FRIB Cryomodule Design and Production

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Outline

- FRIB Project
- FRIB Cryomodule design
- Cryomodule production status
- Summary


2012 FRIB Construction Site

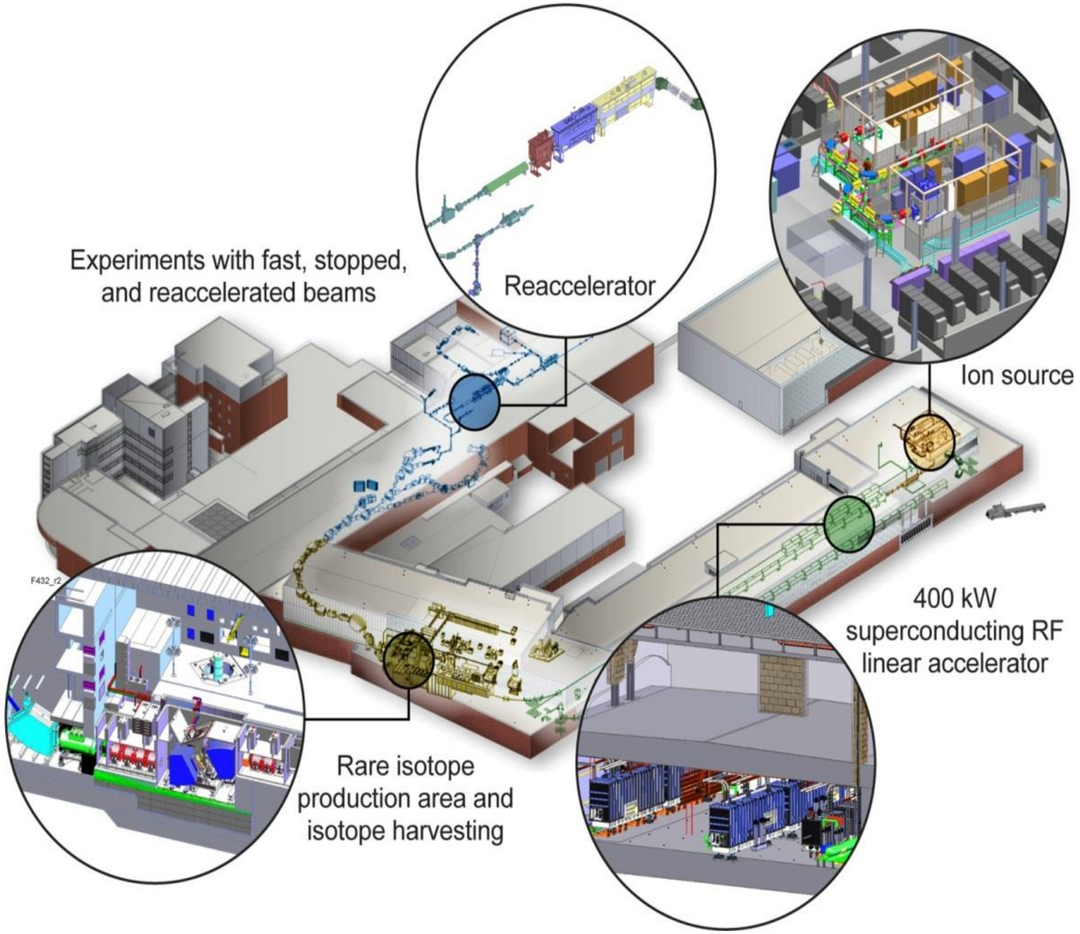

2014 FRIB SRF Highbay


2016 FRIB Overlook


2016 FRIB Tunnel

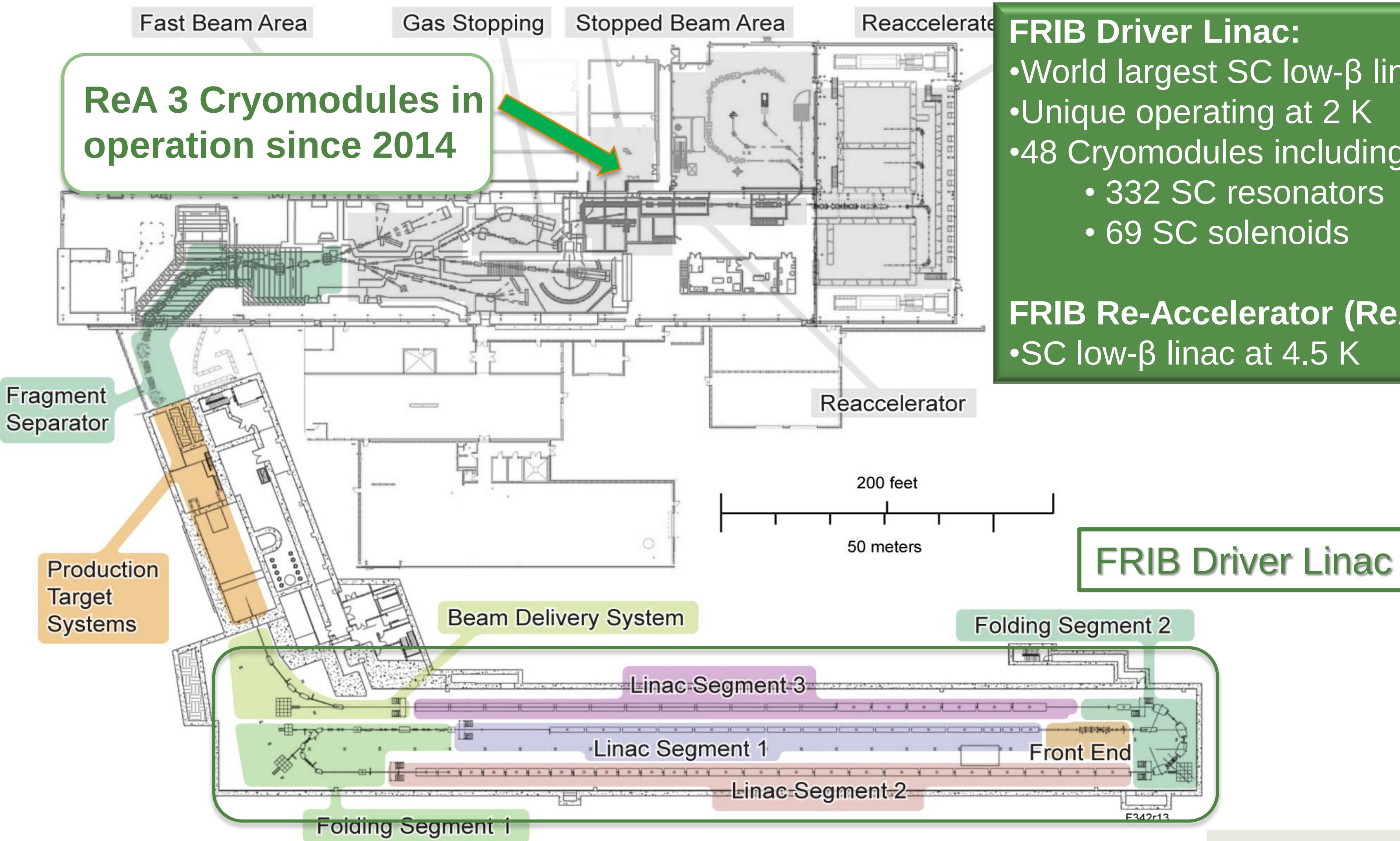
FRIB Project Overview

- 400 kW beam power (5 x10^{13} ^{238}U/s) for all ions from 200 MeV/u superconducting heavy-ion driver linac
- Produce rare isotope beams by fragmentation of fast heavy-ion beams, gas stopping, reacceleration
