Cryomodule Lessons Learned

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International Workshop on Cryomodule Design and Standardization
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SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB Lawrence Berkeley National Laboratory
Argonne NATIONAL LABORATORY
CORNELL UNIVERSITY FOUNDED A.D. 1865
Fermilab
Jefferson Lab

U.S. DEPARTMENT OF ENERGY
Office of Science

Outline

- Introduction
- Lessons Learned during Cavity Production
- Lessons Learned during String Assembly
- Lessons Learned during Cryomodule Testing
- Lessons Learned from Cryomodule Transportation (skipped, see Peterson presentation)
- Summary

Major Lessons Only

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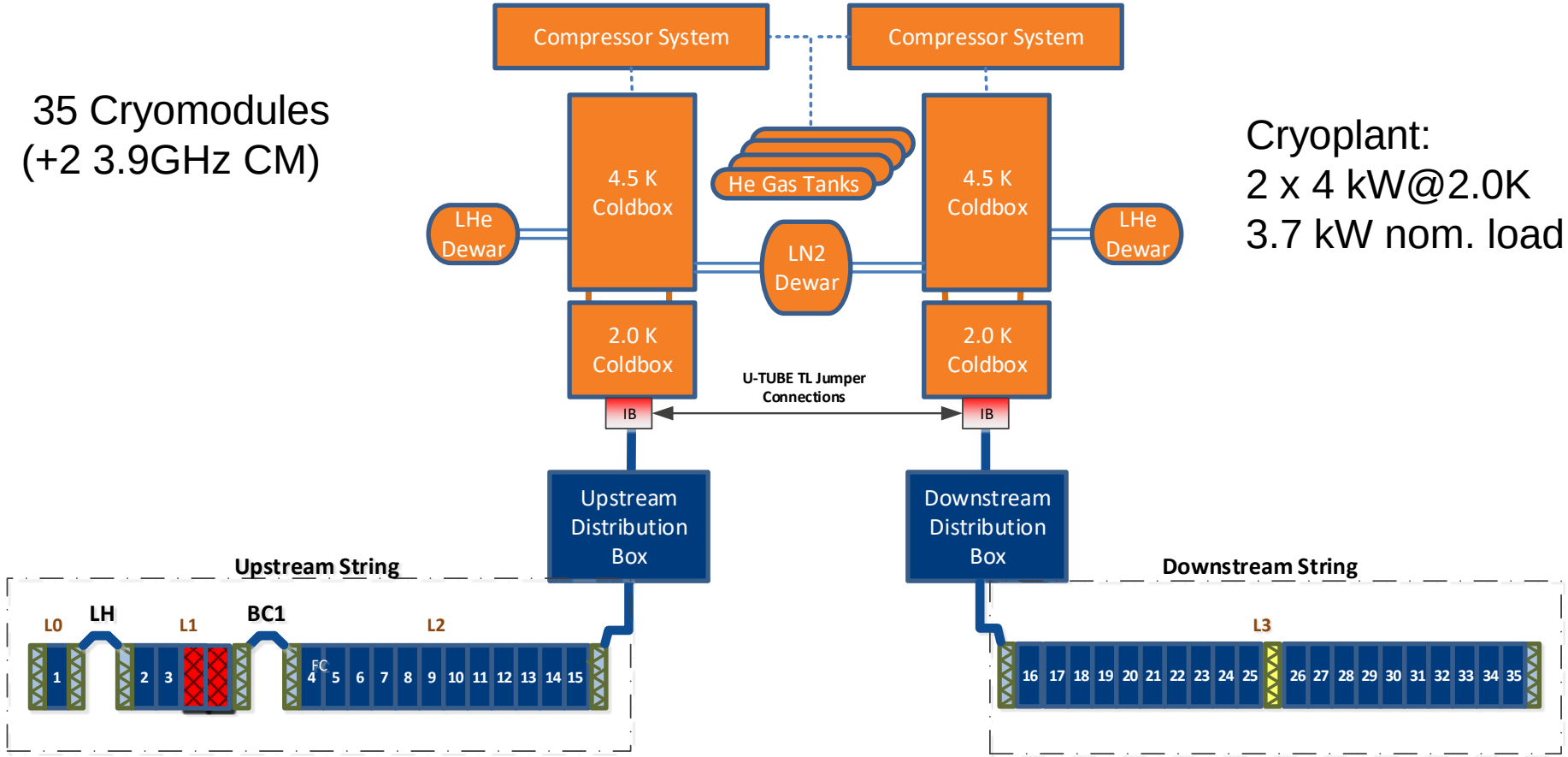
LCLS-II Cryogenic Systems overview:

35 Cryomodules
(+2 3.9GHz CM)



Cryoplant:
2 x 4 kW@2.0K
3.7 kW nom. load

3.9 GHz Cryomodule
1.3 GHz Cryomodule
End/Feed Cap
Vacuum Barrier
Cryogenic Bypass
Cryogenic Transfer Line
Cryoplant
Gas Header
IB
Interface Box

