FRIB

FRIB SRF Cryomodule Performance Testing and Status

John Popielarski

HB 2018

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Cryomodule production status and overview of FRIB cryomodule production process
- SRF cavity and cryomodule certification methods, results and mitigations
- RF commissioning progress in the Linac

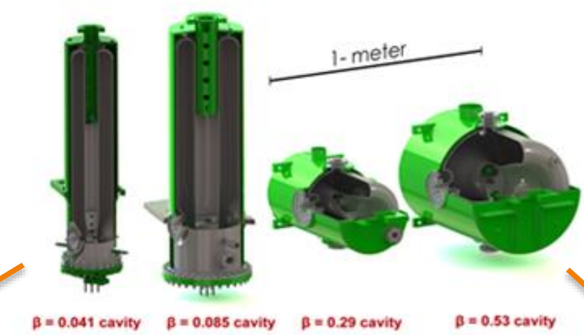
Status

- 79% of cavity certification complete
- 73% of coldmass assemblies are complete (36 of 49)
- 53% cryomodule fabrication is complete (26 of 49)
- 47% cryomodules certified and installed in FRIB linac
- RF commissioning underway for the first three FRIB cryomodules installed in FRIB linac

FRIB Low Beta SRF: 4 cavity types, 6 cryomodule types, 332 cavities, 49 cryomodules

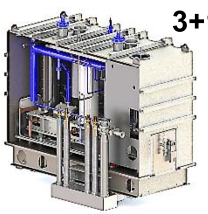
Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.29	0.53
f (MHz)	80.5	80.5	322	322
Accelerating voltage (MV)	0.81	1.78	2.09	3.70
E_a (MV/m)	5.1	5.6	7.7	7.4
Peak E field E_p (MV/m)	30.8	33.4	33.3	26.5
Peak B field B_p (mT)	54.6	68.9	59.6	63.2
Q_0 (VTA)	1.4E9	2.0E9	6.7E9	9.2E9
# of cavities/cryomodule	4	8	6	8
Total Dynamic load to cryoplant (2 K)	7.3	34.8	22.8	65.2
Control bandwith (Hz)	40	40	52	30
Maximum RF power (kW)	0.7	2.5	2.8	5.0
# of cavities needed	12	92	72	148
# of cavities certified	16	69	68	17
# of cryomodules needed	3	11	12	18
# of cryomodules certified	3	5	0	1

16 96 72 148



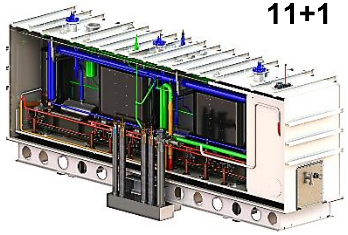
Accelerating

3+1



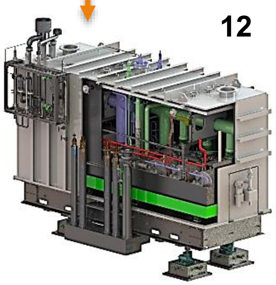
Beta=0.041 (4 cavities, 2 magnets)

11+1



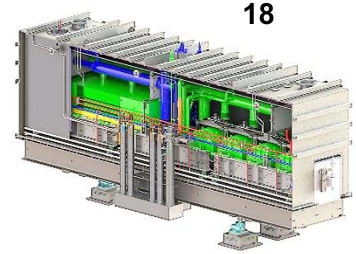
Beta=0.085 (8 cavities, 3 magnets)

12



Beta=0.29 (6 cavities, 1 magnet)

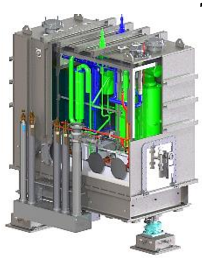
18



Beta=0.53 (8 cavities, 1 magnet)

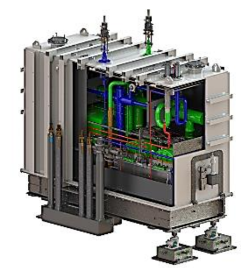
Matching

1+1



Beta=0.085 (4 cavities)

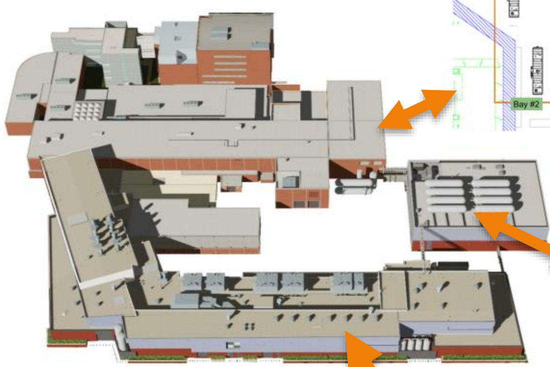
1



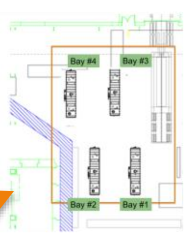
Beta=0.53 (4 cavities)

The FRIB site has all the infrastructure needed for the technical construction and testing of SRF cryomodules

FRIB site at Michigan State University



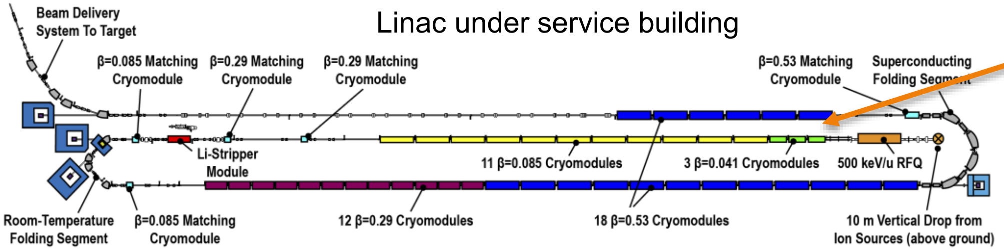
Cryomodule assembly area: 5 construction bays and 1 test bunker