- DOE/MSU jointed project under Cooperative Agreement, project cost shared by both, total cost $730M, and + $300M from MSU
- Accelerator system construction(CD3-b) started October 2014
- Early beam commissioning of the Front End to be started in 2017 – 2020
- Final completion (CD4) in 2022



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:
- 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

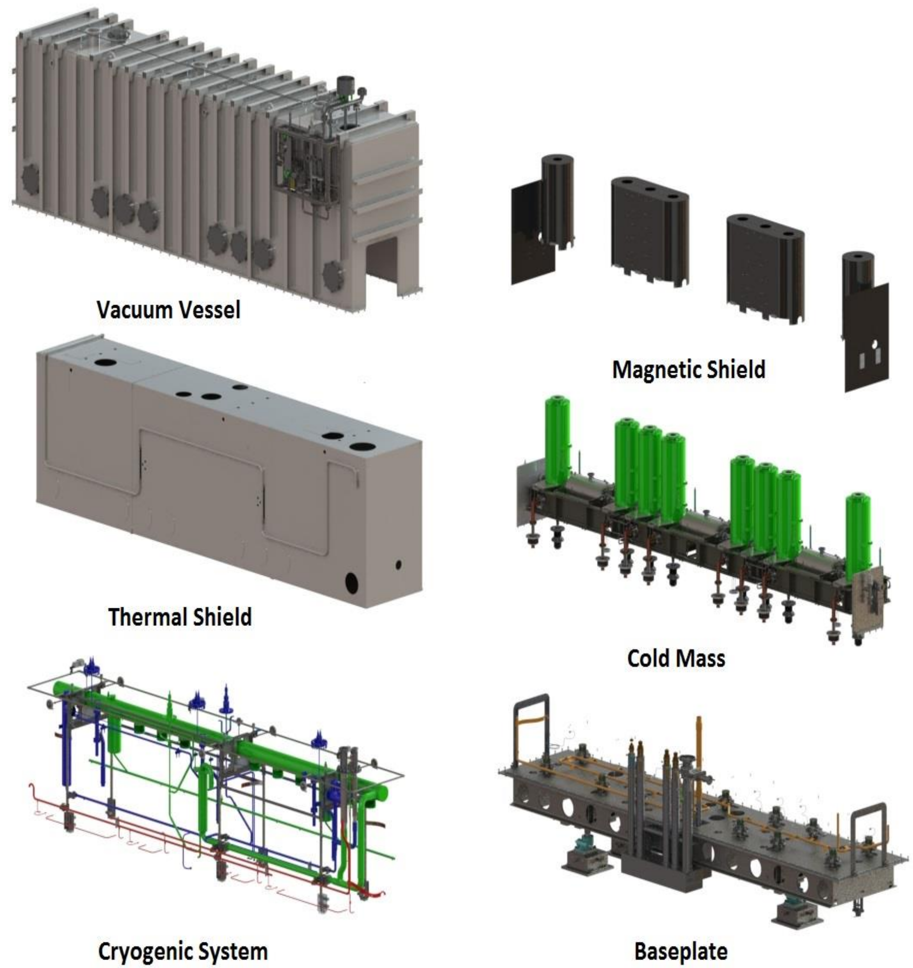
FRIB SRF Components

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

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

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

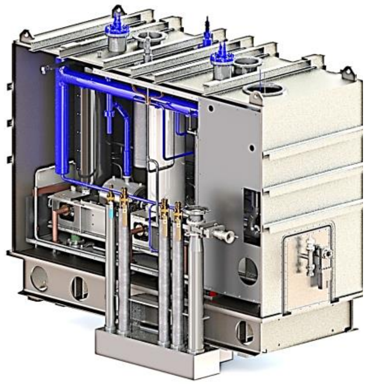


Cryomodule Design Near Completion!

