SRF Development and Cryomodule Production for the FRIB LINAC

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Outline

- Introduction
- FRIB SRF Development
- Cryomodule production status
- Summary

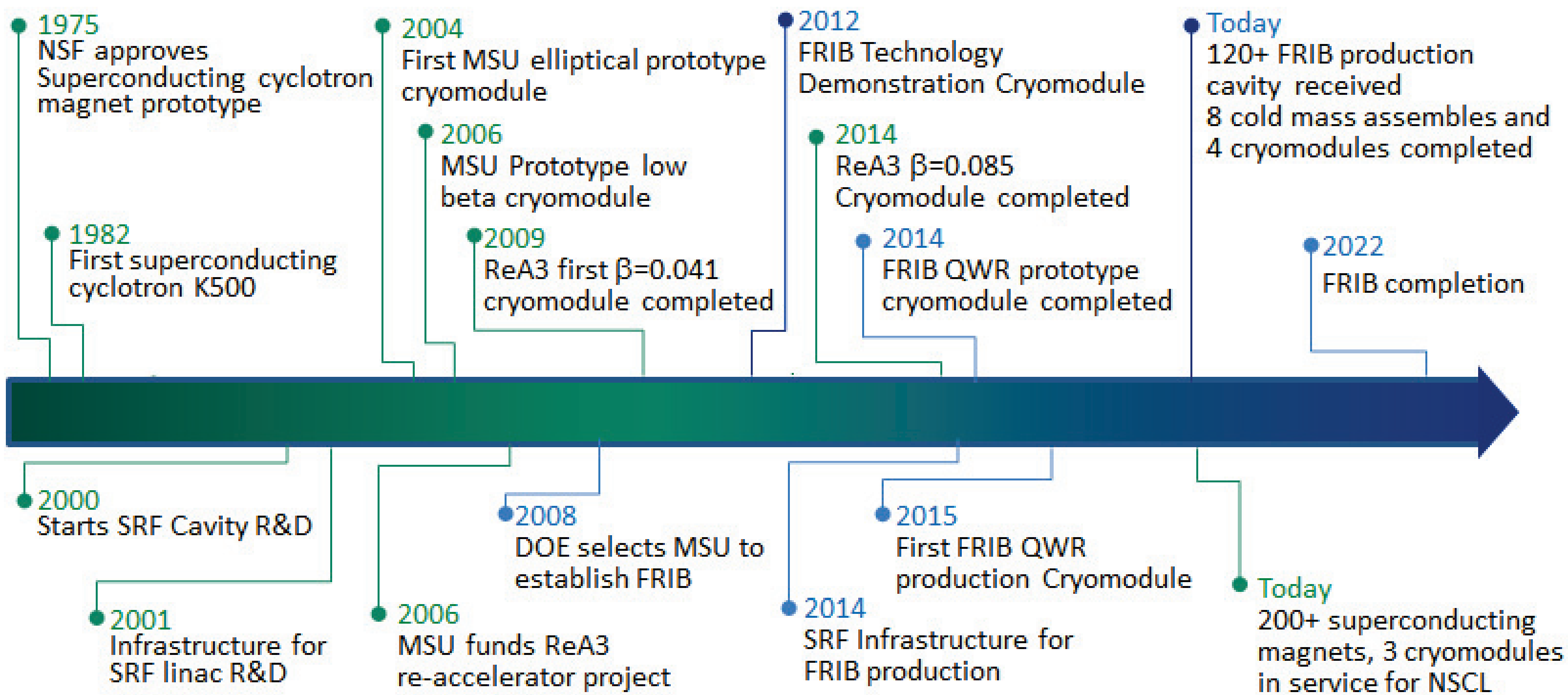

2012 FRIB Construction Site


2014 FRIB SRF Highbay


2016 FRIB Overlook


2016 FRIB Tunnel

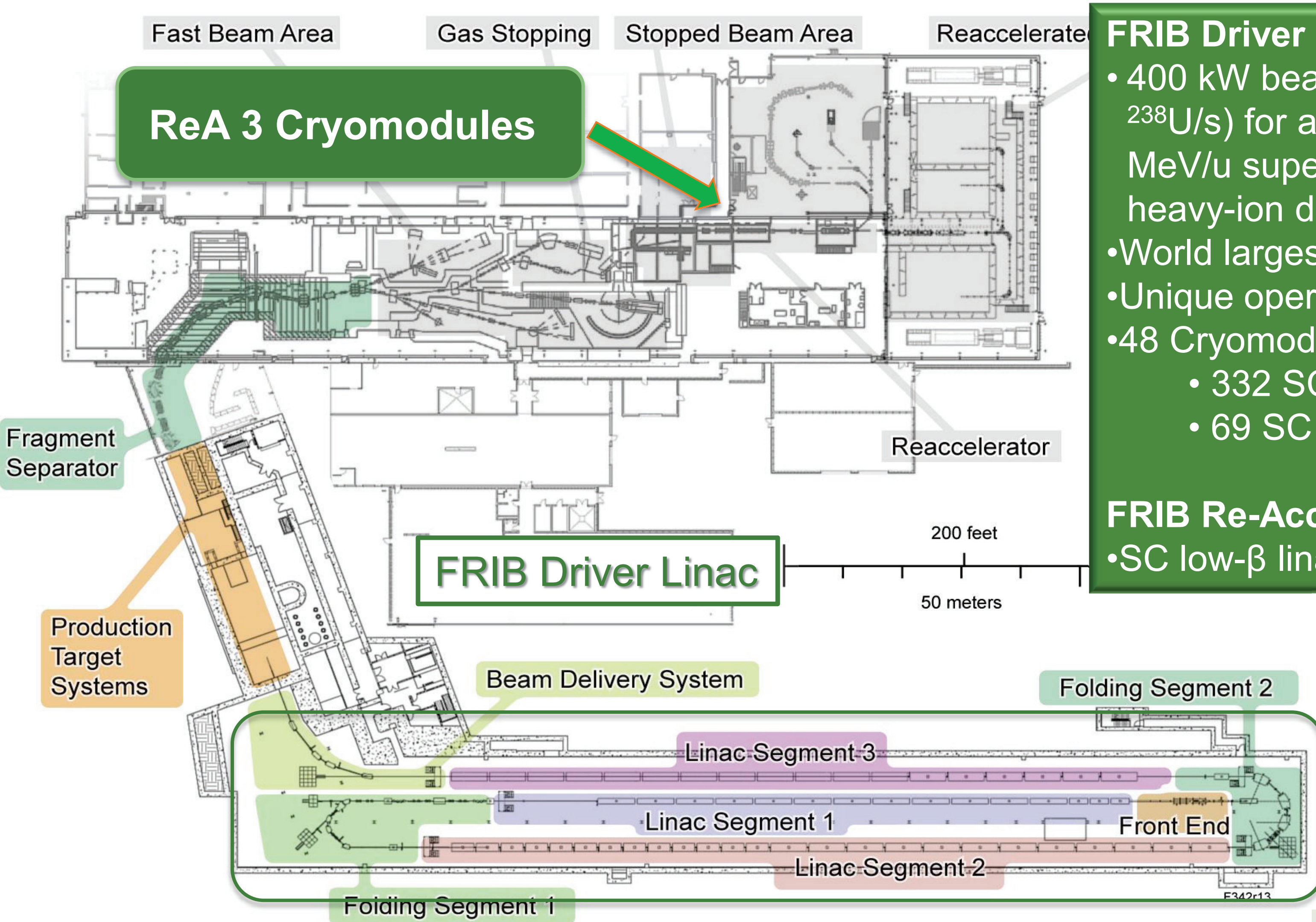
Applied Superconducting Technology Development at MSU



- More than 30 years on superconducting magnets
- More than decade R&D development on SRF

Large Scale of low β Superconducting Linac

332 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



FRIB Driver Linac:
- 400 kW beam power (5 x10^{13} ^{238}U/s) for all ions from 200 MeV/u superconducting heavy-ion driver linac
- World largest SC low-β linac
- Unique operating at 2 K
- 48 Cryomodules including
  - 332 SC resonators
  - 69 SC solenoids

