Performance Testing of FRIB Early Series Cryomodules

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Outline

- FRIB cavity types, design goals and testing status
- VTA results
- SRF Cryomodules certification tests results so far
- Conclusion

FRIB SRF Cavity Design Goals and Certification Progress June 2017

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)**
Total # of Cryomodules Certified (# Cavities)	**3 (16)**	**5 (69)**	**0* (68)**	**1 (17)**

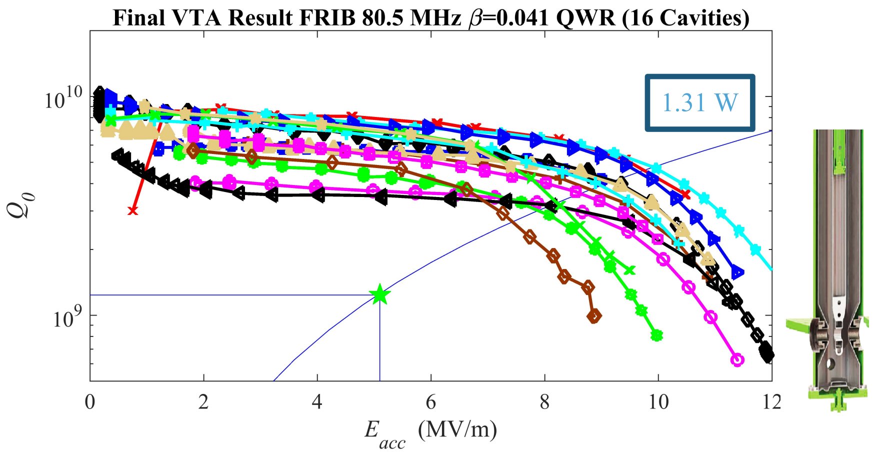
The main VTA certification criteria is to reach 20% higher gradient with specified Q value

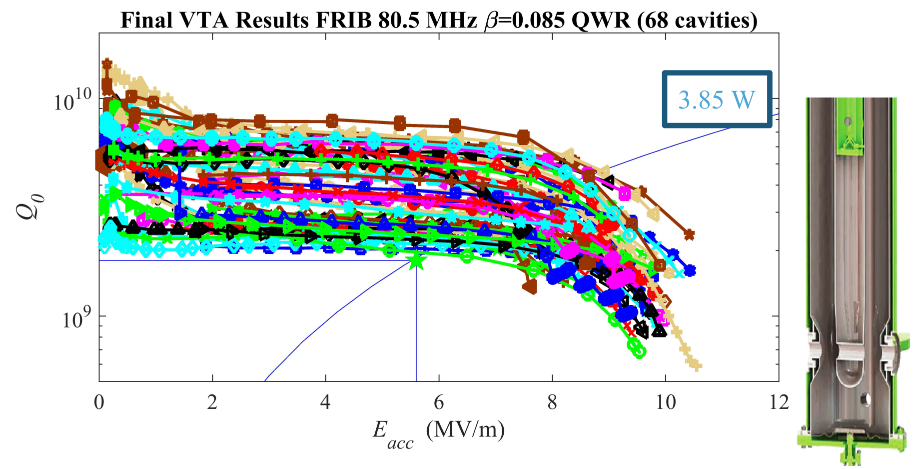
*** The 1st beta= 0.29 Accelerating module is being tested right now**

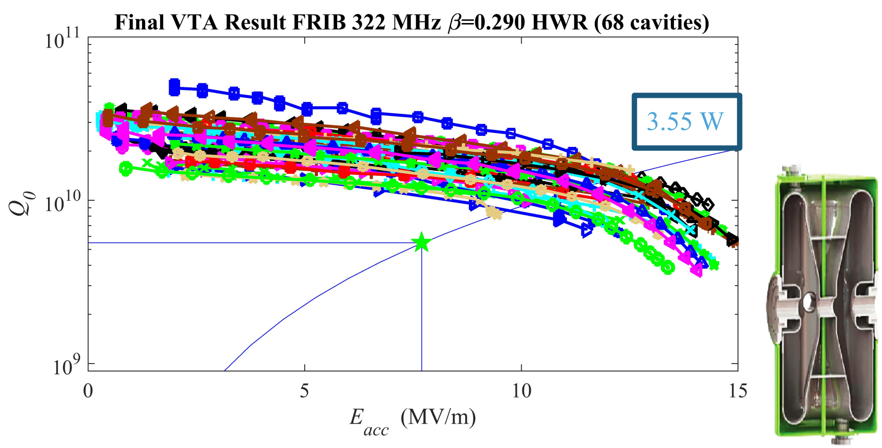
Cavity Production & Vertical Test Status