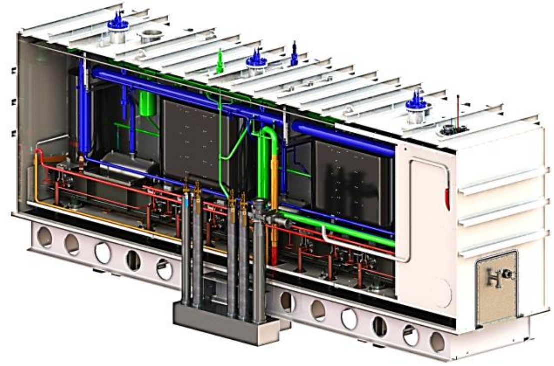
- All six modules using the same bottom-up design approach
- Last design package 0.29 module will be done by Mar 2017
- All cryomodules share large portion of common components to simplify design and facilitate fabrication.
- Collaborate with JLAB on cryomodule design (β=0.041 and β=0.29)
- Collaborate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

Jefferson Lab

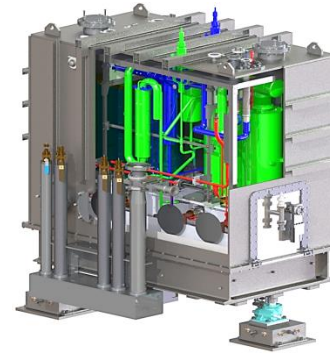
Argonne NATIONAL LABORATORY



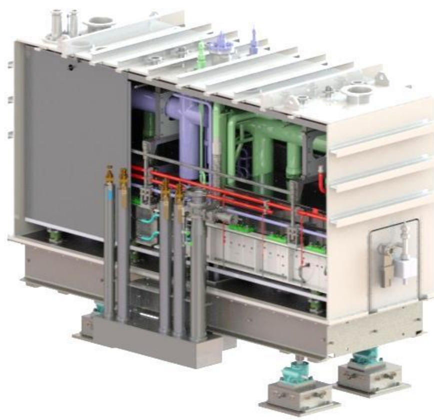
β=0.041



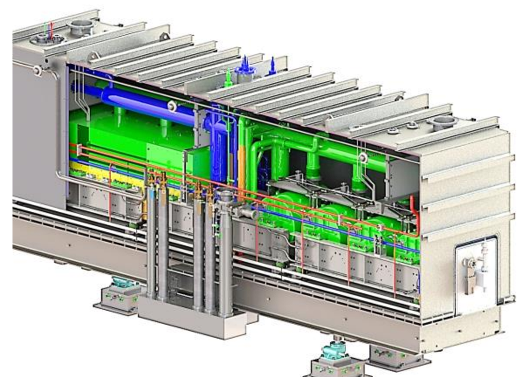
β=0.085



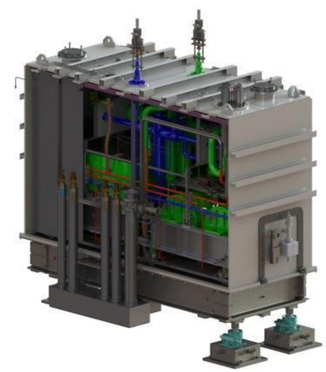
β=0.085 Matching



β=0.29



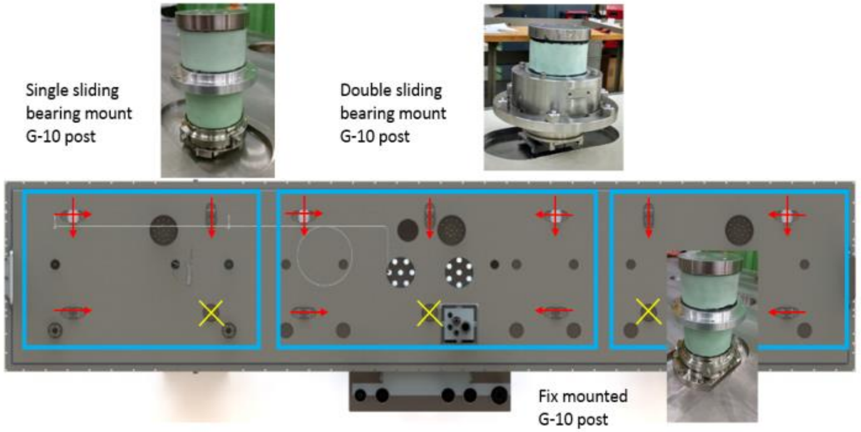
β=0.53

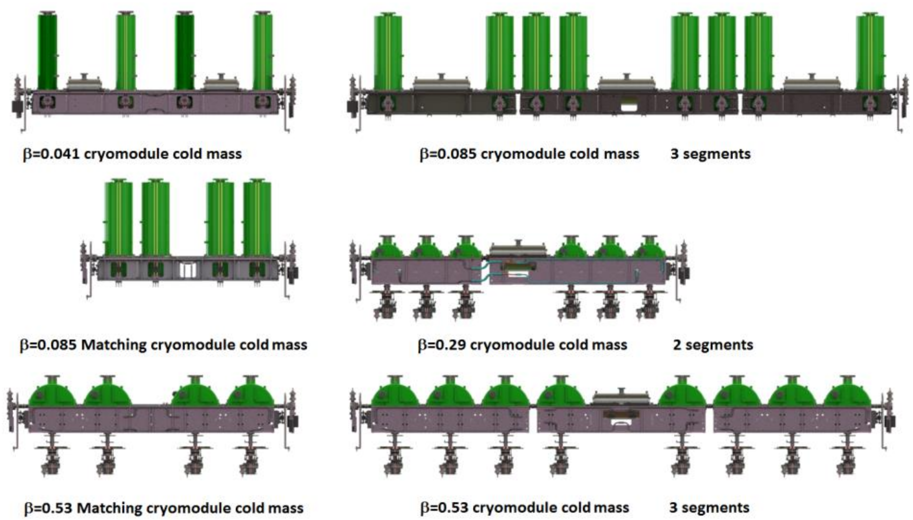


β=0.53 Matching

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.