FRIB Re-Accelerator (ReA):
- SC low-β linac at 4.5 K

FRIB SRF Components

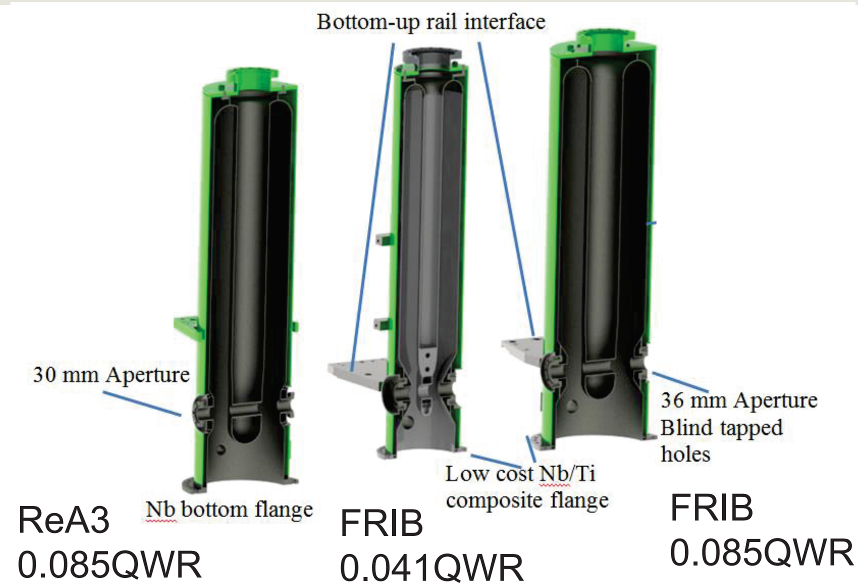
Cavities, FPCs, Tuners, Magnetic shields, and solenoid packages

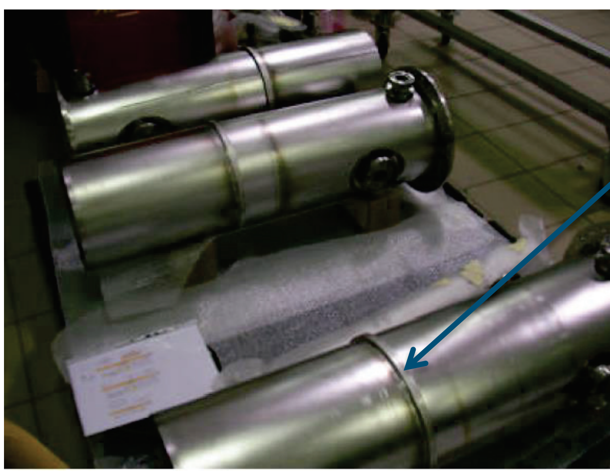
- High gradient and high Q performance with cavities,
- High field (8T) beam focussing solenoid configuration nearby cavities,
- Optimization of solenoid design against cavity/fringe field interaction.
- Local magnetic shielding for cost-effective and reliable magnetic shielding,
- Bottom-up assembly for easy module assembly and better alignment,
- 2K operation for high yields, higher cavity performance and more stable operation against microphonics,
- Mitigation of multipacting in the fundamental coupler.

Quarter Wave Cold Masses				
		Number of Cryomodules	*Number of Cavities*	*Number of Solenoids*
β = 0.041	*Accelerating Cryomodules:*	***3 + 1 spare***	***12 + 4 spare***	***6 + 2 spare***
β = 0.085	*Accelerating Cryomodules:*	***11 + 1 spare***	***88 + 8 spare***	***33 + 3 spare***
	Matching Cryomodules:	***3 + 1 spare***	***12 + 4 spare***	-
Half Wave Cold Masses				
β = 0.29	*Accelerating Cryomodules:*	***12***	***72***	***12***
β = 0.53	*Accelerating Cryomodules:*	***18***	***144***	***18***
	Matching Cryomodules:	***1***	***4***	-
TOTAL		***48 + 3 spare***	***332 + 16 spare***	***69 + 5 spare***

QWR Cavity Development

- FRIB QWRs design is similar to ReA QWR final design
- Larger aperture 36 mm
- Lower Bp and Ep allow higher gradient
- Nb/Ti bottom flange to lower fabrication cost
- Add reinforcement ring to the final production 0.085 QWR OC to increase the buckling resistance



