



PERFORMANCE OF THE FIRST LCLS-II CRYOMODULES: ISSUES AND SOLUTIONS

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Outline

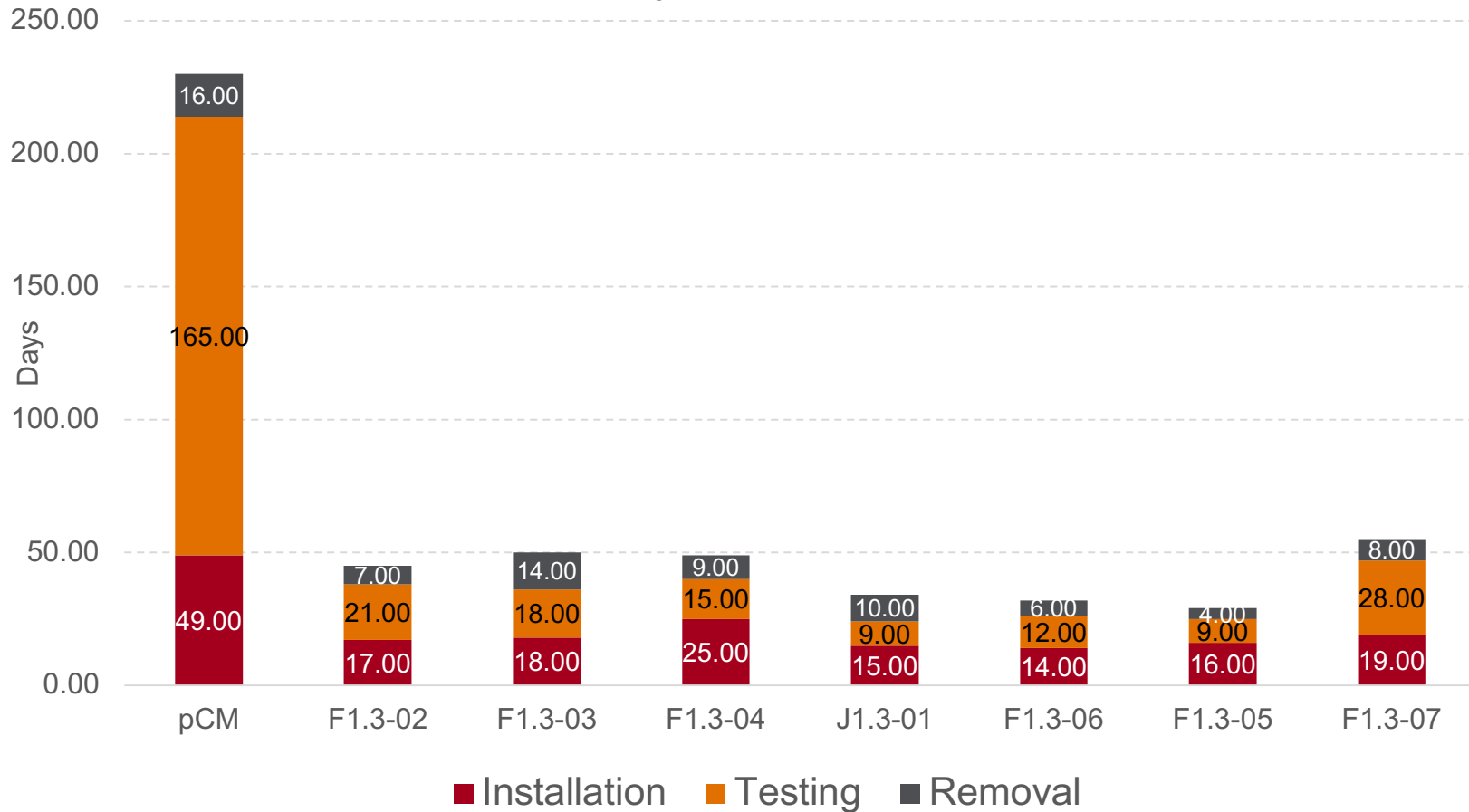
- Introduction
- Throughput & performance
- Acceptance criteria
- Anomalies
- Issues and solution
- Summary

Testing strategy

- Testing strategy
 - Aggressive 28-day schedule
 - Baseline testing addresses acceptance criteria
 - Additional tests as schedule allows
 - Microphonics
 - Q0
 - LLRF
 - Resonance control
- 8 (+1) cryomodules tested to date:
 - **F1.3-01, F1.3-02, F1.3-03, F1.3-04, F1.3-05, F1.3-06, F1.3-07; F1.3-09**
 - **Re-tested JLAB cryomodule: J1.3-01**