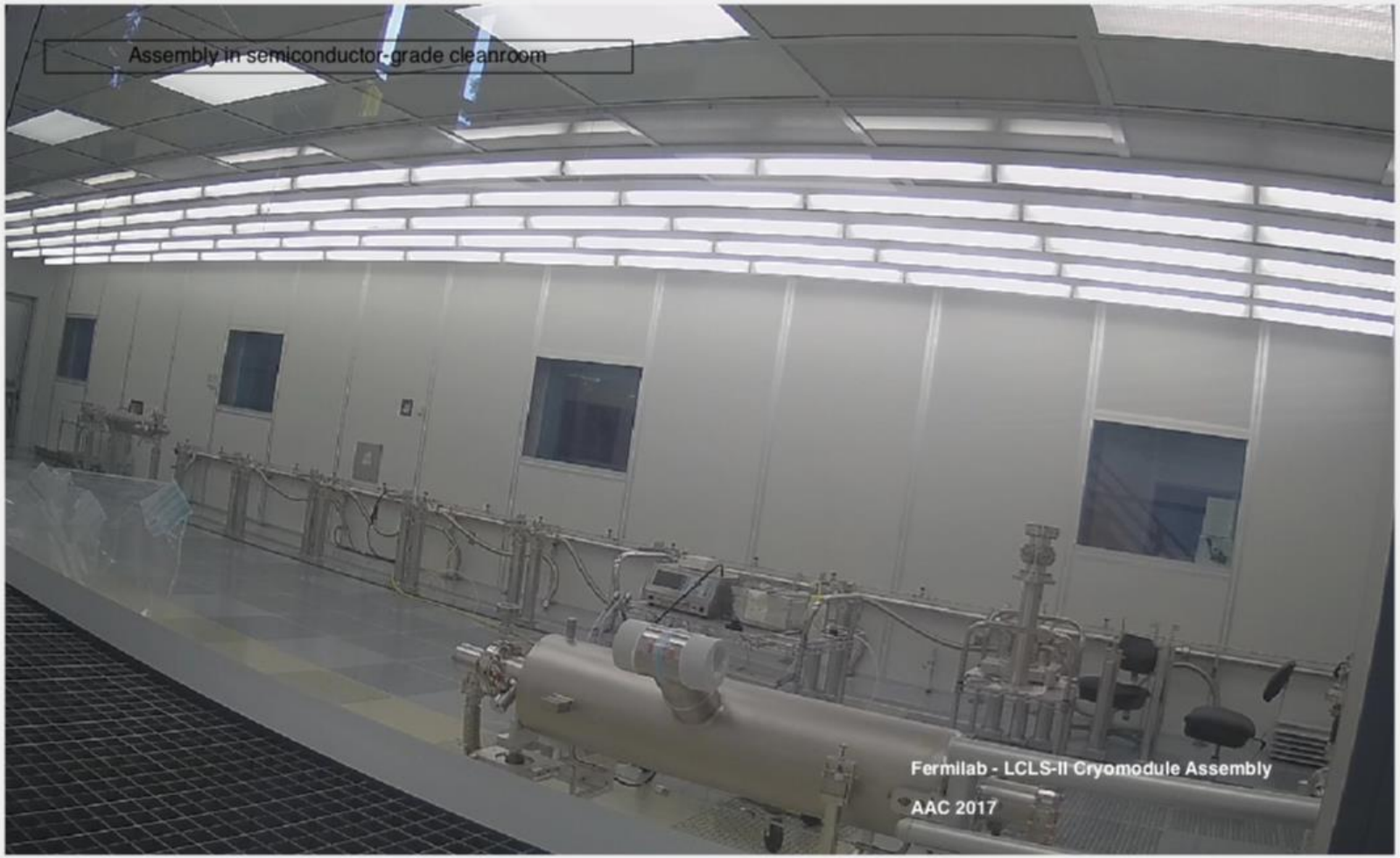
Some Changes during the Production

- Added 5 additional 1.3 GHz CMs
  - 1 spare + 4 production extras
- Added 1 spare 3.9 GHz CM
  - Goal to select best 35 of 40 – 1.3 GHz and 2 of 3 3.9 GHz CMs for linac
  - Maintain extras for field replacement as necessary
- Ordered additional cavities to account for production yield
- Installation of fluxgate magnetometers in all CMs
- Optimized cavity processing recipes for cavity production
- Added cryomodule test cycles for cooldown optimization
- Increased vendor oversight for cavity production

Cryomodule Progress

- 1.3 GHz CM Production
  - 29 of 35 1.3 GHz CMs are in production or complete
  - Six broken for various reasons
- 1.3 GHz CM Testing
  - 11+10 CM tests complete
  - Average Q_0 > 2.7e10
  - Average Gradient > 16 MV/m

Cryomodule Production at Fermilab



Courtesy of Sam Posen

Key Technical Challenges

- CM Assembly
  - Tight Schedule
  - Design changes
  - String leaks outside of the cleanroom
- CM Testing
  - Maintaining high Q_0 in the CM
  - Field emission
  - Microphonics mitigation
  - HOM tuning / end group heating
  - Cooldown optimization
  - String leak after warm-up
  - Transportation