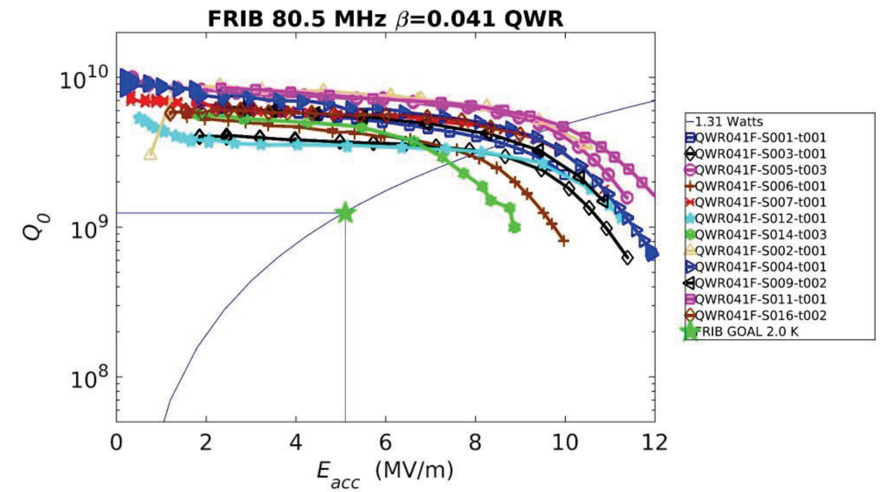


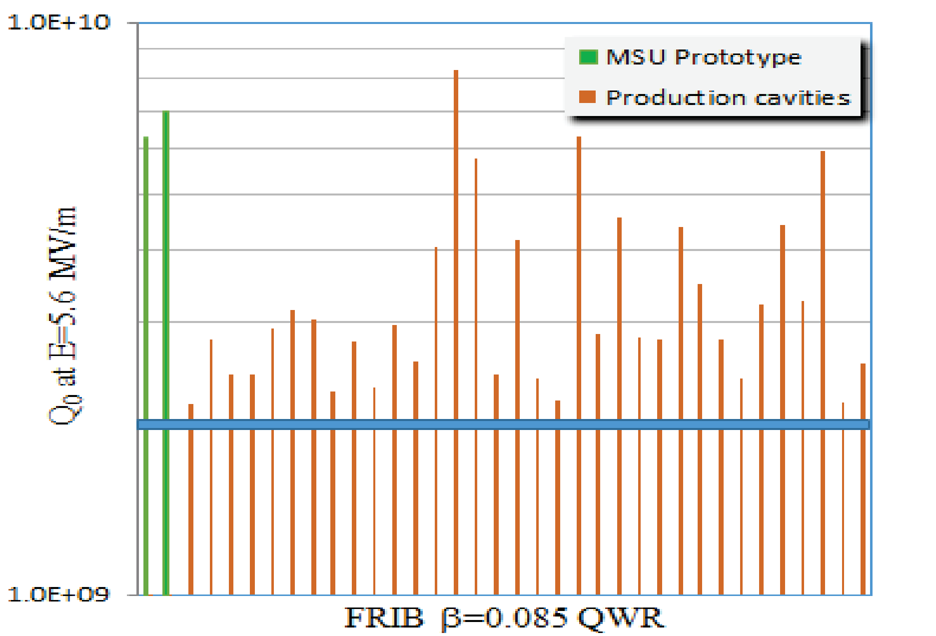
reinforcement ring

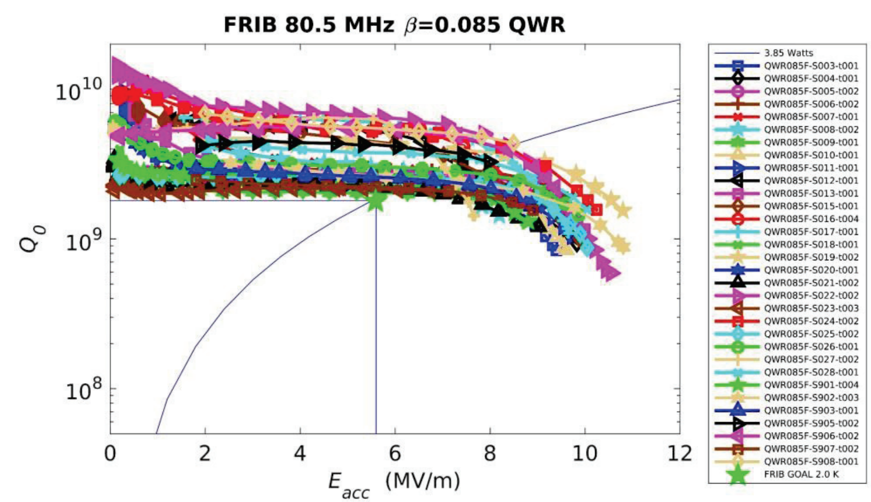
Cavity Type	ReA QWR	FRIB QWR	FRIB QWR
β	0.085	0.043	0.086
f [MHz]	80.5	80.5	80.5
V_a [MV]	1.08	0.81	1.78
E_{acc} [MV/m]	3.4	5.1	5.6
E_p/E_{acc}	6.2	6.1	6.0
B_p/E_{acc} [mT/(MV/m)]	13.9	10.8	12.4
R/Q [Ω]	408	401	455.4
G [Ω]	18	15.3	22.3
Aperture [m]	0.030	0.036	0.036
T [K]	4.5	2.0	2.0
Intrinsic Q [10^9]	0.6	1.4	2.0

FRIB Production QWR Cavity Development

- 0.041 QWRs perform well above FRIB spec: average 9.4 MV/m at FRIB heat load budget
- 0.085 QWRs meet FRIB specification while show a wide spread in Q_0 (average 6.9 MV/m at FRIB heat load budget
- Production cavities performs lower than in-house prototype
- Low df/dp and LFD are consistent with design goals

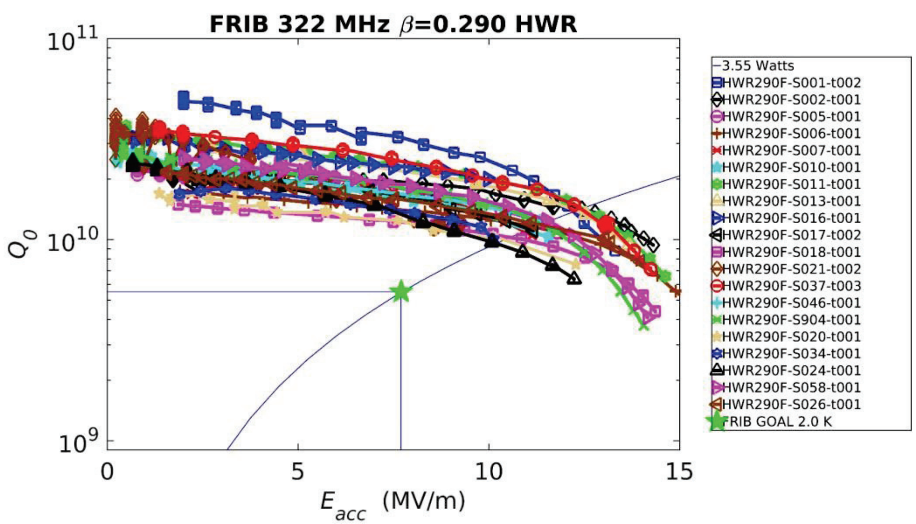


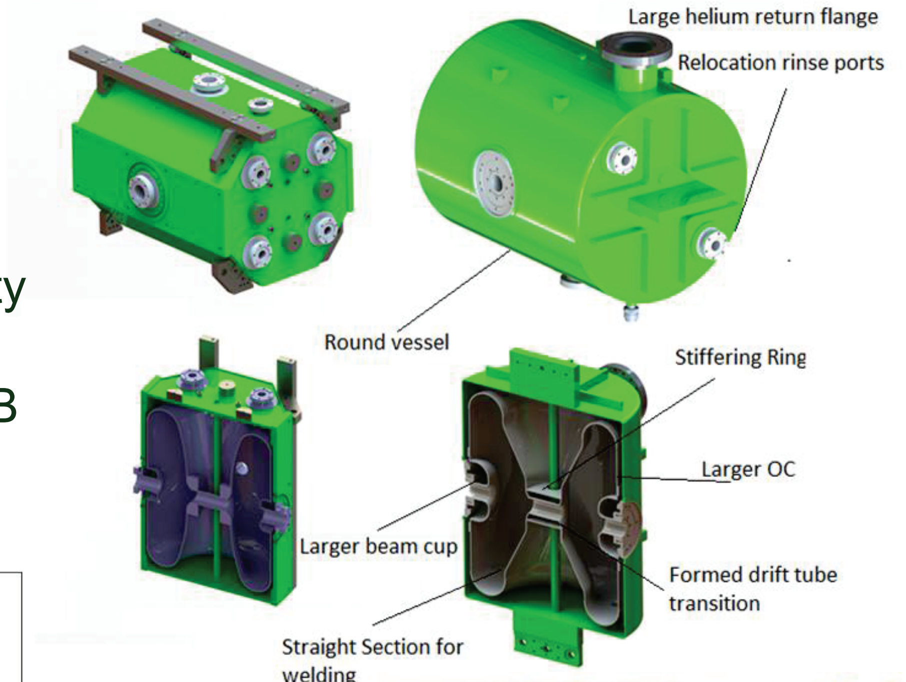




HWR Cavity Development

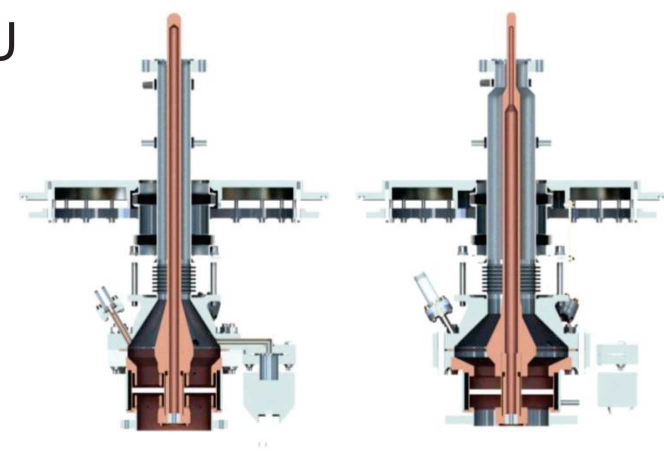
- Design optimized to lower Bp and Ep to improve performance
- Round vessel to facilitate fabrication
- Adapt to pneumatic tuner design
- Special tuning method developed for cavity fabrication
- Production cavity perform well above FRIB spec



