LCLS-II

LCLS-II Cryomodules: Performance update

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BERKELEY LAB Lawrence Berkeley National Laboratory
Argonne NATIONAL LABORATORY
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U.S. DEPARTMENT OF ENERGY
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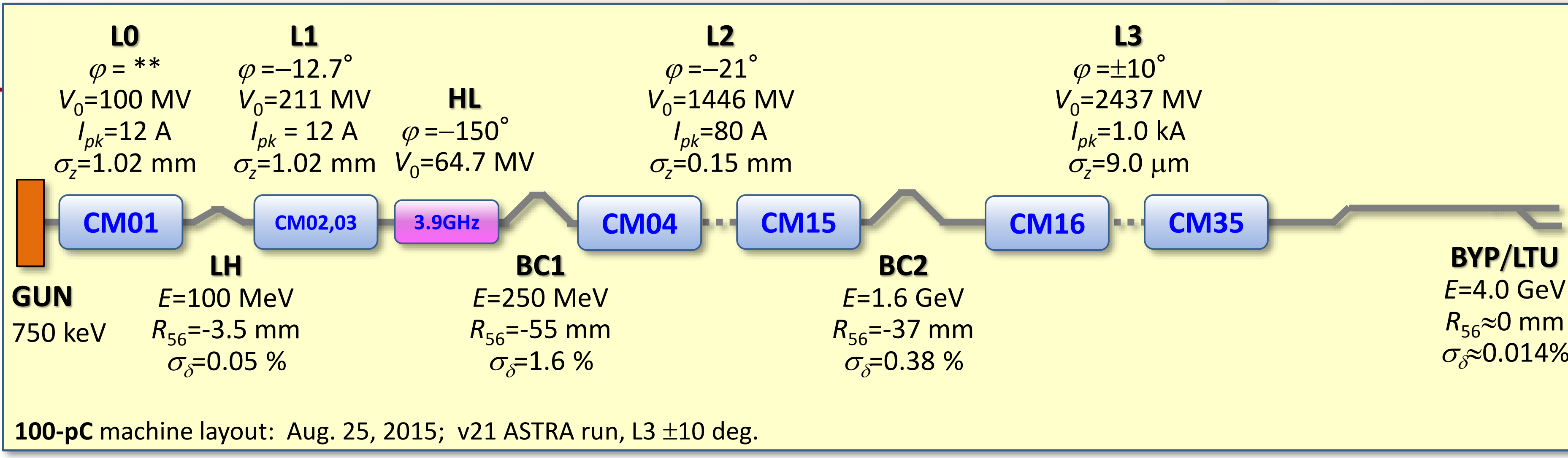
Outline

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

Linac RF and Compression

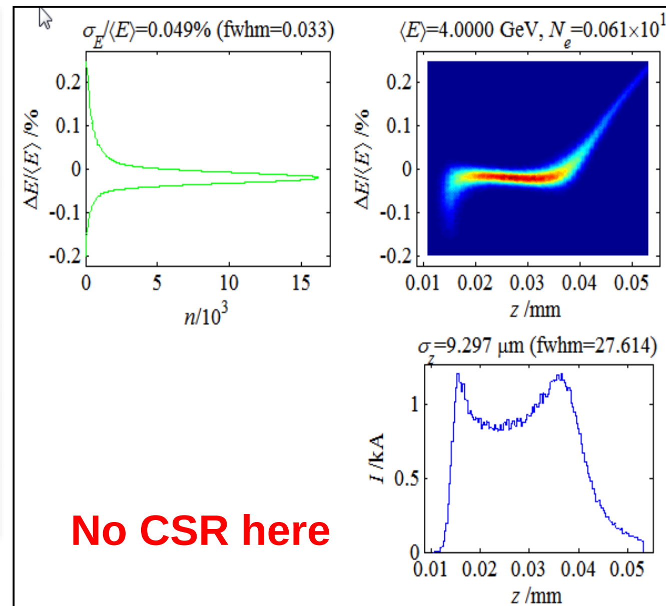


Linac Sec.	V_0 (MV)	φ (deg)	Acc. Grad.* (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cav's per Amp.
L0	100	**	16.3	1	8	0	1
L1	211	-12.7	13.6	2	16	1	1
HL	-64.7	-150	13.4	2	16	2	1
L2	1446	-21.0	15.5	12	96	6	1
L3	2437	±10	15.7	20	160	10	1

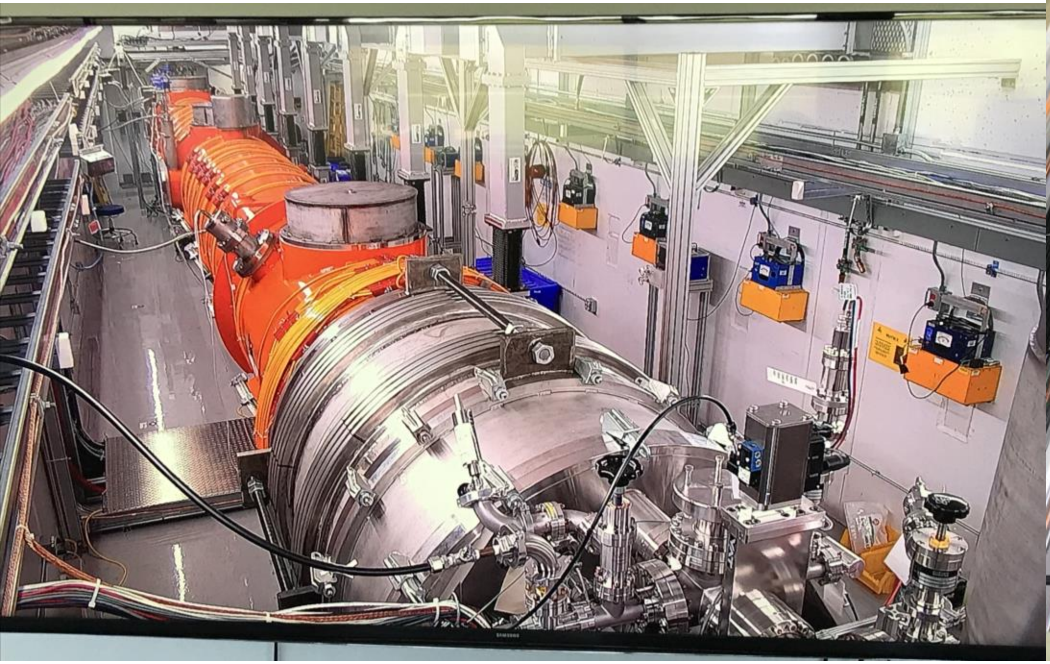
* Nom. crest grads. averaged over powered cavities (worst phasing requires 16 MV/m)

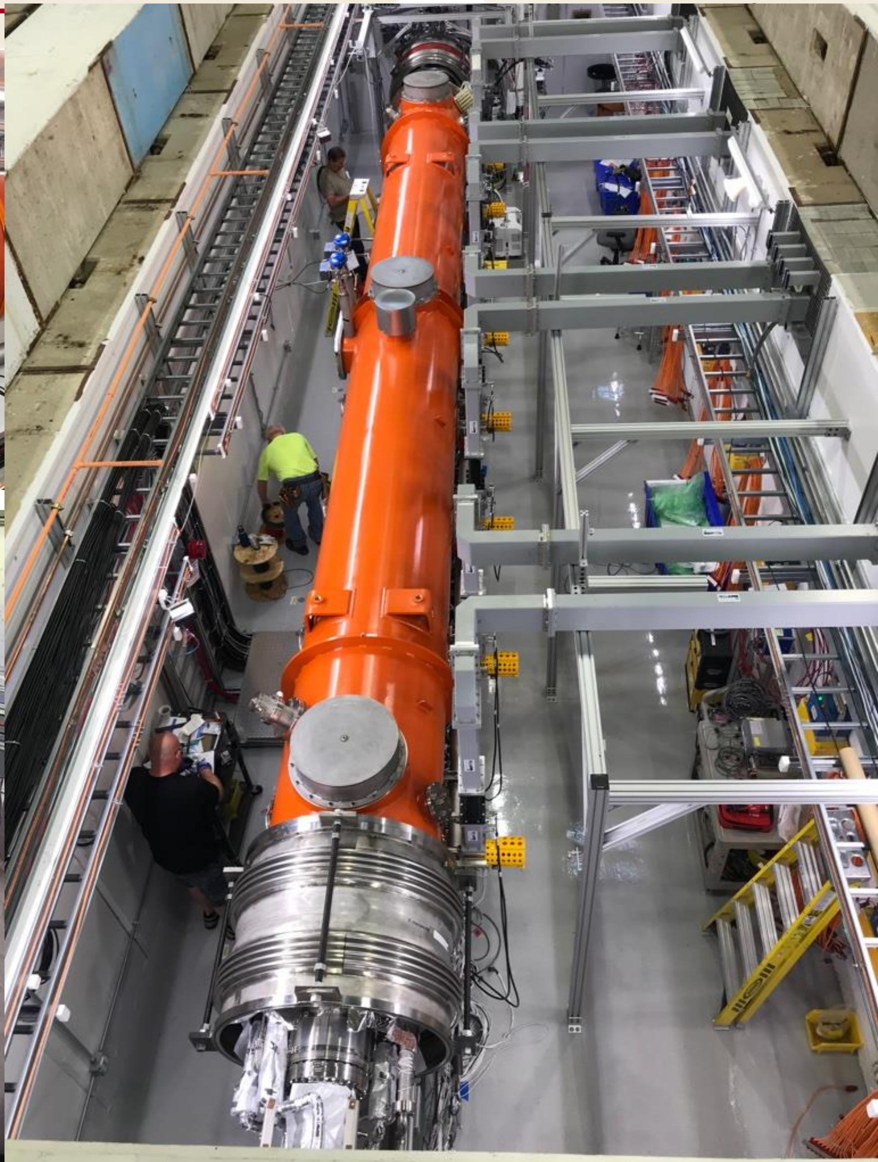
** L0 cav. phases: ~(–4.0°, -, -, 0, 0, 0, 1.25°, 3.0°), with cav-1 at 50%, cav-2 & -3 off.