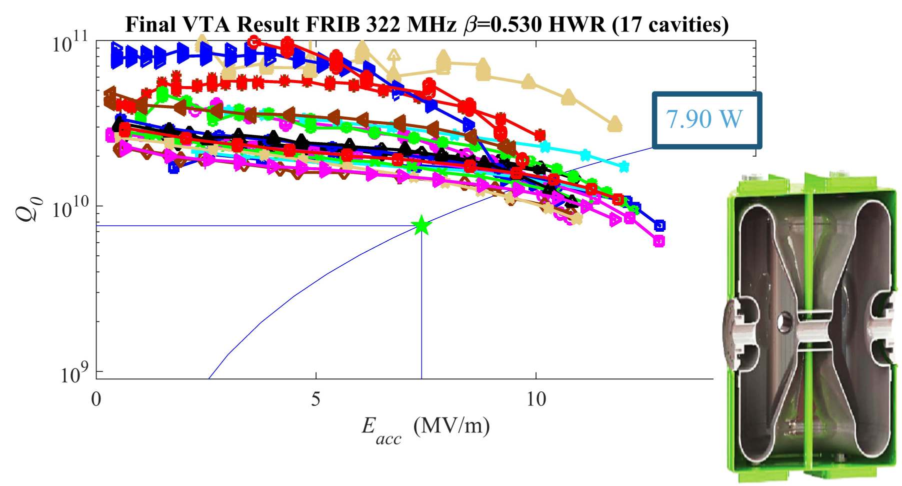
- 73% (240/328) of total cavities for FRIB project received (0.041QWR and 0.29HWR delivery completed) in July 2017
- >96% of the received cavities is accepted to SRF highbay workflow
- 87% (208) cavities accepted is certified to be installed on cold mass
- Four certifications per week in average at one test per day throughput
- We have a less than 20% rework rate (after vertical test)
- 10% reject to vendor (before test) for repair or rework
  - Welding issue, dimensional issue and threads issue
- Project to receive all cavities by end of 2017

FRIB Vertical Test Certification Results
2K, final test before installing to coldmass

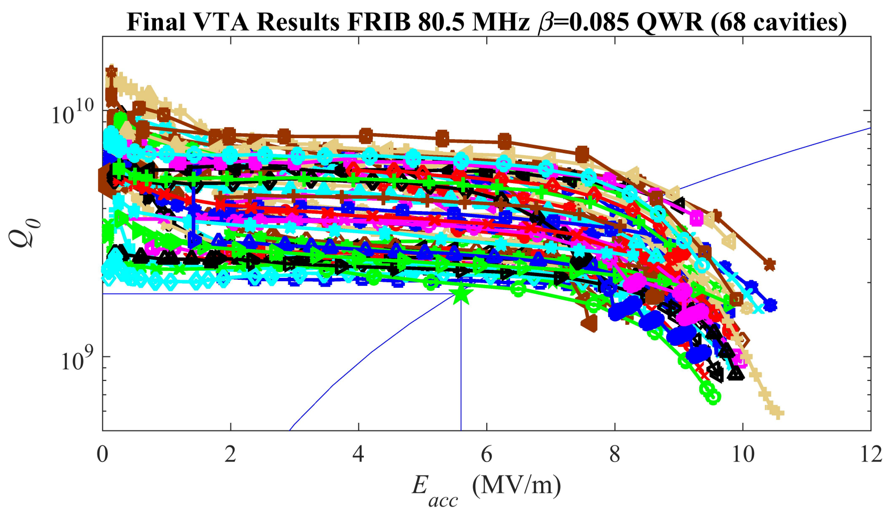


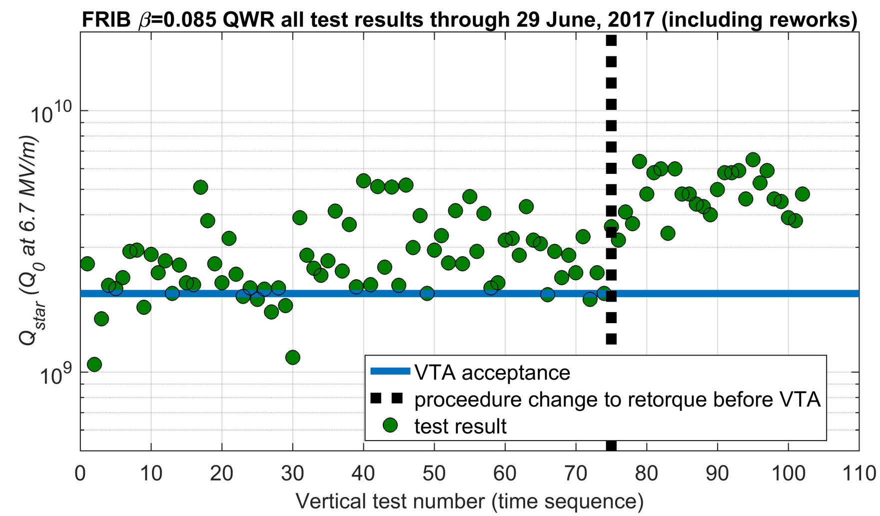






Beta=0.085 QWRs





- Large spread in Q value since start of production
- The Q was lower than we expected from prototype testing and NSCL Reaccerator (one 8 cavity cryomodule)
- Non-passing Q result lead to rework / retesting (including low temperature baking)
- A recent process change has given us higher Q value and much lower rework rate (April 2017)
- The bottom flanges have been always re torqued before installing coldness to cryomodule (explains cryomodule dynamic load measurements)
- In one cavity we thermal cycled several times and found the indium seal stays in good condition