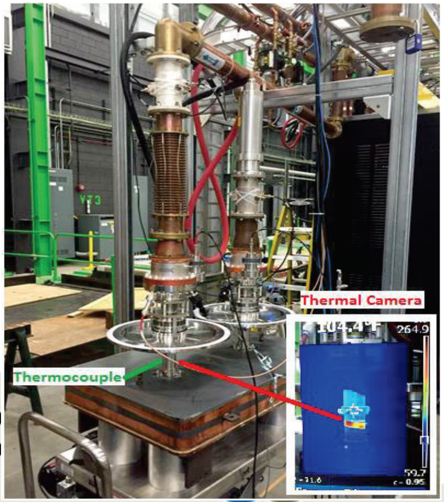


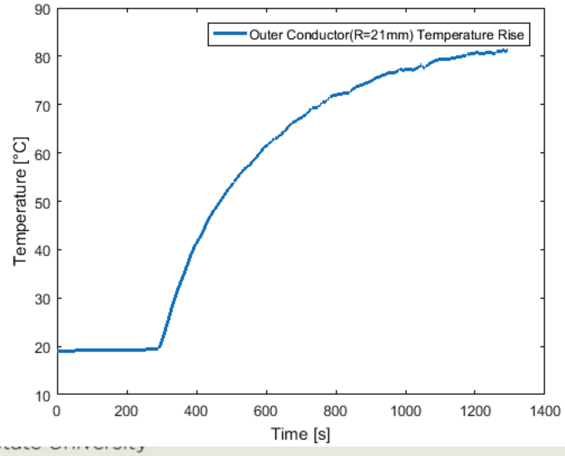
HWR FPC Development

- Two HWR FPC designs are prototyped at MSU
  - Baseline from KEKB and SNS design
  - MPF optimized to suppress multipacting and choke free design
- Baseline FPCs have heavy multipacting heating at 9-10kW (traveling wave model) and very long conditioning time
- MPF FPC perform better in high power RF conditioning
  - No multipacting heating observed
  - Quick conditioning time



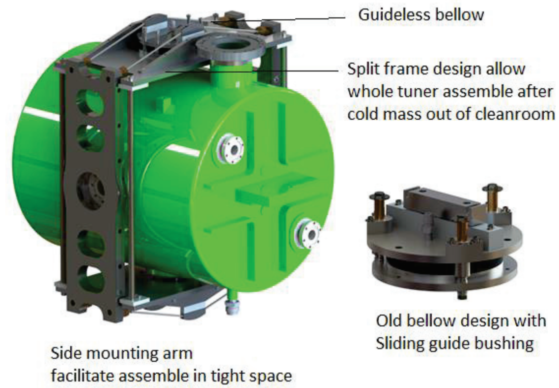
Baseline MPF



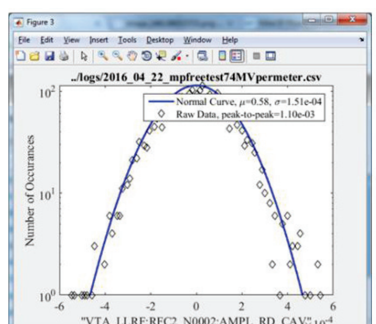


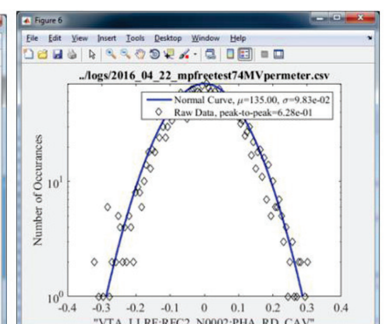
HWR Integrated Test to Validate Subsystem

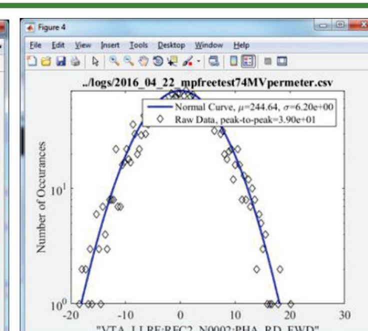
β=0.053 HWR & production coupler and tuner



Statistics collected during final β=0.53 (~3hrs, 7.4 MV/m) integrated test (BW=30 Hz)
Amplitude: 0.17% Pk-PK (.026% rms)
Phase: 0.63° pk-pk (.1 rms)
Forward Phase: 35 deg. pk-pk (15 Hz)

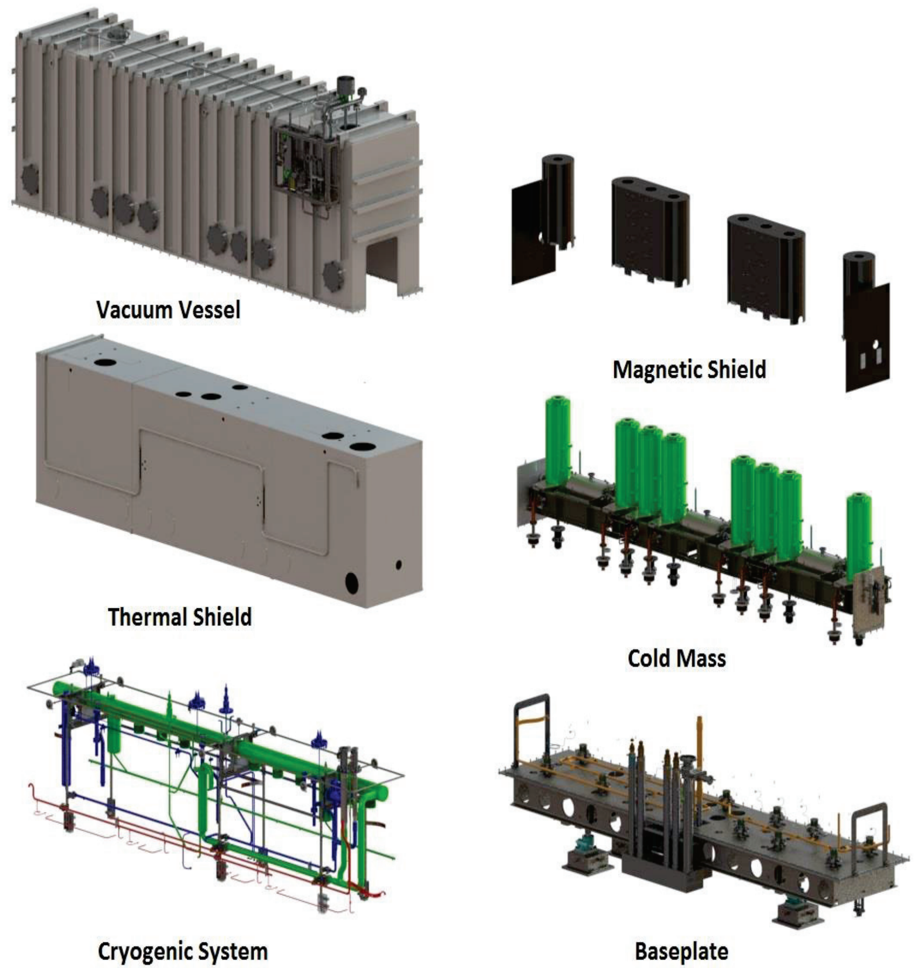






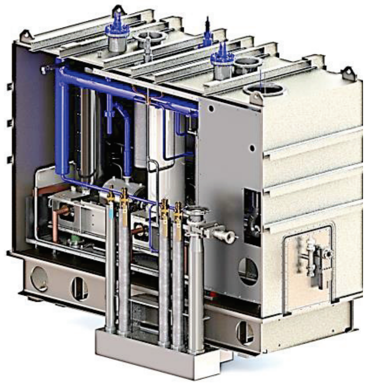
Novel Bottom-up Cryomodules Design Approach

- Resonators operate at 2 K and magnets at 4.5 K and are both supported from the bottom to facilitate alignment
- Cryogenic system is decoupled from coldmass string to isolate vibration to minimize the microphonics
- Optimized and integrated with cryo-distribution
  - Bayonet interface to allow cryomodule be cooldown/warmup and serviced independently
  - 2K-4K heat exchanger inside module to maximize 2K efficiency
- Single layer "local" magnetic shield to be cost effective and less sensitive to magnet operation
- Use common cryomodule designs principles for all six cryomodule types
  - Support rails, cryogenic circuit, thermal shield, vacuum vessel

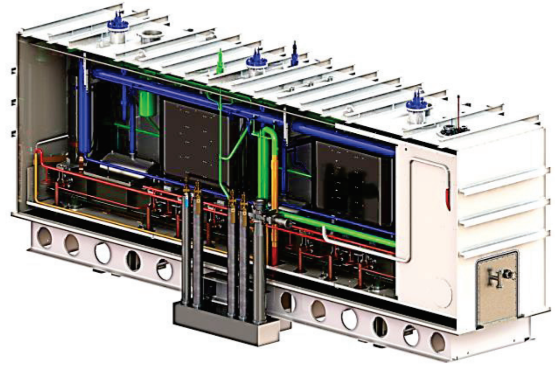


Cryomodule Design Near Completion!