Includes 2.5-km RW-wakes

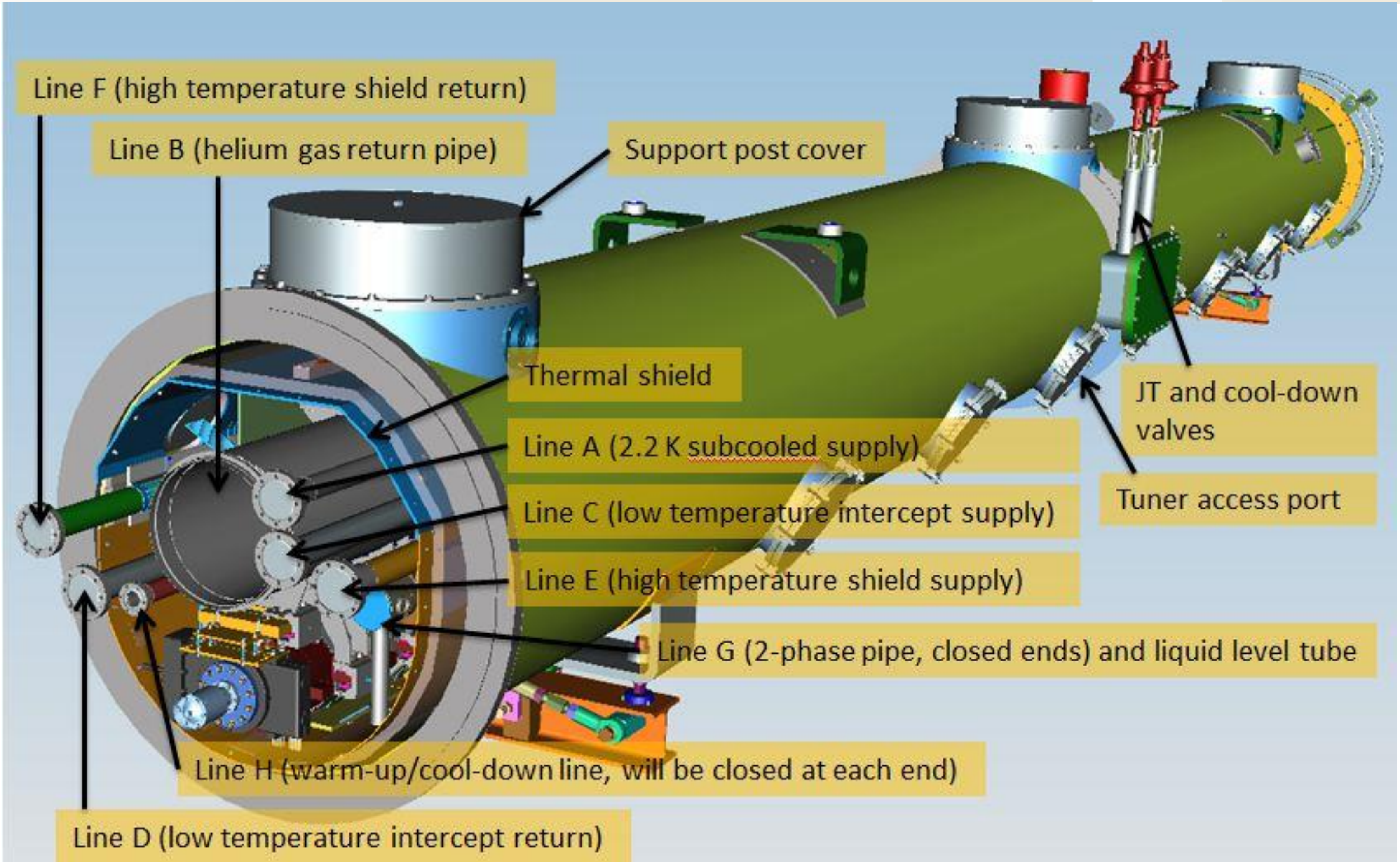


CMTS at Fermilab

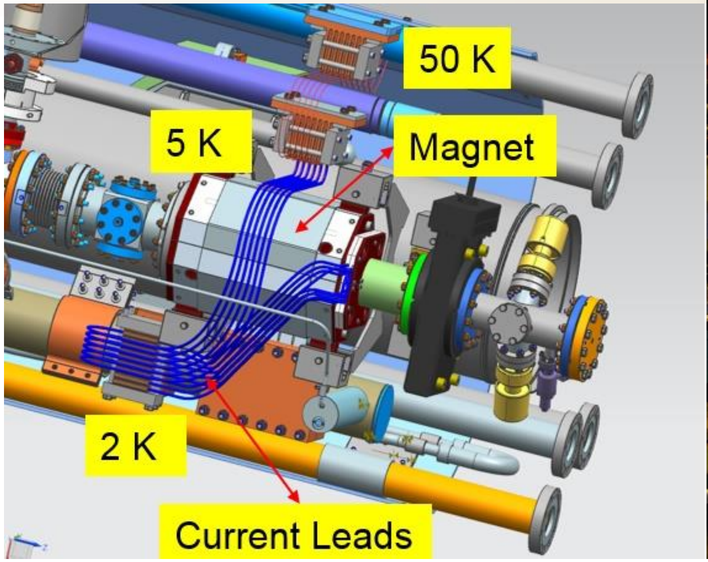


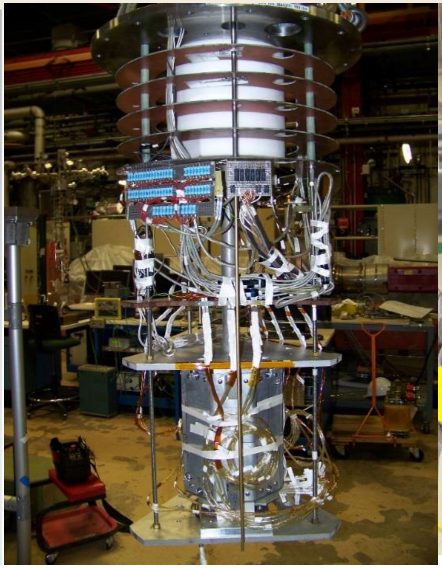


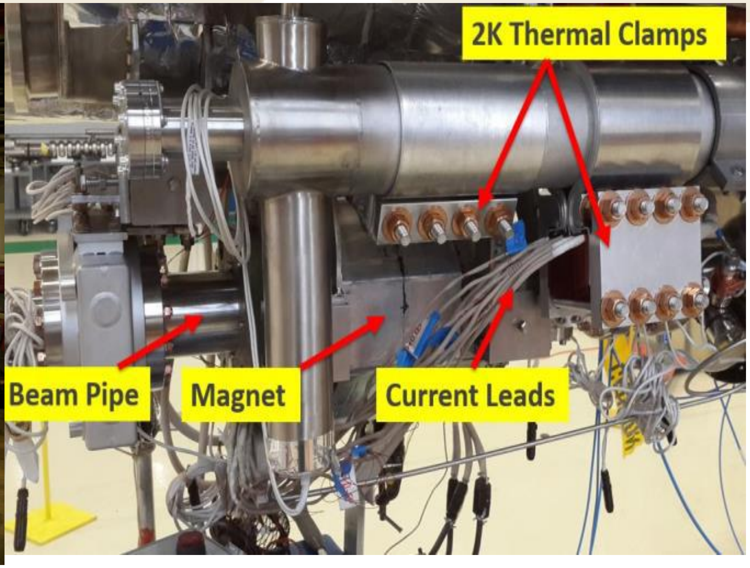
LCLS-II 1.3 GHz Production Cryomodule Labels



LCLS-II Magnet Cold Tests at FNAL





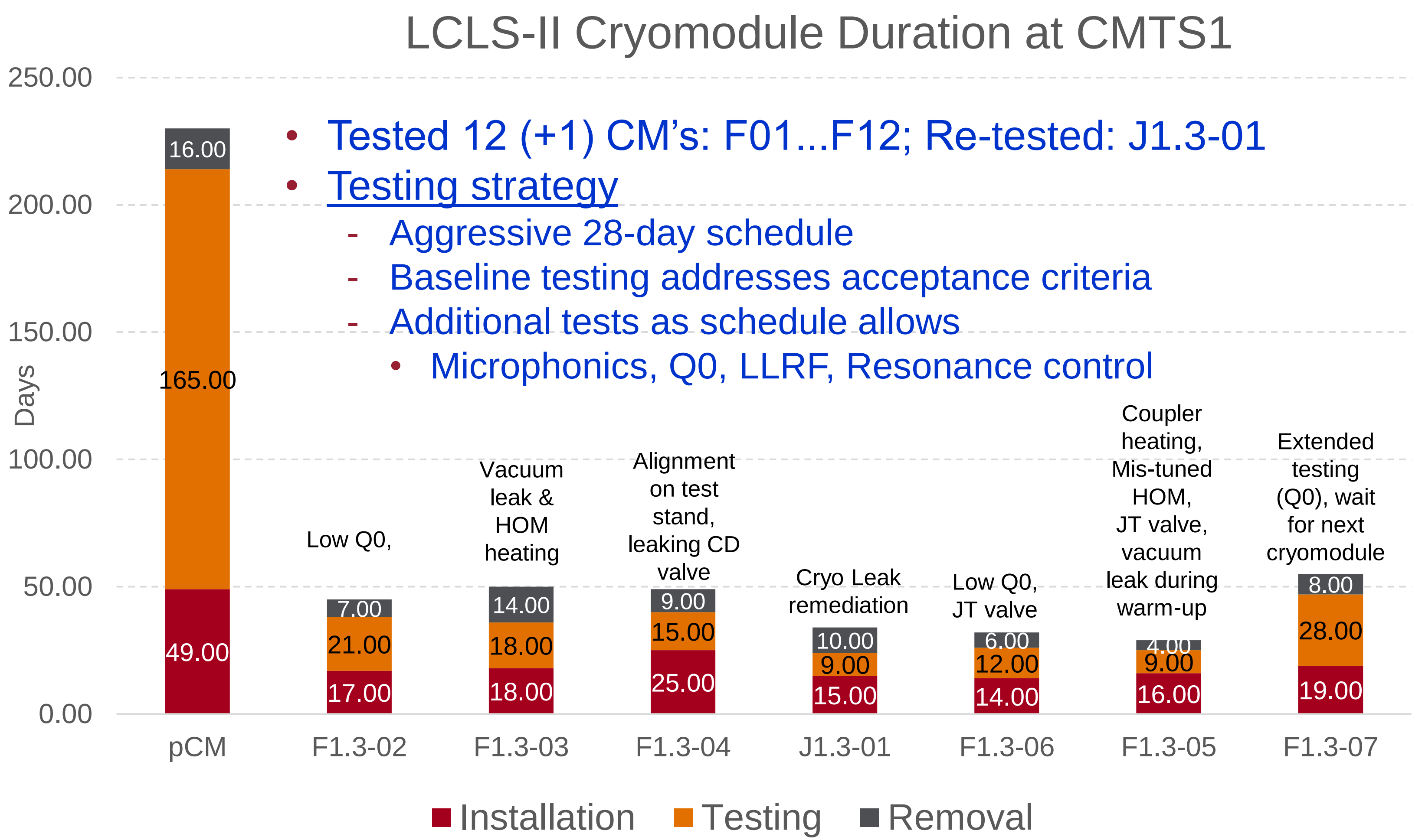


40 SC splittable iron dominated magnets (ILC like design, but shorter).
Conductively cooled through pure Al heat sink.

- ***Test in liquid helium before the installation in the CM to verify performance:***
  - *Quadrupole, and dipoles field quality and coupling at 20A*
  - *Iron and superconductor hysteresis effects.*
  - *Procedures for degaussing and standardization.*
  - *Measured by rotational coil, accuracy of ~1 unit (10^{-4}).*
- ***Fully automated stand is capable to test magnets with the rate of 1 magnet/week.***
- ***All tested showed a good performance, no quenches observed at the peak current.***
- ***Final test at cryomodule***