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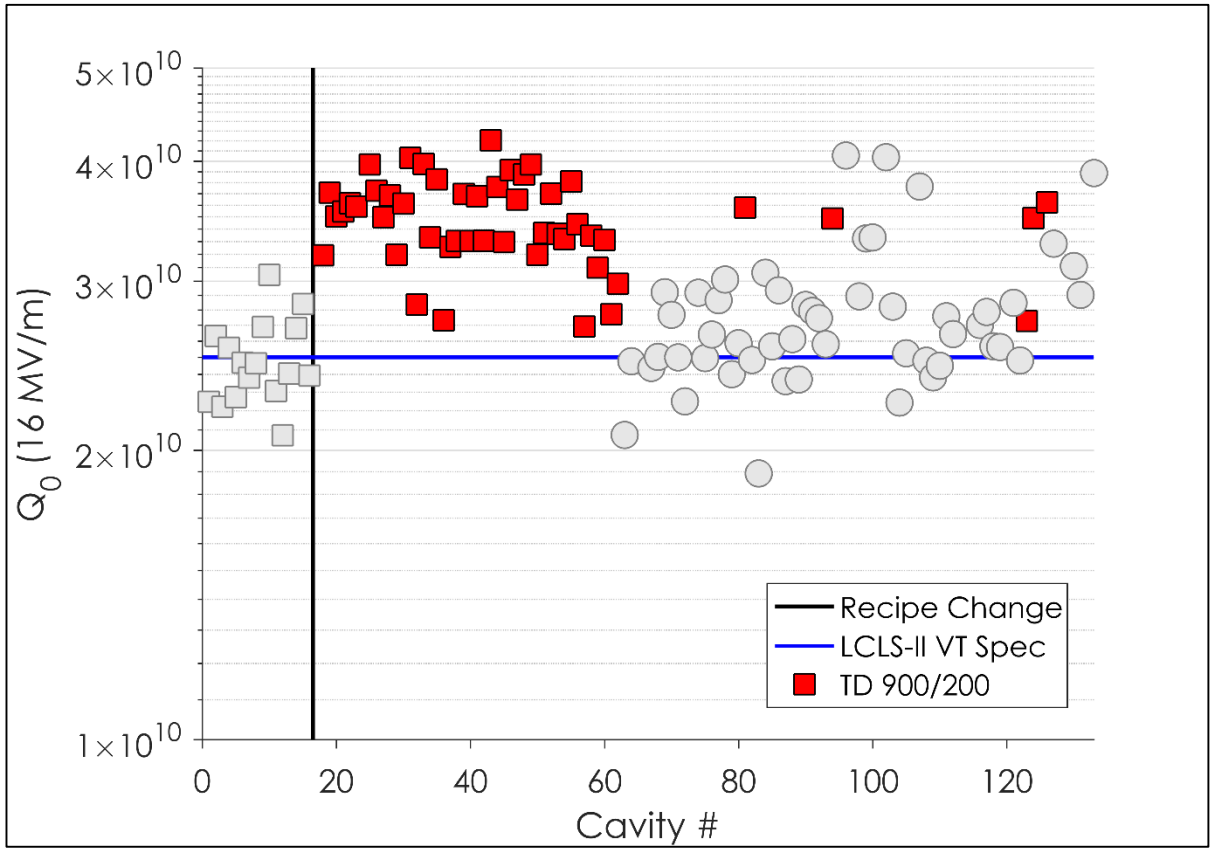
Nitrogen Doped Cavity Challenges

- Cavity production issues:
  - Poor flux expulsion material resulted cavity performance below specification in cryomodule

- Lessons learned
  - Improved understanding of niobium flux expulsion
  - Improved material/cavity processing recipe to recover flux expulsion capability.

RI: Q_0 Results



- RI has completed fabrication of original order of 133 cavities
- 121 cavities have been tested so far at JLab and Fermilab
- TD Cavities 900/200 preparation consistently exceed LCLS-II spec

Slide by Dan Gonnella of SLAC

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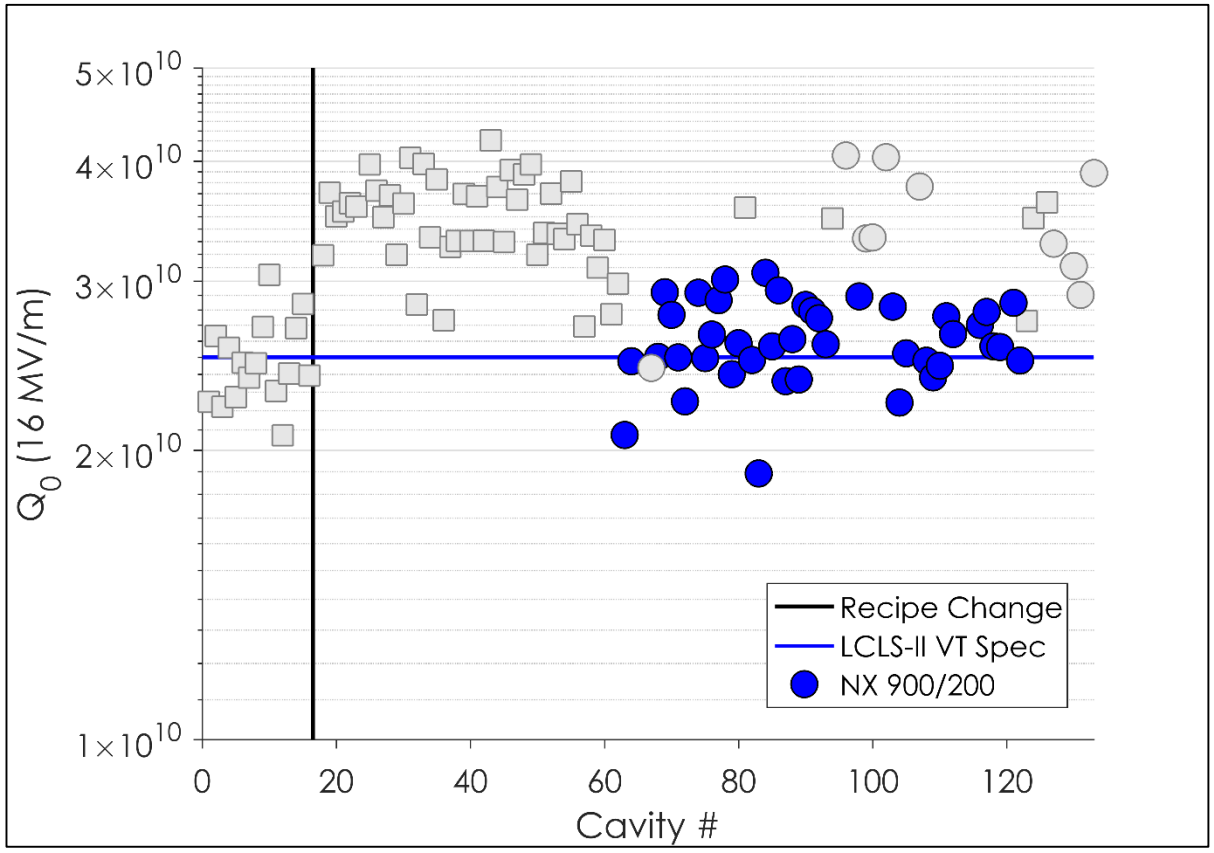

