FERMILAB-SLIDES-21-778-TD

Cryomodule Test

Cryomodule Production Readiness Review – FNAL

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Production Testing of LCLS-II-HE Cryomodules at FNAL

- Excluding the differences between L2 and HE, CM testing procedures are well established from production testing of L2 – therefore test plan nearly identical between L2 and HE
- Planned testing differences primarily come from higher gradient spec 21 MV/m. E.g. anticipating and including in plan some extra time for <u>processing</u> to reach stability at higher gradients
- vCM test helped us to vet planned testing differences and build some lessons learned in this new regime – key for production readiness for CM test

Charge Questions

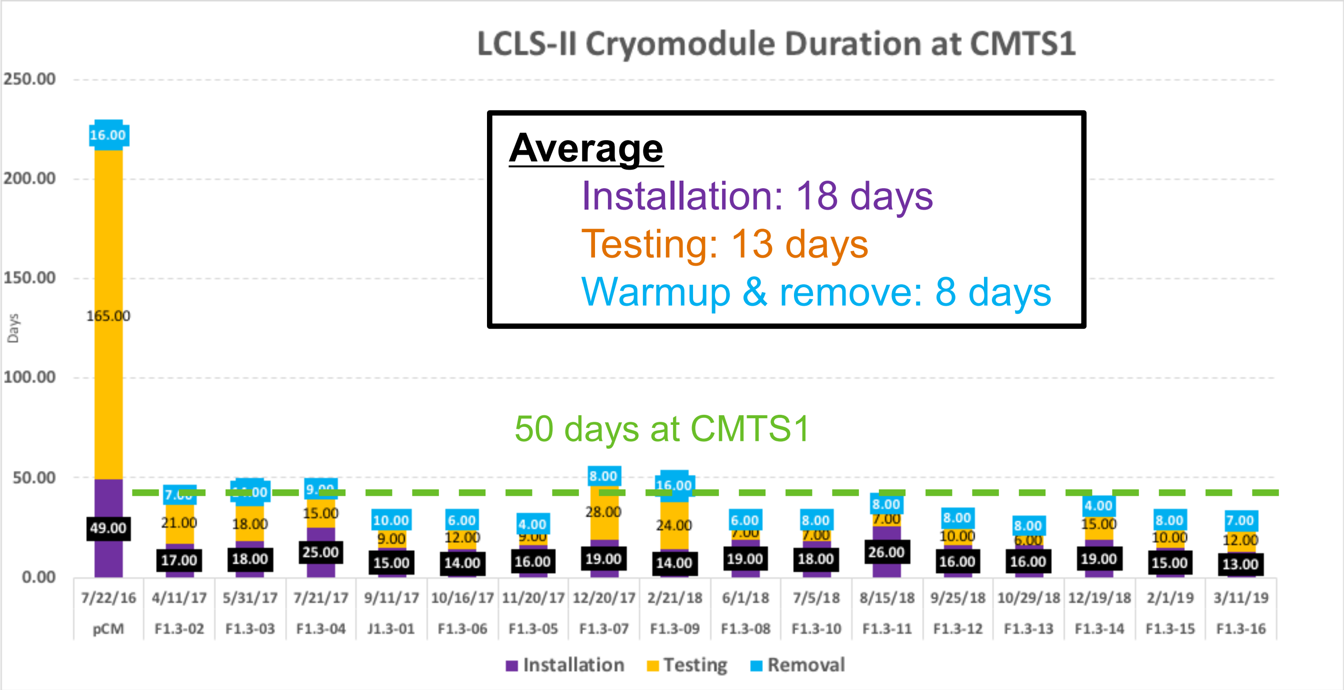
4) Are Fermilab’s processes and procedures for HE CM testing adequately developed, documented, and verified?

5) Has Fermilab demonstrated the adequacy of their CM testing infrastructure for HE CM production?

Fermilab Cryomodule Testing Plan

Cryomodule Testing Throughput at Fermilab

- Based on LCLS-II CMs 02-16, avg is ~39 calendar days/CM
- Calendar for HE allows for up to ~50 calendar days/test



Minimum Acceptance Criteria (production)

Table 2 Production Cryomodule Minimum Acceptance Criteria

Parameter	Value	Minimum acceptable performance during test
Minimum usable gradient for an individual cavity	16 MV/m	Usable gradient – the maximum gradient at which the following 3 conditions are met: • radiation level is below 50 mR/hr, • the cavity can run stably for one hour • 0.5 MV/m below the quench field.
Nominal usable gradient	20.8 MV/m	Individual cavities should reach a nominal usable gradient of 20.8 MV/m.
Minimum Usable CW voltage produced by an individual cryomodule	173 MV	The total CW voltage produced by cryomodule with cavities running at their usable gradients shall be ≥173 MV with all cavities powered simultaneously in GDR/SELAP mode and with the magnet at nominal operating currents for at least one hour with the dark current <30 nA. Additionally, the individual cavity gradients during this run must be recorded.
Stable Operation		For cavities that have a usable gradient above 20.8 MV/m, they must also be shown to be stable (no quenches or trips) at 20.8 MV/m for at least one hour.
Captured dark current	<30 nA	The dark current as measured by Faraday cups at each end of a cryomodule at the minimum CW voltage as defined above shall be ≤30 nA when the cavities are operated in GDR/SELAP mode with the relative phases set to accelerate speed of light electrons. This should be done in such a way to maximize the dark current measured at the Faraday cups.
Individual cavity Q_0		Individual cavity Q_0's must be measured at the expected operating gradient (20.8 MV/m or the usable gradient whichever is lower)
Cryomodule operating duration with RF power during test		Each cryomodule must operate at the minimum CW voltage or greater in GDR/SELAP and with the magnet at operating currents until the coupler temperatures achieve equilibrium or for a minimum of ten (10) hours with 90% operating time, whichever is less, to verify stable operation and confirm acceptable coupler heating.
2 K Dynamic Load at 173 MV voltage		The measured dynamic 2 K heat load of the cryomodule while operating at at total voltage of 173 MV must be ≤ 137 W (equivalent to an average Q_0 of 2.7×10^{10}).
Static heat load at 2 K		The static heat load at 2 K must be ≤7 W
Cryomodule thermometry		All installed thermometry shall be verified functional by observing consistency in output with operational conditions. For sensors measuring identical locations on components within a cryomodule there shall be variation of no more than 0.2 Kelvin under the same conditions at each component and under static load with no power applied to the cavities or magnets
Cavity Microphonics	<10 Hz peak to peak	The microphonics for each cavity must be 10 Hz peak to peak or less, measured over a 1 hour period while at the operating gradient with the JT valve regulating the liquid level (not in a locked position).
Cryomodule liquid level sensors		Liquid level sensors shall be verified functional by observing liquid levels and changes therein consistent with liquid supply rates and estimated boil-off rates
Cryomodule cryogenic valving		JT valve, CoolDown/Warm up, Bypass valves shall all be verified functional during cryomodule operations by consistency with expectations for operational performance, in particular, no valve or actuator is to have ice form on the room temperature components.
Cavity tuning to resonance during test (coarse tuner)		After cool-down to 2 K, each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz. The tuner on the cavity #1 must be able to change the cavity's frequency from 1299.980MHz to 1300.020MHz. Tuners on cavities #2- #8 must be able to adjust cavity's frequency from 1299.535 MHz to 1300.020MHz.
Fine tuner minimum range	0-500 Hz	
Heater performance		All installed heaters shall be verified functional by measuring resistance of 45±6 Ω at 2 Kelvin. Heaters must be demonstrated functional in a cryomodule as verified by heating of the helium: • Six (6) of the eight (8) heaters on the helium vessels • Two (2) of the three (3) heaters on fill lines • Both heaters on liquid level units
Fundamental power coupler 50 K coupler flange maximum temperature	200 K	Measured temperature of FPC 50 K coupler flange must be less than 200 K at the conclusion of the 10-hour full cryomodule run.
Fundamental power coupler warm part maximum temperature	450 K	Measured temperature of FPC warm part must be less than 450 K at the conclusion of the 10-hour full cryomodule run.
Cavity HOM coupler rejection of 1.3 GHz power		$Q_{ext} \geq 2\times10^{11}$, maximum power measured at 1.3 GHz out of a single HOM coupler is 1.7 W at 20.8 MV/m
Magnet electrical verification		The magnet package shall be verified electrically to be without shorts or opens, hi-pot test at 500 V with <1 μA under insulating vacuum, <5 μA in ambient pressure, and can be operated at a current of at least 18 A for a minimum of 30 minutes without quenching
BPM electrical verification and signal balance		The BPM shall be verified electrically to be without shorts or opens, with cross-talk between electrodes ≤ -30dB. The difference in S-parameter (S21) between electrodes is < 1dB over a frequency range of 0.5 to 2.5 GHz
Cryomodule vacuum		Cryomodule beamline vacuum prior to cooldown — 1×10^{-8} Torr Cryomodule insulating vacuum prior to cooldown — 1×10^{-4} Torr Cryomodule warm coupler vacuum prior to cooldown — 1×10^{-7} Torr Cryomodule beamline vacuum at 2 K — 1×10^{-9} Torr Cryomodule insulating vacuum at 2 K — 1×10^{-6} Torr Cryomodule warm coupler vacuum at 2 K — 5×10^{-8} Torr