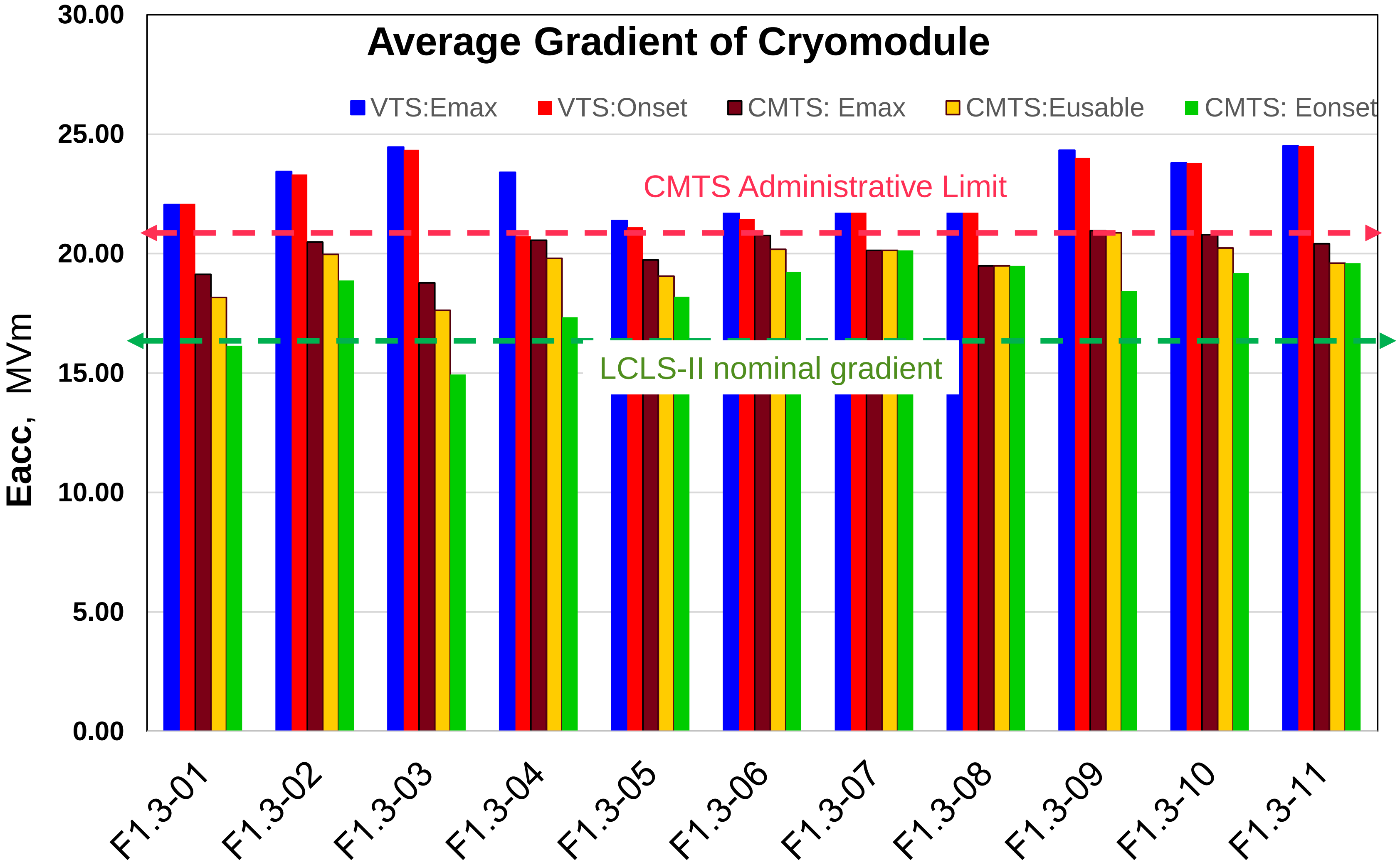
Throughput

- Tested 12 (+1) CM's: F01...F12; Re-tested: J1.3-01
- Testing strategy
  - Aggressive 28-day schedule
  - Baseline testing addresses acceptance criteria
  - Additional tests as schedule allows
    - Microphonics, Q0, LLRF, Resonance control



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

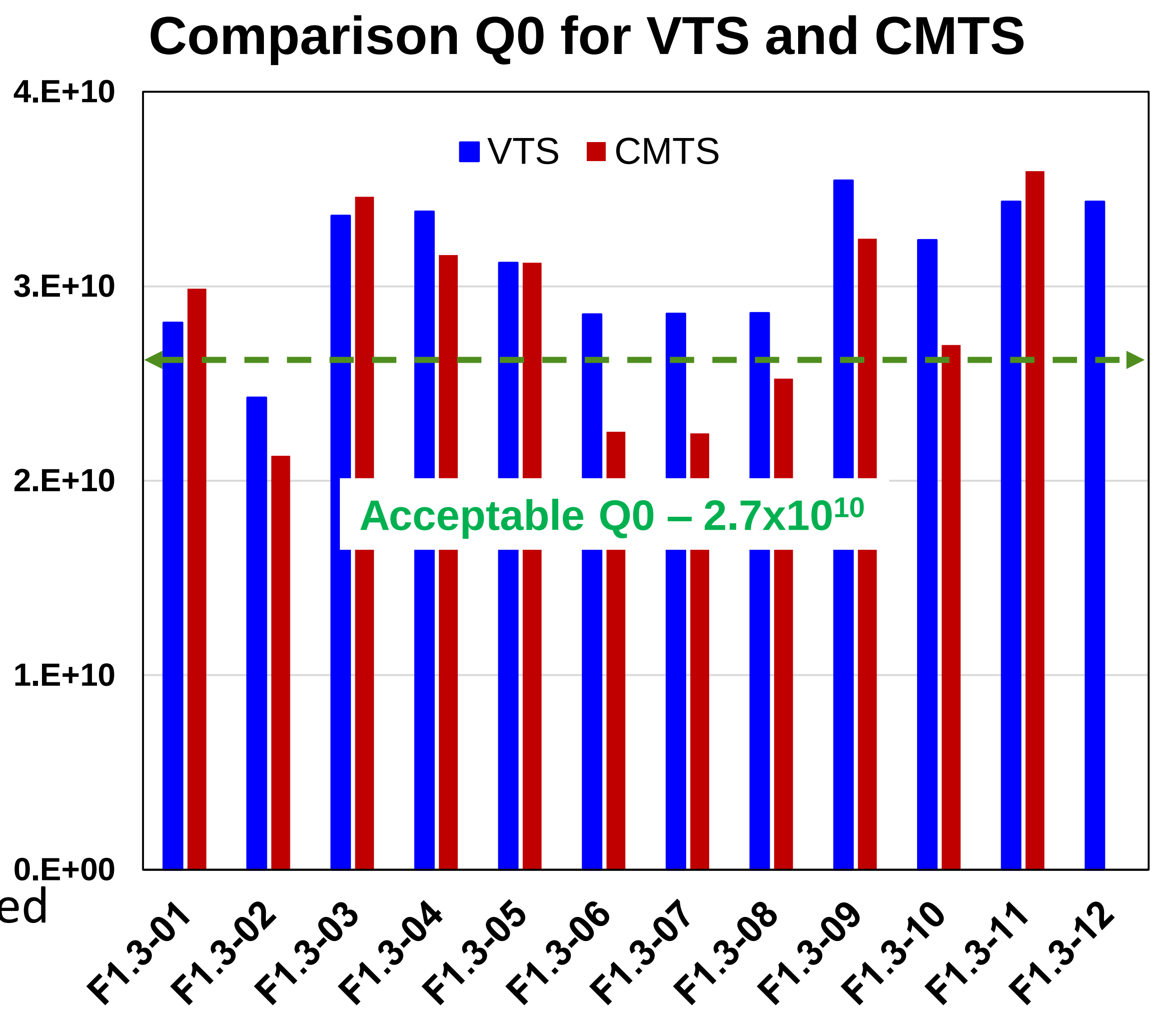
Performance – Gradient (Fermilab built CMs)