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

Service building

Linac under service building

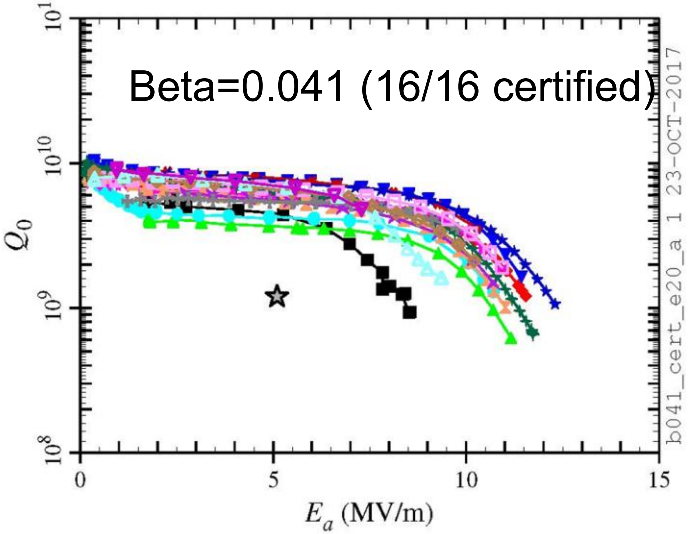


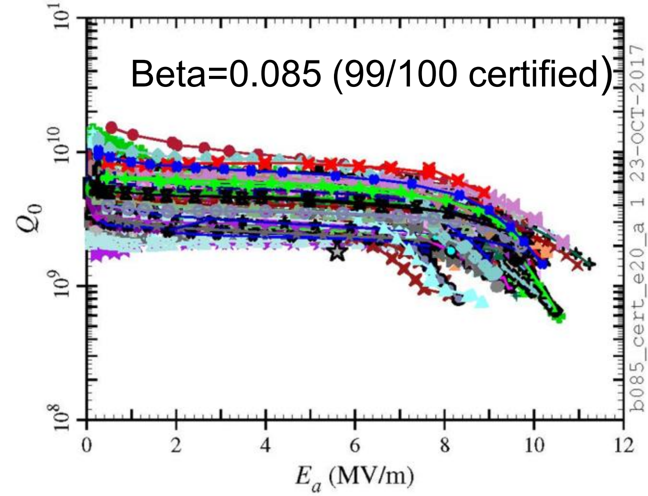
Cryomodules are installed in Linac and RF commissioning has begun

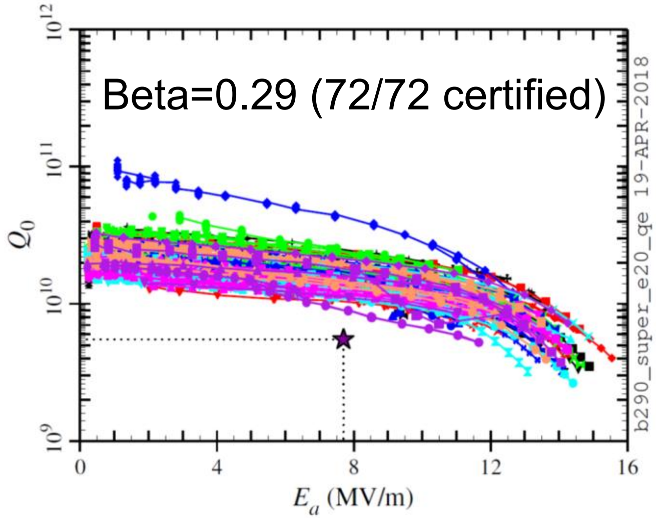
SRF Cavities Certified in Vertical Test Area before Assembled onto the Cold masses

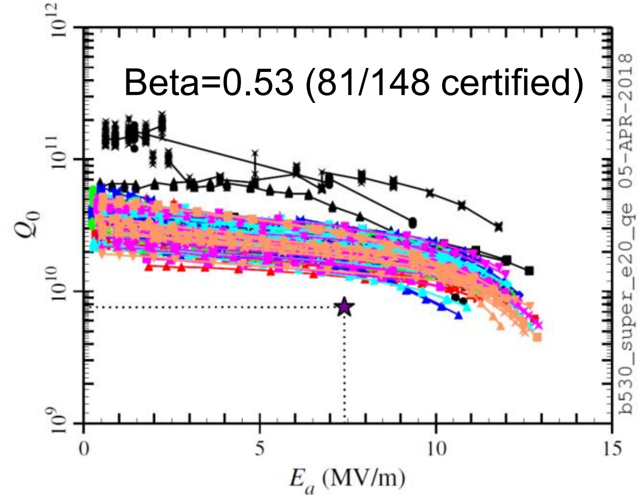
- Vertical Testing of SRF cavities has throughput of one cavity test per day.
- We use 2 Dewar pits and alternate the test location each day.
- After cavities are certified in VTA, they are stored until they are installed on to the cold mass rails

Vertical Test Results



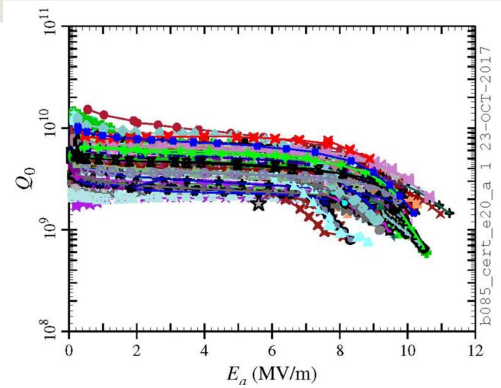


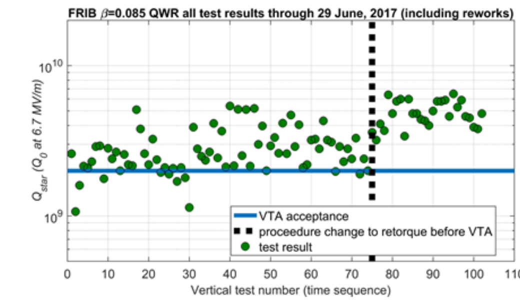


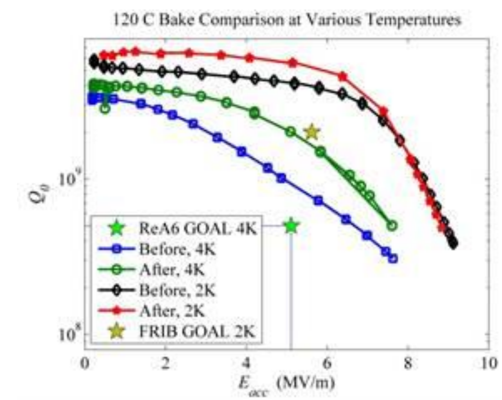


FRIB 085 QWR

- In the first part of the beta=.085 QWR production, we had inconsistent VTA results do to improper sealing of the indium seal flange.
- With the inconsistency, we could not accurately study the effect of low temperature baking (120C, 48 hrs).
- After resolving bottom flange sealing issue, we can study the effect of low temperature bake.
- A test done on June 13 shows improvement in the high field Q at 4K, but not much improvement at 2K.
- This result is similar to a study done for ReA cavities (beta=0.085 QWRs with smaller aperture)