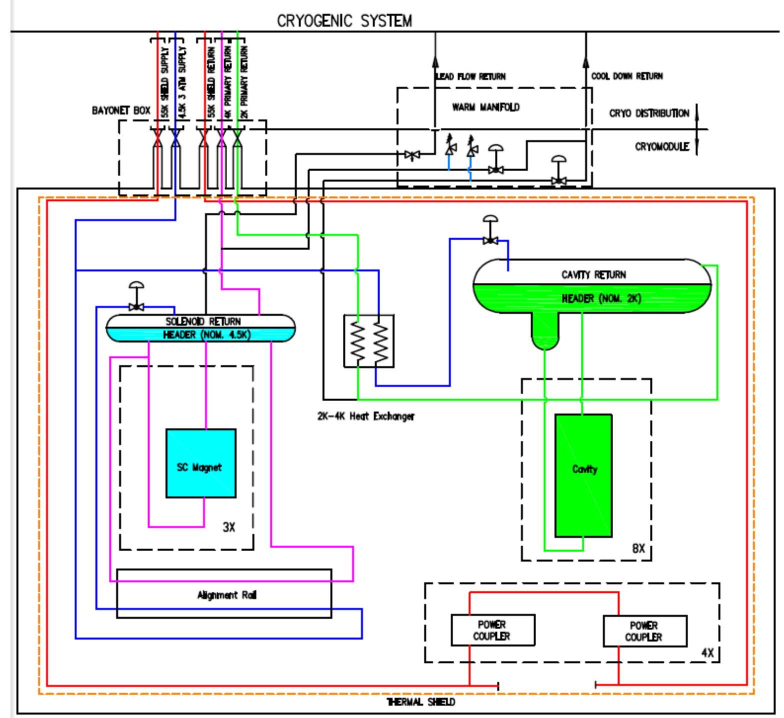
Cryomodule Alignment Survey Results.

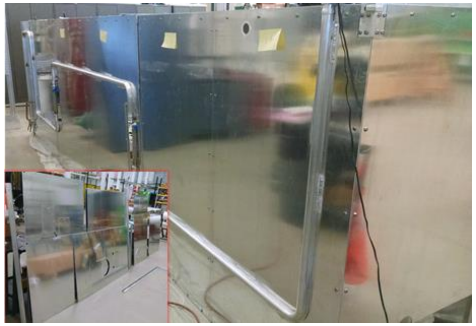
Module	Resonator		Solenoid	
	Transverse (mm)	Vertical (mm)	Transverse (mm)	Vertical (mm)
SCM801	0.449	0.535	0.305	0.433
SCM802	0.37	0.31	0.20	0.26
SCM803	0.44	0.25	0.15	0.21
SCM401	0.25	0.52	0.26	0.07
SCM402	0.14	0.13	0.24	0.13
SCM501	0.807	0.71	0.106	0.096

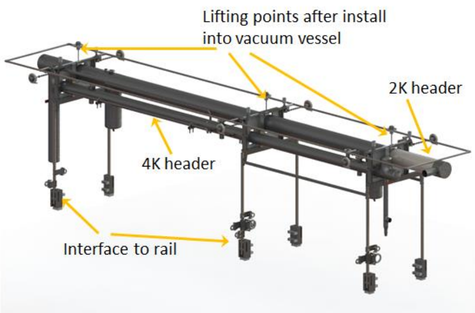
* Cool down error is projected to be <0.33 mm

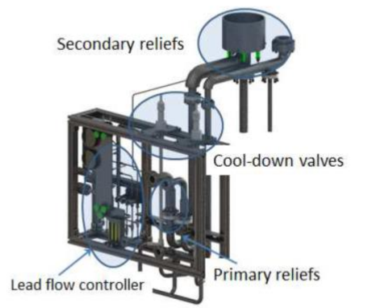
Cryogenic System

- Two primary cooling loop: cavity (2K) and SC magnets (4.5K) to allow independent cool down and warm up. Thermal syphon design allow flow to be self regulated.
- 50K Parallel cooling for FPC intercept
- Cryogenic support system designed to allow cryogenic piping to be supported from top to decouple from cold mass
- Economic 2K-4K heat exchanger (finned tube heat exchangers) tailored for FRIB cryomodule
- Cool down headers outside vacuum vessel to simply cryomodule internal design and allow common design