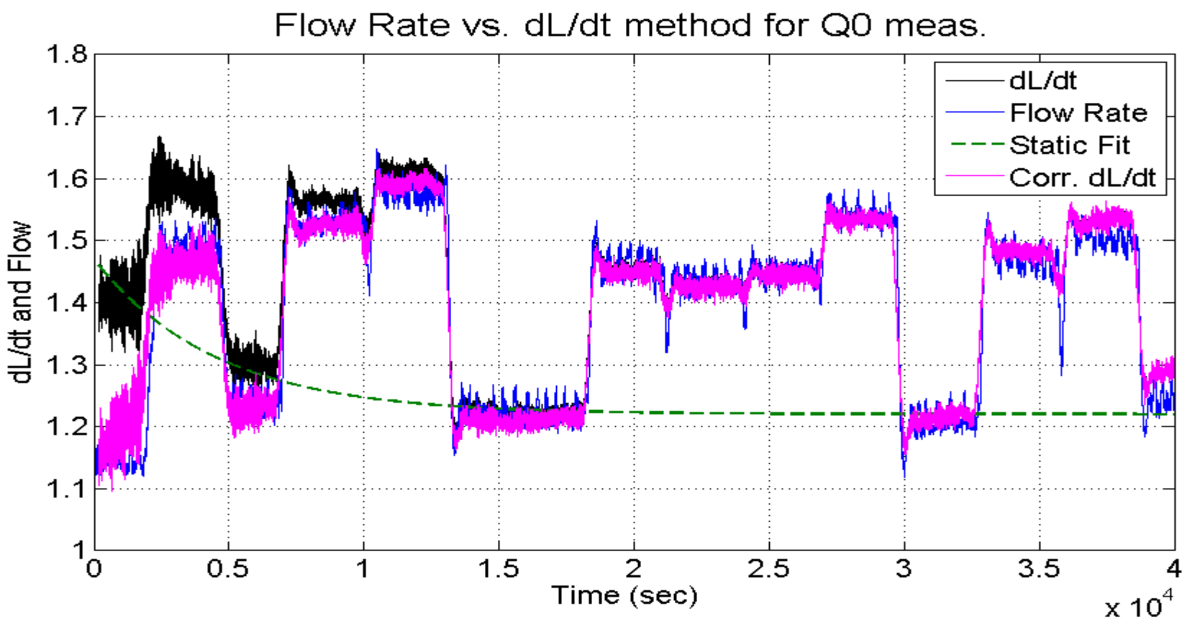
Performance – Q0

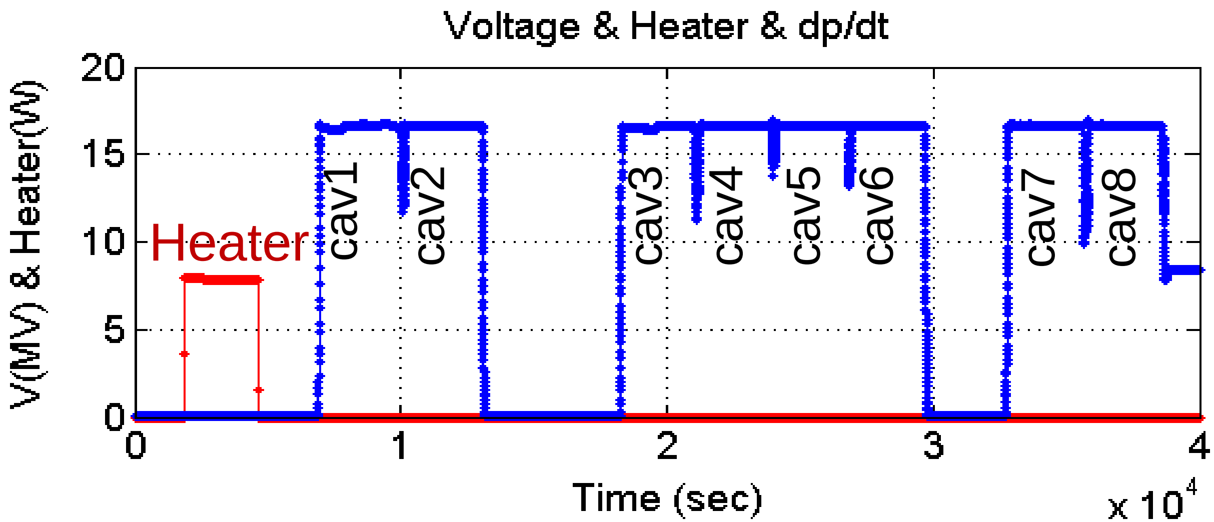
Summary of measurements

- Measurement technique
  - *Helium Flow rate*
  - *dLL/dt – helium Liquid Level*
  - *dP/dt*
- Multiple measurements per cryomodule at beginning of production
  - *Slow and fast cooldown*
  - *Poor flux-expelling material,*
  - *etc.*
- Q0 improve for faster cooldown and longer soaking time
- Recent tests 32 g/s with limited soaking time



Flow rate vs. dL/dt method: Fast Cooldown





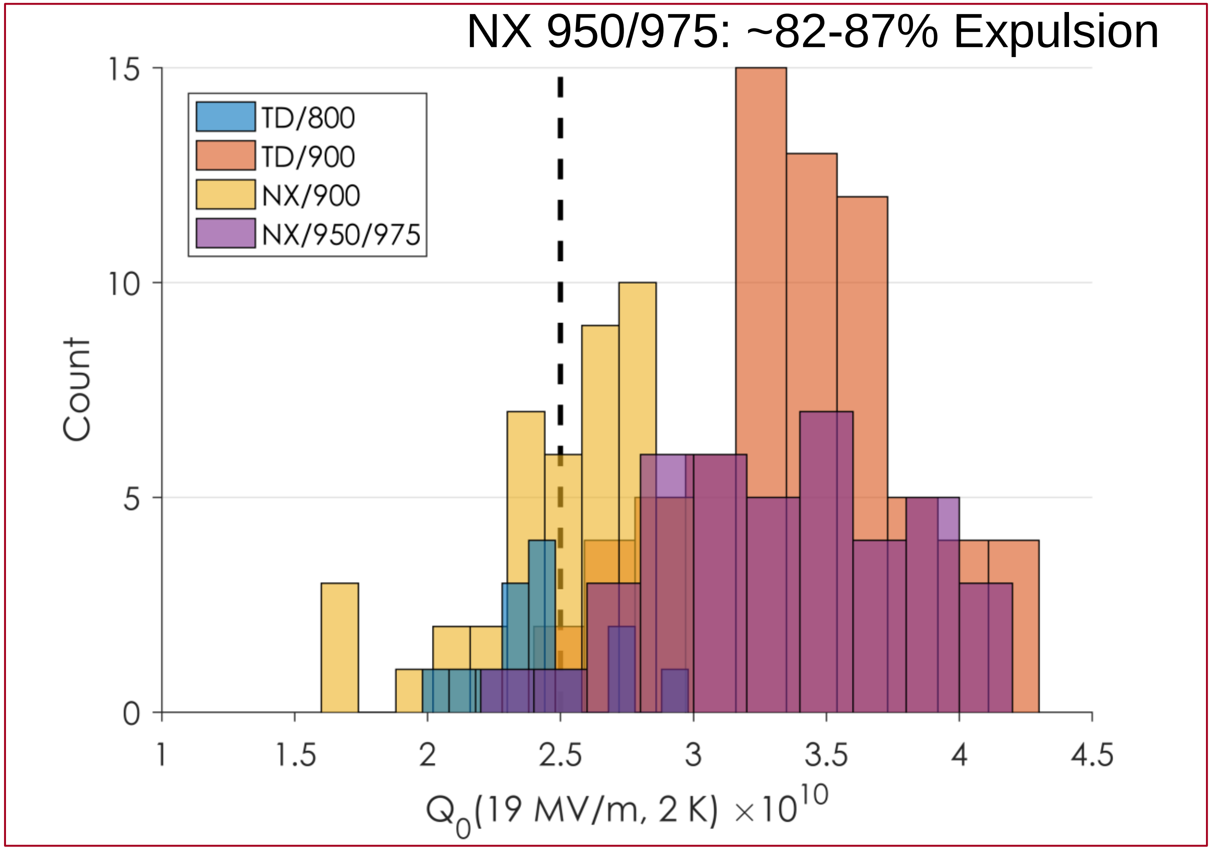
Cooldown rate 80 g/s

Cav #	Q0 $\times 10^{10}$ Flow	Q0 $\times 10^{10}$ 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

Flux Expulsion Dependence on Material and Heat Treatment

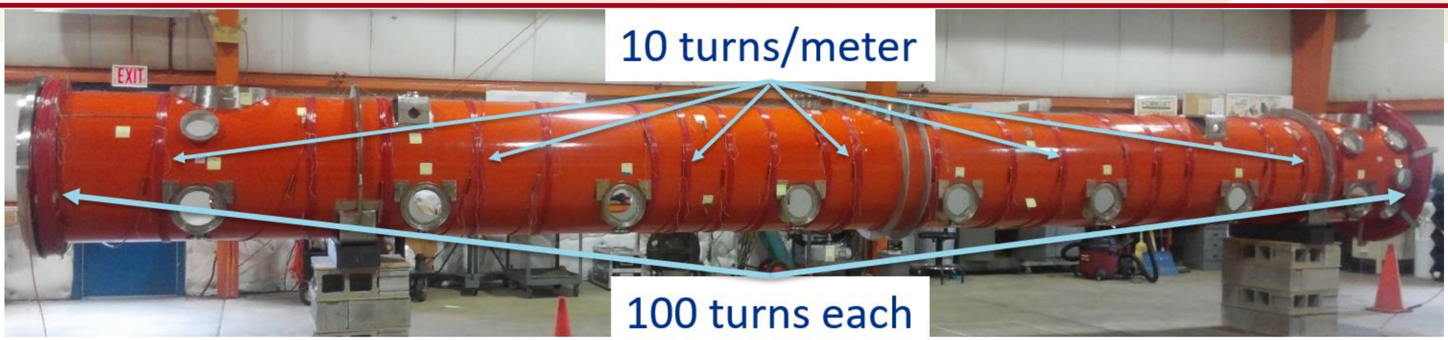
High sensitivity to magnetic field ➔ Requirements: Residual magnetic field <5mG + good flux expulsion to achieve low Q0



Courtesy of Dan Gonnella

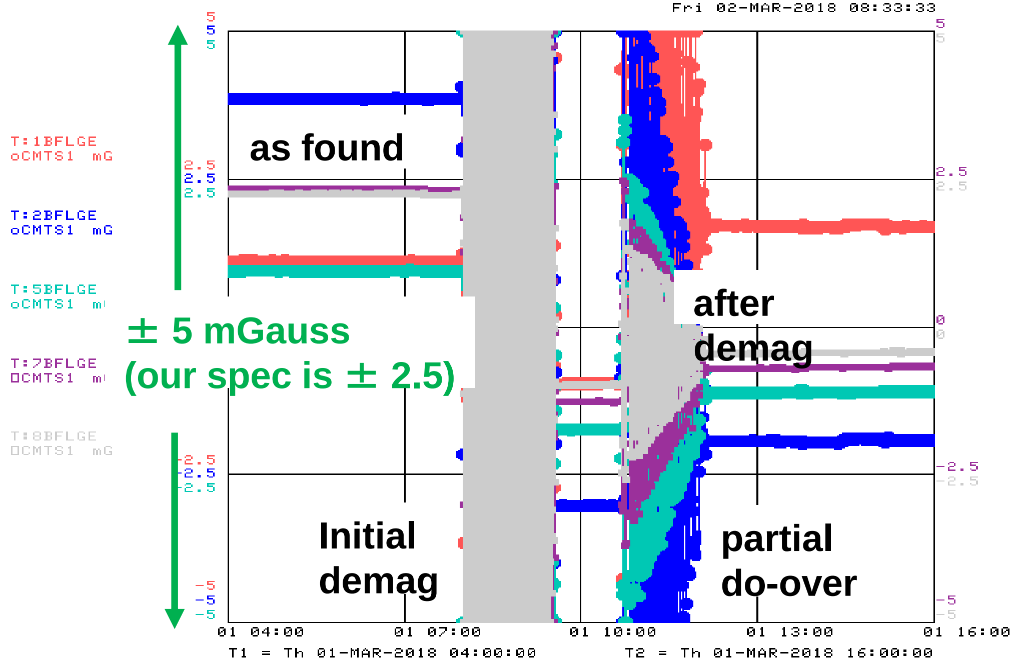
- TD/800 produced cavities with poor Q_0
- Raising the temperature to 900ºC improved performance significantly
- NX/900 produced cavities very similar to TD/800
- Raising the temperature to 950 or 975ºC brought performance in line with TD/900