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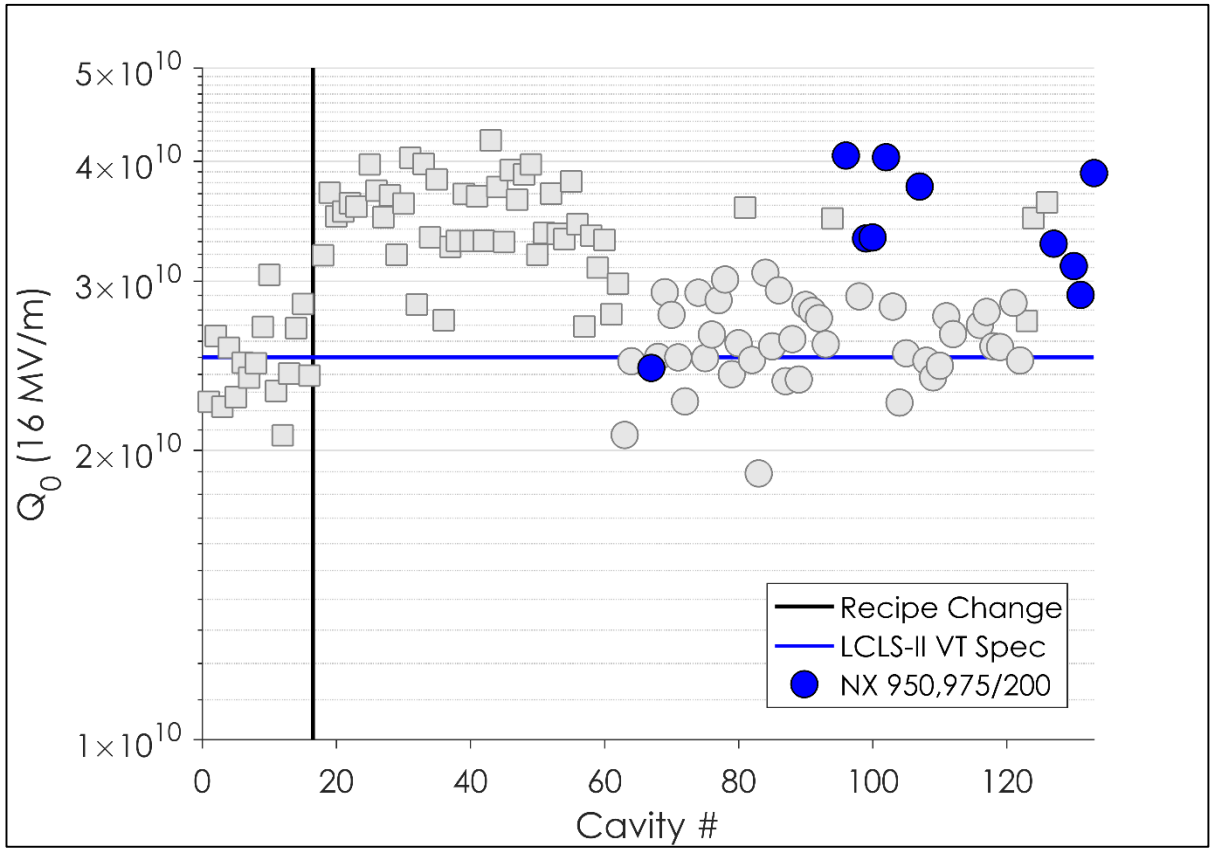

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- 121 cavities have been tested so far at JLab and Fermilab
- TD Cavities 900/200 preparation consistently exceed LCLS-II spec
- NX Cavities at 900°C have middling results
- 950 and 975°C have further improved upon the NX cavities' performance