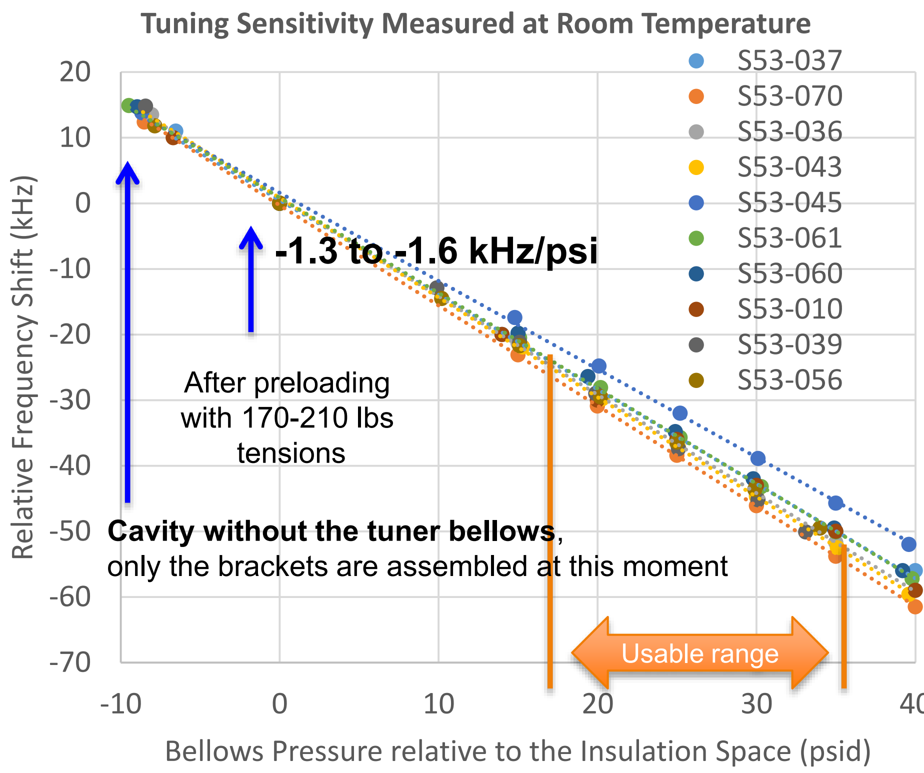






HWR Cavity Tuning: The spread in tuning sensitivity requires a tuning range measurement prior to final chemistry

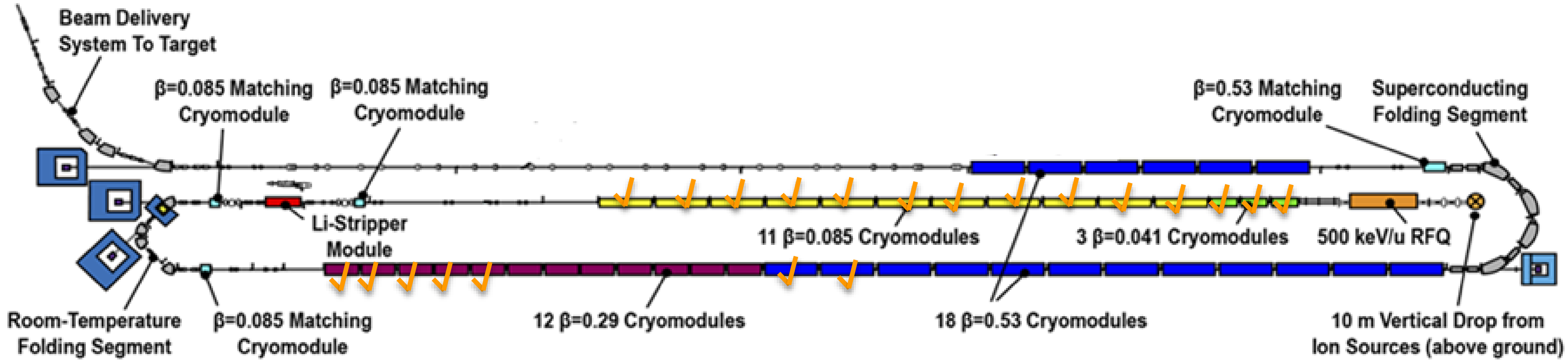
- The usable tuning range is ~30 kHz
- Final tuning of HWR is done by chemical removal on the niobium RF surface
- We can tune to about +/- 10 kHz accuracy at 2K (main spread is the cool down frequency shift)
- Frequency shifts due to tuner brackets and tuning sensitivity are ~ +/- 10 kHz
- The sensitivity and bracket shifts reproducible: A warm tuning range measurement can remove 50% of the uncertainty



FRIB Fundamental Power Coupler for HWR

- The HWR FPC is a warm window coaxial feedthrough
- 128 have been installed in cold masses
- 220 have been shipped from vendor with coupler conditioning completed
- Some of the early shipped FPC’s were contaminated by shipping container. These were cleaned and reconditioned at FRIB site

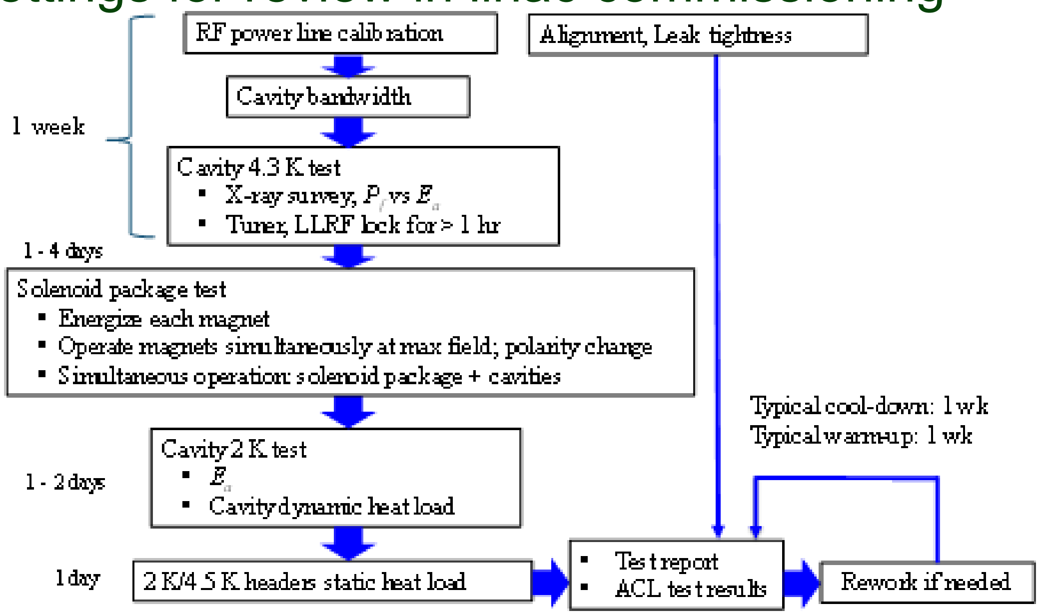
Cryomodule Certification and Tunnel Installation Status