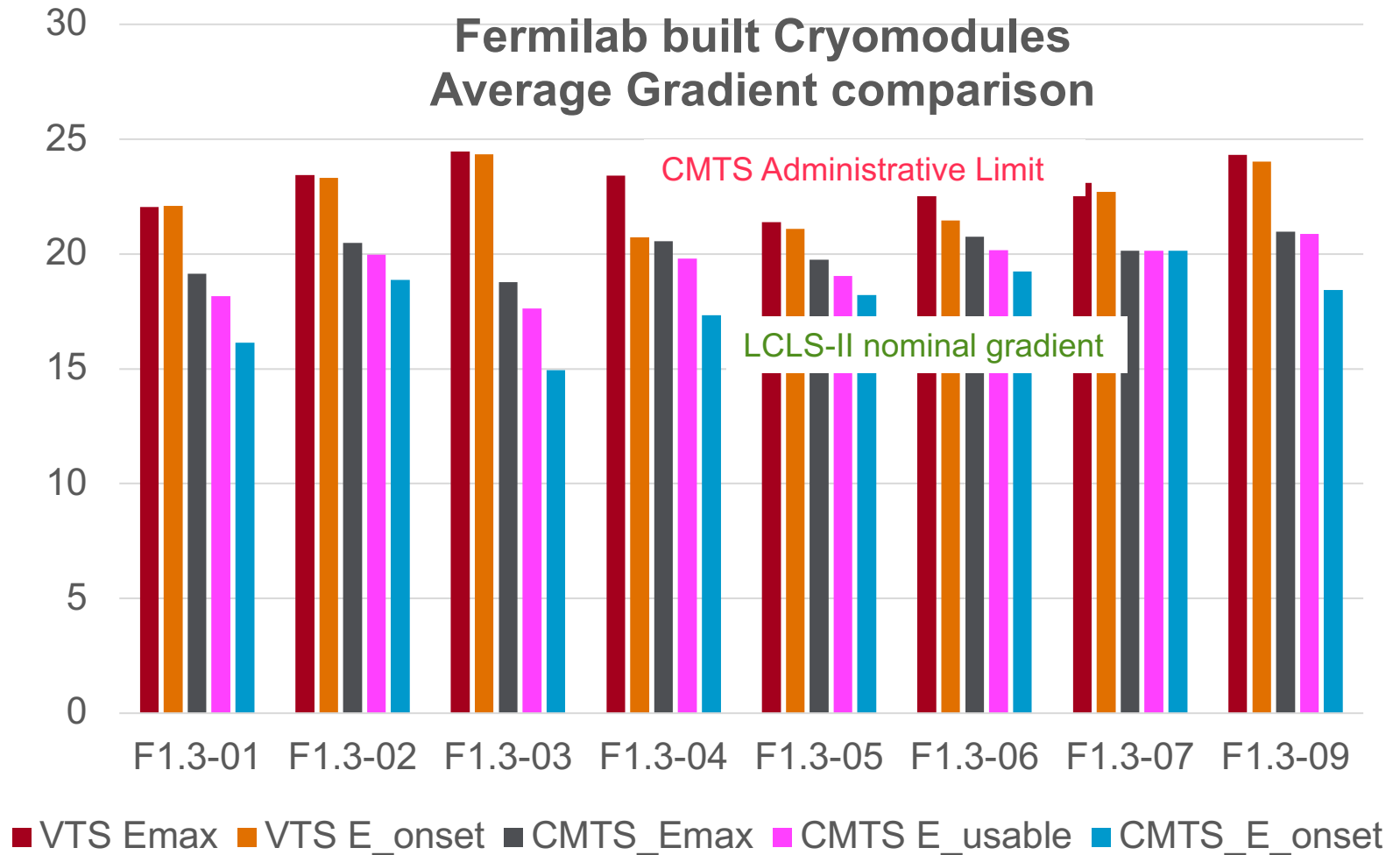
Throughput

LCLS-II Cryomodule Duration at CMTS1



Goal: 13 days installation & cooldown, 8 days cold testing, 7 days warm-up and removal

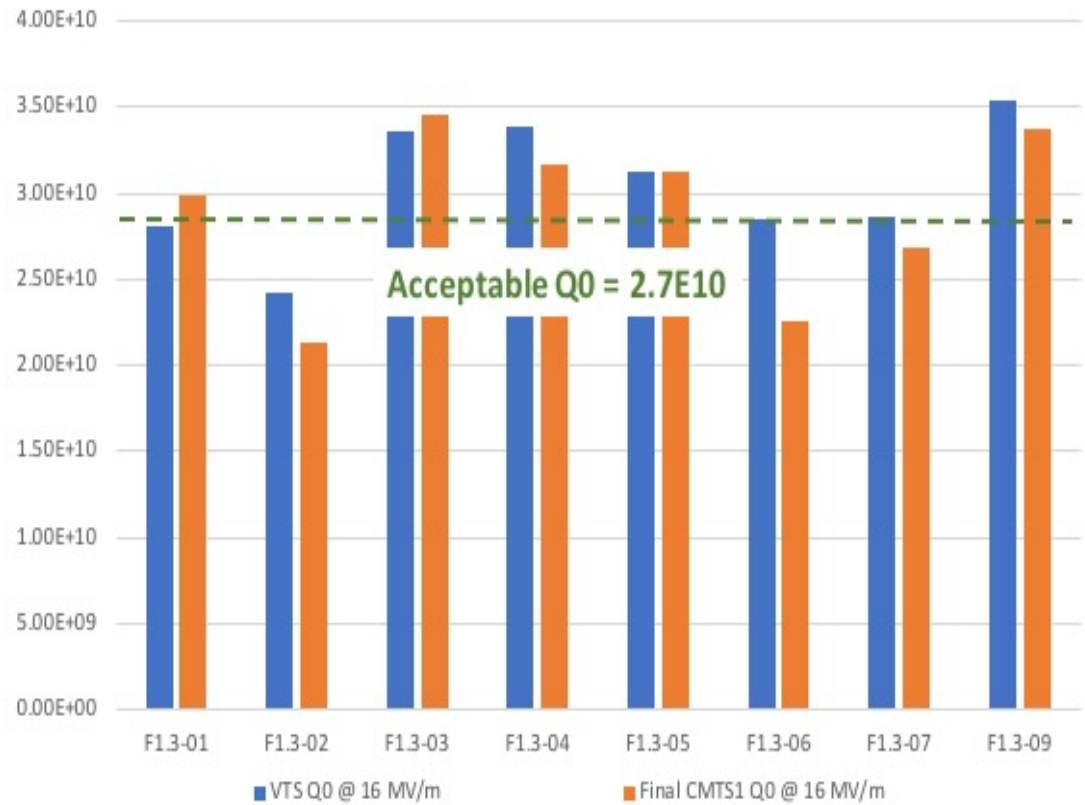
Performance - gradient



Performance – Q0

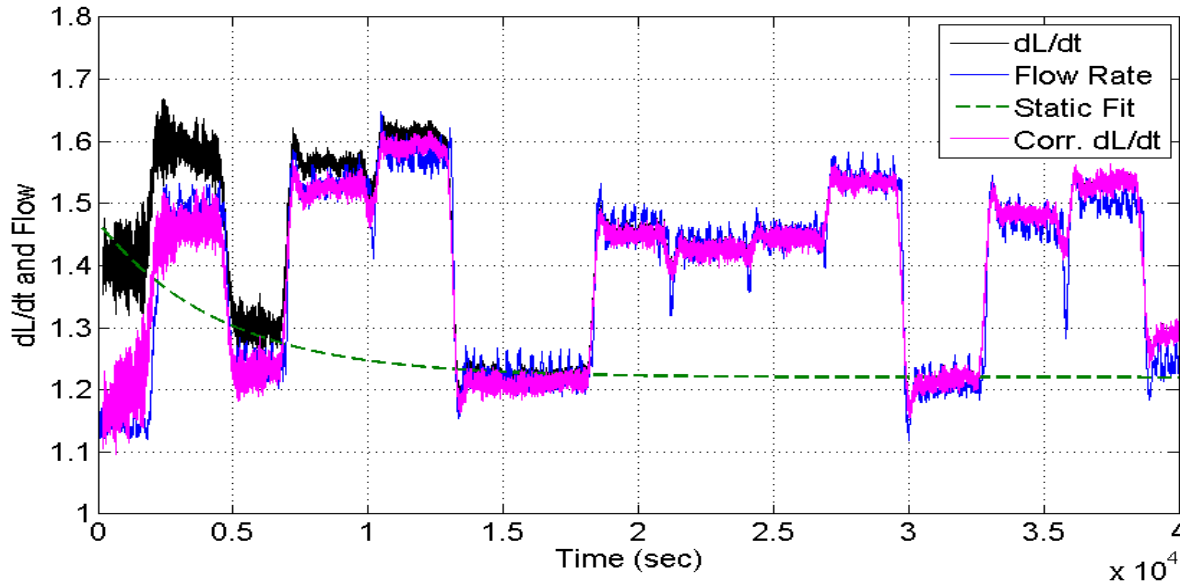
- Summary of measurements
- Measurement technique
 - *Helium Flow rate*
 - *dLL/dt – helium Liquid Level*
 - *dP/dt*
- Multiple measurements per cryomodule
 - *Slow and fast cooldown*
 - *Poor flux-expelling material, etc.*