Slide by Dan Gonnella of SLAC

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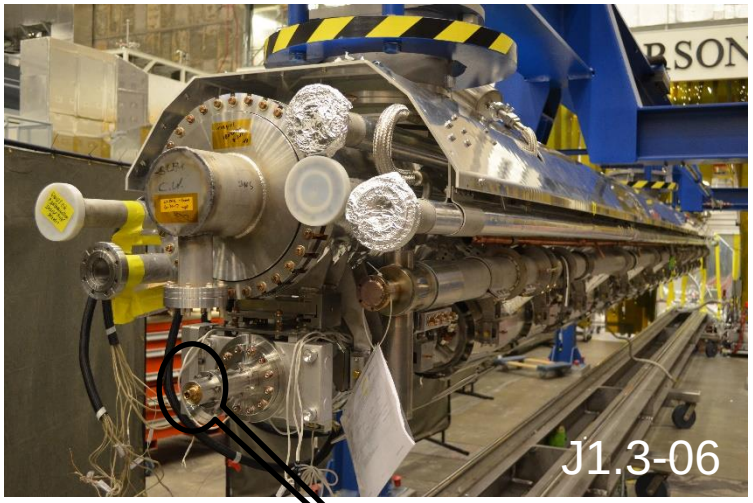
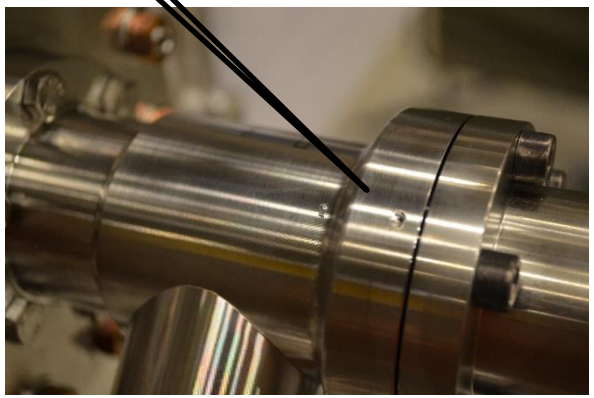
J1.3-06 Status

J1.3-6

- Accidentally vented during preparation for leak check of 2 phase circuit
  - GHRP cap slipped and impacted right angle valve
  - String fast bled up to just under 100 torr.



- Cavity and couplers will require reprocessing



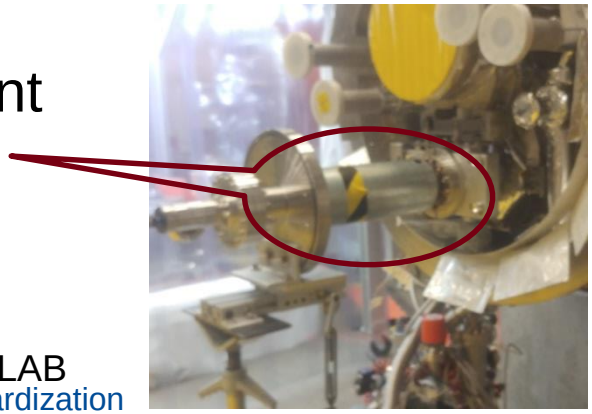
Courtesy of Bob Legg of JLAB

J1.3-06 Lessons Learned

New assembly procedure and tooling for GHRP cap installation at WS3 and WS5.

- Portable lift used to both lift GHRP cap and protect the Right Angle Valve; Safer for both employees and equipment.
- Looking into a plug with o-ring to replace GHRP cap for vacuum leak checks. Lighter, safer.

Metal bellows covers put in place to prevent accidental venting during prep for testing.

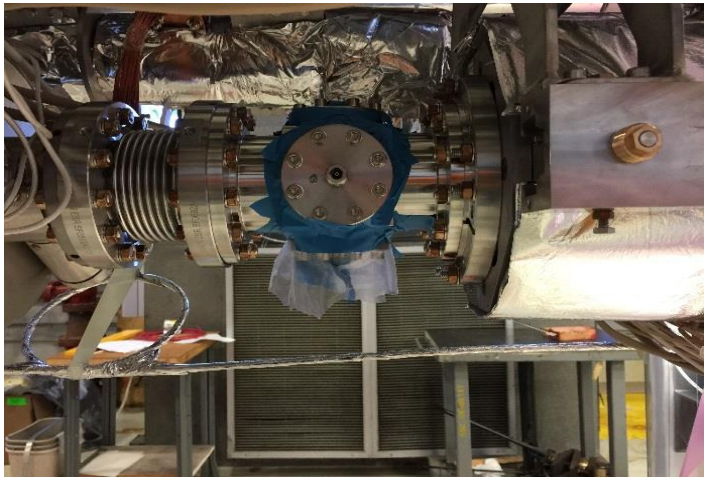


Courtesy of Bob Legg of JLAB

F1.3-03 Cold Leak Developed

F1.3-03

- Cold Leak Discovered during Cryomodule Warm up
- BPM Feedthrough flanges leaked
  - Three out of four seals leaked
  - Leak rate was ~8.5e-5 mbar.L/sec
    - Leak was considered too big for clean beam line.
    - Decision was made to dis-assemble
- Possible stress on magnet spool pieces
- Grade 2 Titanium bolts did not provide sufficient sealing force.