Typical VTA Work Day Breakdown and Acceptance Criteria

- The vertical test insert is prepared in the evening before the test is scheduled.
- VTA cooldown starts by 9AM (not a dunk test, we cool only cavity in the helium vessel and a tank above)
- 4K testing, thorough multipacting conditioning takes 1-4 hours
- 2K testing is completed by 5PM
- Cavity insert is warmed up and removed before the next day (Dewar warms up in <1 day, can be used every other day requiring only 2 Dewars for 1 cavity test per day)

Table 1 Vertical test acceptance ranges for FRIB resonators at 2K

β / *Parameter*	0.041	0.085	0.290	0.530
1. Q_0	$> 1.4\times10^9$	$> 2.0\times10^9$	$> 6.7\times10^9$	$> 9.2\times10^9$
2. E_{acc}	> 6.1 MV/m	> 6.7 MV/m	> 9.2 MV/m	> 8.9 MV/m
3. P_{cav}	$< 1\times10^{-8}$ torr	$< 1\times10^{-8}$ torr	$< 1\times10^{-8}$ torr	$< 1\times10^{-8}$ torr
4. $Q_{ext,2}$	7.8×10^9 to 7.8×10^{10}	4.4×10^{10} to 4.4×10^{11}	9.4×10^{10} to 9.4×10^{11}	2.8×10^{11} to 2.8×10^{12}
5. f_{cold}	80.506 MHz ± 10 kHz	80.504 MHz ± 10 kHz	322.088 MHz ± 25 kHz	322.070 MHz ± 40 kHz

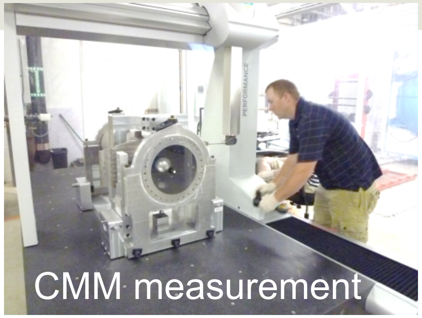
Beta=0.85 QWR hanging on vertical test insert the day after a vertical test

Other measurements include Lorentz for detuning coefficient, Xrays, df/dP, and we can verify there is no cold helium vessel leak. Insulating vacuum is not an acceptance criteria but many times we request after we repair any leaks on the insert cryogenic plumbing

SRF Highbay Infrastructure

- All critical SRF tasks are performed on-site
- Functionalities of the SRF Highbay
  - Acceptance inspection
    - Dimensional inspection by CMM
    - Cold shock test, Leak check, Demagnetization
  - Cavity processing and assembly
    - Large cleanroom
    - Degreasing system
    - Cavity etching (BCP) system
    - **Robotic high pressure rinsing system**
    - Ultrapure water system
    - Hydrogen degassing furnace
  - Cavity vertical test system,
    - 3 Dewars and 4 cold inserts
  - Cold mass assembly
  - Bunker test system
  - Cryogenic system (Dedicated 900W helium refrigerator, helium purification and 2K system)

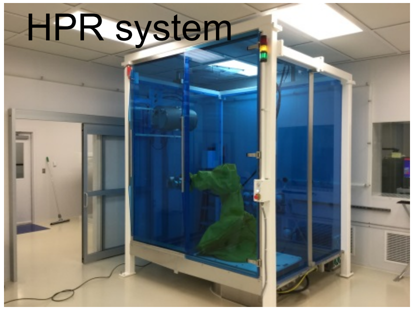

Bunker test system


CMM measurement


Large cleanroom


BCP facility


Cavity assembly


HPR system


Vacuum furnace


Cold box and 5000L Dewar


Vertical test area

Outline of FRIB Cryomodule Testing Program

- FRIB Cryomodules are tested before installation in FRIB tunnel
  - 9 cryomodules tested so far
- We check major issues to ensure cryomodule can proceed to installation or requires rework.
  - Cavity accelerating field (locked to reference with LLRF),
  - Heat load (and cavity 2K operation)
  - Magnet operations (Integrated with cavity).
- We look for degradation in performance from vertical test
- We record data which can be used for future comparison:
  - Total dynamic load (often done in cavity pairs)
  - FE onset for each cavity
  - RF power needs (in SEL and locked to reference)
  - Cavity field level calibration

FRIB Cryomodule Test Procedure

1 week

RF power line calibration

Cavity bandwidth

Cavity 4 K test
- X-ray survey, Pf vs. Eacc
- Tuner, LLRF lock for > 1 hr

Alignment, Leak tightness

1 - 4 days

Solenoid package test
- Excitation each magnet
- Magnets simultaneous operation at maximum field, polarity change
- Solenoid package / cavities simultaneous operation