Performance - external field cancellation



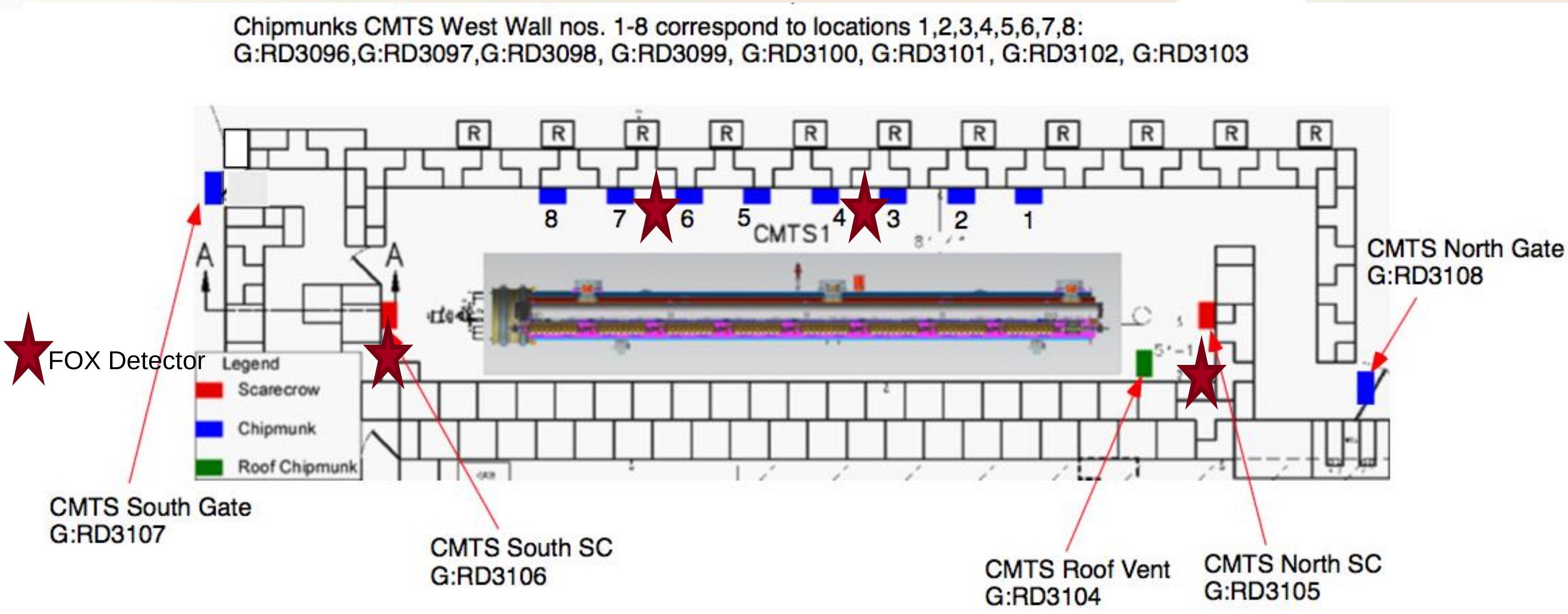
Routine steps

- Demagnetization before cooldown, ~1-2mG achieved
- Measured fields
- Fast cooldown…



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

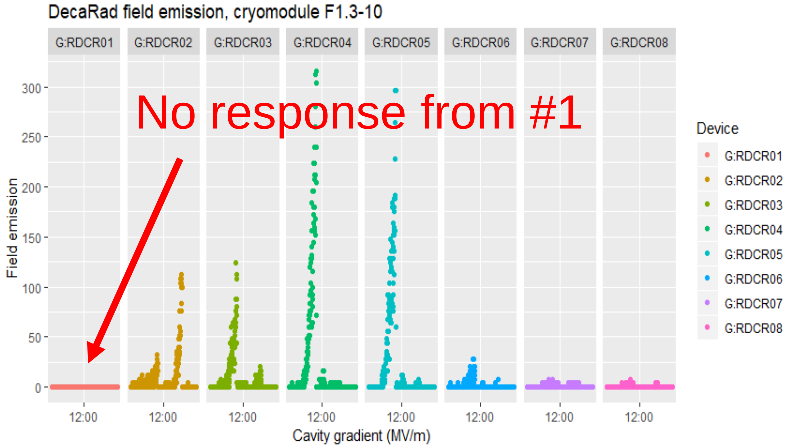
Performance – field emission & dark current

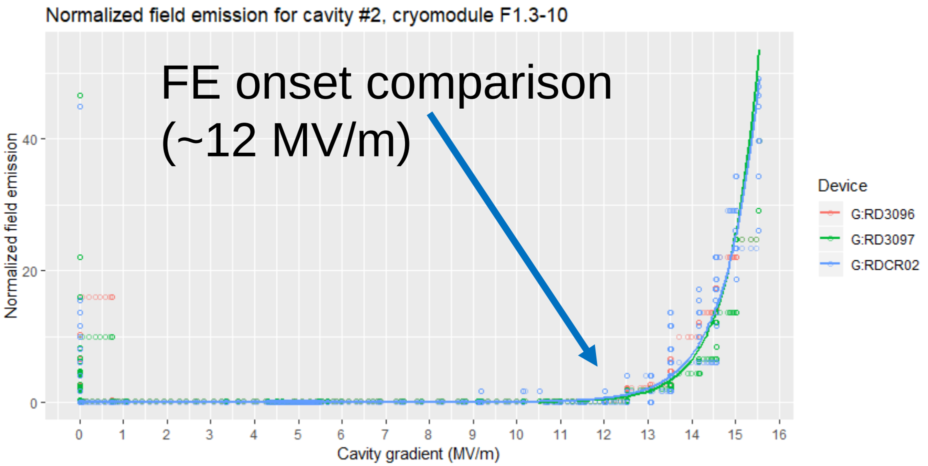


- Extensive array of detectors in place for field emission and dark current detection
- $ArC0_2$ and fiber optic detectors running the length are also installed
- Added – array of dosimetry badges
- DecaRad

DecaRad status

- System installed and functioning in CMTS1
- Detector installed at each coupler
  - #1 needs attention – no response
- Compared FE onset on F1.3-10/2 between DecaRad and wall chipmunks
  - Agreement within 0.35 MV/m
  - DecaRad lower

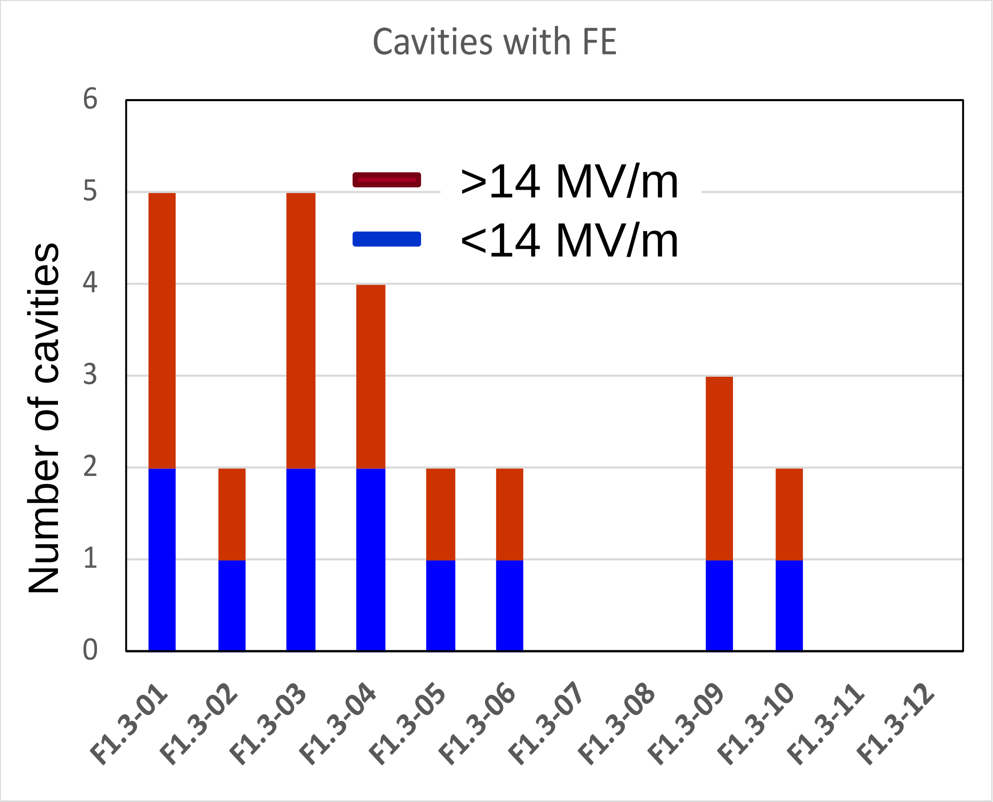


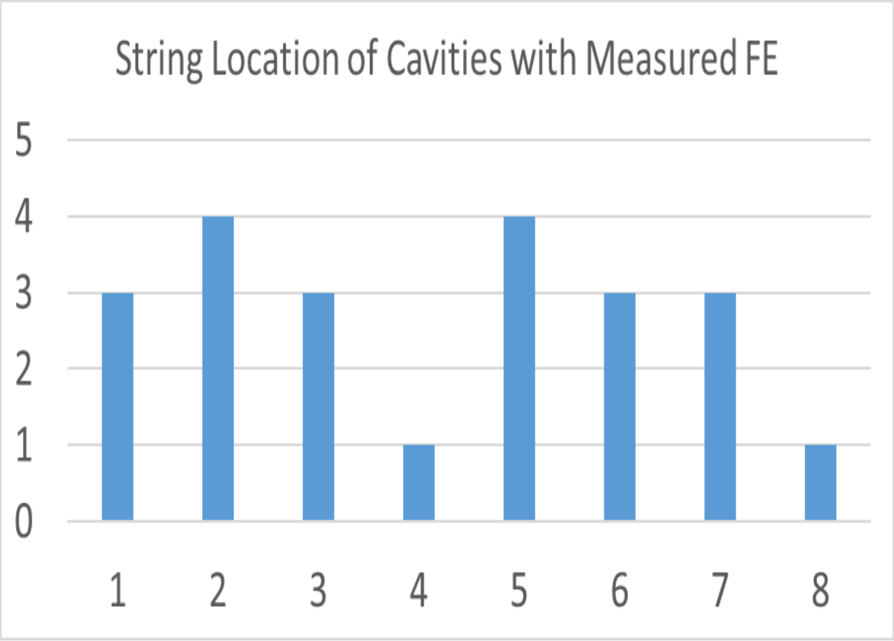


courtesy: Hieu Le

Performance - field emission improved

- Onset of measurable field FE E_{acc} ≥14 MV/m, each cavity (see plot below)
  - few cryomodules with no measured FE, improving
- 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**