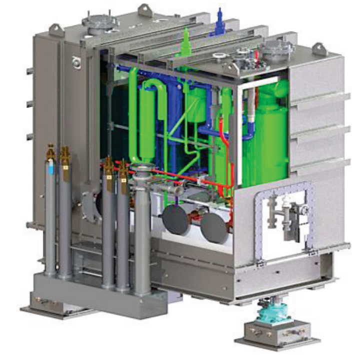
- All six modules using the same bottom-up design approach
- Last design package 0.29 module will be done by Mar 2017
- All cryomodules share large portion of common components to simplify design and facilitate fabrication.
- Collaborate with JLAB on cryomodule design (β=0.041 and β=0.29)
- Collaborate with ANL on coupler and tuner design



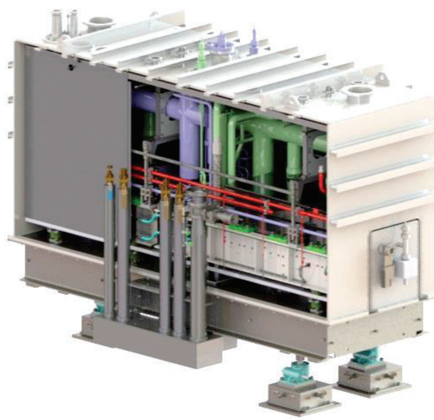
β=0.041



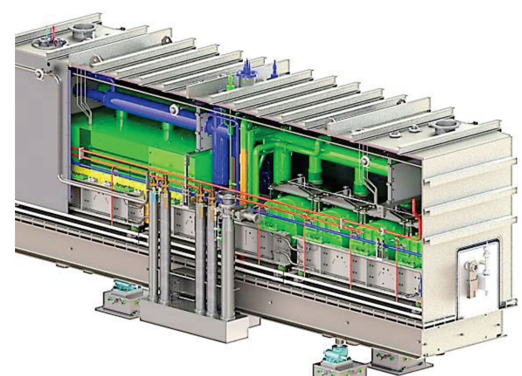
β=0.085



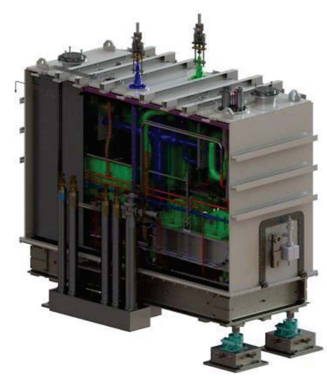
β=0.085 Matching



β=0.29



β=0.53



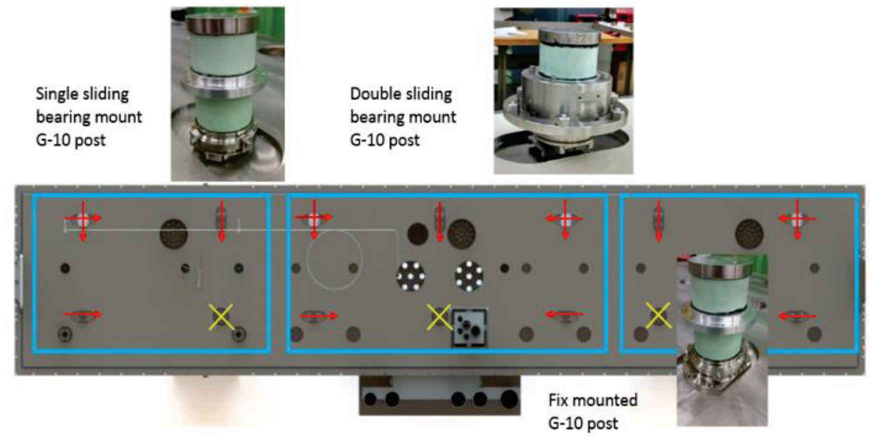
β=0.53 Matching

Jefferson Lab

Argonne NATIONAL LABORATORY

FRIB Cryomodule Alignment

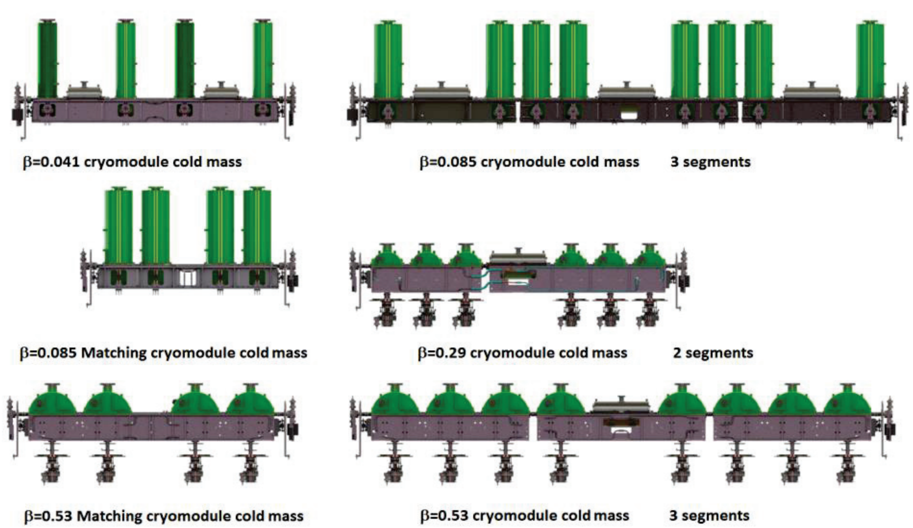
- Rigid baseplate provide stable and reliable platform for the cold mass
- Alignment of cold string is achieved by control stack tolerance of cold mass and baseplate.
- No post assemble alignment adjustment needed
- Rails are made of 316L and annealed before final machining to minimize distortion during fabrication and cool down.



Cryomodule Alignment Survey Results.

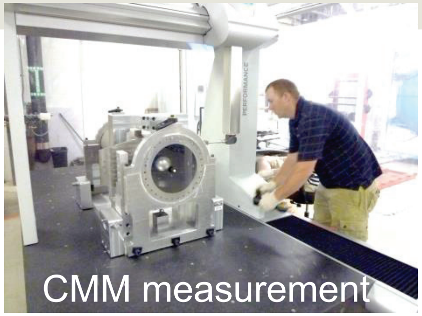
Module	Resonator		Solenoid	
	Transverse (mm)	Vertical (mm)	Transverse (mm)	Vertical (mm)
SCM801	0.449	0.535	0.305	0.433
SCM802	0.37	0.31	0.20	0.26
SCM803	0.44	0.25	0.15	0.21
SCM401	0.25	0.52	0.26	0.07
SCM402	0.14	0.13	0.24	0.13
SCM501	0.807	0.71	0.106	0.096

* Cool down error is projected to be <0.33 mm



Dedicated SRF Infrastructure to Support FRIB Cryomodule Production

- All critical SRF tasks are performed on-site
- 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 4 cold inserts
  - Cold mass assembly
  - Cryogenic system (Dedicated 900W helium refrigerator, helium purification and 2K system)