Fermilab-built LCLS-II Cryomodule
Q0 Comparison

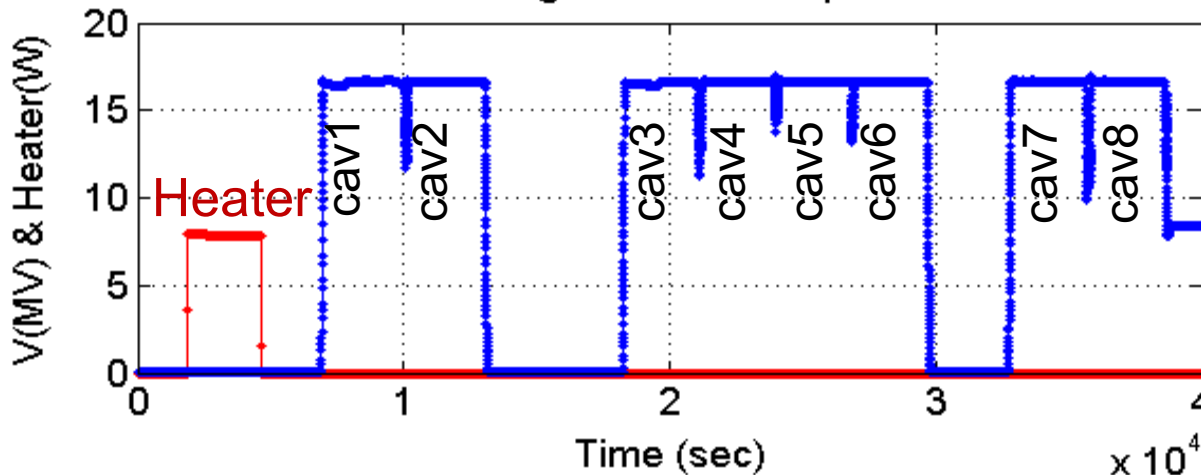


Flow rate vs. dL/dt method: Fast Cooldown

Flow Rate vs. dL/dt method for Q0 meas.



Voltage & Heater & dp/dt



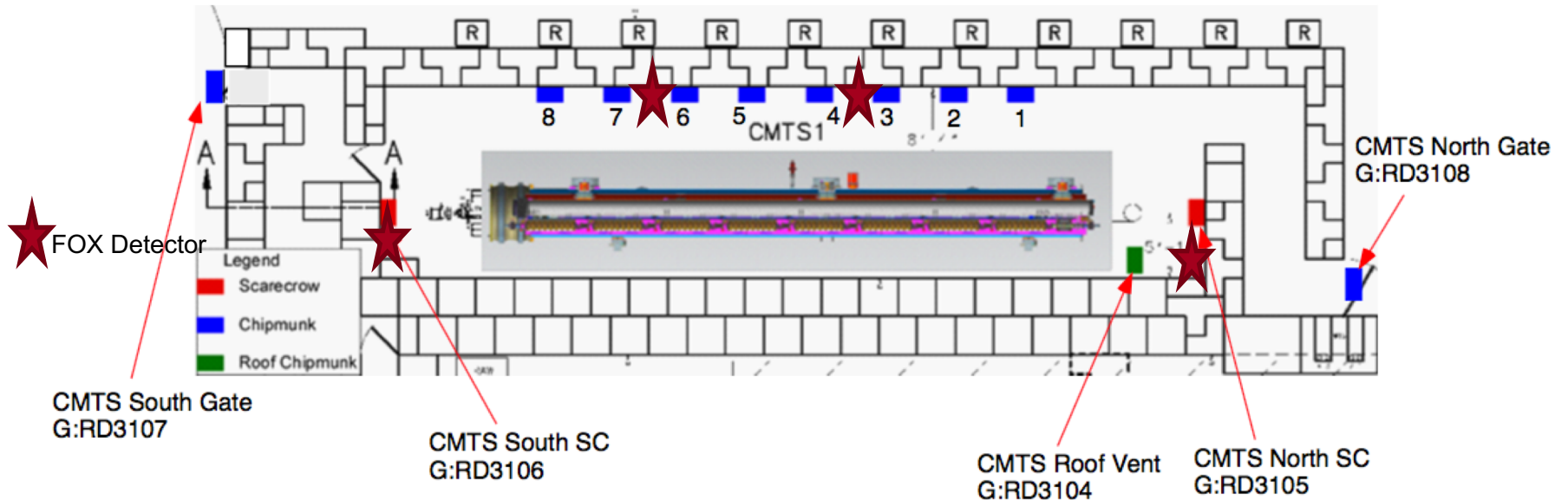
Cooldown rate 80 g/s

Cav #	Q0 x10 ¹⁰ Flow	Q0 x10 ¹⁰ dL/dt
C1	2.82	2.62
C2	2.51	2.17
C3	3.68	3.44
C4	4.18	3.81
C5	3.67	3.64
C6	2.67	2.61
C7	3.41	3.13
C8	3.01	2.60

Good agreement after correction of dL/dt due to decay of static load

Performance – field emission & dark current

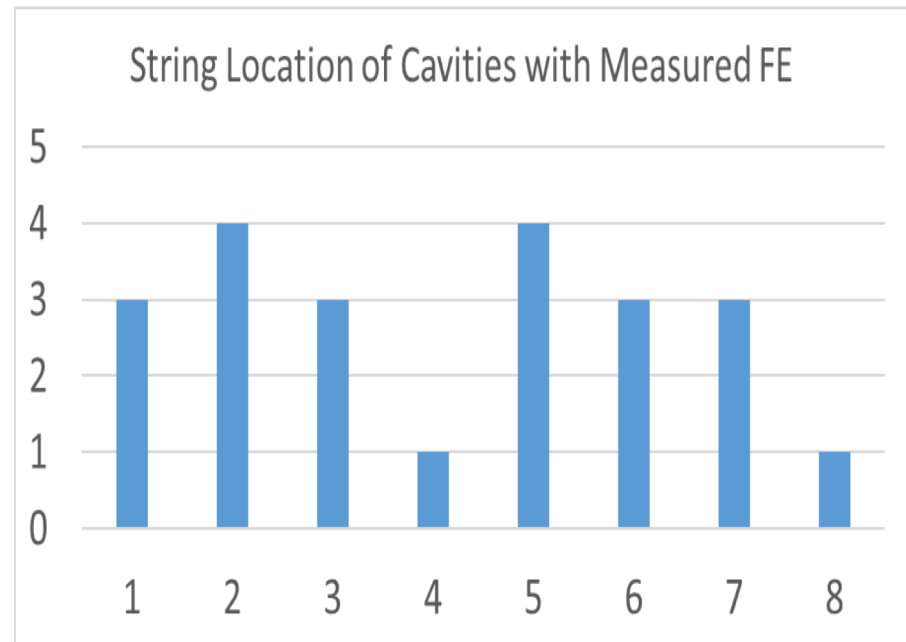
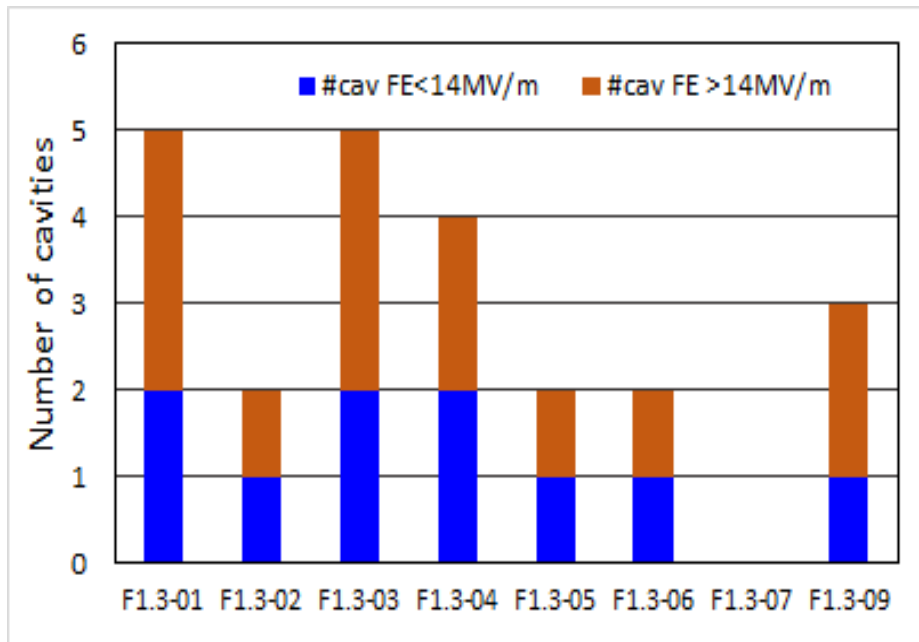
Chipmunks CMTS West Wall nos. 1-8 correspond to locations 1,2,3,4,5,6,7,8:
G:RD3096,G:RD3097,G:RD3098, G:RD3099, G:RD3100, G:RD3101, G:RD3102, G:RD3103