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

TUPRC024


Vacuum furnace


Cold box and 5000L Dewar


Vertical test area

Production Workflow Ramped Up

Cavities in tagging area

Ready for processing

Beta=0.085 cold mass

Beta=0.53 cold mass

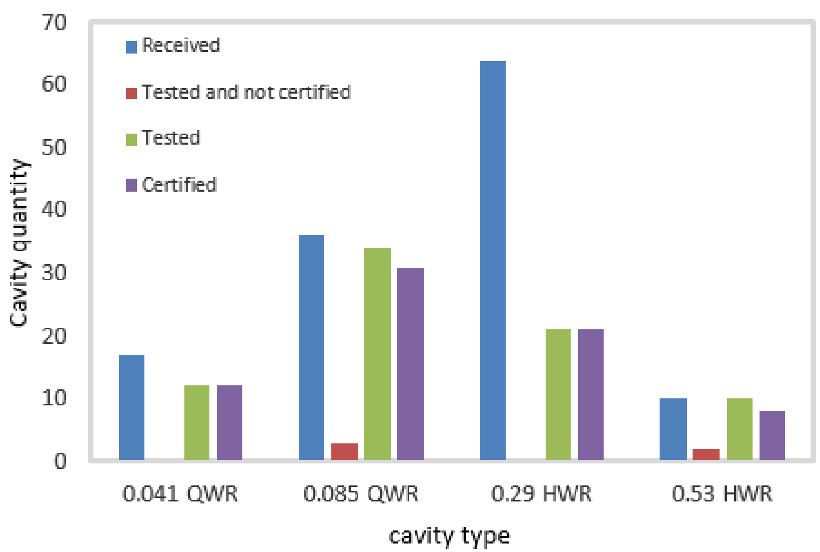
Production routers

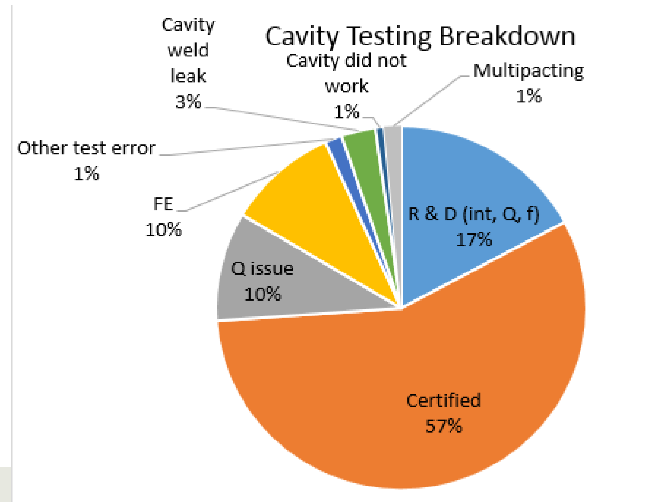
Beta=0.041 cold mass

Certified cavities ready for cold mass

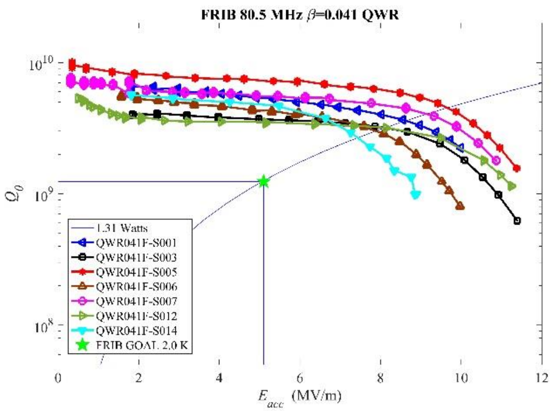
Cavity Production & Test Status

- 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

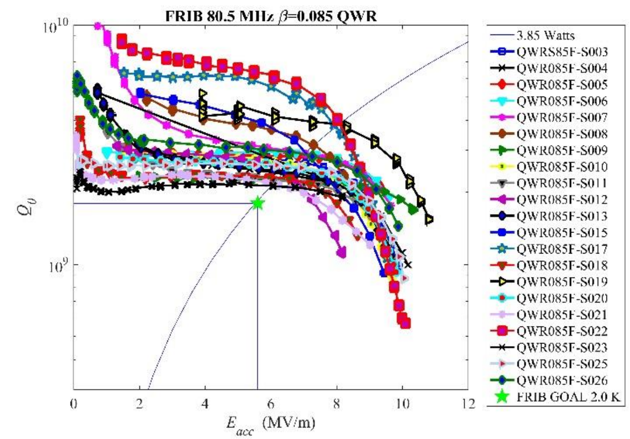


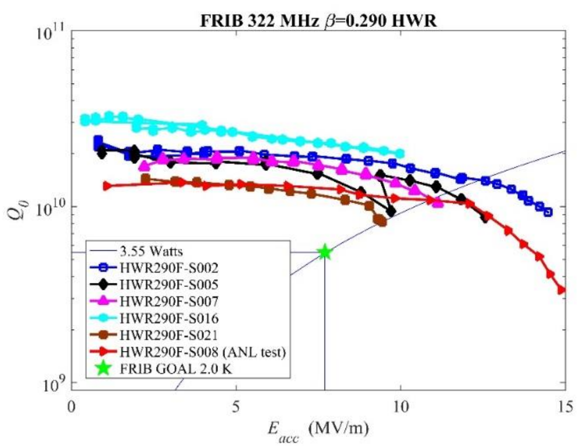


Cavity Performances Exceed FRIB Requirements

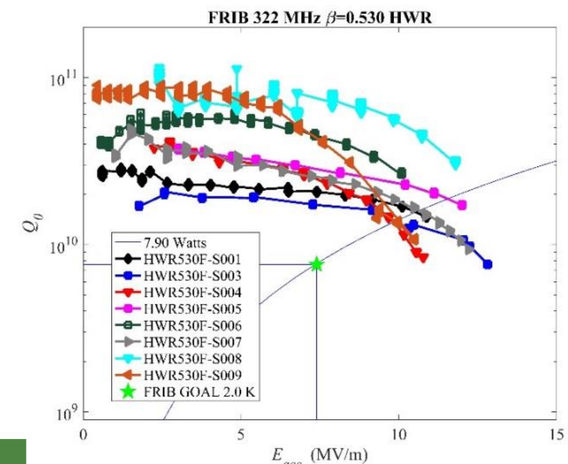


β_0 = 0.041 β_0 = 0.085
Quarter-Wave Resonators
80.5 MHz





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