- LCLS-II HE acceptance criteria document is finalized
- **Major change for HE will be gradient specification increase from 16 MV/m to 21 MV/m**

LCLS-II CM Test Checklist with Additions for HE

Install (11 days)

- ☐ Align
- ☐ Cabling
- ☐ Waveguide
- ☐ Roof on
- ☐ Warm frequency spectra
- ☐ Leak Check

Pre-test Checks (in parallel)

- ☐ ORC sign-off
- ☐ Jumpers removed, HOM attenuators proper
- ☐ Config Control locks
- ☐ LOTO locks removed
- ☐ Digitizers running
- ☐ Tuners powered

Demagnetization (just before cooldown)

Cooldown

50 K/4 K cooldown (3 days)

- ☐ Stabilize/soak (10 hours)
- ☐ Enable alarms

Pumpdown to 2 K (1/2 day)

Stabilize/soak
RF compensation heaters off

Soak (or prior) (~ 1day)

Roof blocks & gate locked
Cave secure
Cavities on resonance/HOMs
Microphonics assessment
Q_{ext} set to $6x10^7$

RF calibration + Initial power rise to 16 MV/m (1/2 day)

Power rise/processing up to 26 MV/m [admin limit] (1-2 days)

- ☐ Raise gradients in individual cavities in pulsed mode watching x-rays, temperatures, and vacuum levels
- ☐ **Process multipacting**
- ☐ Determine Maximum Gradients (limits: admin limit, quench, radiation)
- ☐ Determine Usable Gradients (stable for 60 mins)
- ☐ X-ray & Dark current evaluation
- ☐ BPM check (parasitic)
- ☐ LLRF
- ☐ Magnet check – once leads are cold enough
- ☐ HOMs spectra (2-3 days parasitically)

50 K warm up, fast cooldown (≥32 g/s), pump down to 2K, soak (1 day)

Single cavity Q_0 at 21 MV/m (1-2 days)

- ☐ RF Compensation off
- ☐ Determine optimum JT valve position
- ☐ Heater run
- ☐ No power run
- ☐ Set constants for real-time Q0
- ☐ Cavities at 21 MV/m one at a time
- ☐ No power run in-between

Unit test (1 day)

- ☐ Cavities at 21 MV/m
- ☐ Magnet coils at nominal current
- ☐ Field Emission/Dark current
- ☐ GDR
- ☐ ~12 hour run, until coupler temperatures reach equilibrium

Pre warm-up review

Test complete/Warm-up (3-4 days)

- ☐ Detune cavities back to warm frequency (+40,000 steps)
- ☐ Static Heat Load

Verification Cryomodule

- We got a chance to test everything from the procedures and acceptance criteria thanks to the vCM – incredibly useful experience
- Observations and key lessons learned from high gradient testing will be presented here

Changes to Fermilab Module Testing vs LCLS-II

- Time allotted in schedule for processing multipacting – also keep the module under actively pumping vacuum (new for HE) hopefully will help reduce processing time
- 4 kW solid state RF amplifiers replaced with 7 kW (tested with final LCLS-II 1.3 GHz module, just before vCM)
- Use EPICS-based LCLS-II LLRF control system for testing instead of ACNET

Cryomodule installation and removal

Steps for install/removal controlled by traveler 464547 and referenced procedures. Careful coordination of many groups during this process:

- Mechanical/vacuum
- Alignment
- Instrumentation
- APS-TD RF
- High Level RF
- Low Level RF
- Interlocks
- Cryogenics
- Magnetic Hygiene (Demag)
- Radiation Safety

Minor changes to install procedure to remove NEG/ion pump before DS beamline connection.

Cryomodule installation and removal

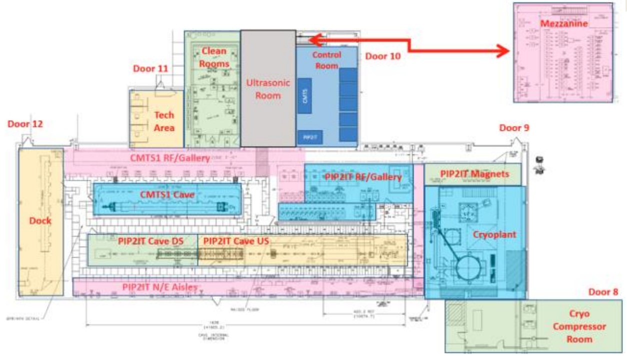
Two changes during installation of the vCM compared to LCLS-II to accommodate plasma processing:

- Added a sliding cleanroom on the upstream end to accommodate both beamline vacuum connection and plasma processing cart connections.

- Remove the faraday window and install a spool in its space to connect beamline vacuum to the upstream beamline vacuum station.

Testing Resources

- CM test personnel are matrixed into project, and are involved in various other lab activities, including other projects, management, R&D – helps to balance staffing for project and creates experts w/ broad experience
- LCLS-II-HE modules are tested in CMTS1 test stand in Fermilab's Cryomodule Test Facility (CMTF) – CMTS1 is now dedicated to LCLS-II-HE
- The other test stand in CMTF is PIP2IT, and a few module tests are scheduled in parallel with LCLS-II-HE, which will share the cryogenic plant, but repair to plant in Aug 2021 should help alleviate capacity concerns
- When conflicts have arisen in the past, communication and coordination have been key – use this approach to continue to find agreeable solutions to meet everyone's needs



Quench Processing to Reach Stability at Higher Gradients

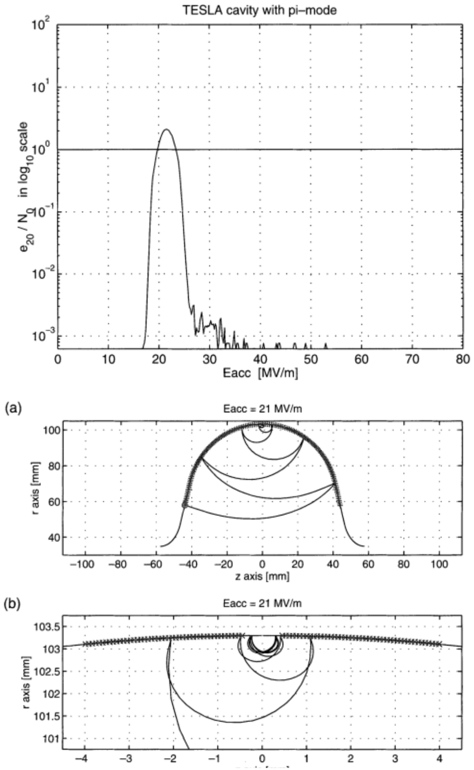
Why Processing is Needed for HE: Evidence for Multipacting-Induced Quenches in LCLS-II CMs

- In LCLS-II CMs, we sometimes saw usable gradients in the 17.5-18.5 MV/m range when the maximum gradient is closer to 20-21 MV/m
- Usable gradient requires 1 hour without quench, but regularly see cavities stable for many minutes then suddenly quench
- What could be causing these "sporadic" quenches?
- Critical for HE – to operate at 21 MV/m on average

		VTS		CMTF Test					
	Cavity	Eacc* [MV/m]	Q0@16MV/m	Max** Gradient [MV/m]	Stable at CMTF*** [MV/m]	Q0 @16MV/m 2K @ 80 G/s	Q0 STDEV	Additional Trapped Field [mG]	Material
1	CAV0139	25.8	3.14E+10	21	19.5	3.32E+10	14.8%	0.24	TD 200/900
2	CAV0225	24	3.50E+10	19.5	18.5	3.74E+10	13.2%	0.22	TD 200/900
3	CAV0096	21	4.03E+10	20	17.5	3.83E+10	13.4%	0.82	TD 200/900
4	CAV0154	24.6	3.91E+10	20	17.5	3.74E+10	10.9%	0.79	TD 200/900
5	CAV0230	24	3.87E+10	19.5	17.5	3.34E+10	15.2%	1.36	TD 200/900

Why Processing is Needed for HE: Evidence for Multipacting-Induced Quenches in LCLS-II CMs

- Fermilab identified multipacting as the mostly likely cause for quenches
- Multipacting – electrons impact surface, release >1 electron each (SEY>1), new electrons hit surface again…
- Supporting evidence for multipacting:
  - Sporatic quenches consistently observed only in multipacting band for TeSLA shape ~17-24 MV/m
  - Quench coincides with burst of x-rays, suggesting electron activity
  - Processing (repeated quenching) helps to increase the gradient
  - No correlation is observed with endgroup temperature



Pasi Yla-Oijala, "Electron multipacting in TeSLA cavities and input couplers," *Particle Accelerators*, Vol. 63, pp. 105-137 (1999)