1 - 2 days

Cavity 2 K test
- Eacc
- Cavity dynamic heat load

1 day

2 K/4.5 K headers static heat load

test report
ACL test results

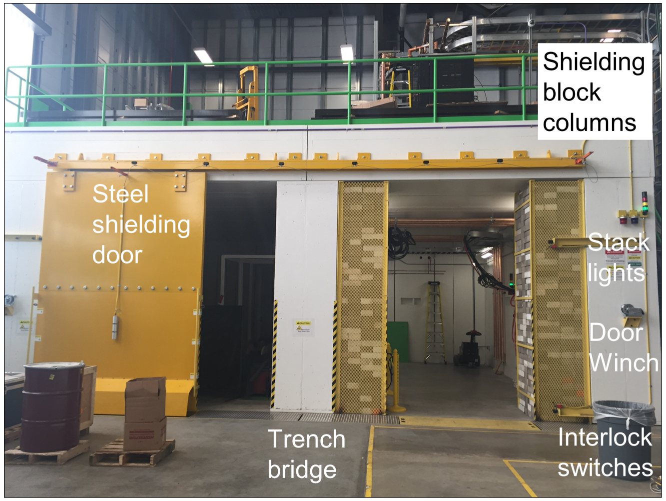
Rework if needed

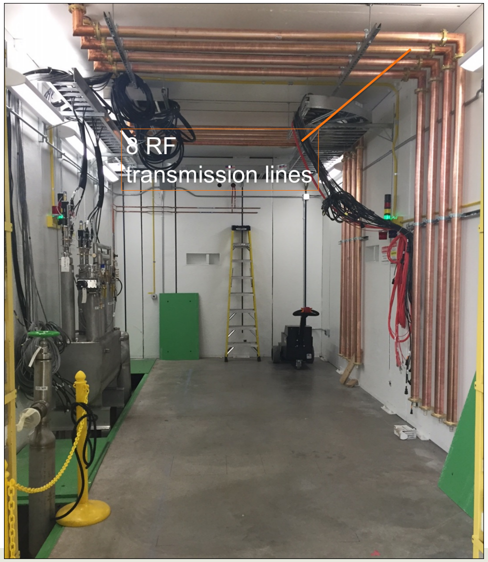
- 2 K dynamic heat load calibrated by heater. We use both dP/dt method and pump speed method
- After 1sty article test, not all cavities' dynamic load are measured, by the reliable cavity performance and limited schedule.
- 2 K/4.5 K header static heat loads are measured by liquid helium level.

typical cool down 1 wk
typical warm up 1 wk

SRF High bay bunker: 1 active bay

- Located in FRIB SRF highbay
- 1 bay is ready with cryo and RF and the other does not have cryo or RF
- 2 RF systems on top of bunker, can toggle between cavities from outside of bunker fairly quickly
- VTA and cryomodule testing can coexist with no issues
- So far, only used for FRIB HWR testing:
  - 1st article Beta=0.53 HWR cryomodule (complete)
  - 1st article Beta=0.29 HWR cryomodule (testing underway)

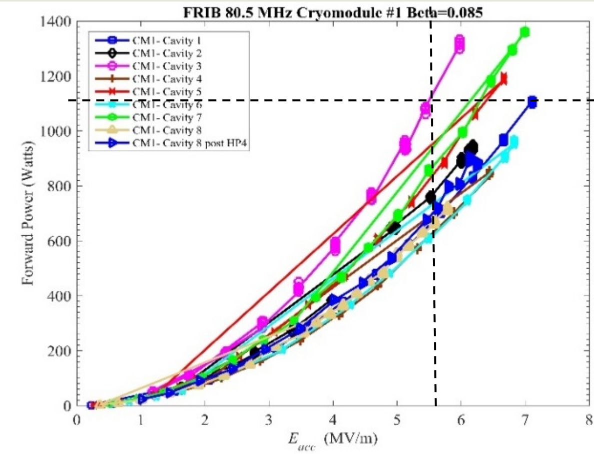




ReA6 Bunker: 1 active bay

- Located in NSCL ReA area in ReA6 upgrade spot
- Close proximity to crymodule production area but separate building from SRF high bay
- 2 RF systems but cavities must be switched inside the bunker
- So far we have tested 9 cryomodules in this bunker (1 prototype)
- Cool down is underway for the 9th production cryomodule test
- We will do upgrade to the bunker in order to test HWR cryomodules

Bunker Test Performance Example: SCM801 (FRIB First 0.085QWR Cryomodule)