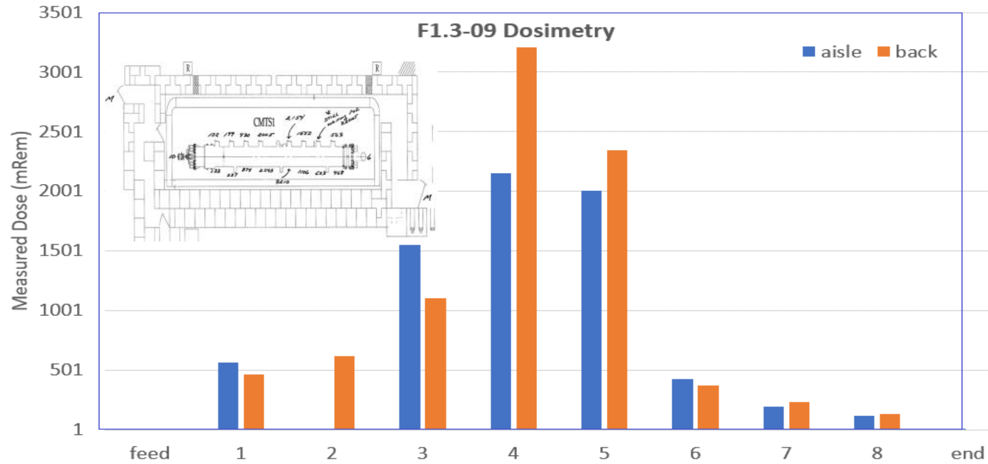


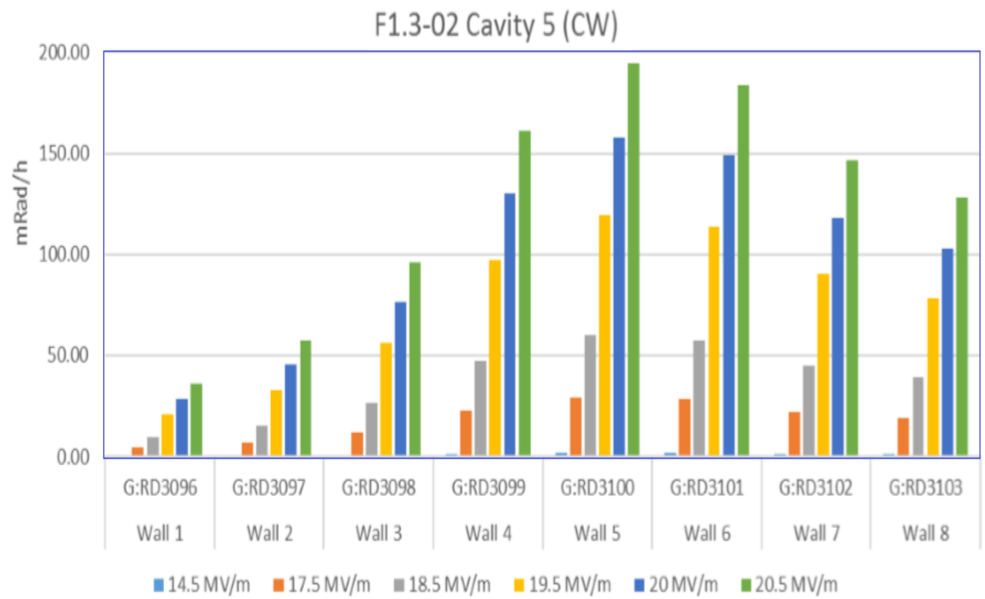


courtesy: Olivier Napoly

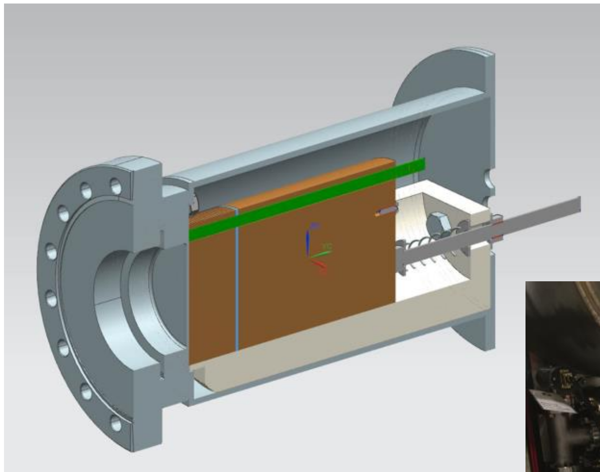
Performance – field emission & dark current

- 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

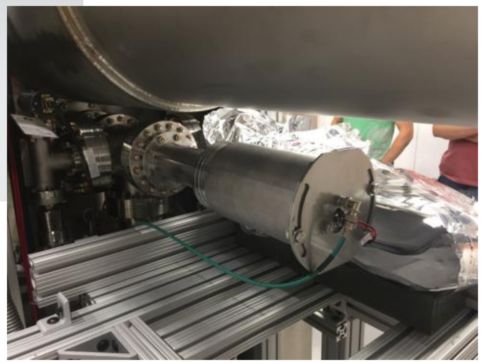


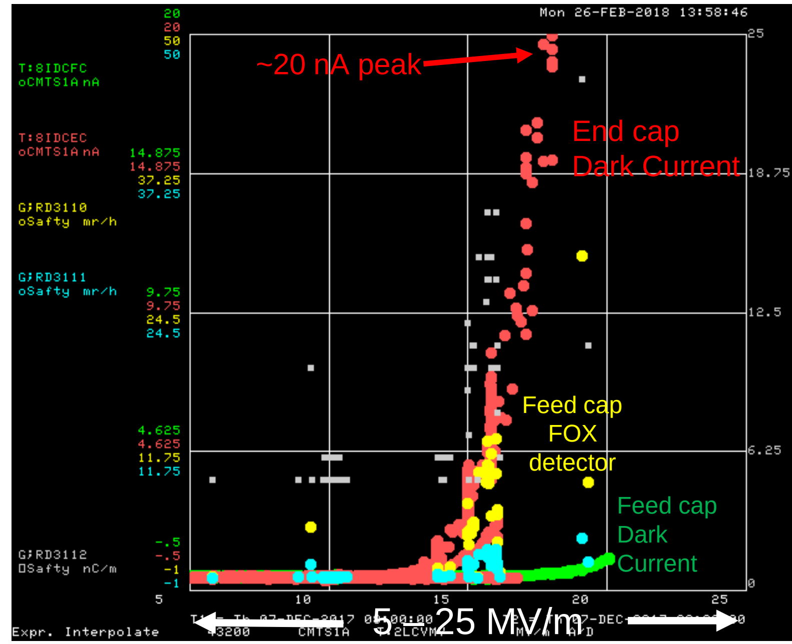


Test results – dark current detection



Courtesy E.Harms

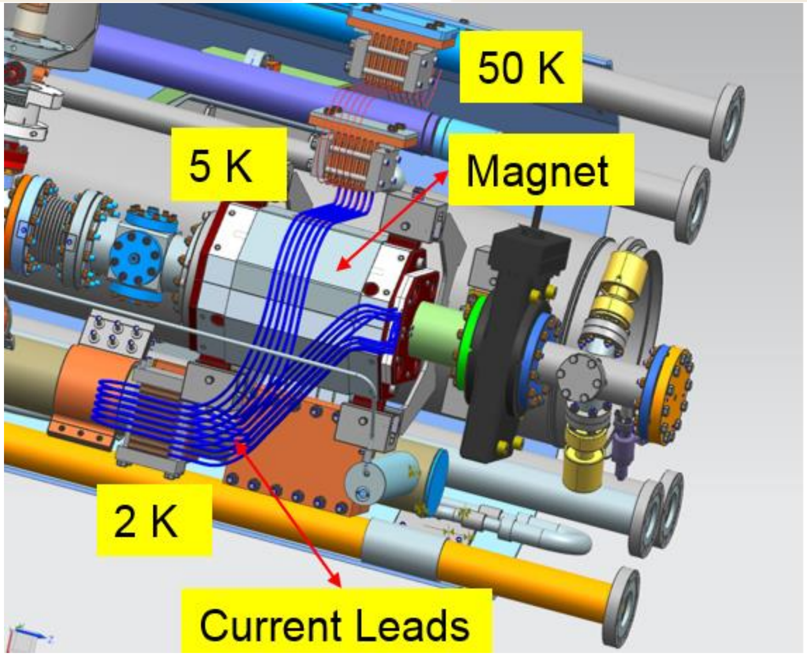




- Faraday cups installed specifically designed for expected LCSL-II dark current energies and current
- Sensitivity ~0.2nA; Calibrated to 10 nA/V
- X-ray (FOX) detectors installed at ends for correlation
- Response on 3 cryomodules/5 cavities – different ends, but mainly End-cup
- \- Mostly fractions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

Performance - magnet

- >25 successful tests during CM 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*
- Lessons learned
  - Long cooldown/warm-up compared to cavities
  - The 5 K and 50 K cooling must be carefully monitored for 20 A magnet currents (need <10A at 4GeV)
  - The recommended cryosystem heaters setup are 4.5 K and 45 K for the peak 20 A currents
- All magnets passed tests at full cryomodule power and peak currents in quadrupole and dipoles coils (Including during unit tests)



courtesy: Vladimir Kashikin

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 ~3kW, ~10MV/m, QL=1.e7,12 hrs*
- *Unit test: ~ 1.6kW, 16MV/m, QL~4e7, 24 hrs*

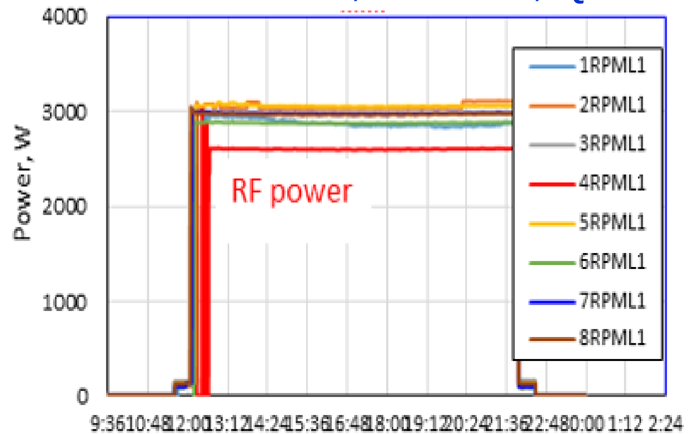
Specification for coupler Temp:

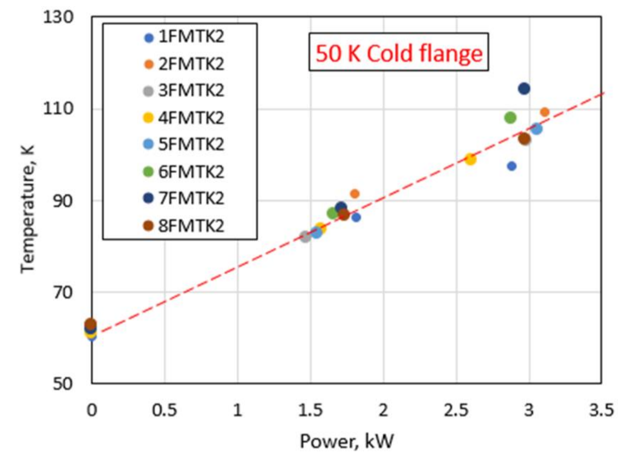
- <150K -CF100 flange
- <450K on inner conductor