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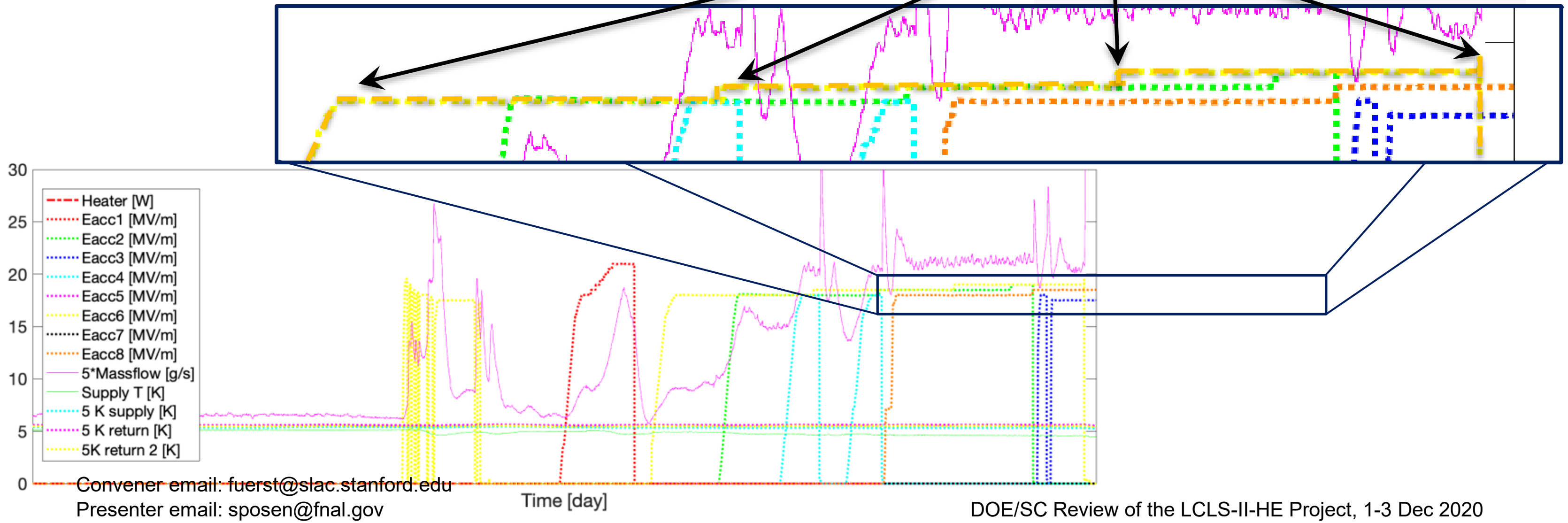
Why Processing is Needed for HE: Evidence for Multipacting-Induced Quenches in LCLS-II CMs

Processing (repeated quenches from applying gradients ~21 MV/m) increases maximum gradient (in this case from <17.25 MV/m to >19 MV/m)

Wed 2019-03-27 07:46:33 F1.3-16 Usable Gradient

Starting with cavity #6 this morning.
Begin at 19.5 MV/m - quickly quenches
19 MV/m - ditto
18.5 MV/m - ditto
18.25 MV/m - 1 minute
18 MV/m begun at 0743, ended at 0747
17.8 MV/m begun at 0748, ended at 0749
17.5 MV/m begun at 0751, ended at 0808.
17.25 MV/m begun at 0809 and off right away.
Let's try some processing. (40 minutes at 21 MV/m, see plot)
18 MV/m begun at 0936, and remained stable to 1036 (1 hr)
18.5 MV/m :1036-1136 (1 hr)
19 MV/m: 1136-1236 (1hr)
Tripped on the way to 19.5.



Evaluating Multipacting Processing During LERF Run

JLab CM 16 cavity 4 perfect candidate to evaluate multipacting processing – measured during July LERF run with participants from JLab, SLAC, and Fermilab

	Serial #	Emax VTA	Emax CMTF	Useable Gradient	FE Onset	Qo VTA	Limit CM
1	L2-0506	25.8	19.5	*14.9	10.6	3.4E+10	Quench
2	L2-0505	23.6	15.1	14.6		3.9E+10	Quench
3	L2-0509	19.3	15.3	14.8		4.6E+10	Quench
4	L2-0218	24.1	**20.2	~17.0		2.5E+10	Quench (?)
5	L2-0219	24.0	21.0	20.0		2.8E+10	***SSA
6	L2-0515	24.3	21.0	~20.0		3.0E+10	***SSA
7	L2-0170	25.2	21.0	*16.3	12.7	3.0E+10	Admin
8	L2-0224	23.8	20.8	17.0		2.9E+10	Quench (?)
		Averages	**19.2**	**16.7**			
		Total Voltage (MV)	**159.7**	**138.7**			

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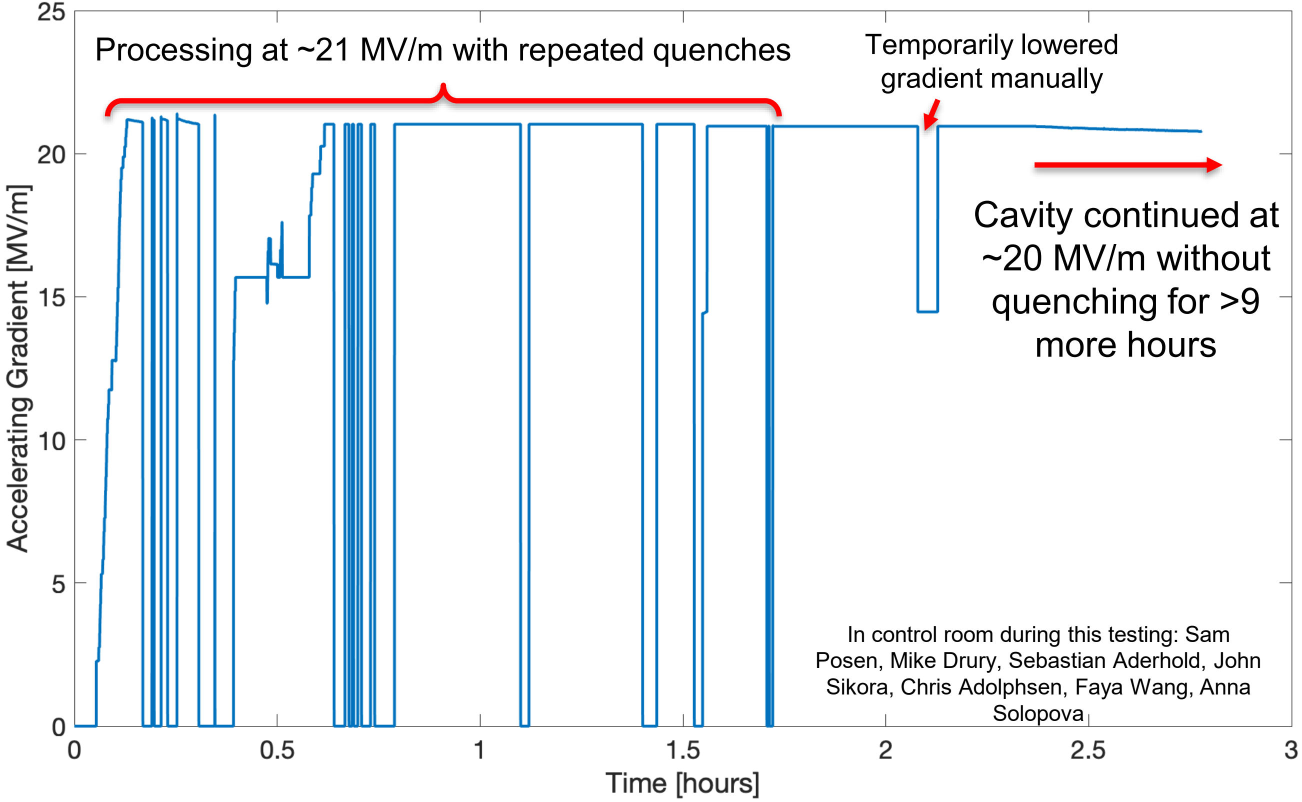
Evaluating Multipacting Processing During LERF Run