- Extensive array of detectors in place for field emission and dark current detection
- ArCO₂ and fiber optic detectors running the length are also installed
- Just added – array of dosimetry badges

Performance - field emission improved

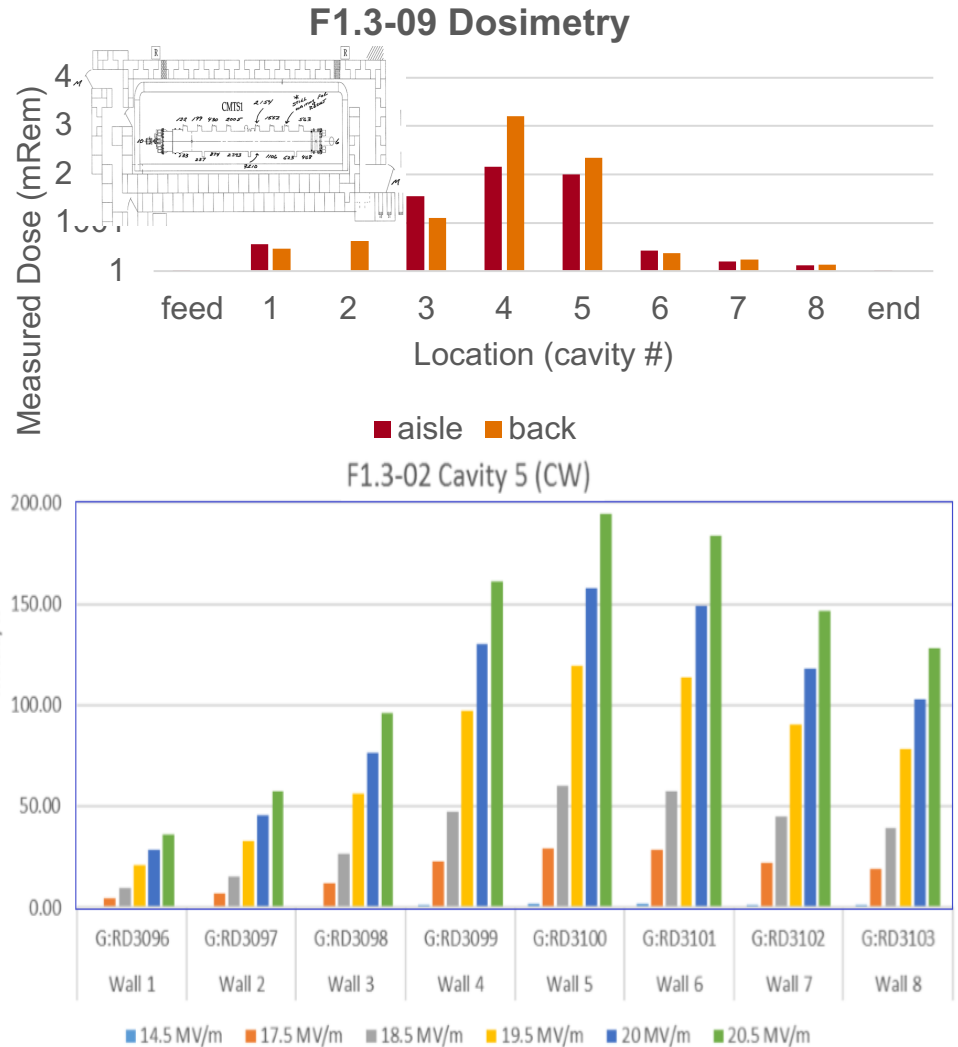
- Onset of measurable field FE $E_{acc} \geq 14$ MV/m, each cavity (see plot below)
 - F1.3-07 first cryomodule with no measured FE
- Usable gradient >12 MV/m; definition requires <50 mR/hr measured outside CM
 - Exceeded for most cryomodules
- **Field emission not dependent on location in string**



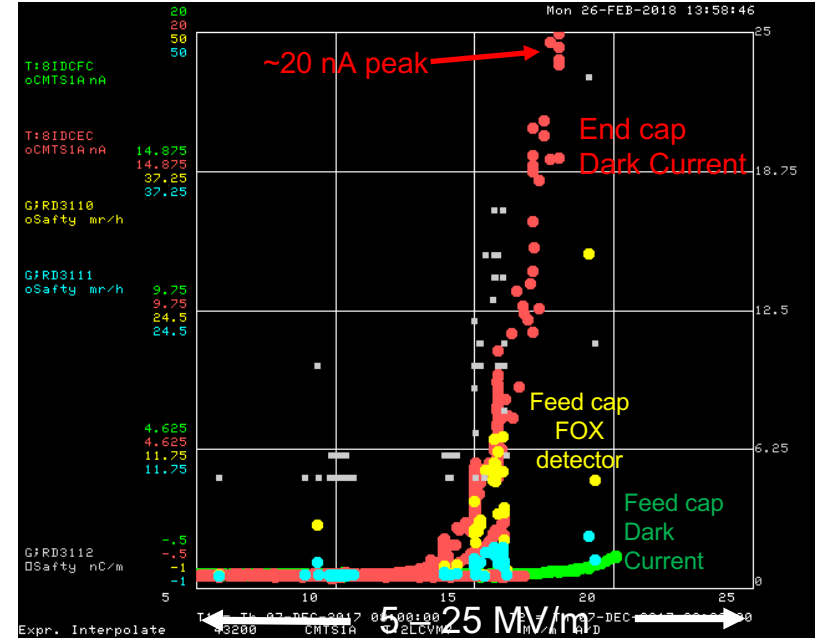
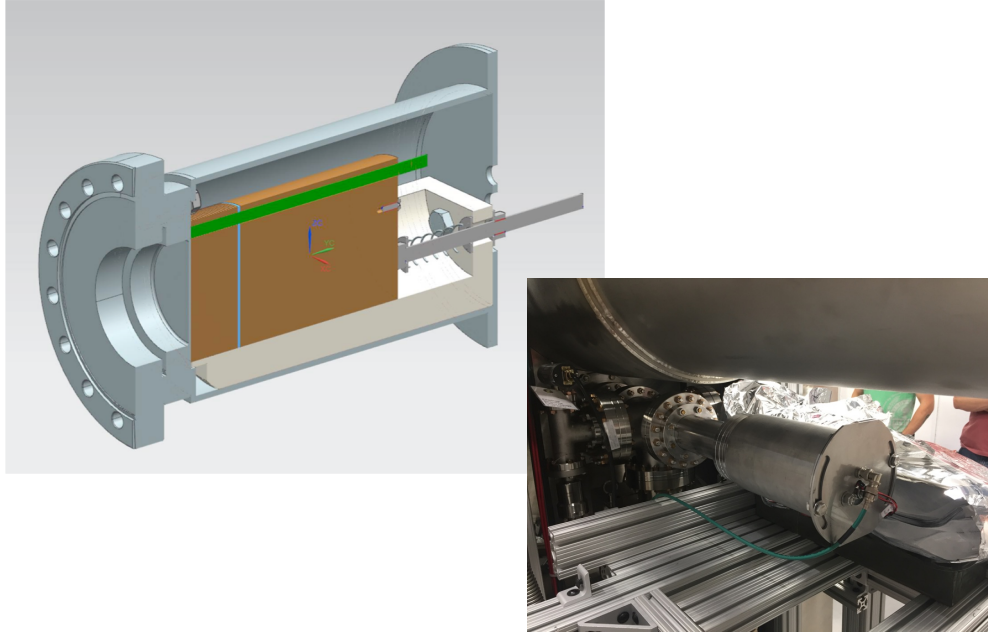
courtesy: Olivier Napoly