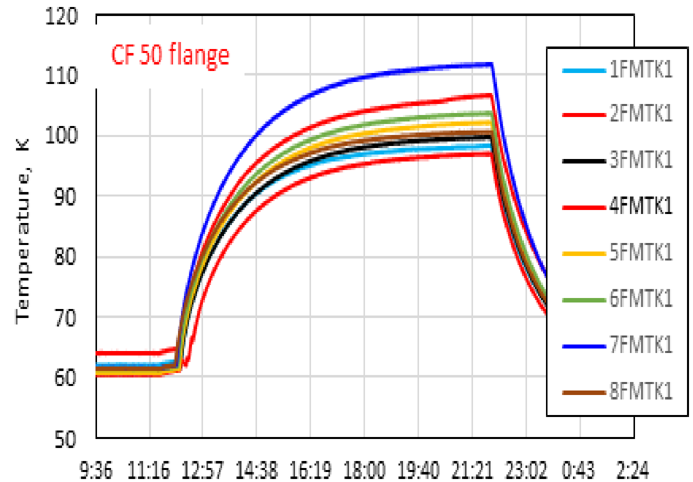
Coupler flange overheating at pCM ~200-220K (3.6kW)

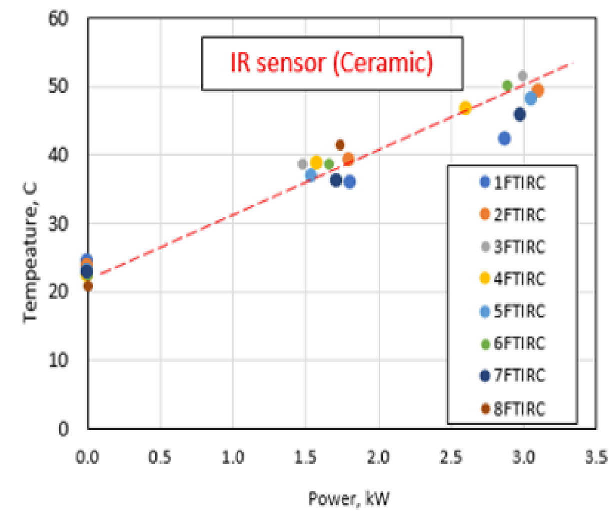
Modified thermal strap connection. Connected to 40K return pipe instead of low 40K thermal shield.

Example for F1.3-09. ➔



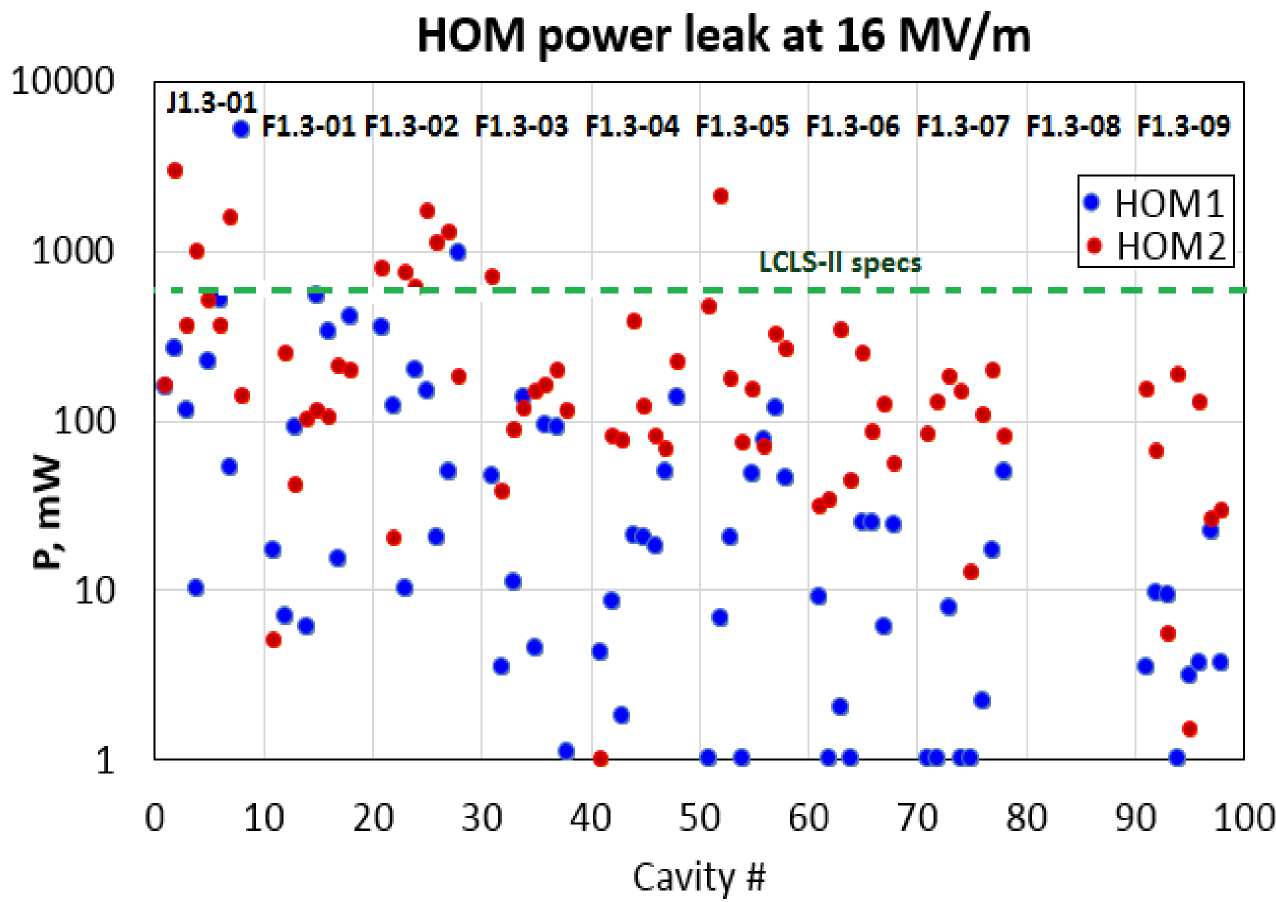






Performance - HOM power at 16 MV/m

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

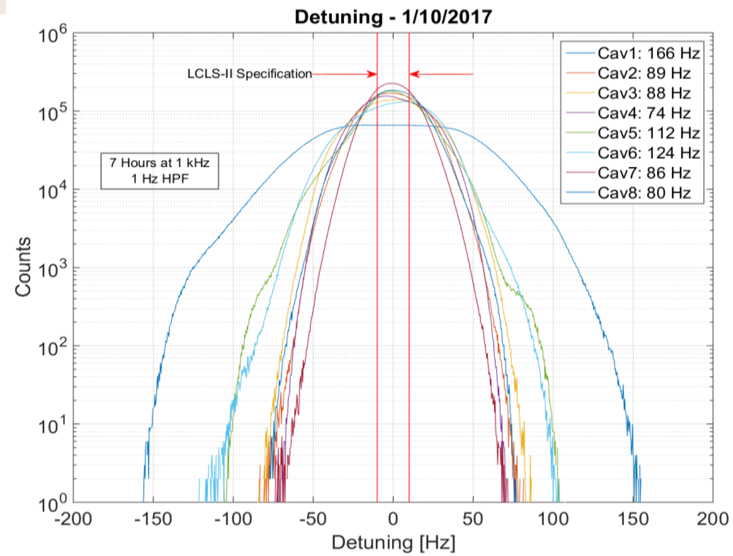


Performance – cryo valves & microphonics

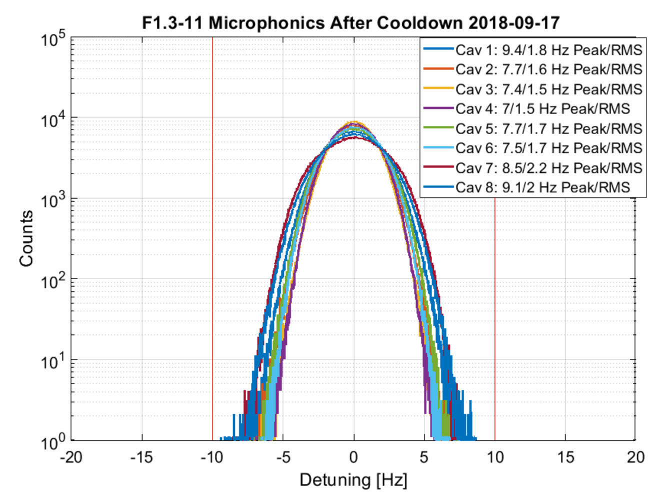
- Comparing performance of the standard cryogenics configuration, the microphonics environment in the F1.3-02/03/04 is a factor of ~10 improved

- Significant improvements in stability of the system, leading to a far more predictable detuning environment

<u>Tuner performance – working as designed, No surprises .</u>



pCM As Cooled Down

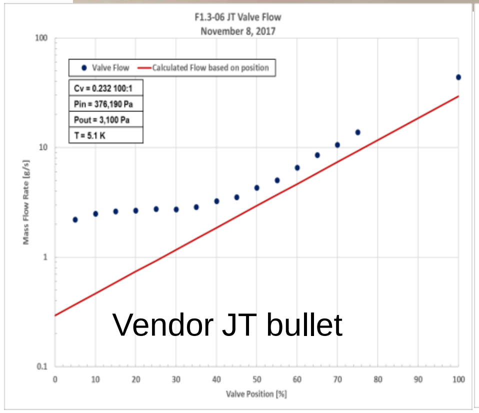


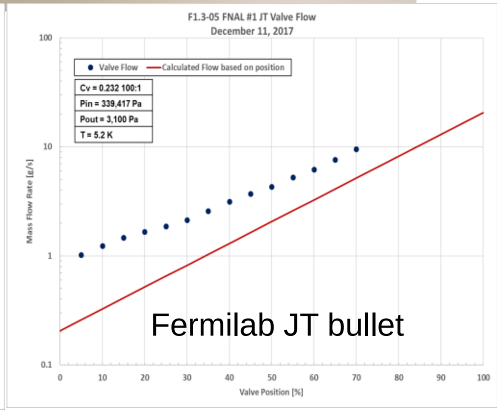
F1.3-02… 12
state-of-the-art

courtesy: Jeremiah Holzbauer

Performance – cryo valves & microphonics

- Observations at CMTS1
  - TAO's – microphonics out of spec 10Hz
  - Valve regulation/bullet shape – unstable Q0 measurements
- Several design modifications in valve to eliminate thermo-acoustic oscillations
- Design modification in CM (2-phase pipe, gate-valve support, etc.) to reduce microphonics, incl. cav #1



