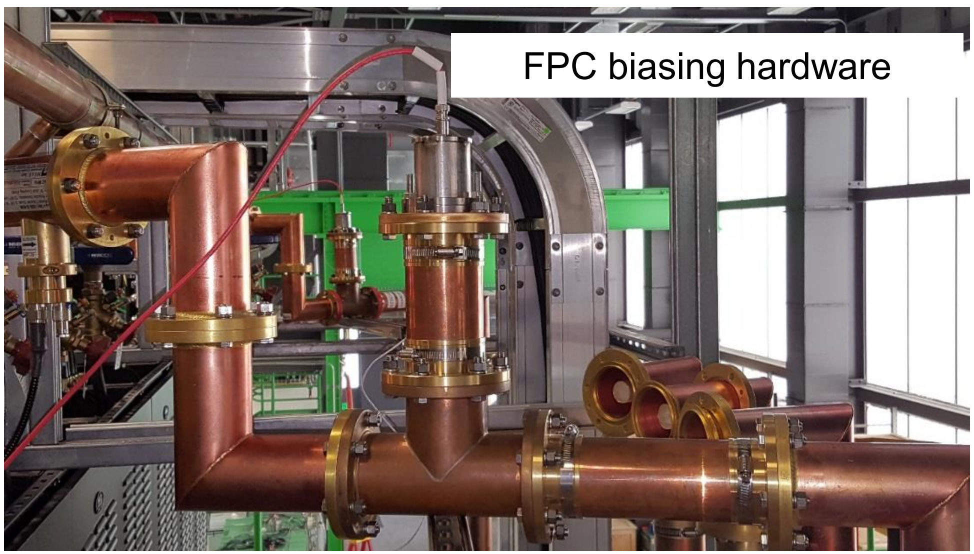


MOPB031

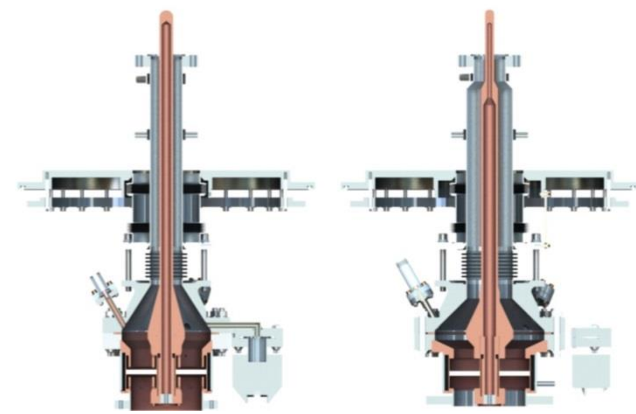
Mitigation of HWR FPC Multipacting

- Strong multipacting at FPC was encountered during SCM501 testing at wide power range
- Multipacting takes a long time (several days) to condition
- Bias voltage was applied to FPC inner conductor to suppress MP
- Production FPC has an improved design to mitigate MP.





FPC biasing hardware

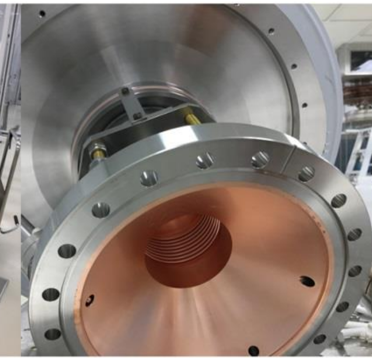


Preproduction Design

Production Design (MPF)
Suppress MP to power level higher than FRIB need

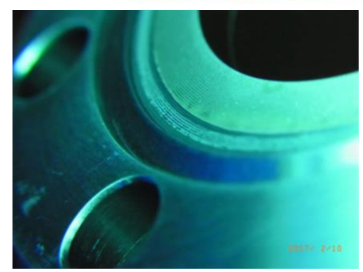
HWR FPC Production and Conditioning Status
High Power RF conditioning at Factory

- Production and delivery status
  - 138 fabricated and high-power conditioned
  - 134 received at FRIB
- QA Program
  - Vendor performs high power RF conditioning (20 kW at 20% duty cycle).
  - FRIB reconditions FPCs after receipt to verify shipping method. Total reprocessing time less than 30 hours (defined by ramping speeds of RF power and duty cycle)
- Quality issue
  - 2 couplers showed heating at vendor due to MP
- Contamination issue and mitigation
  - Contamination caused by early version of shipping caps
  - Collaborated with vendor to improve shipping fixture and decontaminate couplers
  - 16 FPCs with various contamination and cleaning/transportation histories reconditioned successfully at FRIB