Type	Coldmass completed	Cryomodule assembled	Cryomodule bunker tested	Cryomodule in tunnel	Cryomodule needed (Total + Spare)
0.041QWR	4	4	4	3	3 +1
0.085QWR	11	11	11	11	11+1
0.085 Matching	1	1	1	1	1 +1
0.29HWR	12	7	5	5	12
0.53HWR	7	2	2	2	18
0.53 Matching	0				1
Total	35 complete (+1 ongoing)	25 complete (+4 ongoing)	21+1 complete (+1 ongoing)	22	46 + 3
June 2018	33	24	21	19	

Bunker Test

- FRIB Cryomodules are fully tested before installation in the FRIB tunnel. 23 cryomodules have been certified so far.
- We do calibration and check for Xrays, gradient, LLRF locking, heat load, magnet operation, tuning range
- We save the calibration records and LLRF settings for review in linac commissioning

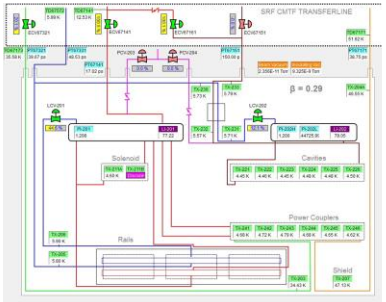


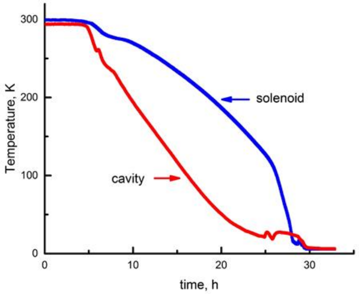
Example: Calibration record for 041 Cryomodules

	Cryomodule SN	SCM401				SCM402				SCM403			
Information	Position	1	2	3	4	1	2	3	4	1	2	3	4
	Cavity SN	**S41-005**	**S41-001**	**S41-014**	**S41-012**	**S41-002**	**S41-011**	**S41-006**	**S41-007**	**S41-016**	**S41-004**	**S41-003**	**S41-009**
	LLRF SN	S01004	S01005	S01006	S01007	S01008	S01009	S01010	S01011	S01012	S01013	S01014	S01015
	Dual Dir. Coupler SN	D1127	D1136	D1142	D1150	D1161	D1169	D1176	D1184	D1195	D1203	D1209	D1218
	Amplifier SN	S01004	S01003	S01002	S01001	S01012	S01013	S01014	S01016	S01008	S01009	S01010	S01011
Warm Calibrations (low level)													
Warm Calibrations and Checks	Pf coupling (ddc)	-50.00	-50.00	-50.00	-50.00	-50.000	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00
	Pr coupling (ddc)	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00	-50.00
	Pf line loss	-1.81	-1.84	-1.87	-1.90	-1.995	-2.05	-2.04	-2.08	-1.83	-1.87	-1.88	-1.94
	Pr line loss	-1.79	-1.86	-1.87	-1.89	-2.02	-2.05	-2.03	-2.05	-1.83	-1.87	-1.91	-1.91
	Pickup line loss	-1.74	-1.82	-1.86	-1.91	-2.01	-2.04	-2.04	-2.09	-1.82	-1.89	-1.89	-1.94
	Pr line |S11| (looking back)	-23.893	-22.92	-20.783	-22.947	-24.255	-23.474	-21.549	-22.443	-25.344	-22.617	-25.766	-24.483
	Pf line |S11| (looking back)	-21.506	-24.43	-21.361	-22.912	-24.845	-24.032	-22.285	-23.411	-24.832	-24.575	-25.649	-25.602
	Pickup |S11|(looking back)	-24.087	-22.85	-21.228	-21.901	-24.013	-23.716	-21.724	-22.301	-24.712	-23.881	-20.2	-24.934
	Input |S11|	-0.0175	-0.0143	-0.0126	-0.0128	-0.0243	-0.0189	-0.0164	-0.0206	-0.017	-0.0151	-0.0165	-0.0179
	Pickup |S11|	-0.4186	-0.4186	-0.4227	-0.3984	-0.4556	-0.4661	-0.4594	-0.4989	-0.4507	-0.4734	-0.4109	-0.4659
Cold Measurements and calibrations (low level)													
Cold Calibrations and low level measuremetns	RF BW	34.6	35.3	34.5	26.8	40.3	35.6	37.0	33.8	37.5	39.5	36.5	37.0
	Decay time (ms, energy -6 d	6.37	6.24	6.40	8.22	5.48	6.20	5.97	6.53	5.88	5.59	6.04	5.96
	|S21|	-34.69	-34.86	-34.45	-34.41	-35.95	-34.90	-35.00	-35.40	-35.67	-35.51	-35.22	-35.06
	input |S11|	-0.028	-0.026	-0.030	-0.027	-0.019	-0.024	-0.008	-0.021	-0.022	-0.030	-0.027	-0.035
	pickup |S11|	-0.251	-0.243	-0.250	-0.223	-0.292	-0.310	-0.276	-0.302	-0.244	-0.324	-0.284	-0.313
	fmin	80.4900	80.4964	80.5000	80.4886	80.4980	80.4980	80.4962	80.4974	80.4944	80.4923	80.4975	80.4940
	fmax	80.5152	80.5081	80.5121	80.5126	80.5095	80.5142	80.5114	80.5058	80.5044	80.5060	80.5069	80.5066
Coupling strenght and LLRF system calibrations	Qe1	2.32E+06	2.28E+06	2.34E+06	3.00E+06	2.00E+06	2.26E+06	2.18E+06	2.38E+06	2.15E+06	2.04E+06	2.20E+06	2.17E+06
	Qe2+	2.6E+10	2.7E+10	2.5E+10	3.2E+10	3.0E+10	2.7E+10	2.7E+10	3.2E+10	3.1E+10	2.8E+10	2.8E+10	2.7E+10
	Ea_scale	2.01	2.03	1.96	2.21	2.15	2.02	2.01	2.20	2.16	2.06	2.07	2.02
	Pt_scale	1.240	1.250	1.256	1.261	1.281	1.287	1.285	1.294	1.250	1.267	1.263	1.273
	PF_scale	389.49	390.62	391.97	393.32	397.88	400.18	399.94	401.56	390.17	392.19	392.42	395.37
	Pr_scale	388.60	391.52	392.19	392.87	398.80	400.18	399.48	400.18	390.17	392.19	393.78	394.00
High Power RF Measurements (Linac Secured)													
High Level RF Measurements	Ea_max						5.61	5.6	5.5	5.6	5.59	5.67	5.6
	Pnom (at Ea = 5.1)	230	235	175	185	250	190	230	260	330	240	215	290
	Xstar (at Ea=5.1)	0	0	0	0	0	0	0	0	0	0	0	0
	decay: ai (dBm)	-26.37	-23.8	-46.22	-47.8	-47.81	-47.24	-47.5	-48.08	-48.51	-32.94	-34.14	-47.95
	decay: dA (dB)	-6	-6.01	-6.01	-5.99	-6	-6.02	-5.99	-6	-5.99	-5.98	-6	-5.99
	decay dt (ms)	6.72	5.4	7.48	8.64	5.96	5.44	6.4	7.32	6.76	5.12	4.88	7.12
QL verrify	QL from decay	2.45E+06	1.97E+06	2.73E+06	3.15E+06	2.17E+06	1.98E+06	2.34E+06	2.67E+06	2.47E+06	1.87E+06	1.78E+06	2.60E+06
RF system settings	FF phase (deg)	170	65	-85	45	-140	160	-75		10	-98	10	-143
	FCO (deg)	-123	-116	-80	-70	65	-83	-97	87	-65	-20	-55	174
	Tuner dead zone (deg)	8	8	10	10	10	8	8	12	10	10	10	10
	Tuner speed	2	2	2	1	2	2	2	2	2	2	2	2
	Amplitude Ramp Rate (MV/m/s)									0.02	0.02	0.02	0.02
	Phase Ramp Rate (deg/s)									0.5	0.5	0.5	0.5
	FF gain	6900	8900	8400	8300	9400	7800	6300	8700	6700	8900	9000	7300
	adrc: BW (Hz)	35	35	34	30	40	36	37	34	38	40	36	37
	adrc: W0/WC	16	16	16	16	8	16	8	16	8	8	16	8
	adrc: BWC (rad/s)	750	750	750	750	600	750	750	600	600	600	600	600
Attenuation	RF Out Attenuation (dB)	10.0	15.5	14.0	15.5	12.0	12.5	13.0	11.0	15.0	13.5	16.5	14.5
	Cav Attenuation (dB)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Interlock Settings	Pf Average (W)	450	430	430	430	450	430	430	480	430	430	430	430
	Pf Average Time (ms)	430	430	430	430	430	430	430	430	430	430	430	430
	Pf Instantaneous (W)	600	600	600	650	600	750	600	700	600	600	600	600
	Pr Average (W)	650	740	740	780	800	740	740	800	800	800	800	800
	Pr Average Time (ms)	5	5	5	5	5	5	5	5	5	5	5	5