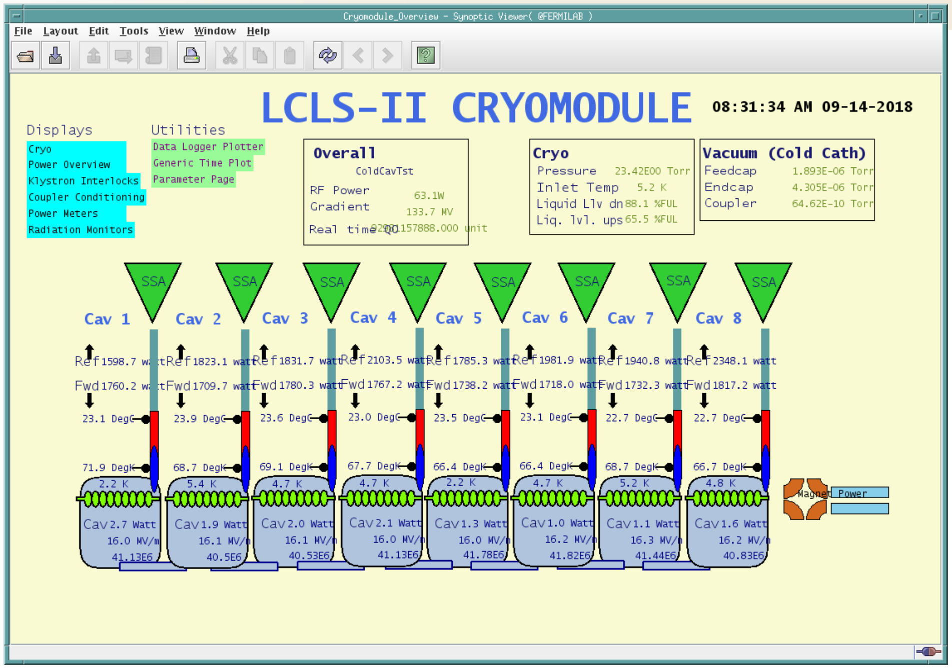


Performance - unit testing

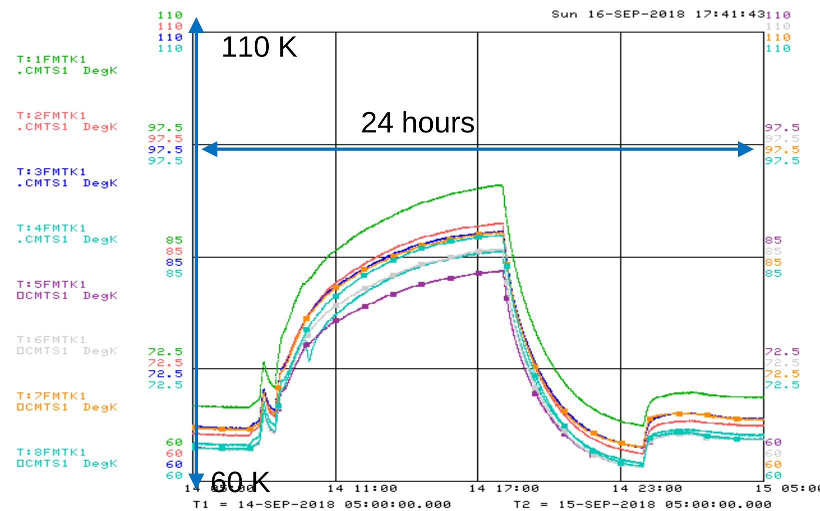
- Unit testing defined
  - Operate at minimum CW voltage:128 MV
  - Cavities powered simultaneously to average ≥15.4 MV/m each
  - Coupler temperatures reach equilibrium or 10 hours (whichever is less)
  - Magnet coils energized – at least 18 A, typically 20 A per coil set
  - Demonstrate stable, reliable operation
  - Cavities phased
- Several attempts at GDR operation
  - Phase cavities: demonstrated
  - Limited by microphonics
- In latest tests major cavities are running in GDR mode.
- 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

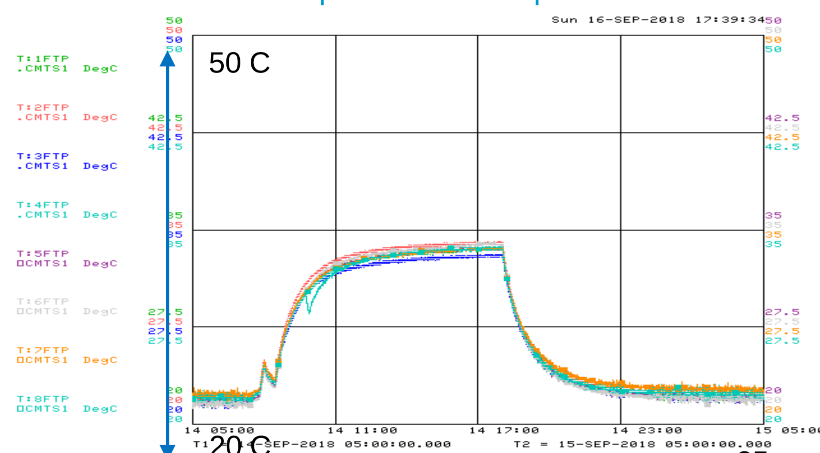
F1.3-11 Unit test



45 K Coupler Temperatures (limit is 150 K)



Coupler Warm Temperatures



- Unit test (typically 8-24 hrs)
  - 9 hours
  - 133 MV sum achieved
  - GDR operation demonstrated on 6 cavities for the bulk of the run
  - Magnet coils at 20 A

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 > 2.7x1010	✓	👎	👎	✓	👎	✓	✓	✓
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

F1.3-11 Acceptance criteria

Table 2 Production Cryomodule Minimum Acceptance Criteria

	Parameter	Value	Minimum acceptable performance during test
✓	Minimum acceptable operating gradient for an individual cavity	12 MV/m	Requires radiation associated with the cavity measured outside the CM be < 50 mR/hr and the quench level be at least 0.5 MV/m higher than the operating gradient
✓	Minimum CW voltage produced by an individual cryomodule	128 MV	The total CW voltage produced by an individual cryomodule shall be ≥128 MV with all cavities powered simultaneously and an average of cavity gradient ≥15.4 MV/m,
✓	Minimum cavity gradient at onset of field emission	14 MV/m	The onset of measurable field emission shall be at a gradient of ≥ 14 MV/m
✓	Captured dark current	<1 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 ≤1 nA when the cavities are operated in GDR mode with the relative phases set to accelerate speed of light electrons.
✓	Average cavity Q_0 within a cryomodule	2.7×10^{10}	Average Q_0 of cavities within a CM ≥2.7×10^{10}, measured at 16 MV/m
✓	Cryomodule operating duration with RF power during test		Each cryomodule must operate at the minimum CW voltage or greater until the coupler temperatures achieve equilibrium or for a minimum of ten (10) hours continuously, whichever is less, to verify stable operation and confirm acceptable coupler heating
	Cryomodule heat load during test at 128 MV voltage		Dynamic 2 K ≤ 86 W; Dynamic 5 K ≤ 8 W; Dynamic 45 K ≤ 92 W Static 2 K ≤ 7 W; Static 5 K ≤ 17 W; Static 45 K ≤ 123 W Total 2 K ≤ 93 W; Total 5 K ≤ 25 W; Total 45 K ≤ 215 W The impact of end caps in cryomodule testing is estimated to be <1 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
✓	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 valves shall all be verified functional during cryomodule operations by consistency with expectations for operational performance, in particular, no valve is to have ice form on the room temperature components.
✓	Cavity tuning to resonance during test (slow tuner)		Each cavity must be able to be tuned to a resonant frequency of 1300.000 MHz with a minimum available tuning range of ± 0.02 MHz at 2 K
✓	Fast 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	150 K	
✓	Fundamental power coupler warm part maximum temperature	450 K	
✓	Cavity HOM coupler rejection of 1.3 GHz power		$Q_{ext} \geq 2 \times 10^{11}$, maximum power measured at 1.3 GHz out of a single HOM coupler is 1 W at 16 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

Summary of Cavity average performance

CM#	Average Q0	Usable Voltage (MV)	Flow Rate (g/s)	Cavity material
pCM	$2.99 \cdot 10^{10}$	150.8	80	WC/800
F1.3-02	$2.12 \cdot 10^{10}$	165.8	80	TD/800
F1.3-03	$3.46 \cdot 10^{10}$	146.4	30	TD/900
F1.3-04	$3.16 \cdot 10^{10}$	164.4	30	TD/900
F1.3-05	$3.12 \cdot 10^{10}$	158.2	80	6-TD,2-NX
F1.3-06	$2.25 \cdot 10^{10}$	167.5	60	1-TD,7-NX
F1.3-07	$2.24 \cdot 10^{10}$	167.2	80	2-TD,6-NX
F1.3-08	$2.52 \cdot 10^{10}$	161.8	80	2-TD/900,6-NX/950
F1.3-09	$3.24 \cdot 10^{10}$	171.3	80	5-TD,3-NX
F1.3-10	$2.70 \cdot 10^{10}$	168.0	80	3-TD/900,5-NX/950
F1.3-11	$3.59 \cdot 10^{10}$	162.7	32	3-TD900/,5-NX/950
Average	**$2.85 \cdot 10^{10}$**	**162.4**		
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

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CM Status Summary

- F1.3-15 (CM015) at WS2 (by mid morning 10/23)
- F1.3-14 (CM14) at WS2 prime
- F1.3-13 (CM13) at WS5 (ready to be moved to CMTS by the end of this week)
- F1.3-12 (CM12) at CMTS
- F1.3-11 (CM11) is at WS6 (start prep & ship)
- F1.3-10 (CM10) at WS6 (start prep & ship)
- F1.3-09 (CM09) at WS6 (start prep & ship)
- F1.3-08 (CM08) at WS6 (prep & ship is in progress)
- F1.3-07 (CM07) at WS6 (prep & ship is in progress)
- F1.3-06 (CM06): (will be re-assembled at the end of 1.3GHz CM production)
- F1.3-05 (CM05) at JLab (as of Monday 10/22)
- F1.3-04 (CM04) at WS6 (prep & ship is in progress)
- F1.3-03 (CM03): will be re-assembled at the end of 1.3GHz CM production
- F1.3-02 (CM02): on hold (project directive)
- F1.3-01 (pCM) is at WS4 for disassembly

F1.3-11 Usable gradient

- Documented Usable gradients based on 0.5 MV/m below quench and/or 1 hour continuous operation at gradient
  - Cavities 1, 5-7 at 21 MV/m, some run in parallel
  - Cavity 8 low VTS quench gradient, consistent CMTS1 result
  - Cavities 2-4 ran for extended periods at slightly higher gradients, but never for an hour. Suspect end group heating.
  - Repeated 2, 3 at end of test run with same result