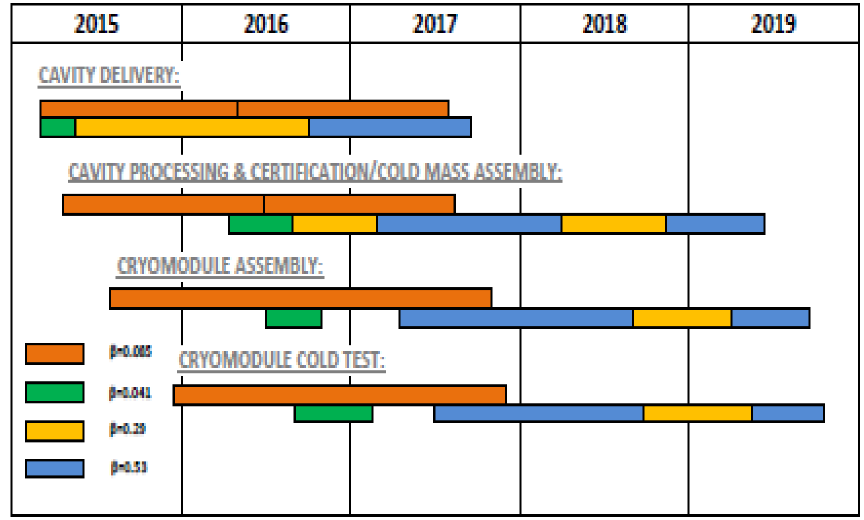
cavity	0.041 QWR	0.085 QWR	0.29 HWR	0. 53 HWR
E_a (MV/m)	☑ >5.1	☑ >5.6	☑ >7.7	☑ >7.4
Q_0	☑ $>1.4\times10^9$	☑ $>2\times10^9$	☑ $>6.7\times10^9$	☑ $>9.2\times10^9$
Df/dP (Hz/mBar)	☑ -2.7	☑ -1.85	☑ -2.2	☑ -6.7
LFD (Hz/(MV/m)^2)	☑ -3	☑ -2.9	☑ -5	☑ -4

TUPLR034

Cold mass Production Status

- 7 cold mass have been completed
  - 3 β=0.041, 3 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



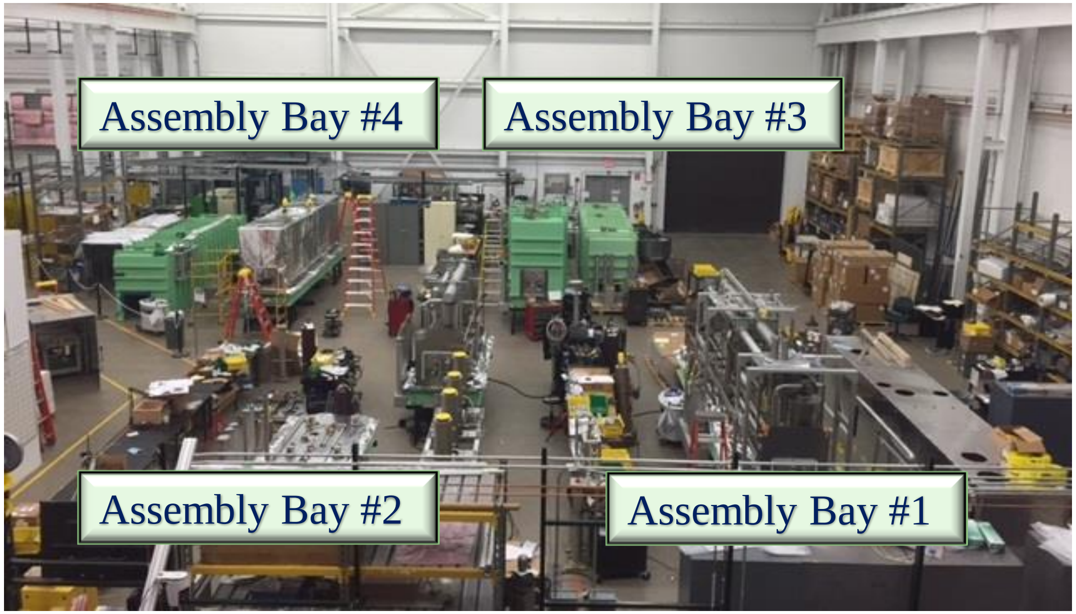

FPC installation tool

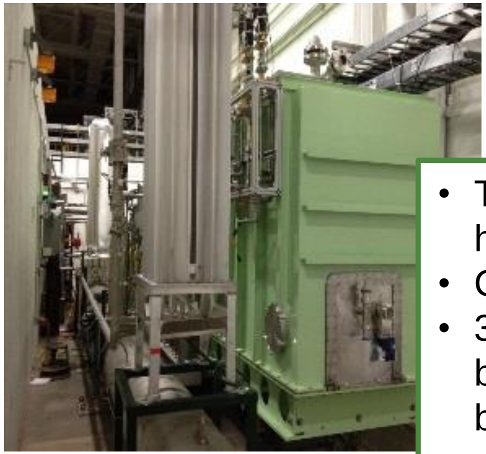
bellow installation tool

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 by end of this month
- 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
- Project to be done by end of Sep 2016
- First module to be tested in this bunker will be the preproduction 0.53 HWR