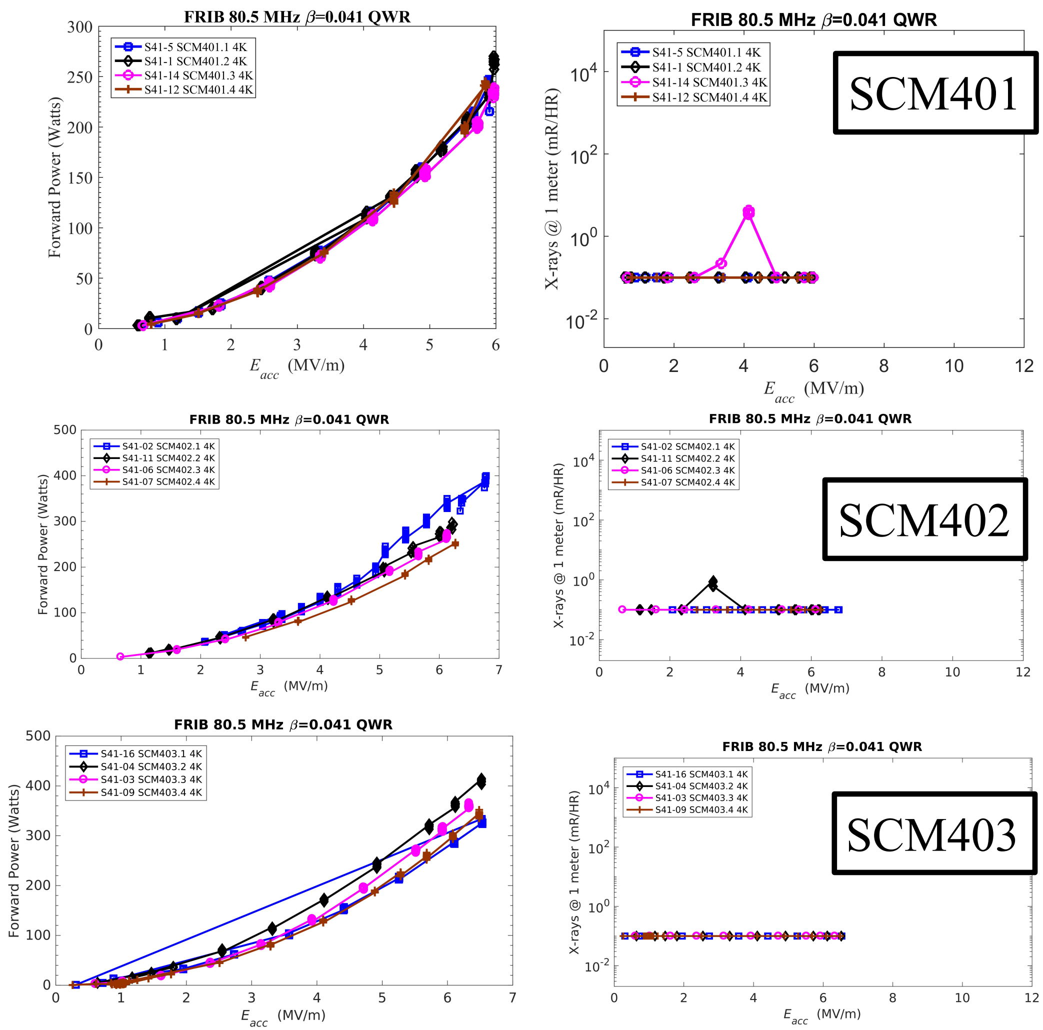
- Cavity gradient (Requirement 5.6 MV/m, P_f < 2.5 kW)
  - Result: Eacc ≧ 6 MV/m @ P_f max= 1.1 kW at 4 K , meets FRIB specifications
  - Bandwidth 31 ± 9 Hz, meets Spec (40Hz)
- Dynamic Loss (spec 3.85 W, Q_0 =1.8 x 10^9 at 2 K)
  - Result: 2.8 W, Q_0=2.5 x10^9 in average at 2 K, ~ 40 % margin for FRIB Spec.
  - No Q-degradation by cold mass assembly (result includes coupler loss 0.25W)
- Coupler and tuner work well
- All cavities are locked in spec at 4.5K for > 1hr, LL control works well.
- Cryogenics system is very stable throughout test period

- Heat loads (Static + dynamic heat loads)
  - Cavity header 28.8W (Spec 36W), meets spec.
  - Solenoid header 23.7W (Spec 22.6W), meets spec within measurement error (10%).

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**

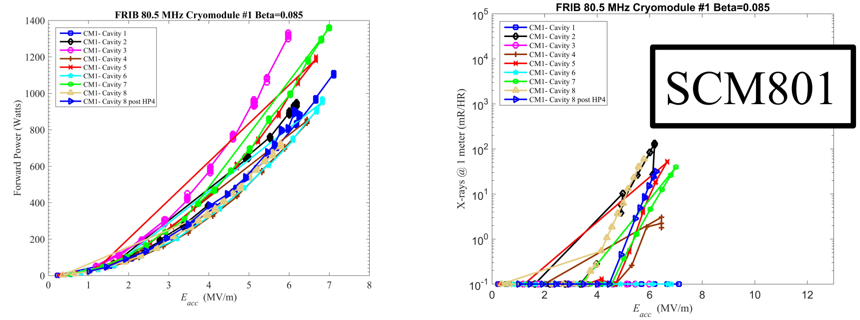
Beta=0.041: 3 cryomodules certified (1 more spare is built and ready for test)

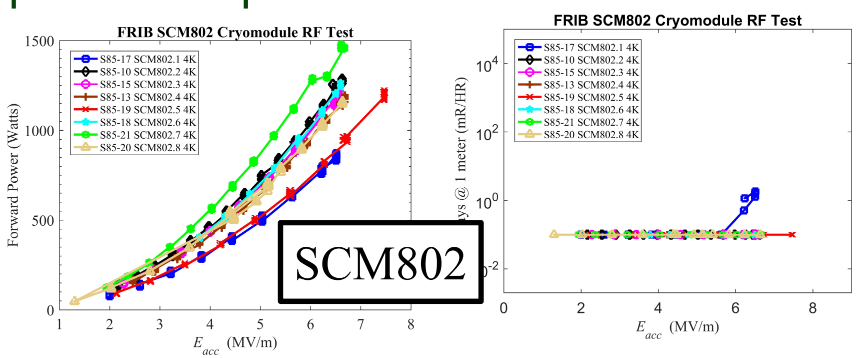
- No Xrays in the beta=0.41 cavities other than some transient Xray which conditioned very easily
- All cavities locked to reference within FRIB specification for at least one hour (at 4K)
- 2K dynamic heat load confirms heat load is much less than the design value