Performance – field emission & dark current

- Field emission seen on at least one cavity of every cryomodule tested - until F1.3-07
- Location and magnitude varies
- ‘Usable gradient’ refers to peak gradient limited by measured FE of 50 mR/hour
- Dark current generally correlated with highest field emitting cavities
- Pulsed Processing has been effective in mitigating some field emitting cavities



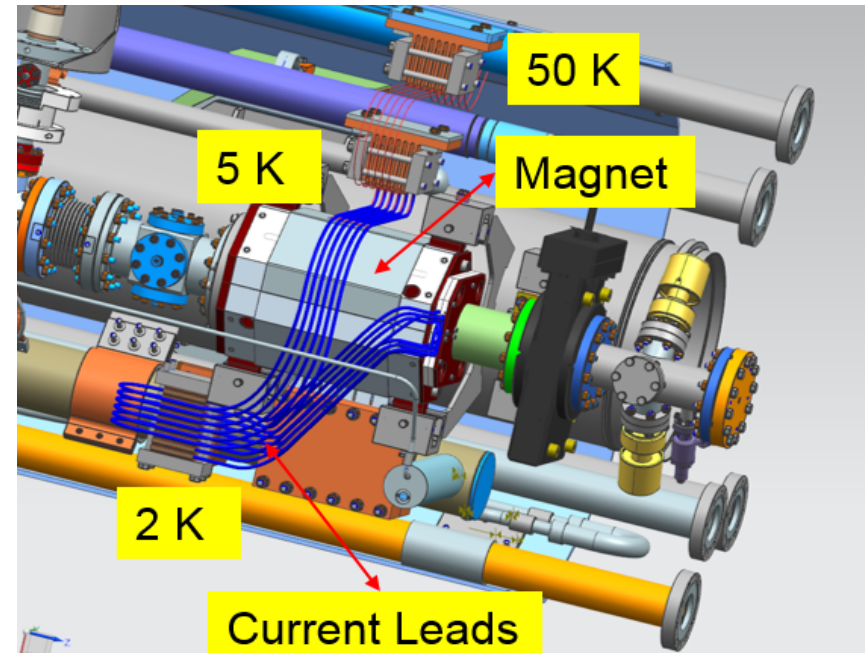
Test results – dark current detection



- Faraday cups installed specifically designed for expected LCSL-II dark current energies and current
- Sensitivity $\sim 0.2\text{nA}$; Calibrated to 10 nA/V
- X-ray (FOX) detectors installed at ends for correlation
- Response on 3 cryomodules/5 cavities – different ends, but mainly End-cup
- Mostly fractions of a nA
- ‘Worst’ response (F1.3-05) correlated to in situ repair during assembly (HOM feedthrough)

Performance - magnet

- 8 successful tests during cryomodule testing
 - No magnet-initiated quenches observed
 - Overheating current leads at 5 K and 50 K temperature intercepts at peak 20 A current.
 - *not a lead design issue but inefficient cryogenic cooling*
 - *performance much stabler after cryoplant/distribution improvements*
 - During first prototype tests were observed: Long external cables from power supply to the magnet had the large voltage drop. Were replaced.
- Lessons learned
 - Long cooldown/warm-up compared to cavities
 - The 5 K and 50 K cooling must be carefully monitored for magnet currents at the peak 20 A
 - All LCLS-II first stage magnets will have less than 10 A currents.
 - The recommended cryosystem heaters setup are 4.5 K and 45 K for the peak 20 currents
- All magnets passed tests at full cryomodule power and peak currents in quadrupole and dipoles coils (Including during unit tests)



courtesy: Vladimir Kashikhin

Performance - BPM

- BPM *electrical* cold check
 - All BPMs have been measured at different stages of the production and testing process
 - BPM electrodes are required to be connected properly, without shorts or open circuit
 - BPM electrodes cross-talk is required to be less than -30dB and the difference between S21 parameters needs to be below 1dB
 - Frequency range of interest goes from 0.5 to 2 GHz
 - All cryomodules have shown BPM characteristics compliant with specifications

courtesy: Paolo Berutti

Performance – Power Coupler

- Two sets of data
- FPC heating at max power $\sim 3\text{kW}$, $\sim 10\text{MV/m}$, $QL=1.e7, 12\text{ hrs}$
 - Unit test: $\sim 1.6\text{kW}$, 16MV/m , $QL\sim 4e7, 24\text{ hrs}$