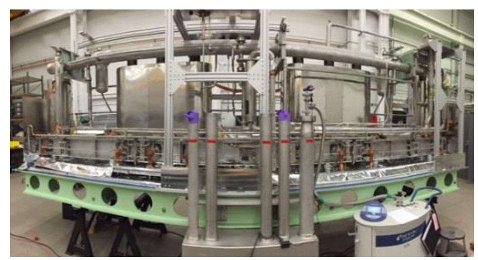
Cryomodule Production Status

- 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

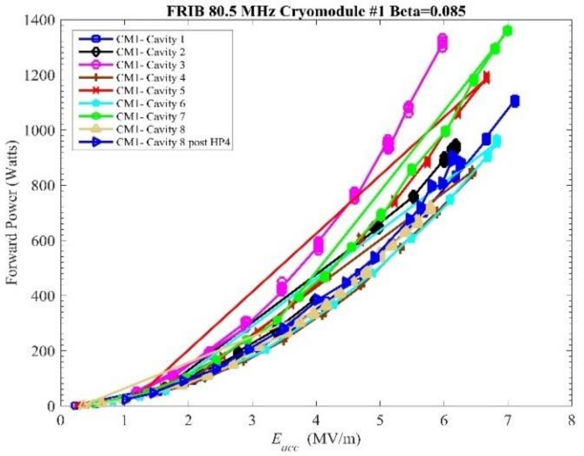
- Cryomodule production ramp up
  - Four cryomodules have been assembled
  - 2 cryomdoule tested and certified
  - LS1 cryomodules are projected to be done by 2017
  - All cryomodules will be done by 2019.

- First module is completed within 6 weeks after receiving cold mass!



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

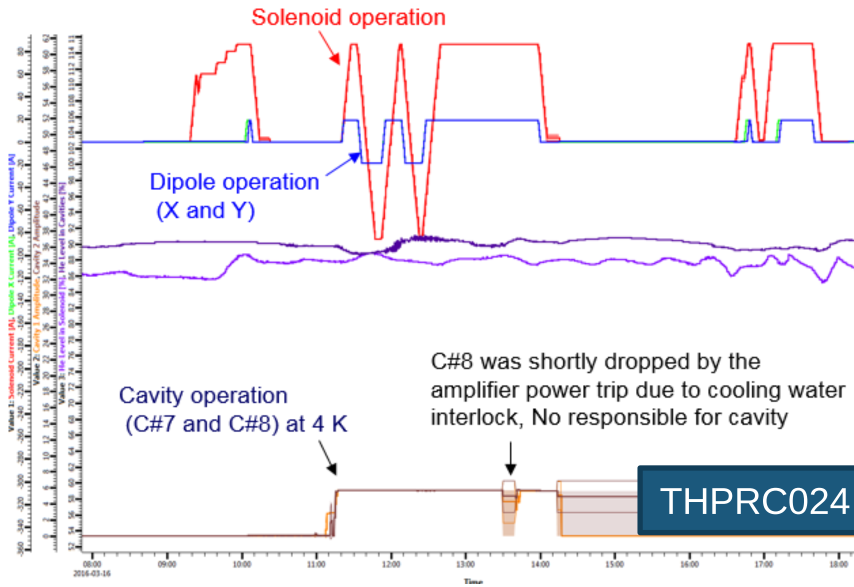
- Cavity gradient (Requirement 5.6 MV/m)
  - Result: Eacc ≧ 6 MV/m at 4 K, meets FRIB specifications
- Dynamic Loss (requirement 3.85 W, $Q_0 = 1.8 \times 10^9$ at 2 K)
  - Result: 2.8 W, $Q_0 = 2.5 \times 10^9$ in average at 2 K with ~ 40 % margin for FRIB spec.
  - No Q-degradation by cold mass assembly
- 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



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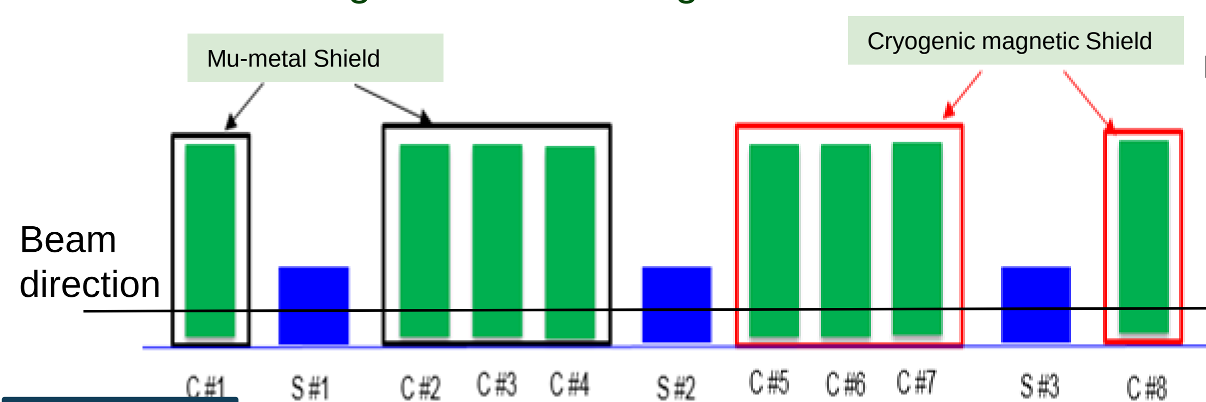