CMM measurement


Large cleanroom


BCP facility


Cavity assembly


HPR system

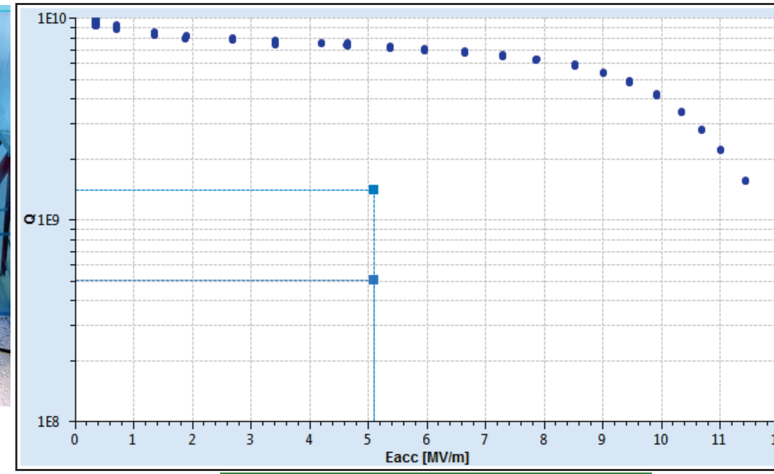

Vacuum furnace


Cold box and 5000L Dewar

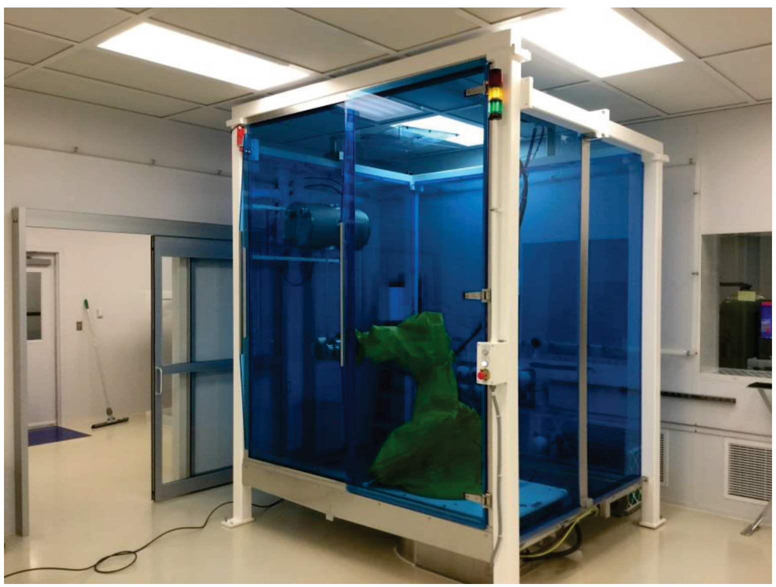

Vertical test area

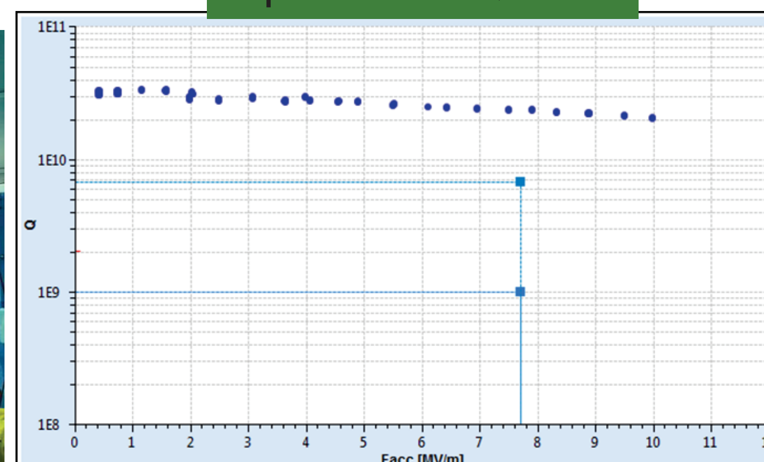
Robotic High Pressure Rinse System
Boost processing rate

- Interface with all 4 type FRIB cavities without changing toolings
- Programmable to run complete rinse cycle without operators
- Liquid particle counts (LPCs) and VTA test results show good performance



β= 0.041 QWR

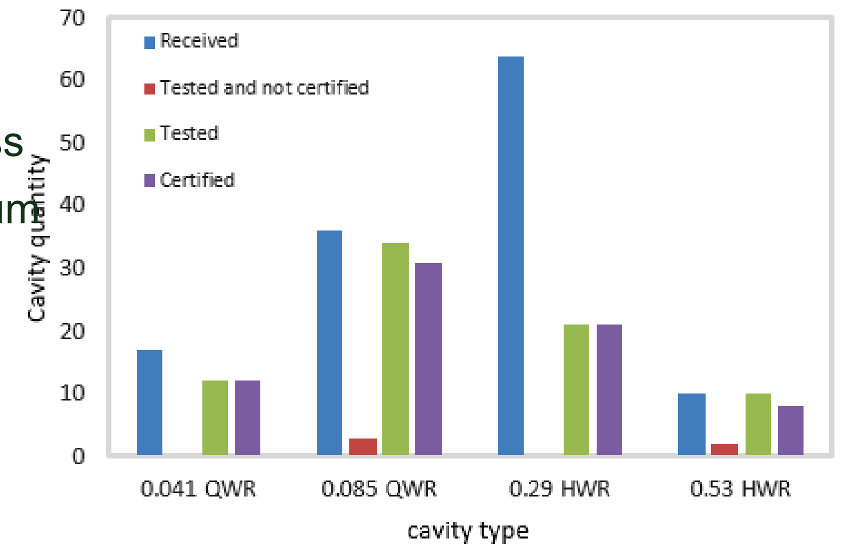


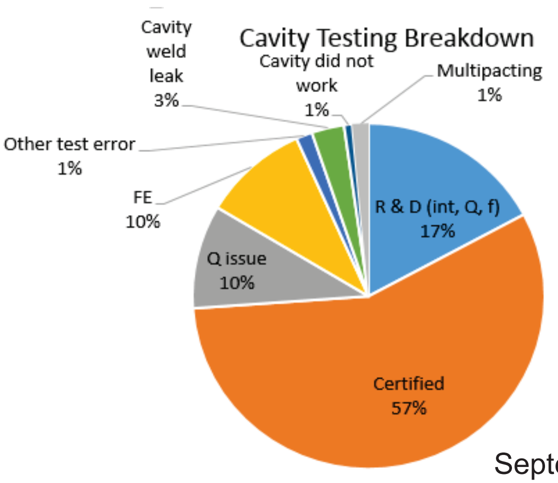


β= 0.29 HWR

Cavity Production & Test Status

- 40% of total cavities (128) for project received (0.041QWR delivery completed)
- 59% (76) cavities certified to be installed on cold mass
- Averaged 2 tests per week since 6/2015 with maximum rate at one test per day
- Less than 20% rework rate
- 4% reject to vendor for repair or rework
  - Welding issue, dimensional issue and threads issue
- Project to receive all cavities by end of 2017



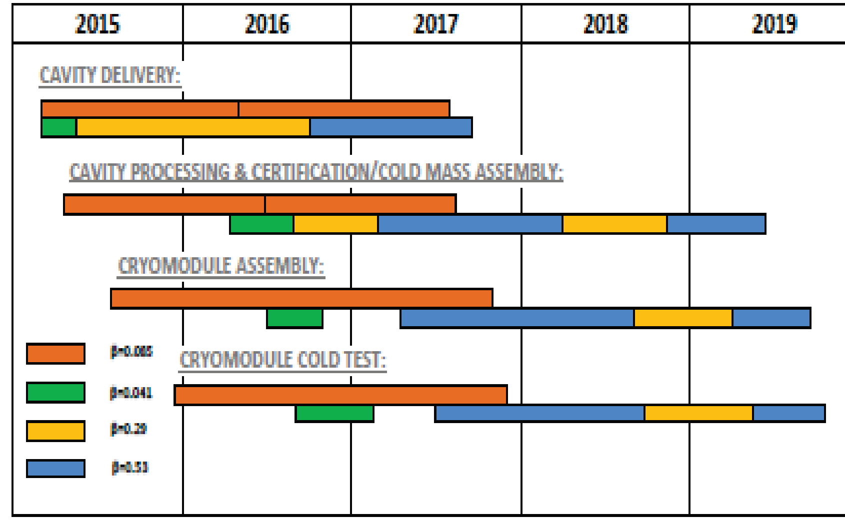


September 2016

Cold mass Production Status

- 8 cold mass have been completed
  - 3 β=0.041, 4 β=0.085, 1β=0.53
- Developed procedures to tuning cavity frequency
  - QWR
    - » Puck height, differential etching
  - HWR
    - » Differential etching, virtual welding
- Cavity clean remove and installation