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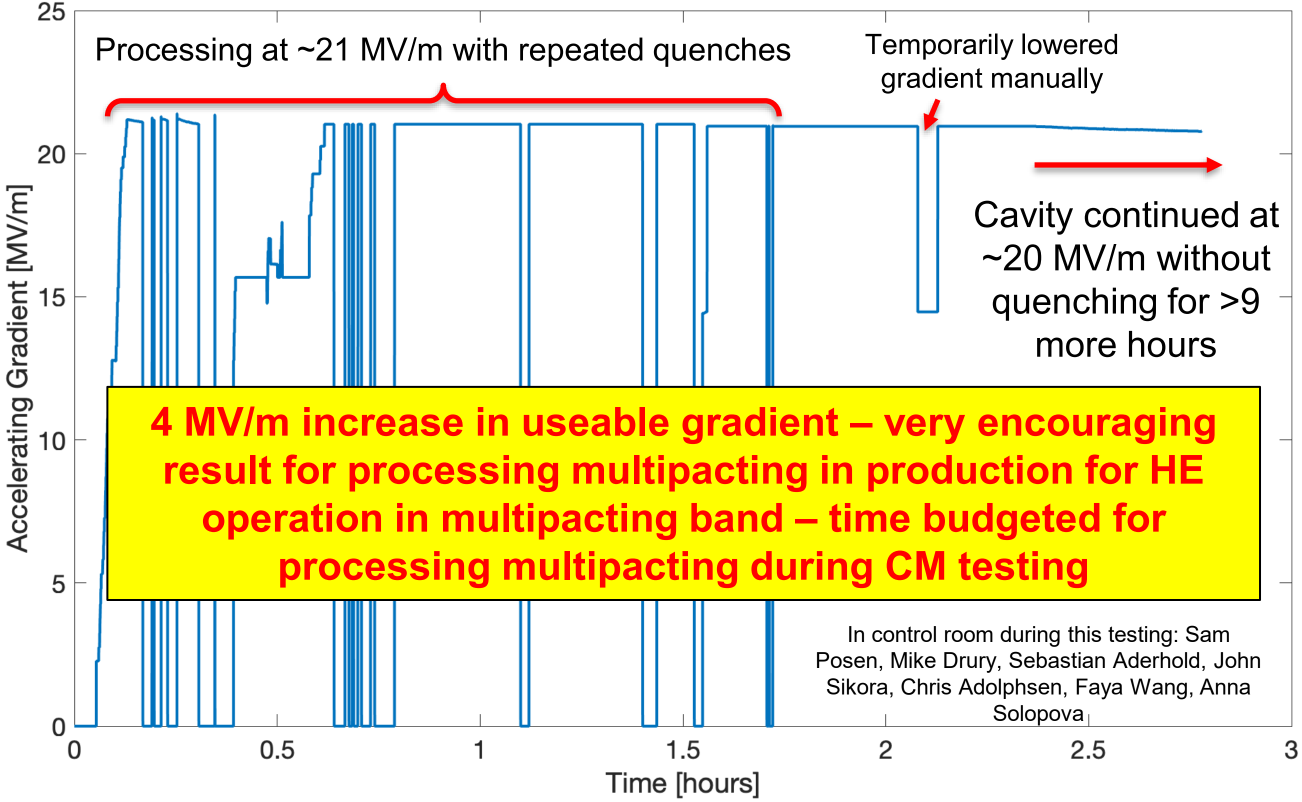
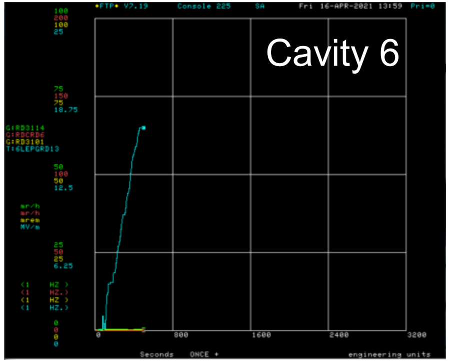
Evaluating Multipacting Processing During LERF Run



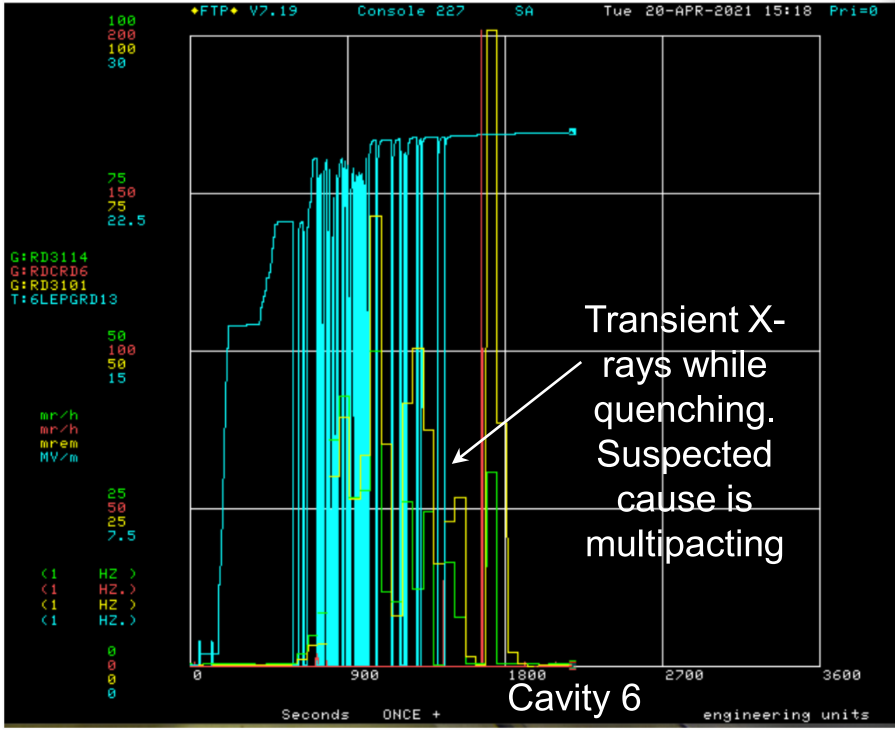
vCM Experience with Quench Processing

Power Rise

- Most cavities ramped to 16 MV/m without issue

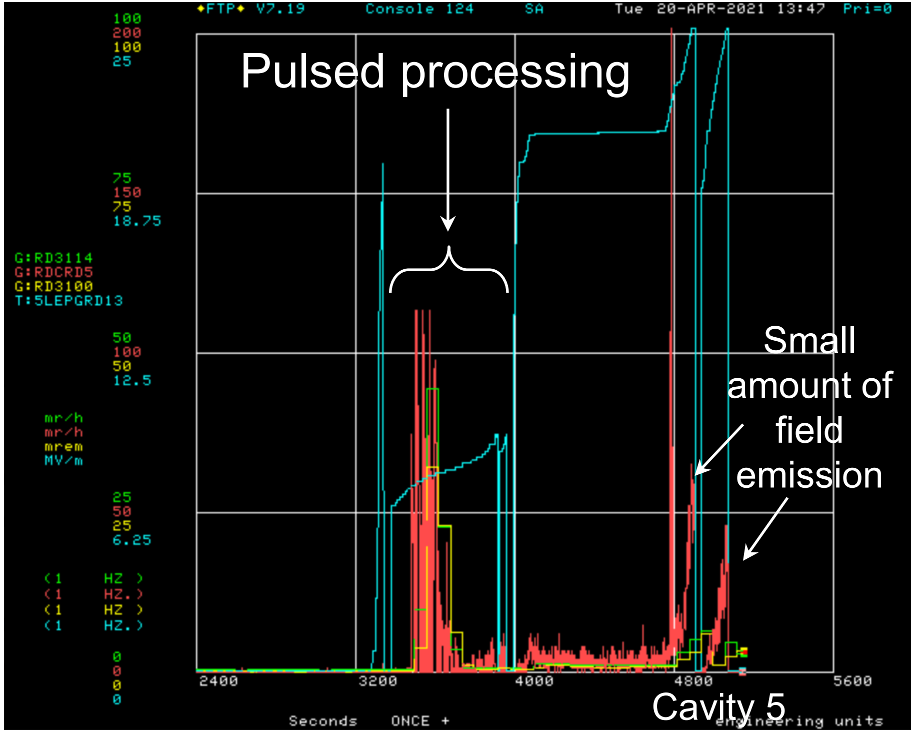


- Rise to maximum gradient more eventful - lots of quenching, but quenches would process with time



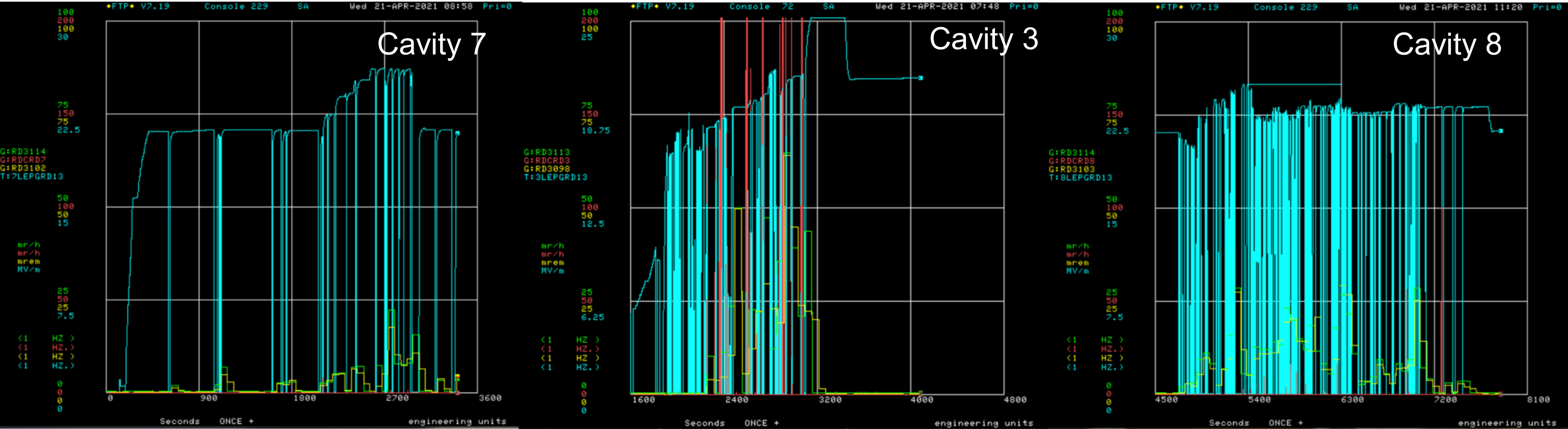
Quench Processing

- Every cavity had to do some quench processing
- Lots of radiation spikes
- Consistent with hypothesis that this is multipacting quenches
- Eventually cavities reach high gradient and are stable