F1.3-03 Lessons Learned

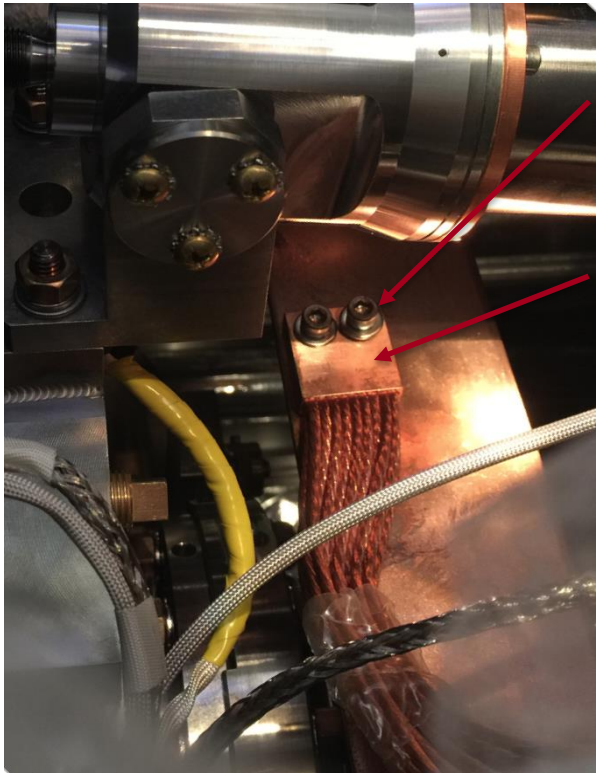
F1.3-03

- Replaced Grade 2 titanium bolts with Gr5 titanium studs.
- Increase the torque strength from 12 to 16 N.m
- Measure seal crush to ensure sufficient sealing cross section
- Improved procedure to avoid any stress to the BPM/magnet spool beam pipe.

F1.3-03 HOM Feedthrough Thermal Strap Loose

F1.3-03

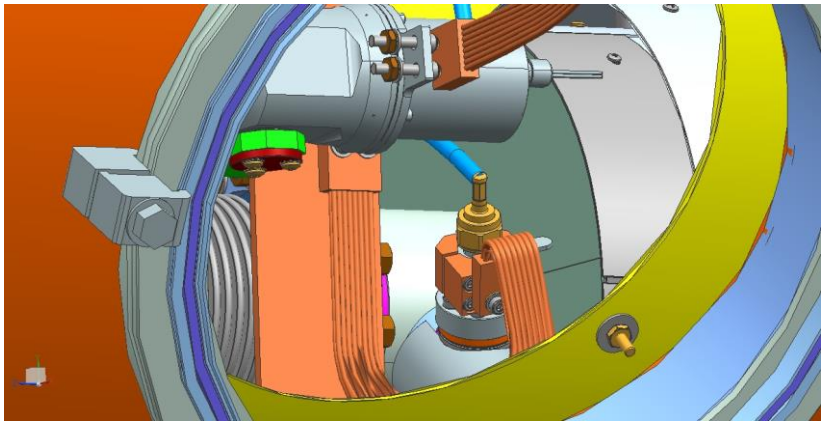
- CAV3 quenched prematurely at 11 MV/m.
  - HOM end group heating