FRIB Cryomodule Schedule



0.085QWR cold mass

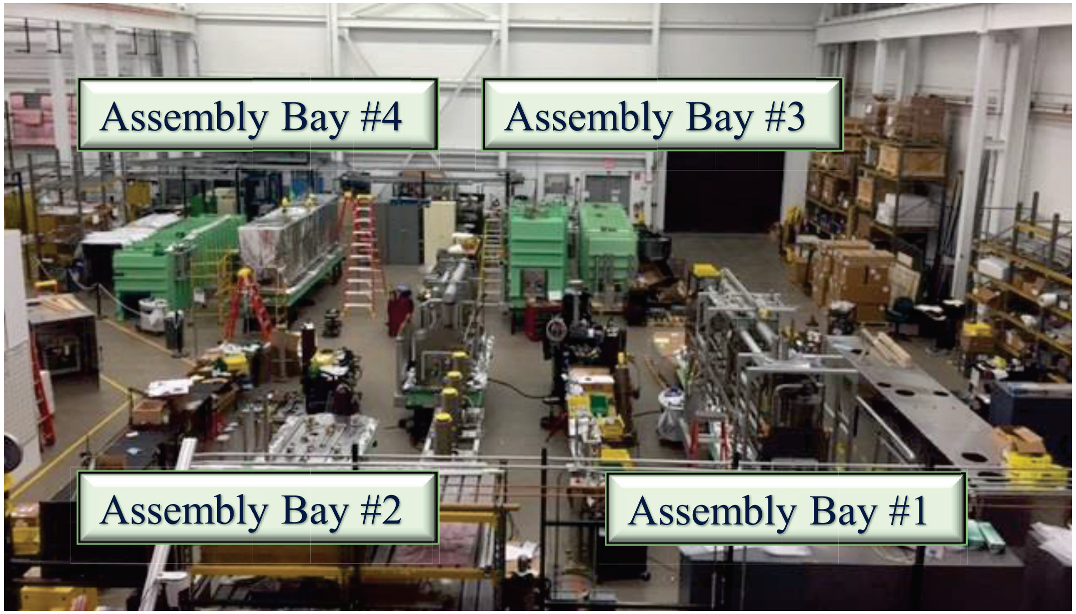
0.53HWR cold mass

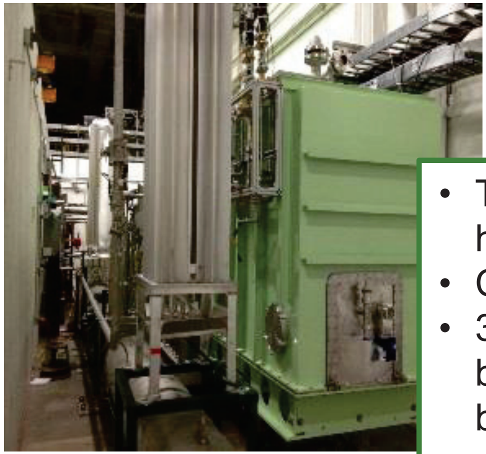
Certified cavities ready for cold mass

Cold mass transportation

Cryomodule Assembly Area

- 4 Cryomodule Assembly bays setup
- Module is fix during the whole assembly process
- Acceptance and load area
- 2 cryomodule test bunkers
- Cryomodule components are breakdown so that subsystem can be pre-fab and out-source





- Test bunker #1 at East highbay
- Commissioned 2015
- 3 QWR cryomodule has been tested in this bunker

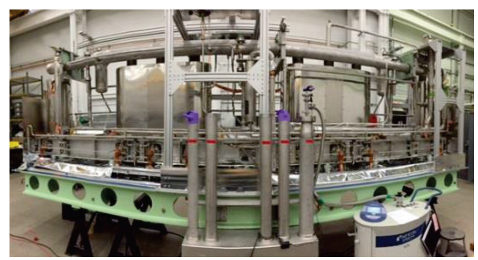
- Test bunker #2 at SRF highbay
- Cryogenics commissioned
- First test in Oct 2016

Cryomodule Production Status

- All Cryomodule major procurements are awarded

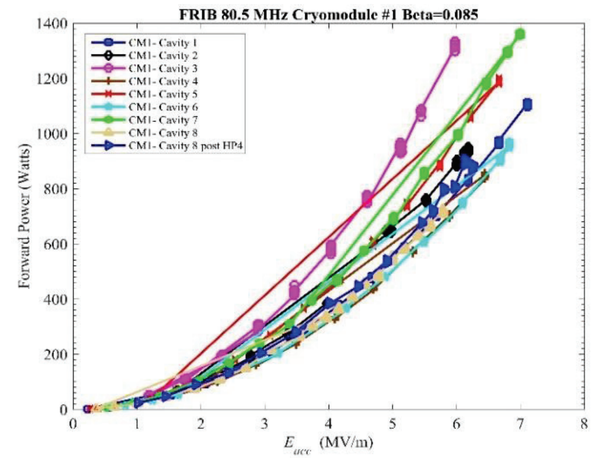
0.041 Cryomodule	95	% Awarded
0.085 Cryomodule	97	% Awarded
0.29 Cryomodule	65	% Awarded
0.53 Cryomodule	87	% Awarded

- Cryomodule production ramp up
  - 4 cryomodules have been assembled
  - 2 cryomdoule tested and certified
  - LS1 cryomodules are projected to be done by 2017
  - All cryomodules will be done by 2019.
- First module is completed within 6 weeks after receiving cold mass!



Extended test (5 Month) on FRIB #1
Validate system by system

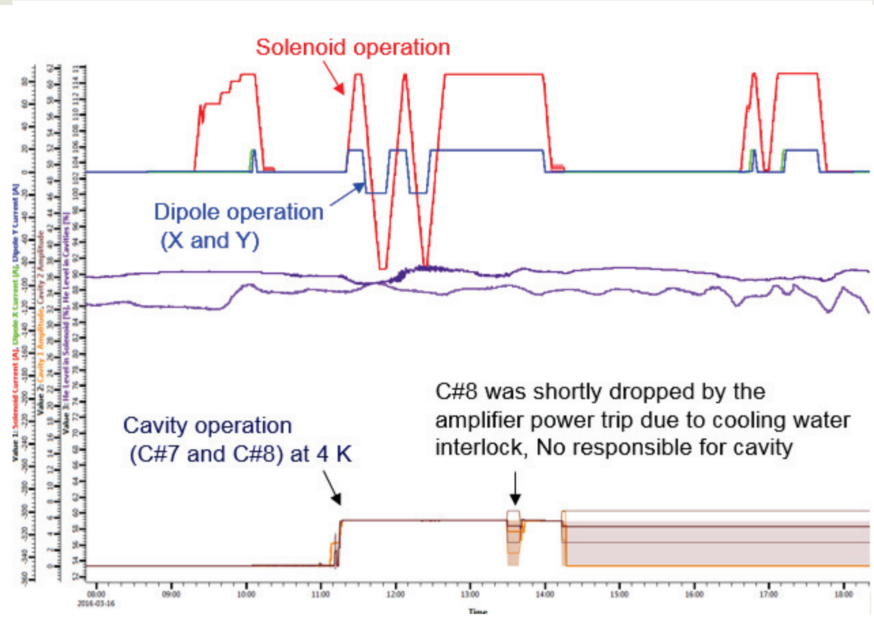
- Cavity gradient (Requirement 5.6 MV/m)
  - Result: Eacc ≧ 6 MV/m at 4 K, meets FRIB specifications
- Dynamic Loss (requirement 3.85 W, Q_0 =1.8 x 10^9 at 2 K)
  - Result: 2.8 W, Q_0=2.5 x10^9 in average at 2 K with ~ 40 % margin for FRIB spec.
  - No Q-degradation by cold mass assembly
- Coupler and tuner work well
- All cavities are locked in spec at 4.5K
- Cryogenics system is very stable throughout test period