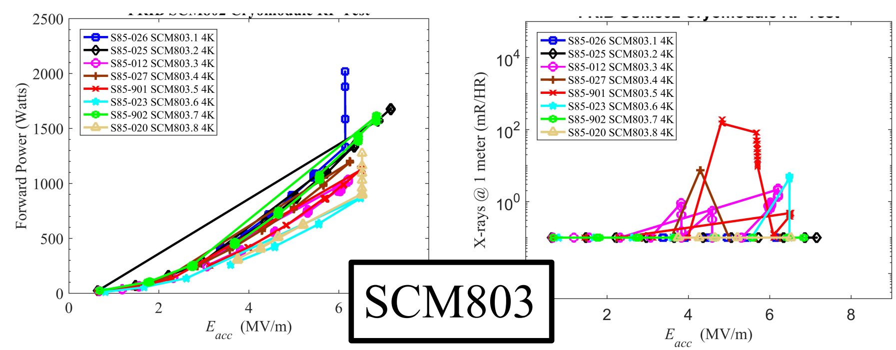


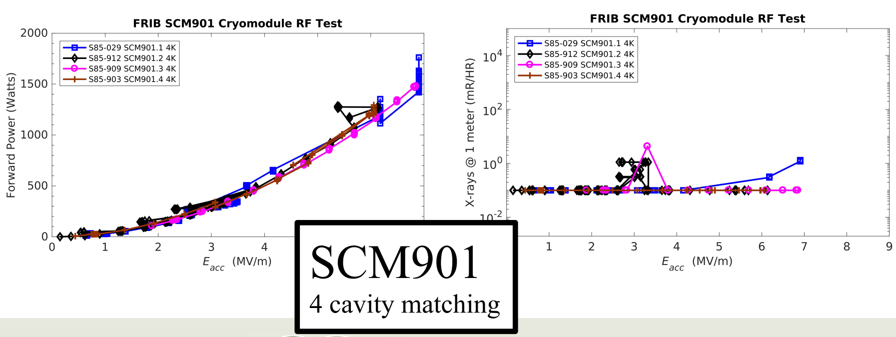
Beta=085: 5 Cryomodules certified, one is cooling for test right now

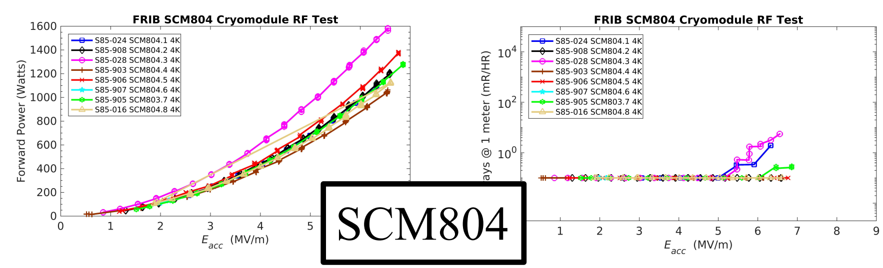
- All cavities locked to reference within FRIB specification for at least one hour (at 4K)
- 2K dynamic heat load confirms heat load is less than the design value
- X-rays reduced from 1st cryomodule due to process improvements











SCM501 (FRIB First Beta = 0.53 HWR Cryomodule)

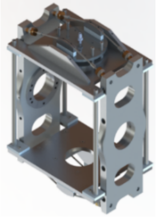
Cavity gradient (FRIB spec 7.4 MV/m, P_f < 5kW max.)

- Result: Eacc ≧ 7.4 MV/m @ P_f max 3.5 kW at 4 K, meets Spec
- Two cavities need more power due to FE but are expected to improve by more RF conditioning at weak coupling
- Bandwidth 33 ± 9 Hz, meets Spec (30Hz)

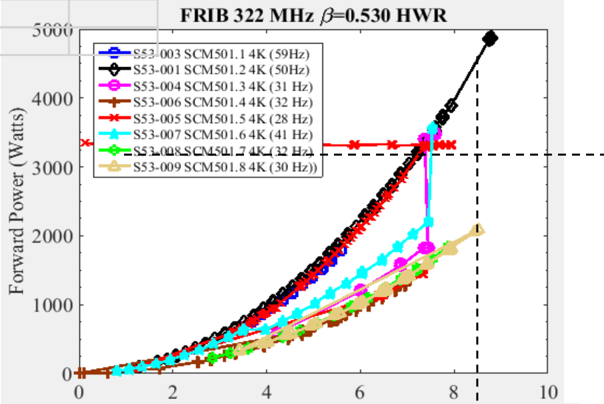
Dynamic Loss (Spec 7.9W, Q_0 =7.6x 10^9 at 2 K)