Bunker Test Results: Example Beta=0.29 322 MHz HWR

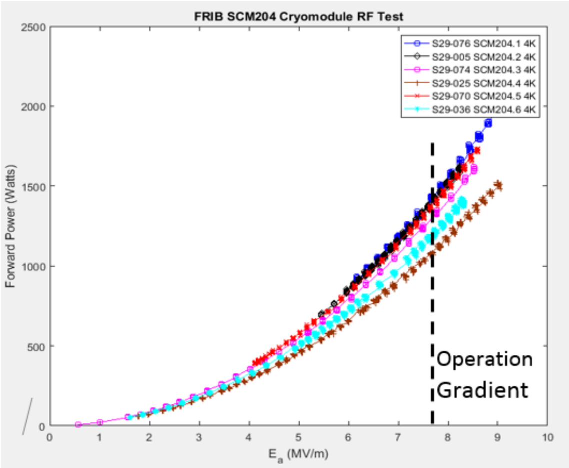
- **Bunker test took place over 2 weeks after cool down**
  - **Bandwidth, pass**
    - FRIB specification: 57.0 Hz
    - 70.3 ± 5.5 Hz, larger a little but okay

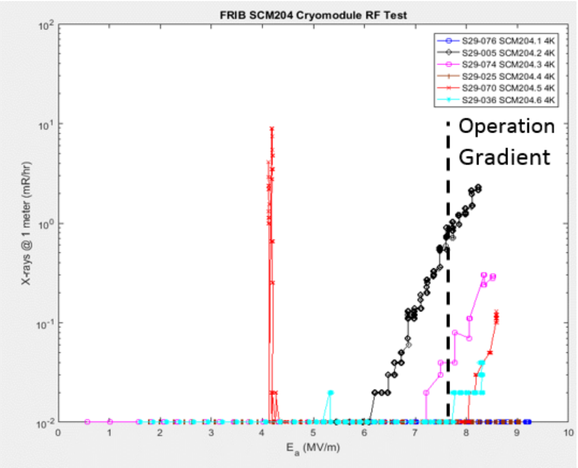




  - **4K High Power Test, pass**
    - Cavities were excited > 7.7 MV/m with forward power < 2 kW
    - Field emission on Cavities 2,3,5, and 6 has X-ray < 2 mR/hr at the operation gradient 7.7 MV/m.