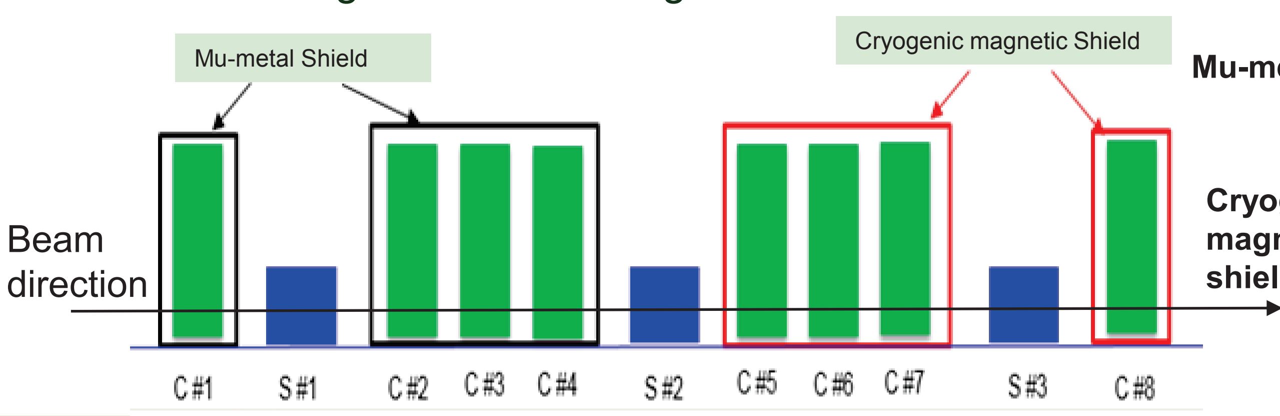


CAVITY	AMPLITUDE		PHASE		BW	FORWARD POWER			FORWARD PHASE		DETUNE	
#	Pk-Pk (%)	RMS (%)	Pk-Pk (deg)	RMS (deg)	BW (Hz)	Pnom (W)	Pave (W)	Pmax (W)	Pk-Pk (deg)	RMS (deg)	Pk-Pk (Hz)	rms
1					20.2	487						
2	0.64	0.05	0.58	0.07	38.6	931	1005	1552	68	7.7	29.2	3.3
3	0.08	0.01	0.09	0.01	43.6	1052	1163	1274	28	1.5	13.4	0.7
4	0.09	0.01	0.25	0.03	37	893	1076	1318	28	2.9	11.5	1.2
5	0.26	0.01	0.53	0.07	24.8	598	488	858	72	7.9	19.6	2.2
6	0.09	0.01	0.09	0.01	27.1	654	650	681	9	1.4	2.7	0.4
7	0.06	0.01	0.31	0.02	26.5	639	702	835	23	2.1	6.8	0.6
8	0.14	0.01	0.32	0.04	26.3	634	645	924	49	5.7	14.2	1.7
Average	0.19 ±0.21	0.02 ±0.02	0.31 ±0.19	0.04 ±0.03	30.5 ±8.1	736 ±196	818 ±259	1063 ±318	40 ±24	4.1 ±2.9	13.9 ±8.6	1.4 ±1.0
Spec	**2.00**	**0.25**	**2.00**	**0.25**	**40.0**				**90**		**< 20**	**< 2.25**

Solenoid Operation and Magnetic Shield Validation

- Successful robust solenoid package operation with cavities
  - Solenoids ramped to full fields without training quench.
  - Integrated test with cavity at 5.6 MV/m at 4.5 K.
  - Vapor cooled current leads operate well, flow controller regulates the lead voltages stable.
- Magnetic shield material with $\mu > 9000$ at cryogenic temperature meets FRIB requirement: Bin < 15 mG
- Validated: Mu-metal against remnant field for FRIB local magnetic shield design





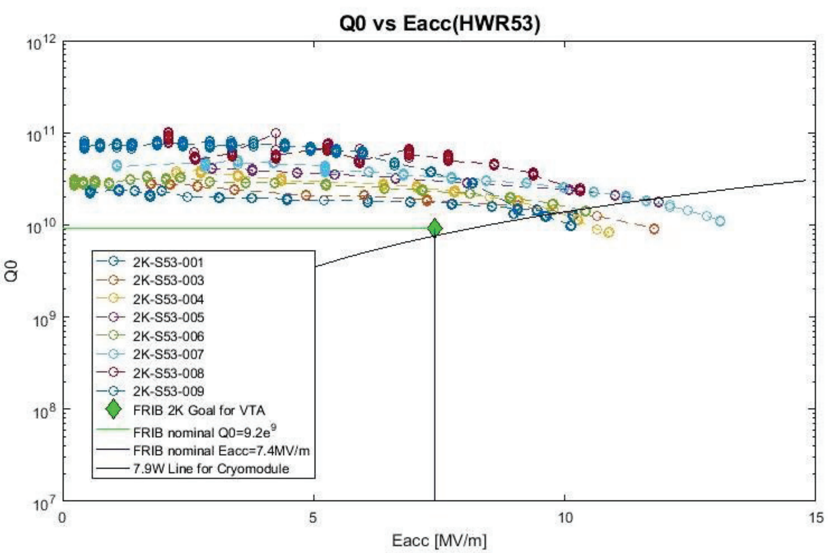
Mu-metal
- Cavity 1: 6.2W
- Cavity 2: 2.4W
- Cavity 3: 2.5W (split)
- Cavity 4: 1W (seems low)

Cryogenic magnetic shield
- Cavity 5: 2.4W
- Cavity 6: 2.5W (split)
- Cavity 7: 2.4W
- Cavity 8: 2.6W

Dynamic heat load measurement at 2 K for each cavities

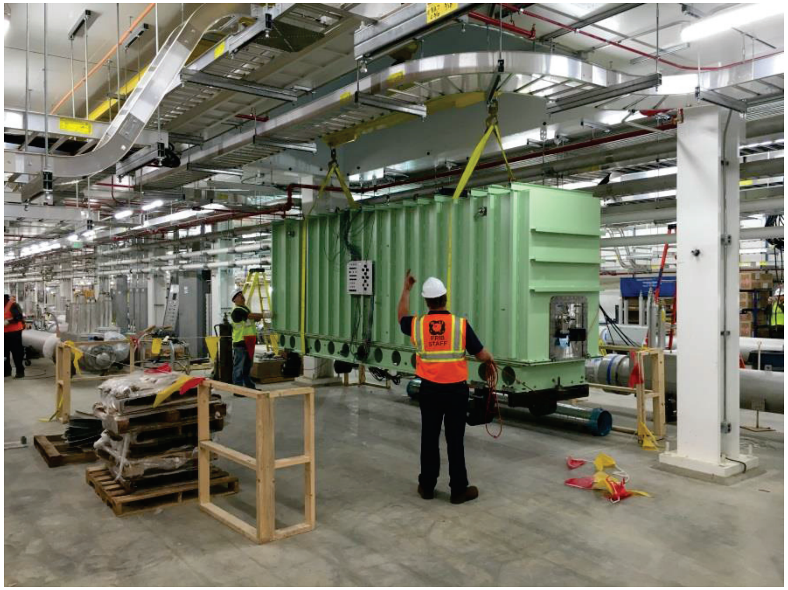
Preproduction 0.53HWR Cryomodule Ready for Testing



Summary

- Over decade technical development in SRF at MSU provide solid ground for FRIB project
- All SRF critical components for FRIB cryomodules are validated
- Full SRF infrastructure established and fully operational to support cavity processing and cold mass assembly
- FRIB cryomodule production started 2015 and is ramping up
- Cryomodule tunnel installation started



First FRIB 0.085 QWR cryomodule moved into tunnel Sep 2016

NAPAC2016