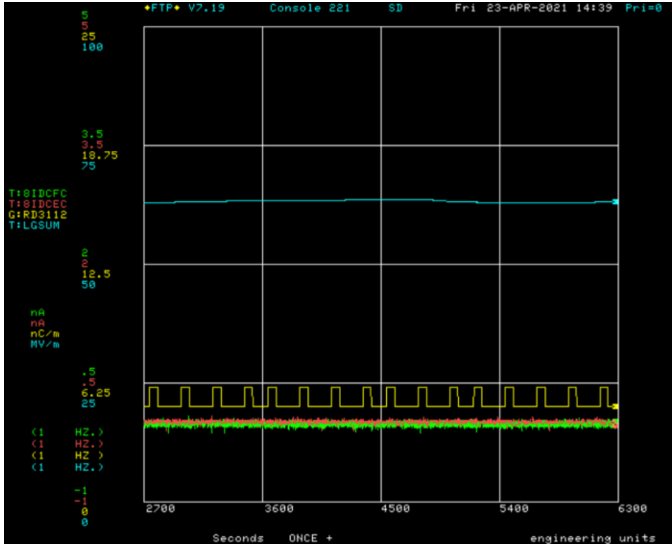
Multipacting Processing

- Some cavities were more stubborn than others – initially processed until arbitrary milestone of 10 mins w/o quench at 21 MV/m
- More processing was required to reach 1 hr at 21+ MV/m



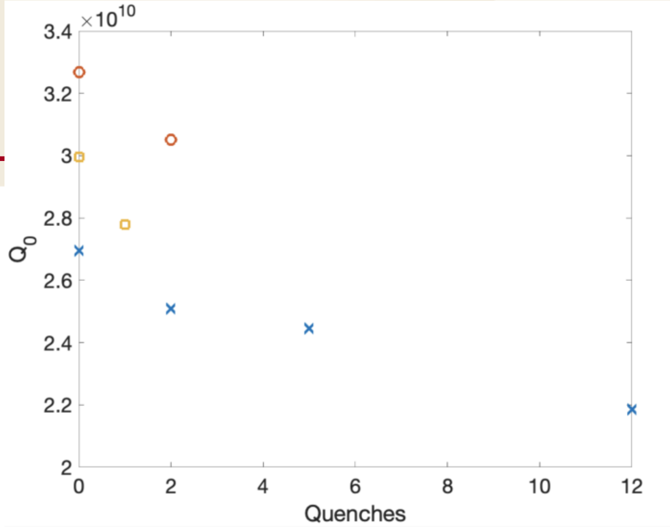
Lessons for Multipacting Processing in Production

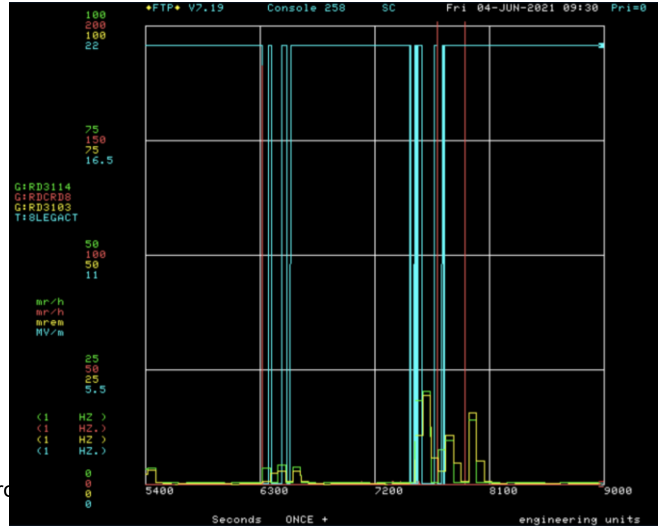
- Testing plan already had extra time built in for multipacting processing – based on vCM experience, expect this time will be needed in production
- Quench can trap flux & degrade Q_0 , and thermal cycle needed to recover
- We thermal cycle before Q_0 measurement. Don't want to degrade Q_0 by quenching before measurement is completed!
- We did 4 hour 'soaks' at 21 MV/m with multiple cavities to try to shake out any more quenches



Quench Degradation Measurement

- Quench Q_0 degradation measured in 3 cavities in vCM directly
- Same day, quenches occurred one after another





vCM Test Summary of Accomplishments (next section is issues & troubleshooting!)

March 2021 – Install

Sun	Mon	Tue	Wed	Thu	Fri	Sat
F6a removal						
Install + Alignment + electrical checks						
Vacuum connections + roof install						
Vacuum + cryo connects						
Cabling + demag						

April 2021 – Qualification Testing

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Vacuum + cabling						
Cabling + demag						
Cooldown		Interlocks+RF Cal				
Power rise / MP Processing						
Warmup + Fast cooldown				Q_0 Meas.		

vCM performance informs final go-ahead for cavity processing – needed by end of May

May 2021 – Thermal Cycle, Studies

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Study quench Q0 degradation / piezo setup / LLRF + microphonics studies						
Room temp thermal cycle for TAO, …						
…coupler fix, multipacting evaluation						
Study gradient measurement, multipacting eval, cavity 1 ramp-up, check gradients						

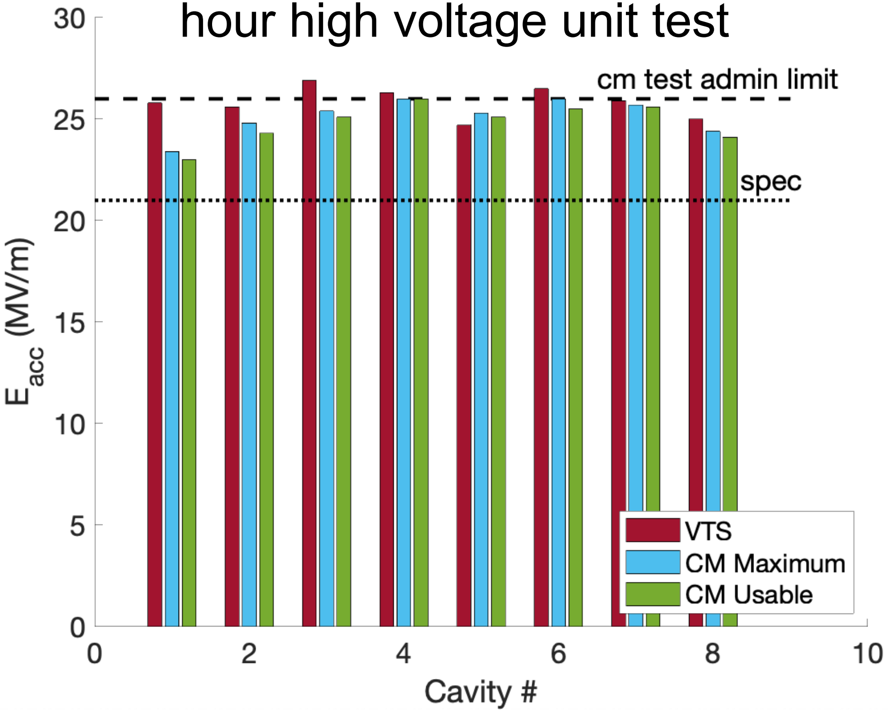
June 2021 – Unit Test

Sun	Mon	Tue	Wed	Thu	Fri	Sat
40 K Thermal Cycle/80 g/s		Q_0 Meas.				
Extended Unit test/microphonics						
Extended Unit Test						
Extended range tuner test						
Warmup						