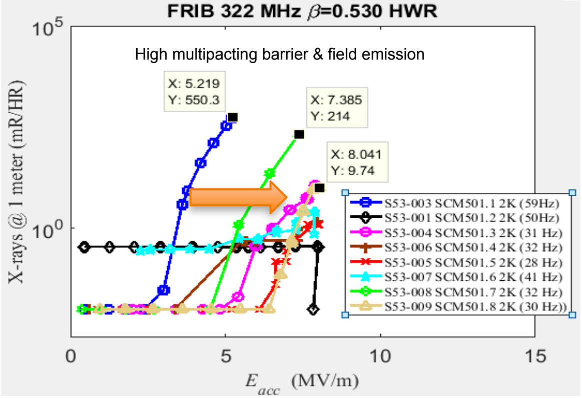
- Result: 4.09±1.5 W, Q_0=(1.58 ±0.37) x10^{10} in average at 2 K, ~ 100 % margin for FRIB Spec.
- Qo in the bunker test is high enough, no remarkable Q-degradation by cold mass assembly
- Needed RF conditioning to mitigate field emission (we suspect the FE comes from too aggressive conditioning of cavity multipacting barrier: lesson learned: keep X ray level low)

Position	Field (MV/m)	2K heat load (W)	% (field spec)	goal (MV/m)
1	7.5	4.5	101.4%	7.4
2	8	3.5	108.1%	7.4
3	**8**	**2.6**	108.1%	7.4
4	**8.1**	**3.5**	109.5%	7.4
5	8	3.5	108.1%	7.4
6	**8**	**2.6**	108.1%	7.4
7	**7.4**	**7**	100.0%	7.4
8	7.5	**5.5**	101.4%	7.4
Averge	**7.81**	**4.09**	105.6%	7.4
Total 2K dynamic load		32.7		
Specified 2K dynamic load		63.2		



- Couplers needs -1KV bias operation to suppress multipacting using the preproduction couplers
- Pneumatic tuner works well.
- All cavities are locked in spec at 4.5K for > 1hr, LL control works well.
- Heat loads (Static + dynamic heat loads):
  - Cavity header 38.7W (Spec 71.7W), meets spec.
  - Solenoid header 12.3 ± 0.7W (Spec 29.4W), meets Spec.
- Repeated Dynamic heat load measurement after using magnet (w/ degaussing) and after complete thermal cycle → no degradation



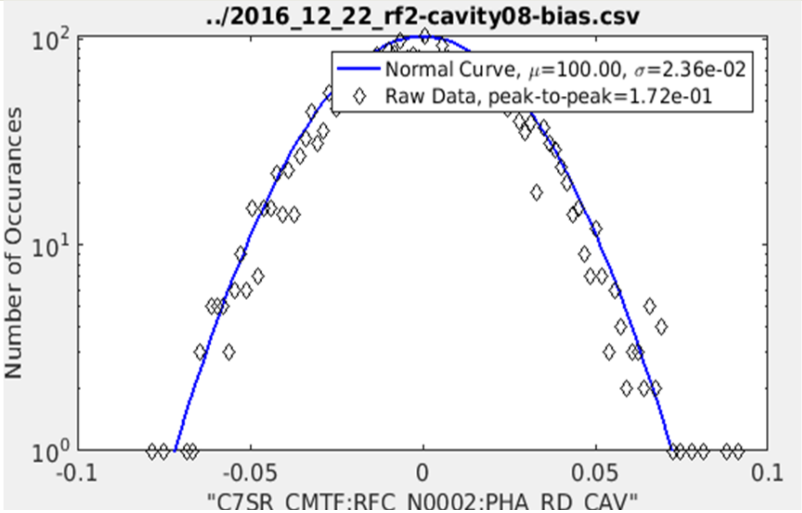


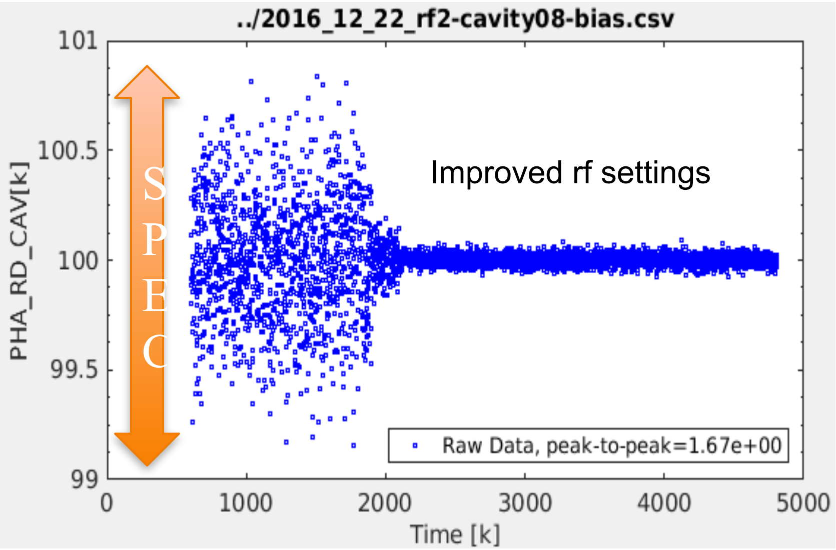
β=0.53 HWR LLRF Locking Validation

- All cavities locked > 1hr at 30 RF Hz BW, 4 K within amplitude and phase specification: < 2 deg pk-pk phase stability, < 2% pk-pk amplitude stability with DC bias -1.0 kV
- All cavities locked at greater voltage than the design value (5.6% higher overall for the cryomodule)
- More optimized LLRF control parameter produced higher phase stability