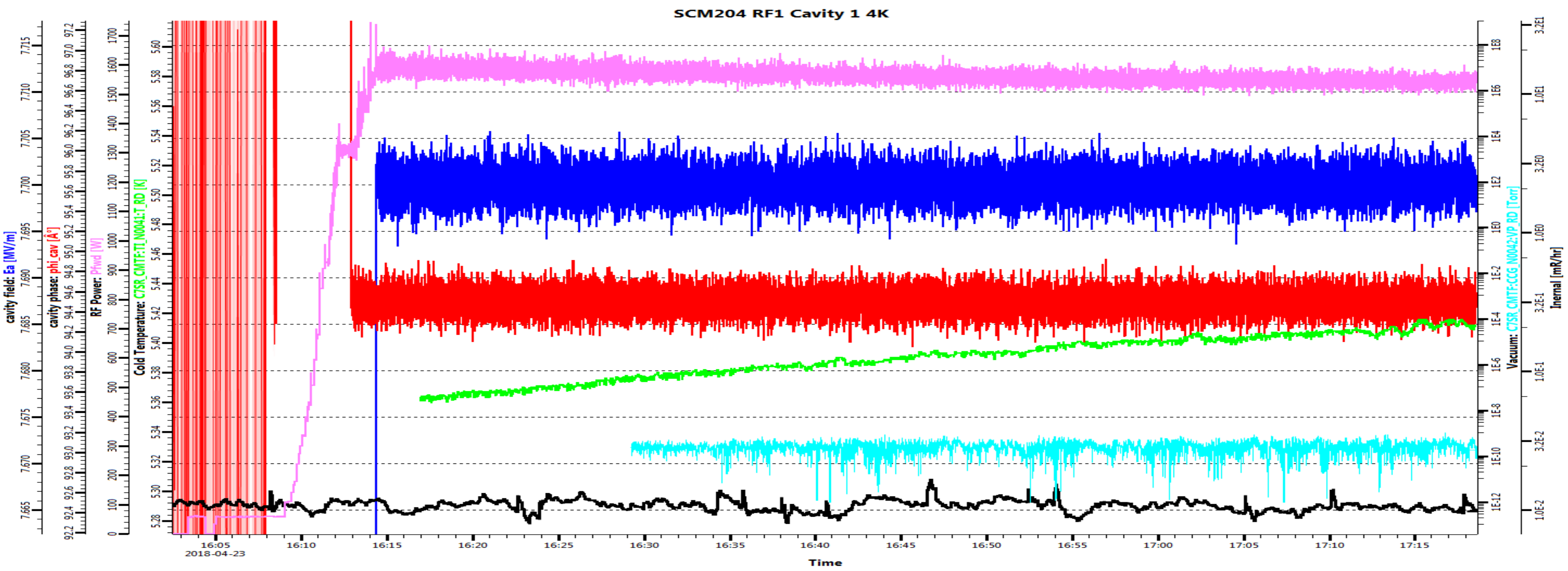
Cavity ID	Cavity S/N	Bandwidth (Hz)
1	S29-076	75
2	S29-005	75
3	S29-074	70
4	S29-025	60
5	S29-070	72
6	S29-036	70
	Average	70.3 ± 5.5





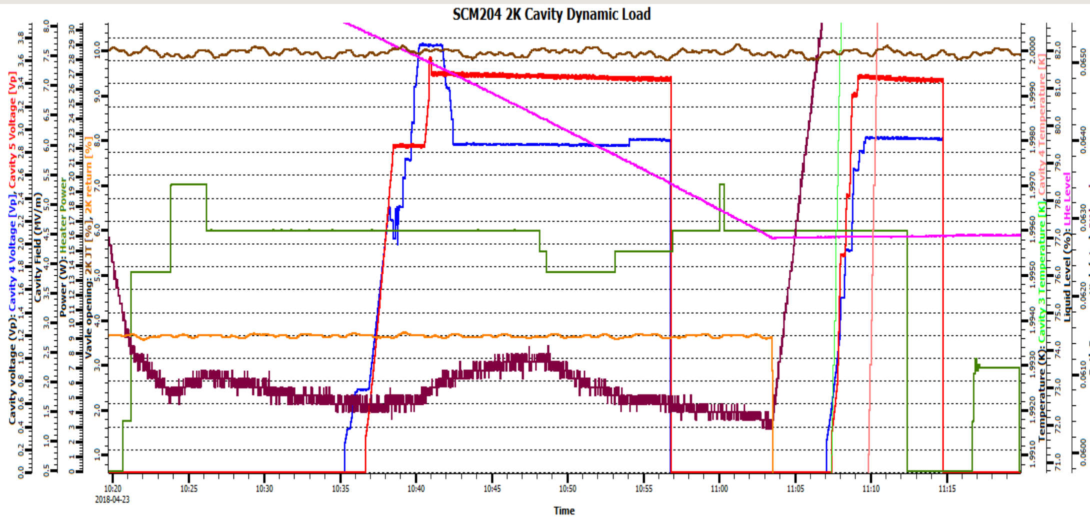
SCM204 Bunker Test Result, continued

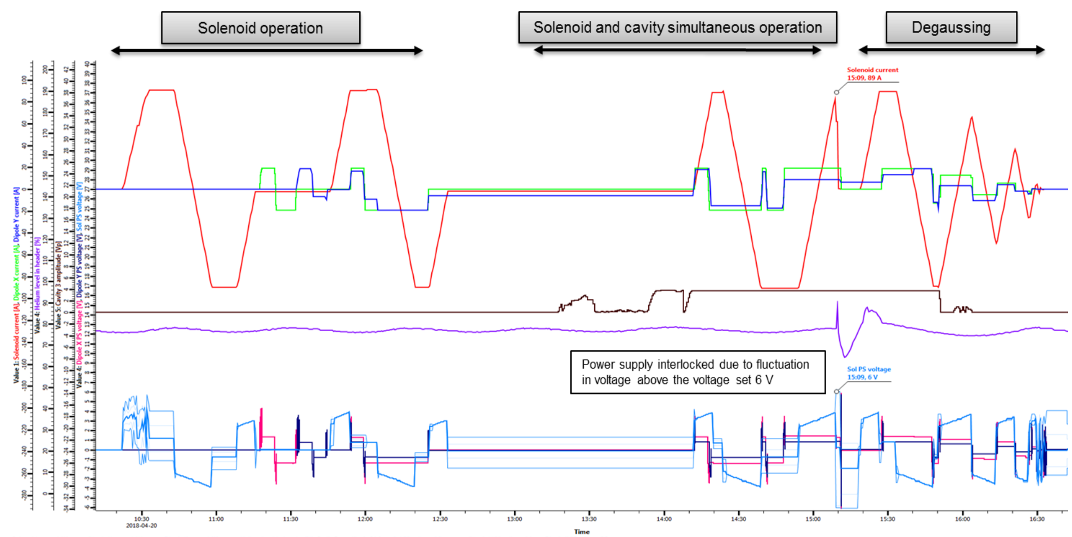
- **RF locking for all cavities at 4K for > 1hr, pass**
  - All cavities except cavity 3 were successfully RF locked at 7.7 MV/m for 1 hr at 4.3 K with -1 kV coupler bias voltage.
  - Cavity 3 was locked 0.5 hr, then tripped due to outside building construction noise.
  - All cavities meets the spec: cavity field amplitude± 1%, phase stability±1^{O}.