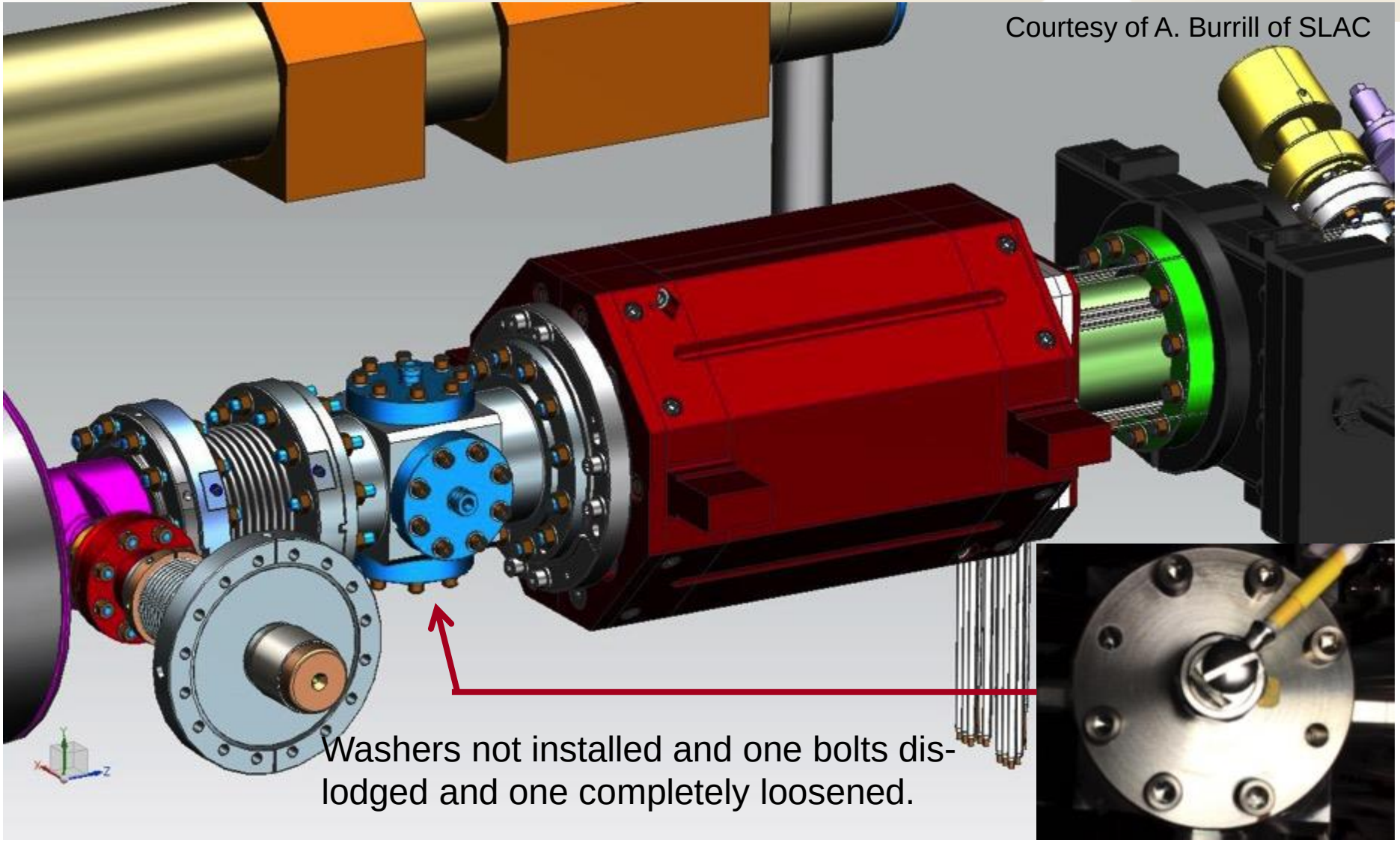
F1.3-03 Lessons Learned

F1.3-03

- Improved procedure to double check the integrity of the HOM thermal Straps



F1.3-06 BPM Bolts Loosened



F.13-06 BPM Lessons Learned

In addition to lessons learned as in F1.3-03:

- Added QC step in traveler to inspect all fasteners and their torques both in component level, as well as completed string assembly.

J1.3-09 and J1.3-11 Helium Vessel Bellows Damaged

- J1.3-09 Bellows was found damaged on 5 July,
  - Visual inspection of all bellows on in process cryomodules (J1.3-09-11-12-13) followed
  - We found one additional bellows damaged on J1.3-11
  - Completed cryomodules (J1.3-02 – J1.3-07) will be inspected during subsequent work
  - JL1.3-08 and JL1.3-10, were in the process of acceptance testing, no leaks found

J1.3-09

J1.3-09 damage was found after a failed leak check and disassembly of the cryomodule

J1.3-11 was in an earlier stage of assembly and the damage was found during a visual inspection

J1.3-11

Courtesy of E. Daly of JLAB

J1.3-09 and J1.3-11 Lessons Learned

- The JLab team has extended the risk matrix to all bellows in the cryomodule
  - Continuous improvement extends this to the cryomodule as a whole
  - FNAL will be included
- Apply lessons learned to other cryomodule production activities
  - CEBAF cryomodule production and rework
  - Cryomodules for other projects (SNS PPU, LCLS-II HE)
- Training matrix developed as part of the improved work controls identifies individual's qualifications
- Matrix is now the basis for staff development plans and will be a continuing part of the cryomodule production at JLab
  - Every supervisor has the matrix and only assigns work to qualified technicians
  - Every technician and supervisor has their own qualification matrix
  - Each individual is expected to know their qualifications and work only those activities they are qualified for

Courtesy of E. Daly of JLAB

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Microphonics Sources and Mitigations

- Cryogenic Valve Plumbing
  - Thermal Acoustic Oscillations in the Valve Stems
  - Helium Leakage into Cooldown Circuit
- Cavity 1 Mechanical Support
  - Modification and Retrofit Options

Cryogenic Valve Plumbing – Improved Valve Stems

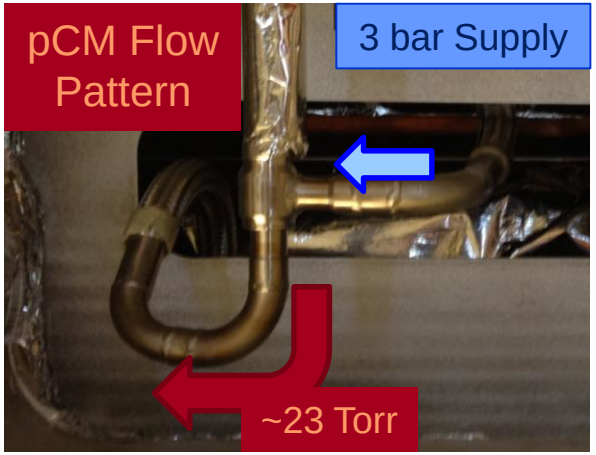
- TAOs are a pressure/temperature oscillation in cryogenic lines (in this case, valve stems)
  - During testing, wipers were added to close space in valve stem, acting as a damping term for the TAOs
  - Significant improvement in heat load and microphonics levels and stability for *both* F1.3-01 and J1.3-01
  - Optimized valve stems with wipers were used during F1.3-02 testing, *and will be used going forward for both labs*
    - 4-5 wipers, positioned to keep temperature ratio <4 as recommended by literature
    - Radiation hard material (PEEK)