The scatter in the left of the bottom Figure still meets FRIB spec(< 2% peak to peak), the right shows the stability under the more optimized LLRF control parameters

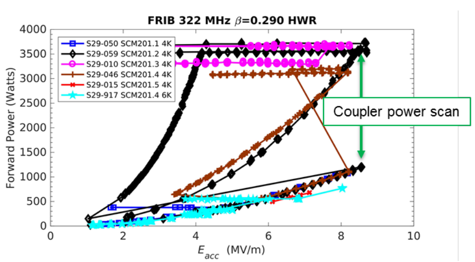
Stability improved about one order of magnitude

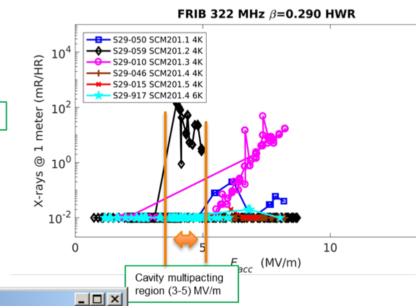


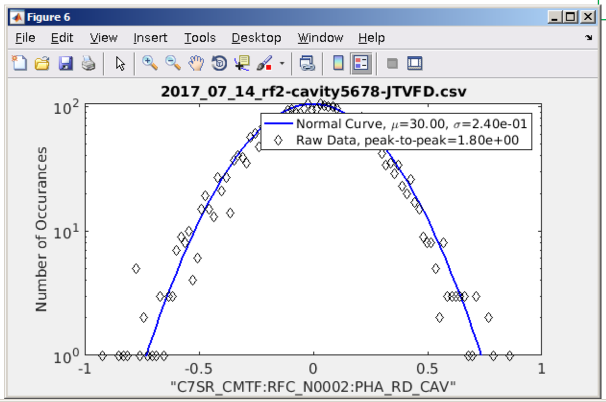


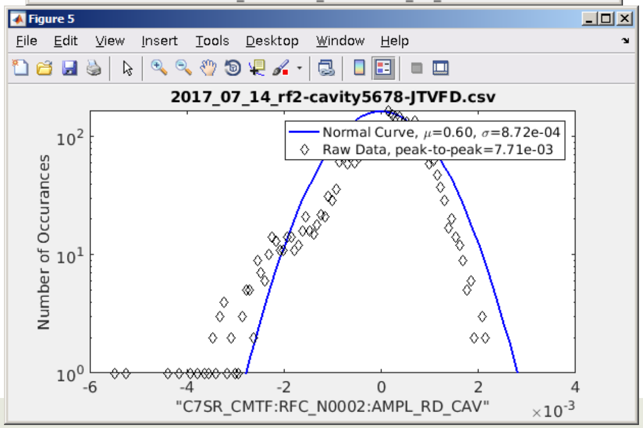
SCM201 (FRIB First Beta = 0.29 HWR Cryomodule)

- Testing is currently underway at FRIB
- As with other first article testing, we spend more time on this cryomodule
- Have scanned all cavities to ~8.5 MV/m and Pf ~3.5 kW.
- Multipacting is reduced using the production coupler but so far we are still using bias
- Have locked 5/6 cavities for greater than 1 hour at 4K (@ 8 MV/m)
  - Phase locking is +/- 1.8 degrees
  - Amplitude locking as +/- 0.6%
- High multipacting barrier (3-5 MV/m) needs to be fully conditioned, doing so seems to reduce field emission









2 K/4.5 K Heat Loads Data Accumulated

- 2 K heat loads
  - 2 K static heat load is high but 2 K total heat load : Static +Dynamic is within budget thanks to high Q cavity performance, Spec T30200-TD-000244

2K heat load	Averaged static heat load [W]	Averaged 2K heat load/CM [W]
0.041QWR SCM with 3 CMs	**4.3**	**8.3**
0.085QWR SCM with 4 CMs	**8.7**	**32.1**
0.53QWR SCM with SCM501	**6.0**	**38.8**

- 4.5 K heat load
  - 4.5K static heat load is high but the total 4.5K heat load overall FRIB SRF might be within budget thanks to the 0.53 half-wave resonators (HWR) good cryomodule performance

4.5K heat load	Averaged static heat load [W]	Averaged 2K heat load/CM [W]
0.041QWR SCM with 3 CMs	**14.6**	**16.8**
0.085QWR SCM with 4 CMs	**28.2**	**31.5**
0.53QWR SCM with SCM501	**12.3**	**13.4**

- Update projection of CM's heat load based on real data
  - Current projection is within 10% of T30200-TD-000244 (2349 W at 4.5 K, 1195 at 2 K)
  - Need more data on HWR cryomodules for better projection

Conclusion

- Total 9 cryomodules are bunker tested by July 2017. The final “first-article” cryomodule test (beta=0.29 HWR) is underway and is progressing well.
- Cavity Dynamic loads in cryomodule are comparable to VTA.
- Cavities can be controlled very well within the installed RF power limits
- SRF highbay production processing, cavity certification rates, and cryomodule test rates are moving at a pace we had originally conceived.