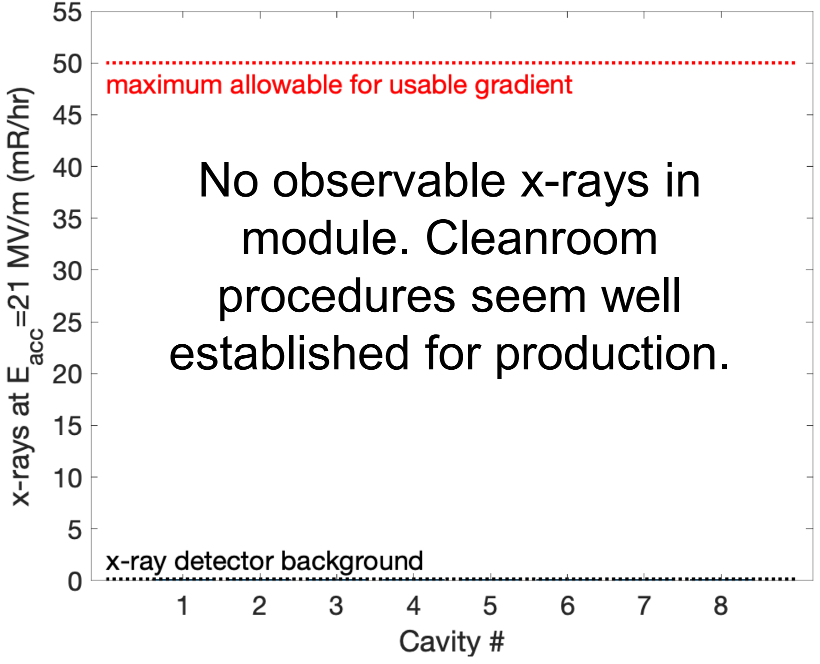
vCM Test Timeline

Cavity Gradient Performance Summary

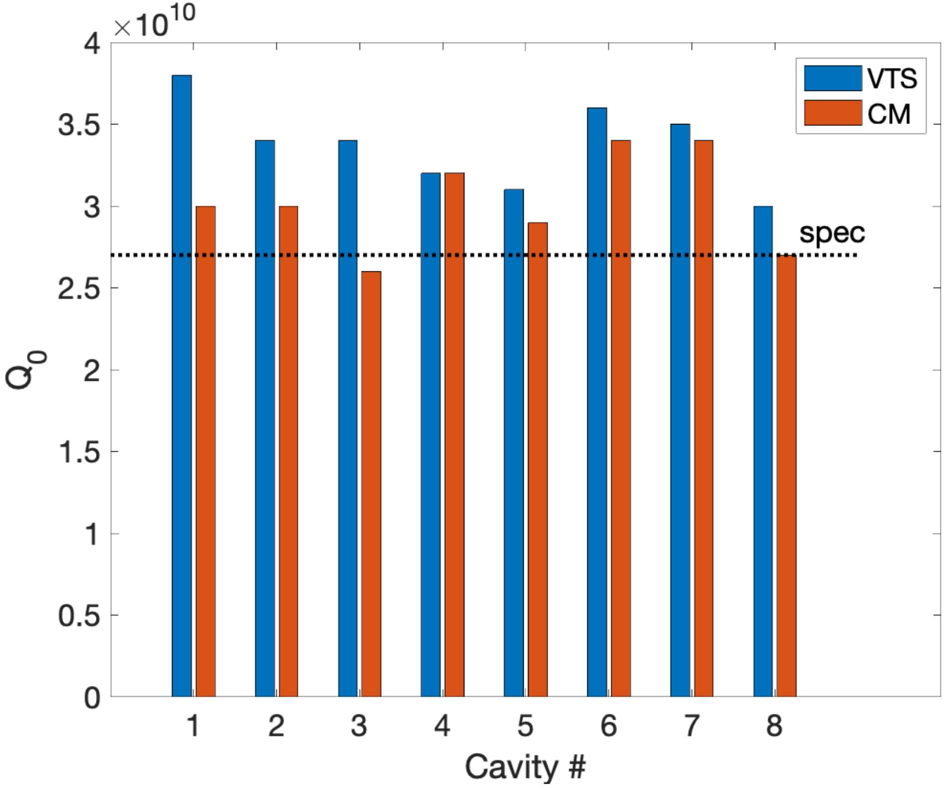
Usable gradient increased during 1 hour high voltage unit test



No observable x-rays in module. Cleanroom procedures seem well established for production.



Cavity Q_0 Performance Summary



Go-Ahead for Cavity Production

- Performance of module was excellent
- Found that flux expulsion was sufficiently good to create high Q0 with 32 g/s cooldown
- Go-ahead was given to cavity vendor on processing

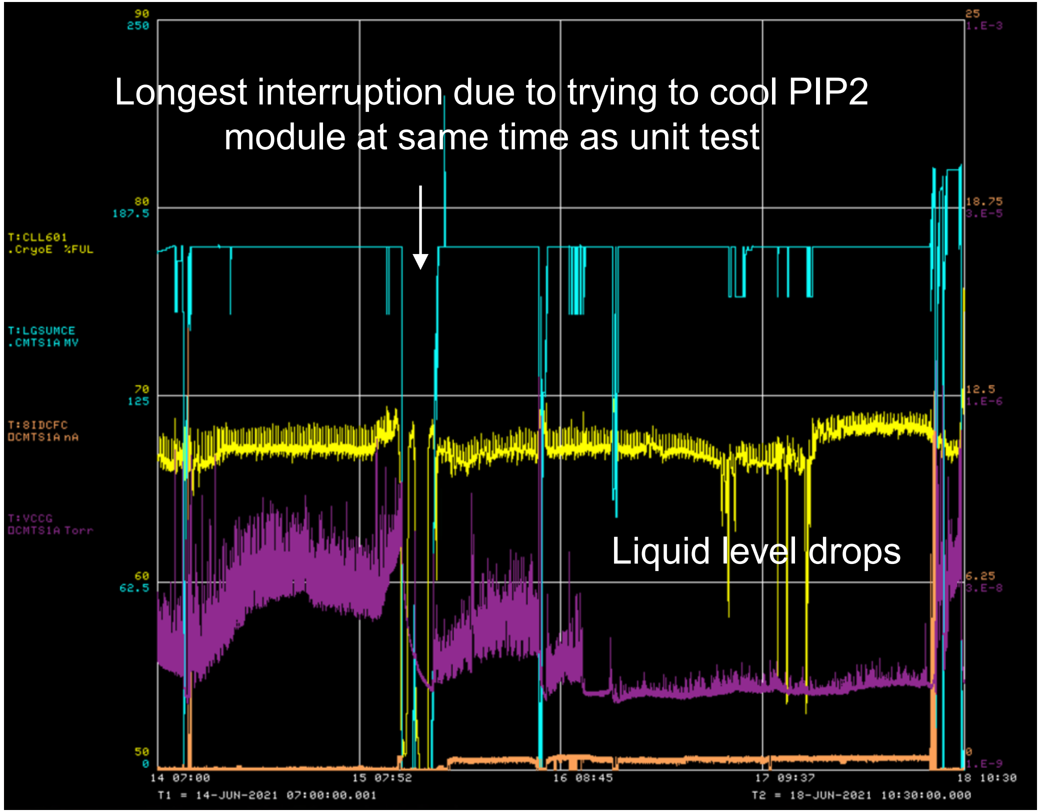
Extended Unit Test

- Part of vCM test plan was an extended unit test – try to operate all 8 cavities in SELAP at nominal module voltage 173 MV
- SLAC operators travelled to Fermilab and took shifts so that at least one operator would be in the control room 24/7
- Duration: 12 days

SLAC visiting operators: Sebastian Aderhold, Bob Legg, Janice Nelson, James Maniscalco, Lisa Zacarias
FNAL RF operators: Andrew Cravatta, Sam Posen

Voltage Overview During Week of 6/14-18

Next section discusses the troubleshooting and lessons learned from unit test (really useful experience!). Managed to get good stability in 2nd week, mostly limited by upstream liquid level drops (yellow line).



Coupler Temperatures After Reaching Stability

Compiled by Sebastian Aderhold

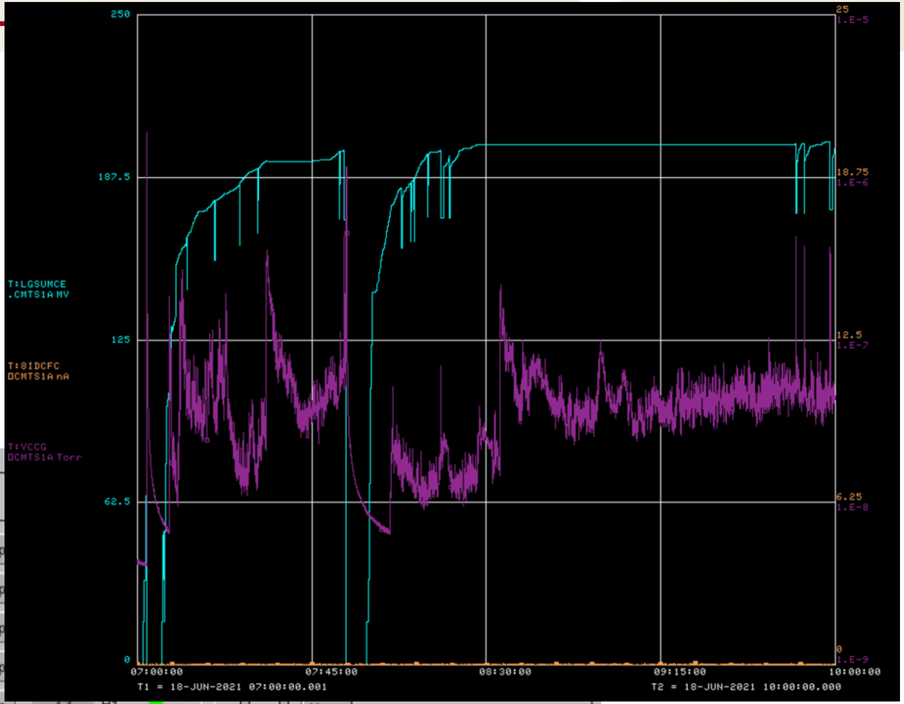
ACNET variable name	Description	Unit	Cavity 1	Cavity 2	Cavity 3	Cavity 4	Cavity 5	Cavity 6	Cavity 7	Cavity 8
T:[1-8]LEGACT	cavity gradient	MV/m	16.1	21.7	21.7	21.7	21.7	21.7	21.7	21.7
T:[1-8]FMTK1	12 o'clock RTD	K	115	151	136	136	135	150	141	143
T:[1-8]1MTK2	6 o'clock RTD	K	88	140	138	140	138	149	138	152.5
T:1CT23[1-8]	RTD coupler 5K	K	8.9	8.9	9.5	10.5	10.2	9.5	8.9	9.8
T:[1-8]FTIR	Inner Cndctr IR Temp	C	50.5	51.5	53	53.7	53	54	50.1	50.1
T:[1-8]FTIRC	Ceramic IR Temp	C	32	43	46.8	42	40.7	43	43.7	52.9
T:[1-8]RPML1	Forward power	W	~1300	~2600	~2900	~2600	~2500	~3000	~2600	~2800
T:[1-8]LEPFWD	Forward power	W	~1450	~2500	~2500	~2800	~2300	~2600	~2450	~2600