Vendor prepare conditioning system for mass production

Discolored IC of contaminated FPC after conditioning



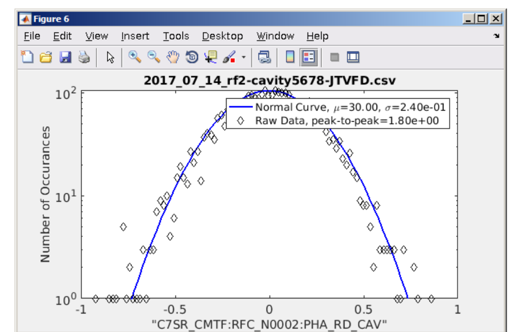
Plastic contamination

Improved shipping cap

First β=0.29 Cryomodule Completed Cold Test On-going

- First β=0.29 cryomodule was completed two months after design completion
  - Engineering change orders have been issued based on assembly feedback (rail, MLI, magnetic shield, thermal shield, vacuum vessel, cryogenic system)
- Early completion of first article and procurements takes advantage of early completion of cavity certification

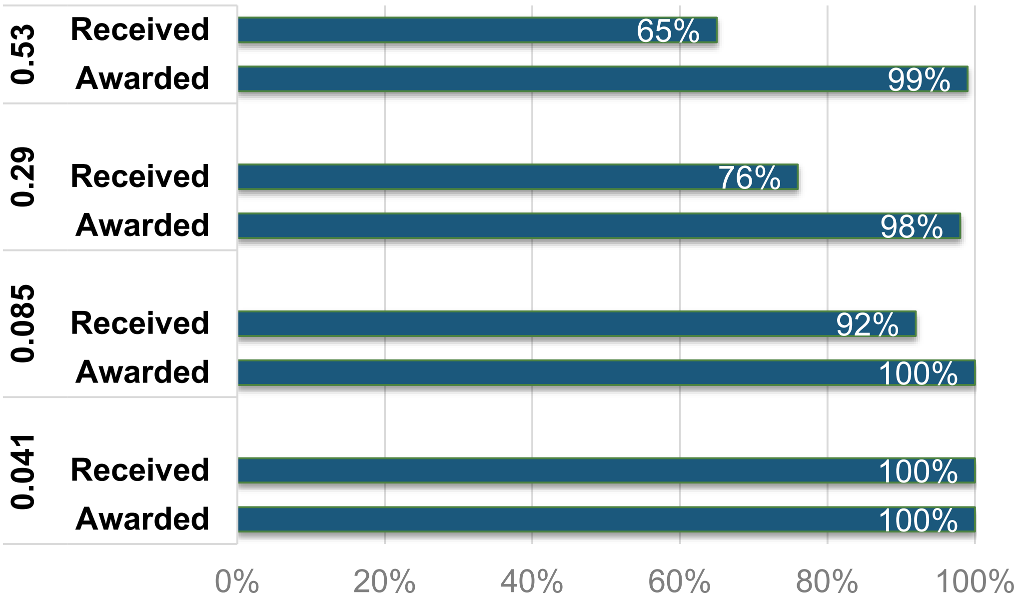
β=0.29 cryomodule in SRF Test Bunker



Assembly process for β=0.29 cryomodule

FRXAA01 THYA01

Cryomodule Major Procurement Status



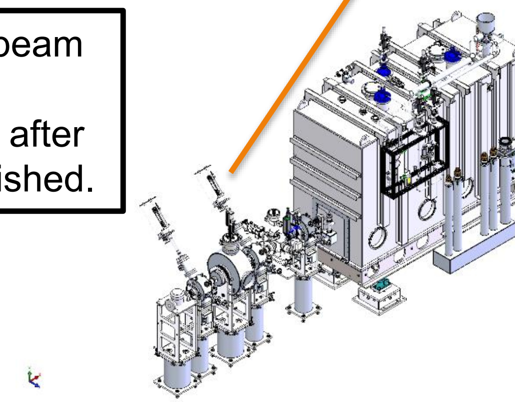
- LS1 QWR cryomodule subcomponents are received and accepted except 0.085 cavities
- LS2/LS3 HWR cryomodule subcomponents are contracted and in mass production
- HWR module subcomponents have been released for mass production after SCM501 test
- β=0.53 matching module procurement packages are ready to be on market

- All Cavities will be delivered by second quarter of 2018
- QWR FPCs are all received.
- HWR FPCs will be done by first quarter of 2018
- All superconducting solenoids are received.