SCM204 Bunker Test Result, continued

- **2K dynamic static load, pass**
  - 1.6 W/cavity, corresponds to Q_O=1.2 E10
  - Conserves the high Q performance in cryomodule VTA Q_O = 1.4 ± 0.2 E10
- **Demonstrated robust solenoid package operation, pass**
  - No quench
  - Operated solenoid at ± 91A, dipoles ±19A
- **Static heat load, pass**
  - 2K header 6.3W (spec 5.1W)
  - 4K header not measured

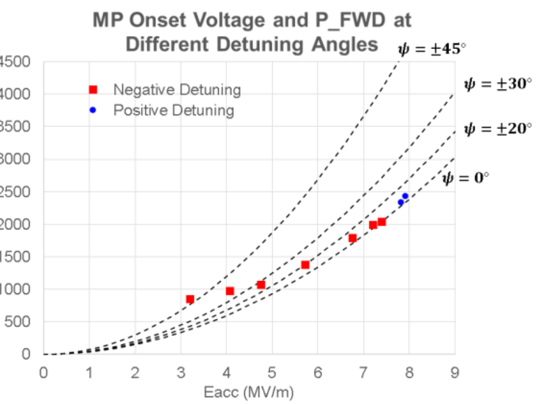




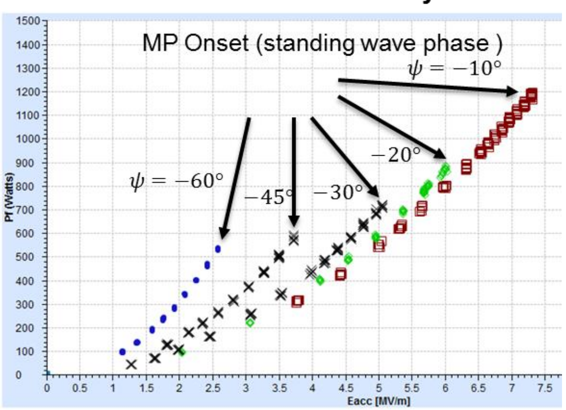
The Coupler Multipacting in HWR cryomodule depends on cavity field and standing wave phase

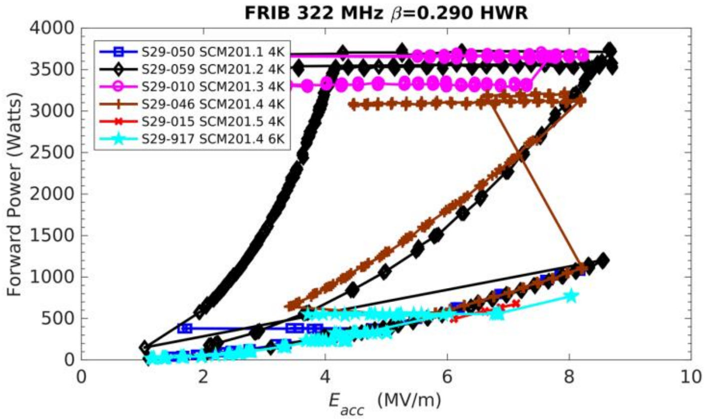
- Without DC bias
  - RF trip due to coupler vacuum pressure rise: >2x10^{-7} Torr
    - » X-rays and minor temperature rise were also detected
    - » Cavity field drops were observed in SCM202, thought to be cavity quench
  - The onset level (RF power/cavity voltage) changes with the detuning phase (more detuning, lower onset power)
- We are installing DC bias for all HWR FPCs (so far in all the bunker tests there are no multipacting when DC bias is used)
- Bias operation is validated by operating max power, detuned (worst case according to the model)

SCM502 Cavity 8



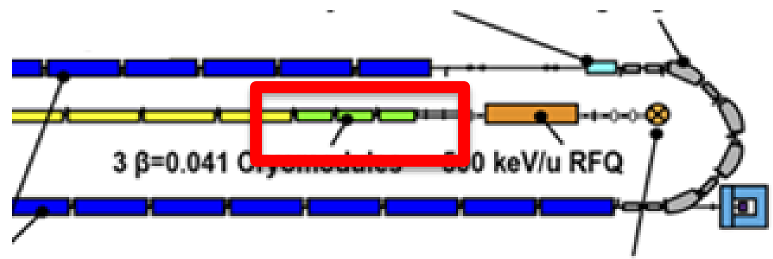
SCM202 Cavity 4



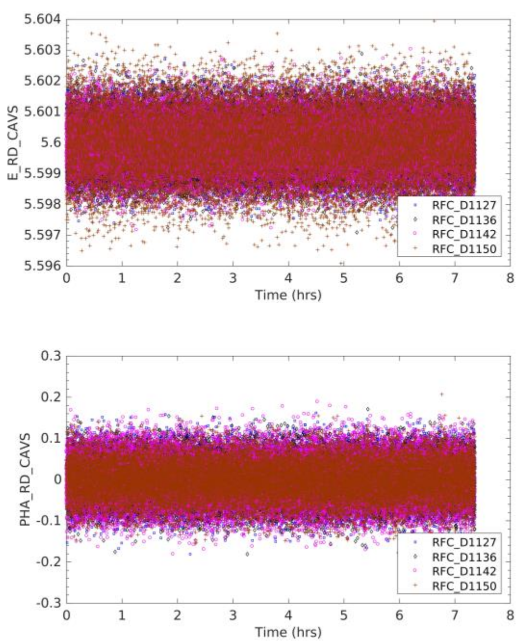


CA RF Commissioning: Beta=0.041 cryomodules

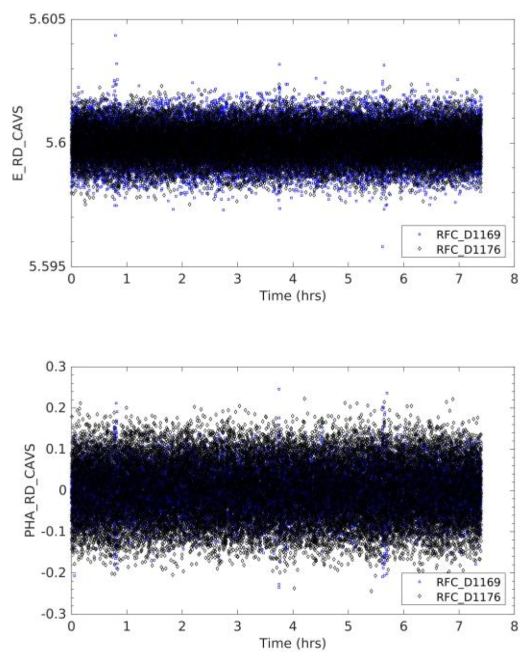
- RF Commissioning on 1st 3 cryomodules in progress
- So far 10 Cavities (of 12) locked at 10% higher gradient than the specification (5.1 MV/m Eacc)