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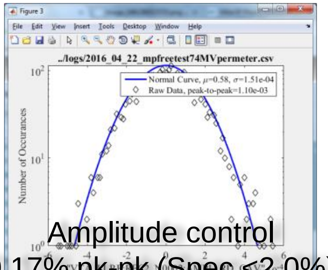
Mu-metal
- Cavity 1: 6.2W
- Cavity 2: 2.4W
- Cavity 3: 2.5W (split)
- Cavity 4: 1W (seems low)

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

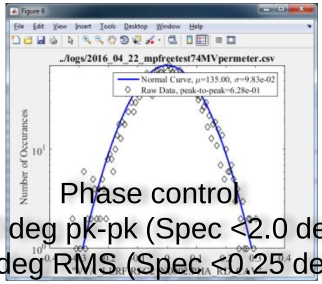
Dynamic heat load measurement at 2 K for each cavities

HWR FPC Prototype Qualified and FRIB Choice MPF for Production

- Integrated tests with baseline FPC
  - Verify RF control with pneumatic tuner up to 7.4 MV/m with baseline coupler @ 4K
  - Confirm 30 Hz cavity bandwidth
- Integrated test with MPF couplers
  - Confirm no multipacting barriers with MP-free coupler
  - Confirm RF control equivalent to baseline FPC
- Baseline FPC conditioning
  - 9 out of 10 Baseline Model are conditioned but has heavy multipacting heating at 9 -10 kW (traveling wave model) and very long conditioning time.
  - #9 can not reach vacuum goal during after 140 hour conditioning
- MPF FPC conditioning
  - No multipacting heating observed
  - Quick conditioning time



Amplitude control
0.17% pk-pk (Spec <2.0%)
0.026% RMS (Spec <0.25%)



Phase control
0.63 deg pk-pk (Spec <2.0 deg)
0.1 deg RMS (Spec <0.25 deg)

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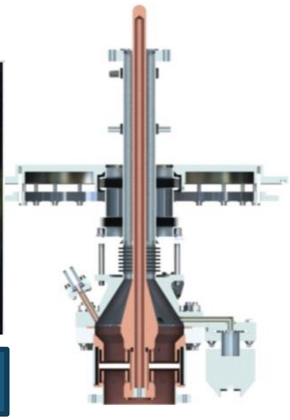
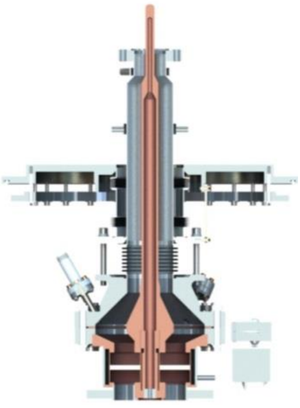


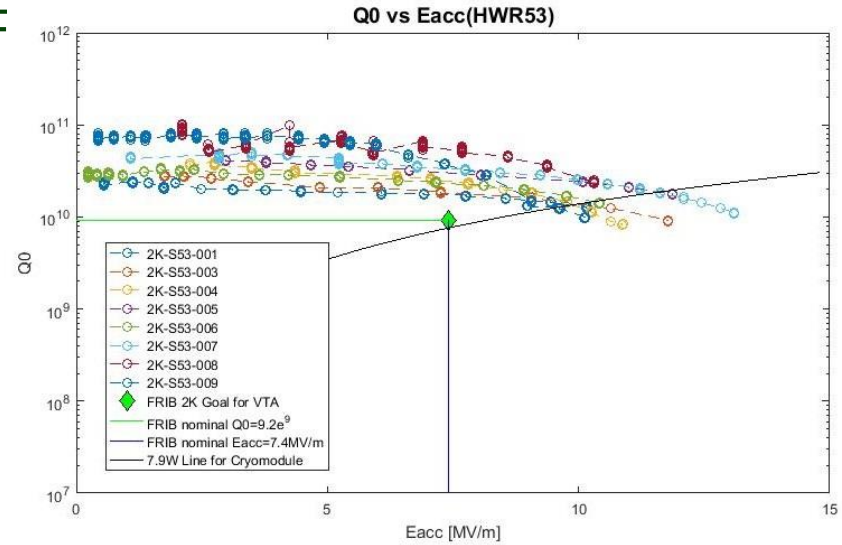
Base line

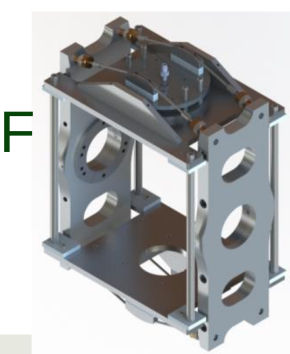


MPF

β=0.53 Preproduction Module Status

- Cryomodule will be ready for install to SRF test bunker at end of Sep 2016
- Key technical cold test tasks
  - High Q performance
  - Local shielding performance
  - Narrow bandwidth 30Hz LLRF control in cryomodule environment
  - Pneumatic tuner long term stability
  - Cavity frequency goal
  - Cryogenic system performance
- Validate major components to allow production start
- Last technical milestone for SRF





THPRC013 TUPLR029

Summary

- Success of FRIB-1 cryomodule is important milestone for production start.
- FRIB cryomodule design will be completed by Mar 2017
- FRIB cryomodule is in production phase and ramp up
- 0.53 preproduction online testing will be important milestone to complete technical campaign of FRIB cryomodule
- SRF highbay is fully operational and reach the design capability for cavity processing and cold mass assembly

LINAC 16
28TH LINEAR ACCELERATOR CONFERENCE
East Lansing, MI USA
25-30 September