Push for Module Voltage in SELAP

Total voltage: 200.0 MV

Total Gradient: 192.7 MV/m

Duration >1 hour (ended by cavity quench when pushing more)

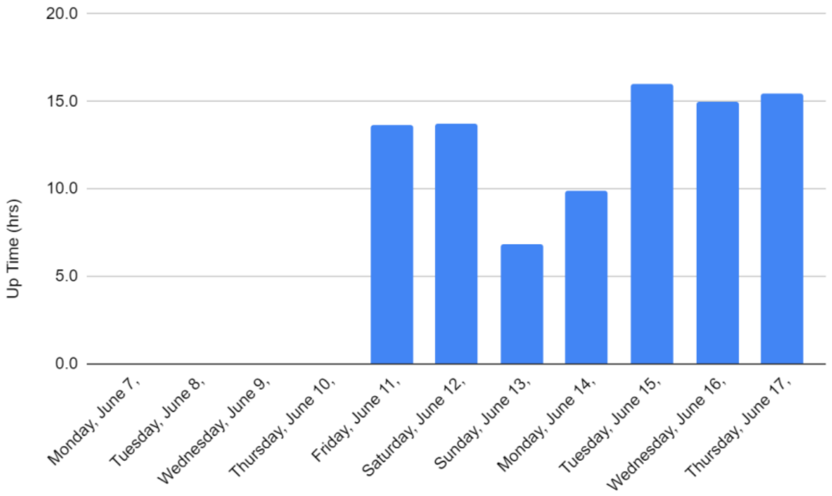


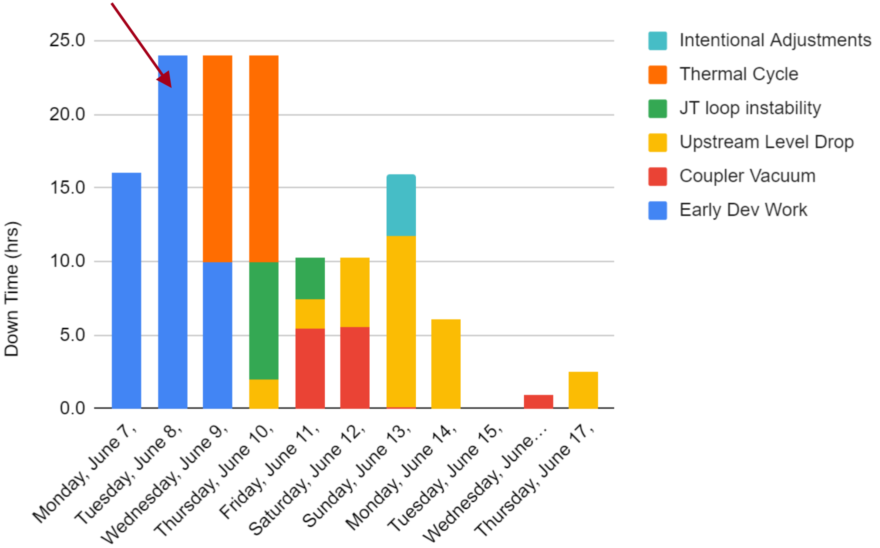
Note that reactive power fraction set to 0.15 for all cavities for this test

vCM Unit Testing Troubleshooting

Up Time / Down Time Statistics

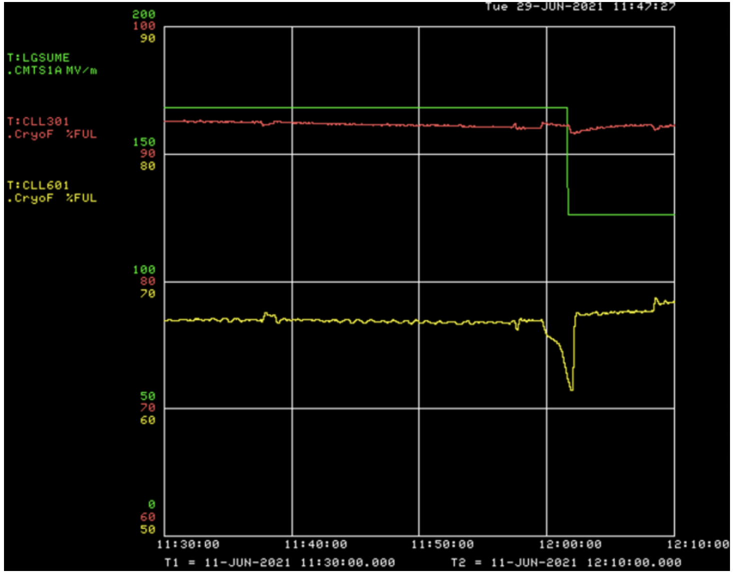
First few days spent building understanding how to deal with cryo limitations, LLRF issues, etc. – key also for unit testing in production





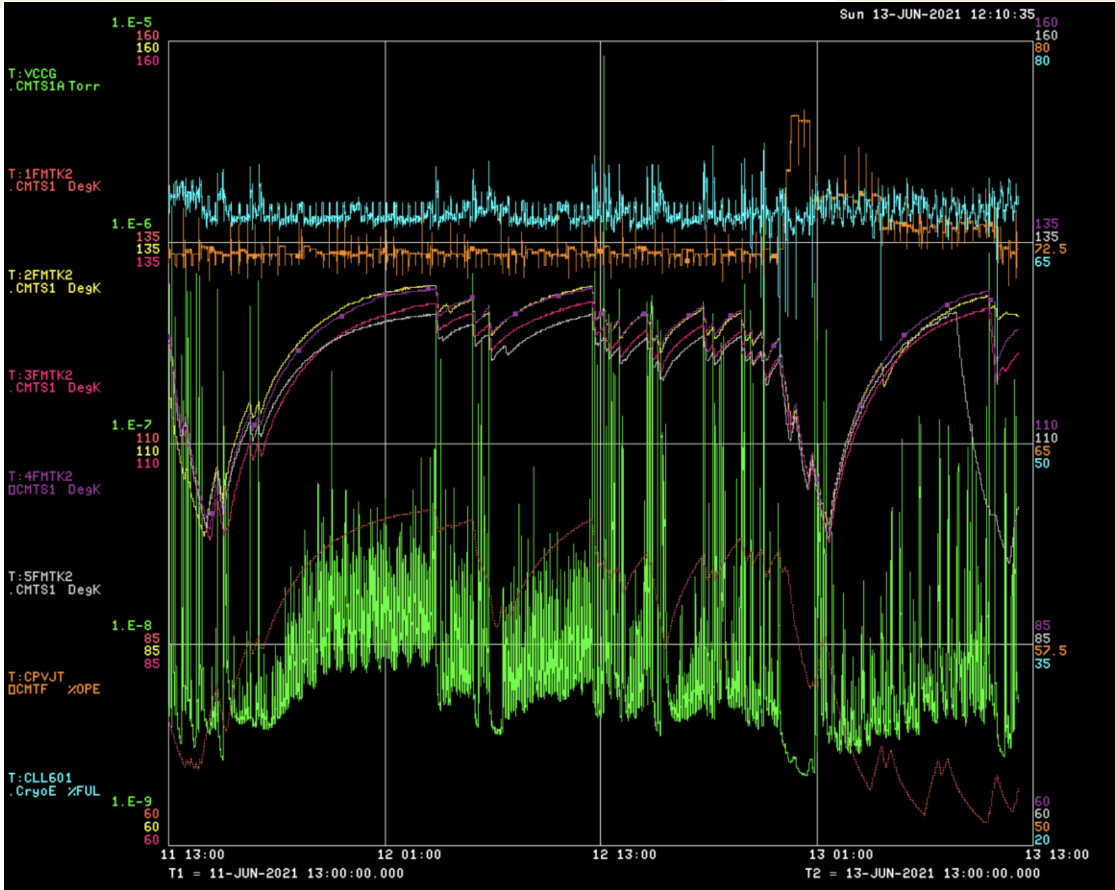
Upstream Liquid Level Drops

- In unit testing, found that liquid level in upstream can would sometimes drop
- Mitigated by reducing gradient of cavity 1, increasing others (still meets all specs including 173 MV voltage)
- Seems to be due to 1) slope, 2) large gas flow due to flash from incoming 5 K liquid (vapor damming)
- Not expected to be issue in linac with lower T incoming liquid, but expect to be issue for production unit testing



Coupler Vacuum Blips

- Coupler vacuum trip level was 5e-7 torr
- SELA no issues, but blips occurred in SELAP – possibly due to microphonics
- Mitigated by reducing reactive power overhead and coupler processing with low Q_L