Cryomodule Tunnel Installation Started

- Total 8 cryomodules have been transported to tunnel
- All 3 β=0.041 cryomodules have been installed in the final location and aligned.
- Rest cryomodules are temporary staged in tunnel off the beam line to allow other system installation

Temporary Diagnostic Station for staged beam commissioning
First β=0.085 cryomodule will be installed after β=0.041 module beam commissioning finished.

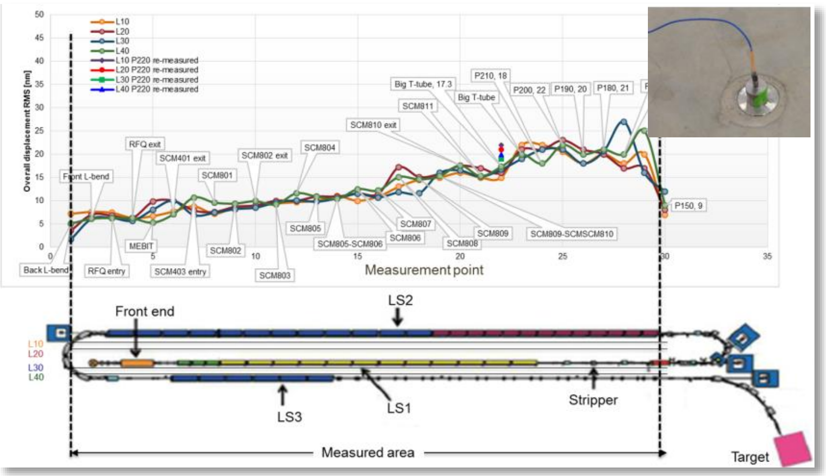


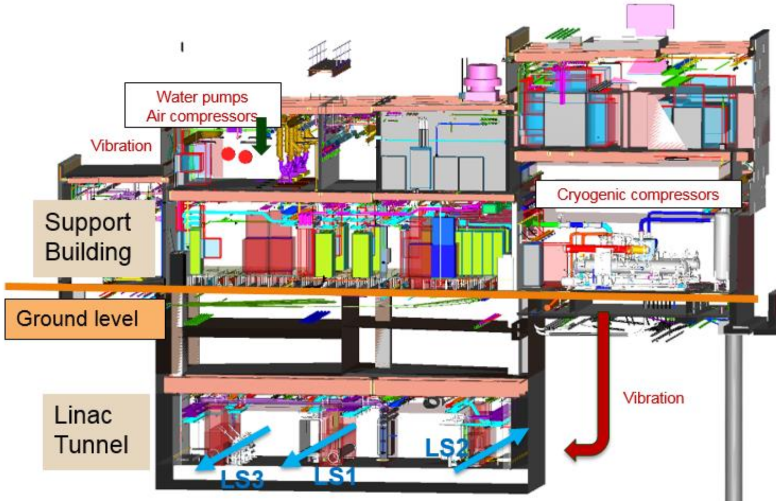
β=0.085 cryomdoules in tunnel at LS1

β=0.53 cryomdoule in tunnel at LS3

Background Vibrational Displacement in Linac Tunnel Measured Less than Cryomdule Test Bunker

- FRIB specification for the tunnel floor vibration is less than 40 nm (RMS) between 5 and 100 Hz.
- Measurement method
  - Maximum displacement (Δz) observed with (1-axis) Accelerometer and CSI 2130 machinery health analyzer
    - » Displacement calculated in the analyzer using double integral
  - Overall displacement evaluated by integrating from 5 to 100 Hz
- ReA6 Cryomodule Test bunker ≤ 30 nm RMS
  - All cavities locked successfully in spec
  - Major resonances < 20 Hz
- Measurement of background noise in the tunnel as utilities and systems have been tuned on.





Summary

- FRIB cromodule design has been completed and validated
- SRF infrastructure established and fully operational to support cavity processing and cold mass assembly
- FRIB LS1 cryomodule production is on track to be completed in 2017
- FRIB HWR cryomodule production is ramping up
- Cryomodule tunnel installation started

- July 20 2017 11:05 Oral Presentation by John Popielarski
  - THYA01 Performance Testing of FRIB Early Series Cryomodules Presented by John T. Popielarski
- July 21 2017 8:00 Oral Presentation by Chris Compton
  - 8:00 FRXAA01 Production Status of Superconducting Cryomodules for the Facility for Rare Isotope Beams Poster July 17 2017 14:00-17:00
- July 17 2017 14:00-17:00 Poster
  - MOPB031-Fabrication and Cold Test Result of FRIB Beta=0.53 Pre-Production Cryomodule
- July 18 2017 14:00-17:00 Poster
  - TUPB094-Resolving High Field Q-slope in Buffered Chemical Polishing