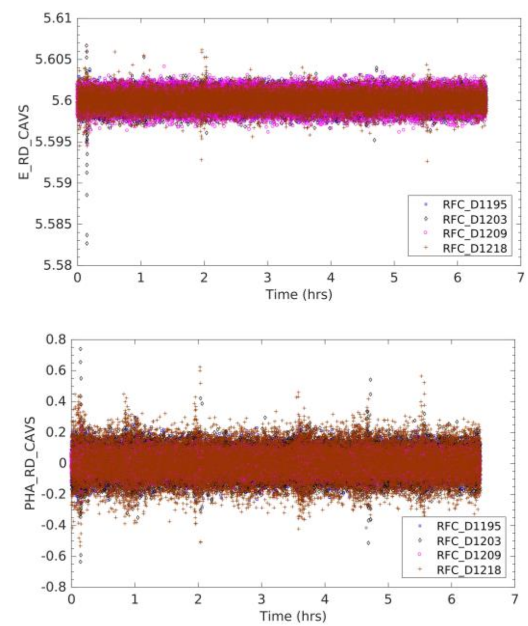
CA01: all 4 cavities at 5.6 MV/m



CA02: 2 cavities at 5.6 MV/m



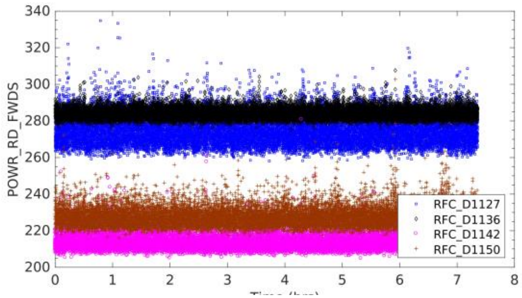
CA03: all 4 cavities at 5.6 MV/m

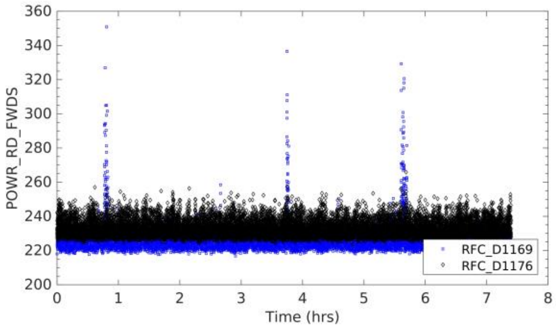


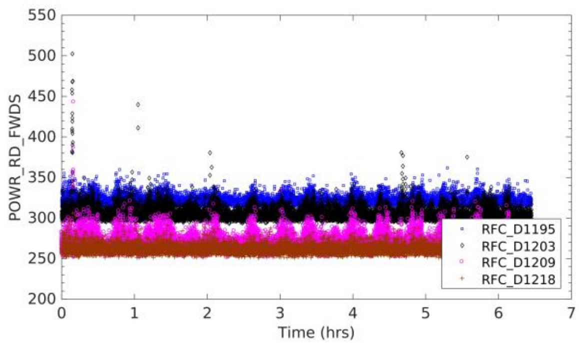
RF commissioning status: Still doing the final system debugging

Position	Gradient	Amplitude Stability (%)		Phase Stability (degree)		RF Power use (W)		Lock time
	(MV/m)	pk-pk	rms	pk-pk	rms	Average	Peak	HRS
1	5.6	0.13	0.01	0.37	0.04	274	335	7.5
2	5.6	0.13	0.01	0.35	0.04	284	307	7.5
3	5.6	0.13	0.01	0.37	0.04	213	281	7.5
4	5.6	0.13	0.01	0.37	0.04	227	302	7.5
5	Work in Progress							
6	5.6	0.15	0.01	0.48	0.05	225	350	7.5
7	5.6	0.09	0.01	0.47	0.07	232	265	7.5
8	Work in progress							
9	5.6	0.1	0.01	0.37	0.04	321	381	6.5
10	5.6	0.1	0.01	0.37	0.04	306	502	6.5
11	5.6	0.1	0.01	0.37	0.04	270	443	6.5
12	5.6	0.1	0.01	0.37	0.04	261	306	6.5

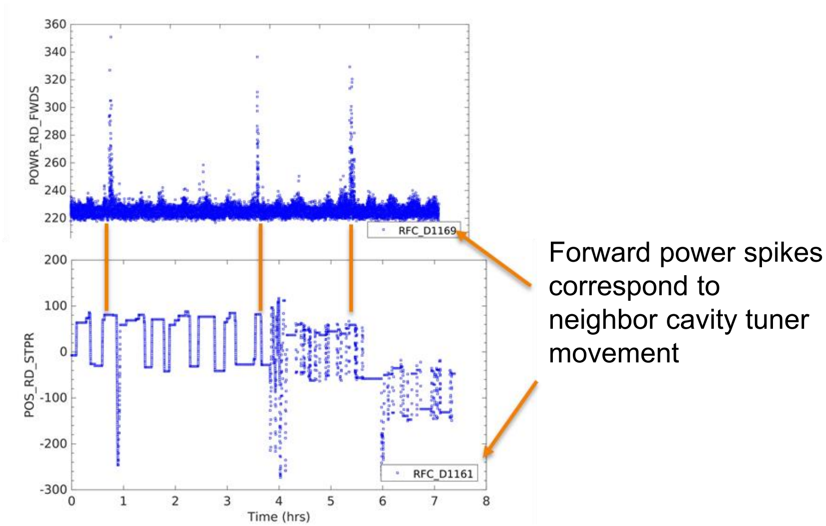
Linac RF Commissioning: Detuning and forward power use







- In cryomodule 2 and cryomodule 3, there is still some forward power spikes even though the cavities stay locked and within control specification
- We have found matching patterns in other PVs and we are still working to debug the system



RF Commissioning Goals

- Bench mark field emission before opening gate valves and beam commissioning.
- Calibrations checked, cavities can lock to reference within amplitude and phase specifications (<1%, <deg pk-pk)
- Cavities can turn on with automatic process in the software
- Amplitude, phase adjustments can be made as needed for beam commissioning.
- Verify long term stability

Conclusion

- Cryomodule performance testing is staying on pace with the cryomodule production and linac installation
- Bunker testing will continue for every cryomodule
- No major setbacks in bunker tests
- Linac RF commissioning is underway in the 1^{st} segment