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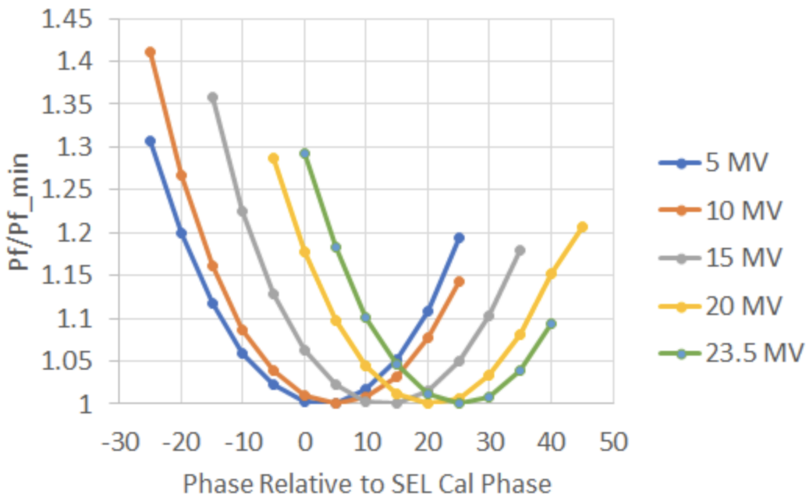
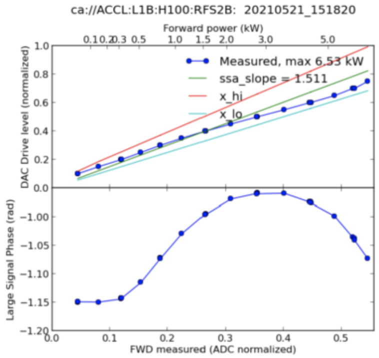
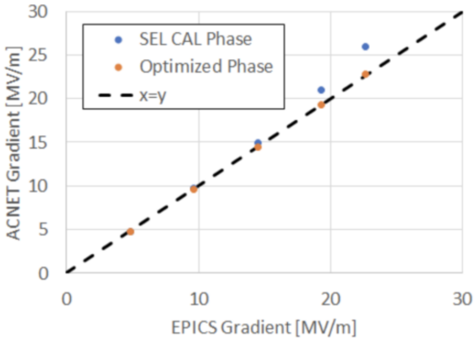
EPICS vs ACNET

- Discovered that there was a significant difference between ACNET and EPICS gradient measurement >20 MV/m (was very close at 16 MV/m for L2)
- Phase slewing seems to be culprit
- Lesson learned: if phase isn't optimized, believe only EPICS, not ACNET







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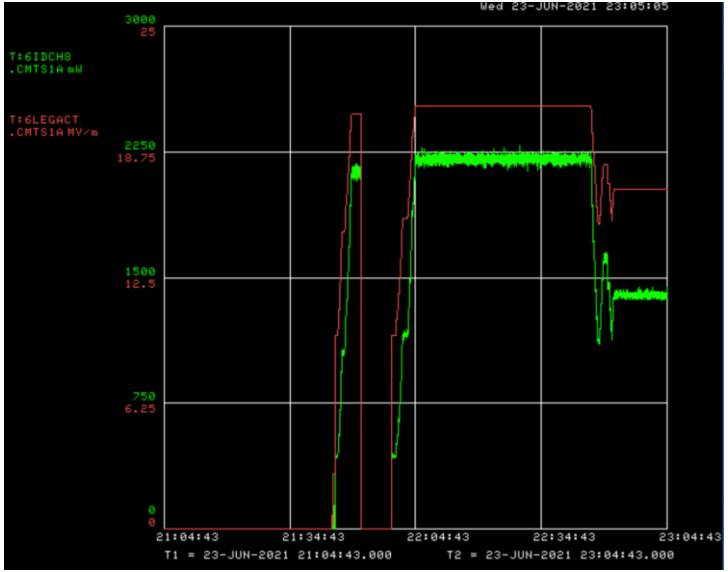
vCM Key Lessons Learned

- Believe EPICS gradient. ACNET is affected by phase slewing.
- It will take time to process multipacting – need to make sure it's done thoroughly before thermal cycle for Q_0 measurement
- For unit testing, cannot run cavity 1 at very high gradient due to upstream liquid level instability
- Coupler vacuum blips may be substantial at these gradients in SELAP. Processing may be required for reactive power fraction >0.15
- Could use more dedicated time for LLRF system development – e.g. expert intervention used to tune gains
- Configuration control of cryo if warmup-cooldown occurs

Off Frequency Operation

Off Frequency Operation

- Requirement to detune cavities by ~465 kHz for “OFO”
- Cavity detuning proceeded without issue in vCM, but discovered that one HOM power was now out of spec (2.2 W at 21 MV/m vs 1.7 W spec)
- Seems notch frequency was no longer well aligned with pi mode



vCM Key Lessons Learned

- Believe EPICS gradient. ACNET is affected by phase slewing.
- It will take time to process multipacting – need to make sure it's done thoroughly before thermal cycle for Q_0 measurement
- For unit testing, cannot run cavity 1 at very high gradient due to upstream liquid level instability
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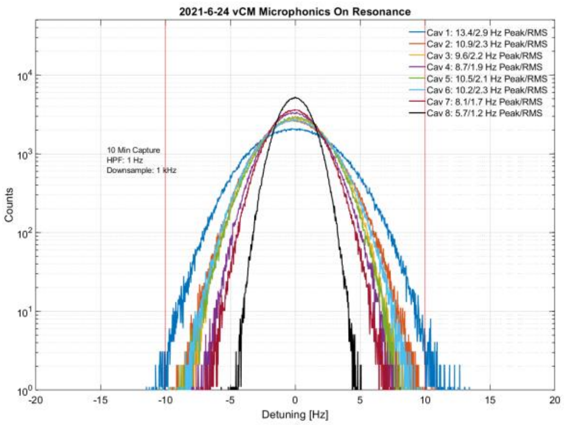
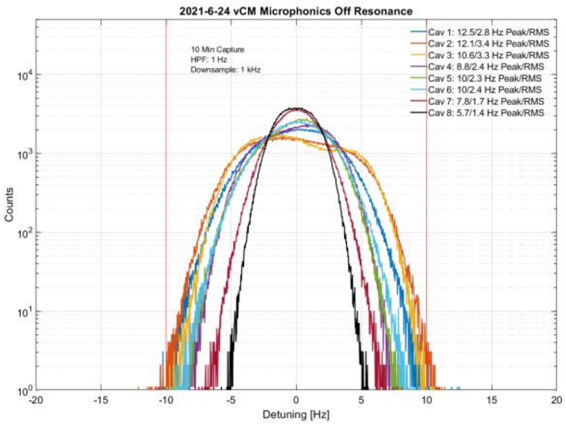
- Could use more dedicated time for LLRF system development – e.g. expert intervention used to tune gains
- Configuration control of cryo if warmup-cooldown occurs
- **Be careful with notch filter tuning in off frequency operation**

Microphonics





10 min capture. Microphonics On resonance (1.3 GHz).

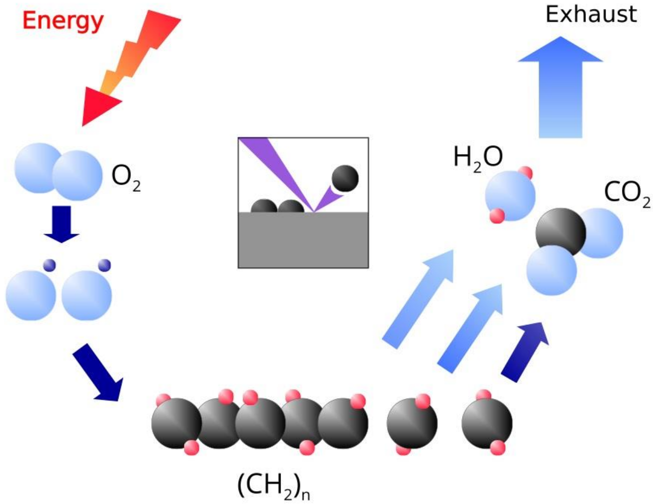
10 min capture. Microphonics off resononance -465 kHz from 1.3 GHz.

Microphonics overall similar to LCLS-II, no big differences between 1.3 GHz and OFO. Some extra microphonics observed during early vCM testing, thought to be caused by instrumentation capillary line that will go away for production modules

Plasma

Plasma Processing

- We plan to attempt plasma processing on the vCM this month, test after plasma
- If no degradation of vCM, could be new tool in our toolbox in case of field emission in the future on production modules
- Not needed in production, but could provide an advantage



Summary

Production Testing of LCLS-II-HE Cryomodules at FNAL

- Excluding the differences between L2 and HE, CM testing procedures are well established from production testing of L2 – therefore test plan nearly identical between L2 and HE
- Planned testing differences primarily come from higher gradient spec 21 MV/m. E.g. anticipating and including in plan some extra time for processing to reach stability at higher gradients
- vCM test helped us to vet planned testing differences and build some lessons learned in this new regime – key for production readiness for CM test