Specification for coupler

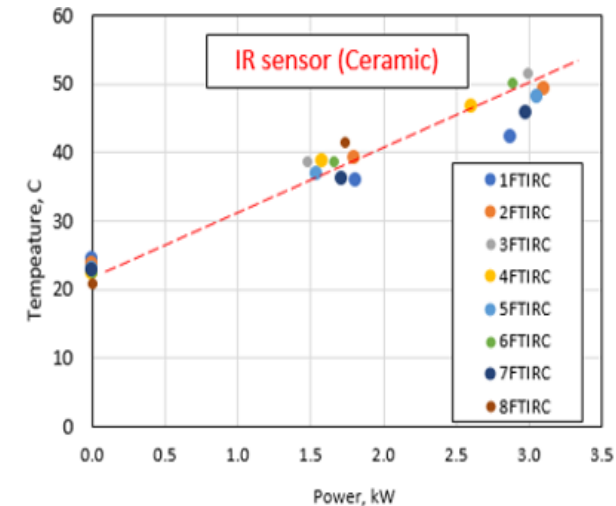
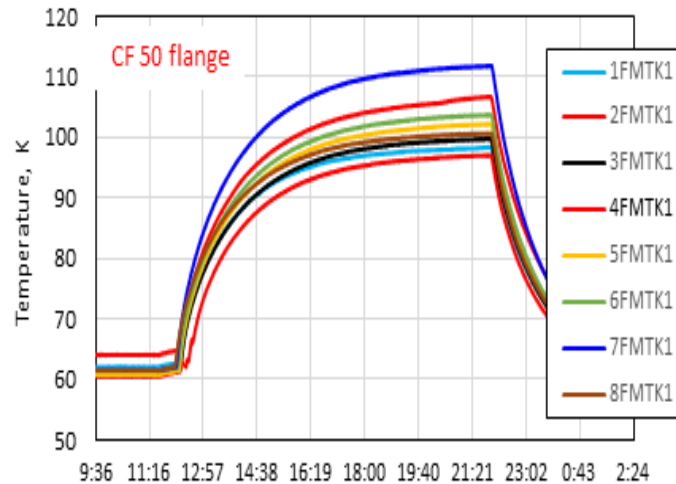
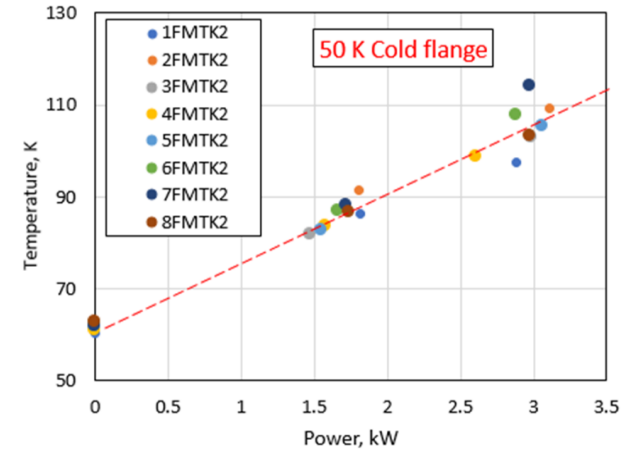
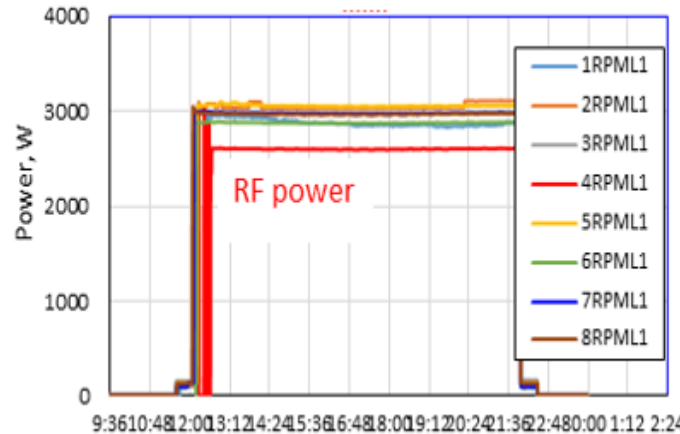
Temp:

- $<150\text{K}$ -CF100 flange
- $<450\text{K}$ on inner conductor

Coupler flange overheating at pCM $\sim 200\text{-}220\text{K}$ (3.6kW)

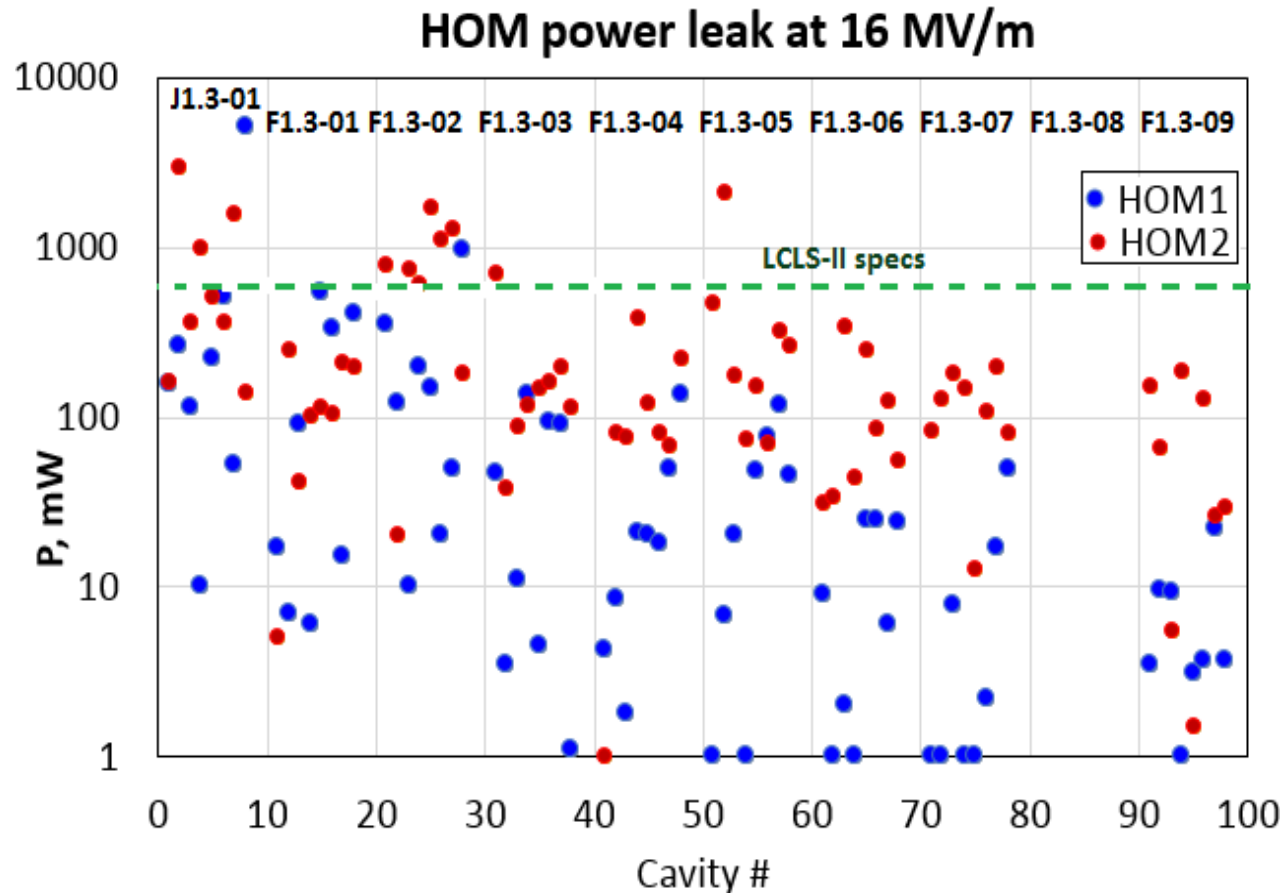
Modified thermal strap connection. Connected to 40K return pipe instead of low 40K thermal shield.

Example for F1.3-09. →



Performance - HOM power at 16 MV/m

- Notch frequencies of the HOM couplers are tuned at the last stage of CM assembly at RT.
- The LCLS-II specifies HOM power $<0.5\text{W}$ at 16MV/m , $Q_{\text{HOM}} > 5.4 \cdot 10^{11}$.
- CM02 showed some HOM signals above specification due to an error in the tuning process. → Fixed



Performance - unit testing

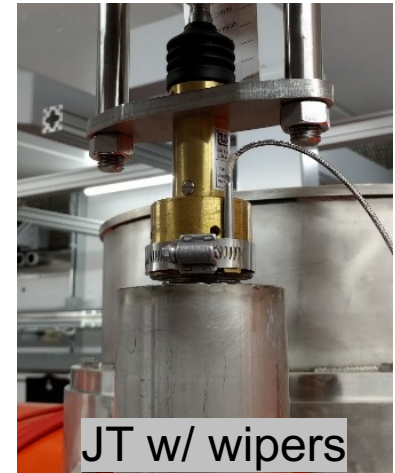
- Unit testing defined
 - Operate at minimum CW voltage: 128 MV
 - Cavities powered simultaneously to average ≥ 15.4 MV/m each
 - Coupler temperatures reach equilibrium or 10 hours (whichever is less)
 - Magnet coils energized – at least 18 A, typically 20 A per coil set
 - Demonstrate stable, reliable operation
 - Cavities phased
- Several attempts at GDR operation
 - Phase cavities: demonstrated
 - Limited by microphonics
 - Expect success with next one
 - See J. Holzbauer's presentation
- 24-hour test on the docket

	Duration	Magnet Current (A)
pCM	6 hr, 6 min	10 A – all coils
F1.3-02	4 hr, 44 min	18 A, then 20 A – all coils
F1.3-03	5 hr, 48 min	17 A – all coils
F1.3-04	2 hr 40 min, 7hr 45 min	17 A – Q, V only; 20 A – all coils
F1.3-06	3-1/2 hours	10 A – all coils
F1.3-05	20 hours	18 A, then 20 A – all coils
F1.3-07	12+ hours	20 A – all coils
F1.3-09	24 hrs	20 A – all coils

Performance – cryo valves & microphonics

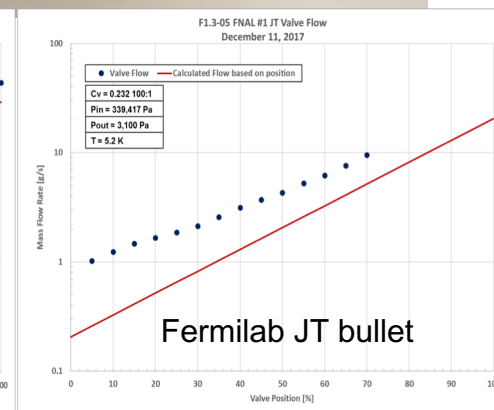
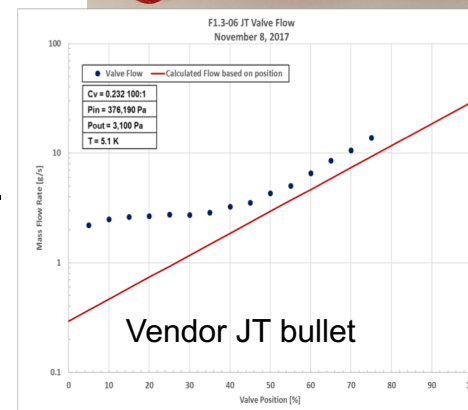
- More details – J.Holzbauer

- **WEPML001:** *Passive Microphonics Mitigation during LCLS-II Cryomodule Testing at Fermilab*
- **WEPML006:** *Modified Slow Tuner Design for Cavity 1 Inside LCLS II Cryomodules*
- **WEPML007:** *Active Microphonics Compensation for LCLS-II*



- Observations at CMTS1

- TAO's – microphonics out of spec 10Hz
- Valve regulation/bullet shape – unstable Q0 measurements



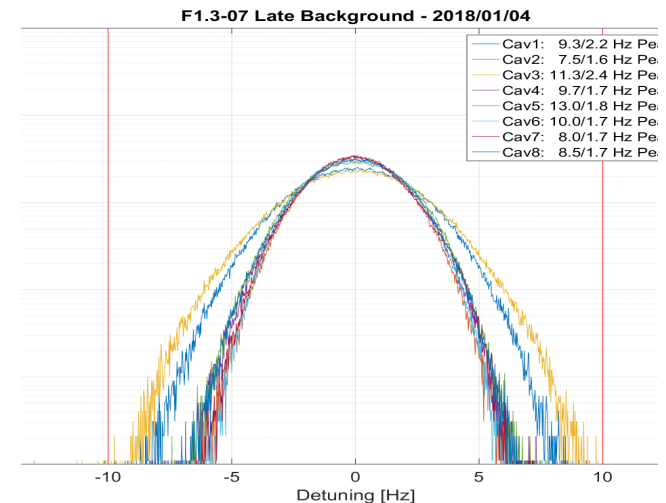
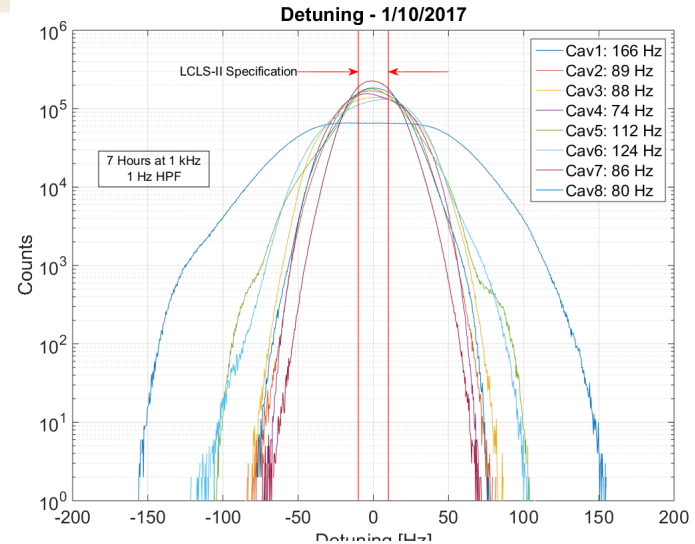
Performance – cryo valves & microphonics

- Comparing performance of the standard cryogenics configuration, the microphonics environment in the F1.3-02/03/04 is a factor of ~ 10 improved
- Significant improvements in stability of the system, leading to a far more predictable detuning environment

Tuner performance – working as designed, No surprises .

more details in presentation:

WEPML004 Production Tuner Testing for LCLS-II Cryomodule Production

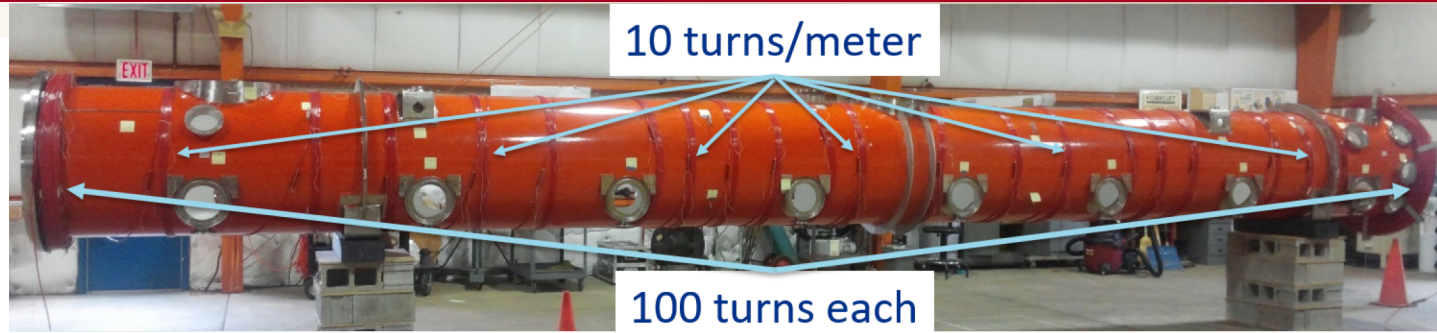


courtesy: Jeremiah Holzbauer

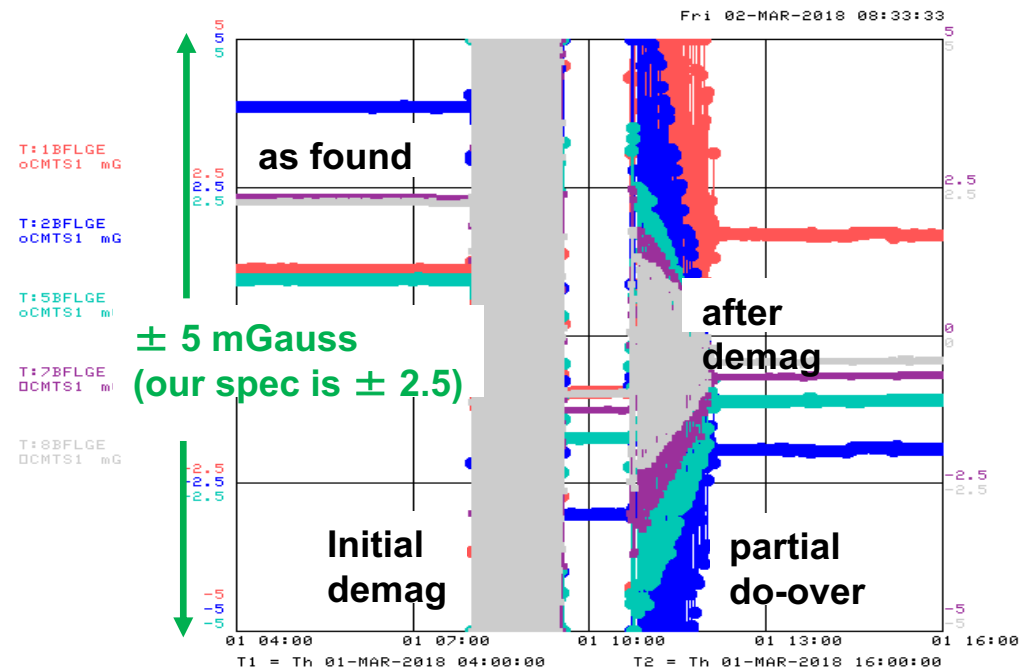
PCM As Cooled Down

F1.3-02... 09
state-of-the-art

Performance - external field cancellation



- Routine steps
 - Demagnetization before cooldown
 - Measured fields
 - Fast cooldown...



Before & after pre-cooldown demag (F1.3-09)

Acceptance criteria. Summary

- ✓ - pass
- ✗ - partial credit
- - fail

Parameter	F1.3-01	F1.3-02	F1.3-03	F1.3-04	F1.3-06	F1.3-05	F1.3-07	F1.3-09
Operating gradient > 12 MV/m	✓	✓	■	✓	✓	✓	✓	✓
Cryomodule voltage > 128 MV	✓	✓	✓	✓	✓	✓	✓	✓
FE onset > 14 MV/m	✓	✗	■	✗	✗	✗	✓	✗
Dark current < 1 nA	✓	✓	■	✓	✓	■	✓	✓
Average Q0 > 2.7x10 ¹⁰	✓	■	■	✓	■	✓	✓	✓
Unit test	✓	✓	✓	✓	✓	✗	✓	✓
Heat load acceptable	✓	✓					✓	✓
Thermometry	✓	✓		✓	✓	✓	✓	✓
Liquid level sensors	✓	✓	✓	✓	✓	✓	✓	✓
Cryogenic valving	✓	✓	✓	✓	✓	✓	✓	✓
Slow tuner	✓	✓	✓	✓	✓	✓	✓	✓
Fast tuner	✓	✓	✓	✓	✓	✓	✓	✓
Heater performance	✓	✓	✓	✓	✓	✓	✓	✓
Coupler flange temperatures	✓	✓	✓	✓	✓	✗	✓	✓
HOM's	✓	✗	✓	✓	✓	✗	✓	✓
Magnet performance	✓	✓	✓	✓	✓	✓	✓	✓
BPM	✓	✓	✓	✓	✓	✓	✓	✓
Vacuum (warm & cold)	✓	✗	✓	✗	✗	✓	✓	✓

- ✓ - pass
- ✗ - partial credit
- - fail

Summary of Cavity average performance

CM#	Average Q0	Usable Voltage (MV)	Flow Rate (g/s)	Cavity material
pCM	$2.99 \cdot 10^{10}$	145.3	80	WC/800
F1.3-02	$2.12 \cdot 10^{10}$	159.7	80	TD/800
F1.3-03	$3.46 \cdot 10^{10}$	141.0	30	TD/900
F1.3-04	$3.16 \cdot 10^{10}$	158.4	30	TD/900
F1.3-05	$3.12 \cdot 10^{10}$	148.4	80	6-TD,2-NX
F1.3-06	$2.25 \cdot 10^{10}$	161.4	60	1-TD,7-NX
F1.3-07	$2.24 \cdot 10^{10}$	161.1	80	2-TD,6-NX
F1.3-09	$3.24 \cdot 10^{10}$	171.3	80	5-TD,3-NX

Average $2.82 \cdot 10^{10}$ **161**

Specification $2.7 \cdot 10^{10}$ **128**

Anomalies

There have been unique issues with most of the cryomodules tested to date

- F1.3-01 (prototype) – microphonics/TAO
- F1.3-02
 - Low Q0
- F1.3-03
 - Vacuum leak
 - HOM heating
- F1.3-04
 - Alignment on test stand
 - Cooldown valve leaking
- F1.3-06
 - Low average Q0, NX-900 material
 - First CM shipped to SLAC
- F1.3-05
 - Vacuum leak during warm-up
 - Coupler heating (?)
 - Mis-tuned HOM
 - JT valve
- F1.3-07
 - Low average Q0, NX-900 material
 - Cooldown valve leaking
 - **Meets all specs**

Issues and solutions

Several others issues have been identified during cryomodule testing. Immediate actions were applied to solve these deficiencies including changes in the design, procedure or work flow.

- Cavities from one vendors not meeting gradient or Q0 specification. Actions: increase vendor oversight, improved procedures, changed processing recipe, and rework cavities to meet requirements.
- Large level of microphonics. Actions: JT valve change including addition of thermal 'wipers,' flow reversal, and gas-guarding; modifications in the two-phase pipe and cavity1 to gate valve interface.
- HOM Tuning: a few HOMs were out of specification. The tuning procedure was reviewed and improved. .
- Field emission in CM. Action: changes in the High Pressure Rinse technique, cleanroom audits leading to improved performance.
- Power coupler overheating at 70K flange. Action: connect thermal straps to 50K return pipe directly instead of connection to low part of 50K thermal shield.

Summary

- 8 test runs completed
- Infrastructure largely reliable
- Testing results for the most part successful
 - Recent FE encouraging
 - Q0 a work in progress
 - Significant development work for LCLS-II
 - Especially LLRF & resonance control
 - Estimated testing throughput appears achievable
 - A team effort

Looking ahead

- Continue CM testing
- Give time to activities beyond baseline testing as needed
 - LLRF/Active Resonance Control
 - Q0
- Testing sequence is mature, but...
 - Identify means to streamline testing process, tighten weak links
 - Maximize time available for thermalization prior to Q0 measurements
- Planned throughput is achievable...
 - **Production vs. R&D**



ACKNOWLEDGMENTS

The authors greatly appreciate the large contribution to this work from the entire Fermilab LCLS-II team and particularly the cryogenics engineers and technicians as well the staff responsible for cryomodule installation and operation.