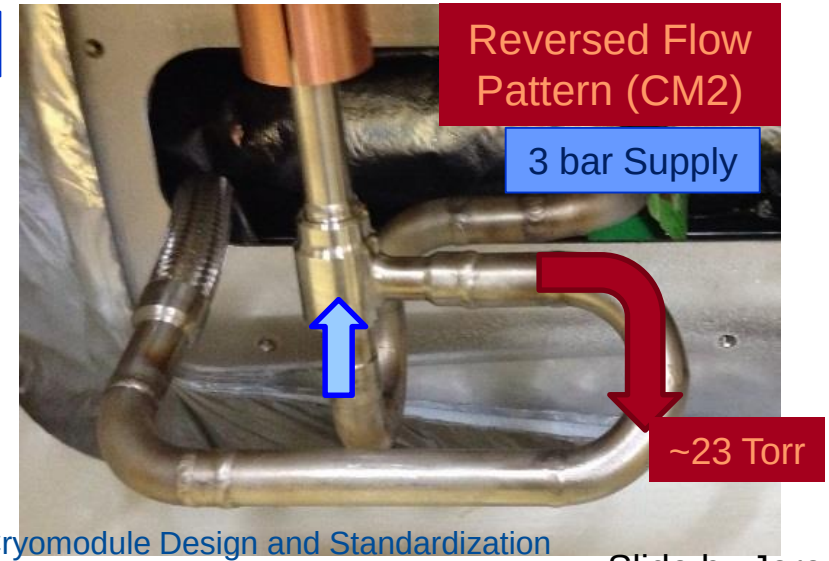
Optimized wiper placement going forward

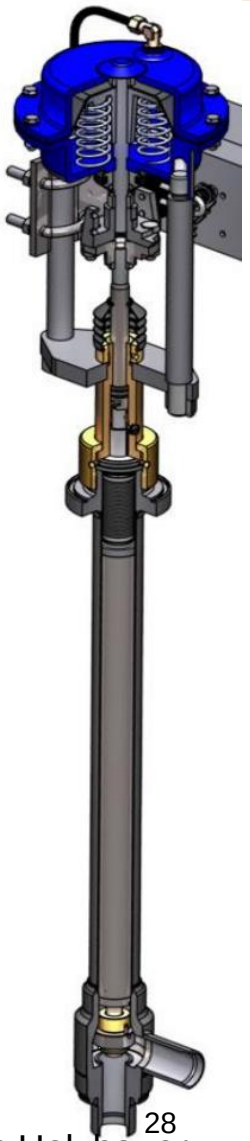
Slide by Jeremiah Holzbauer

Cryogenic Valve Plumbing – Reverse Flow Path

- Test results show valve reversal (lower press in stem) significantly reduces/eliminate TAOs there
  - F1.3-01 configuration has valve stem at supply pressure (~3 bar)
  - Reversing flow will lower this pressure to sub-atmospheric, requiring guard gas to prevent contamination
  - All cryomodules will have guard gas, reversed valves
- Additional effort to mitigate TAOs in cryogenic distribution system should improve inlet temperature at test stand



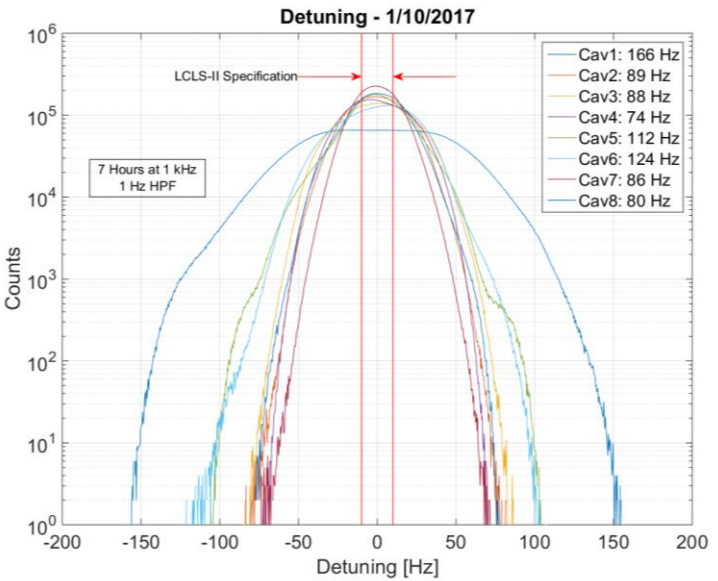




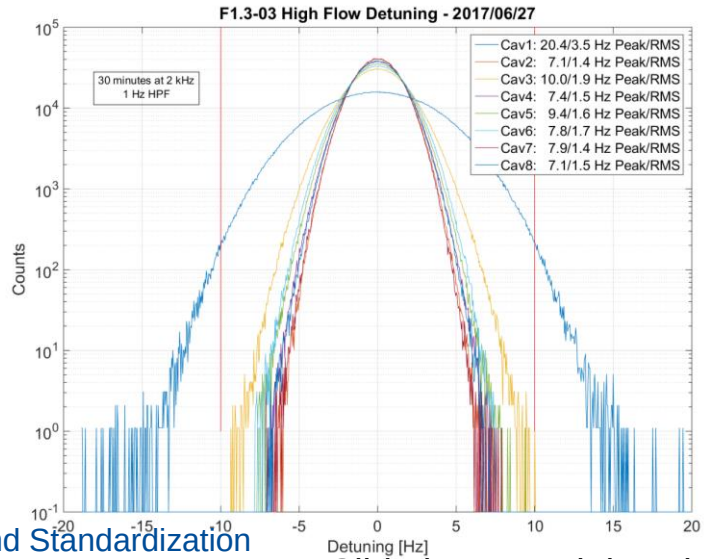
Slide by Jeremiah Holzbauer

Valve Modification Improvement

- 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



pCM As Cooled Down

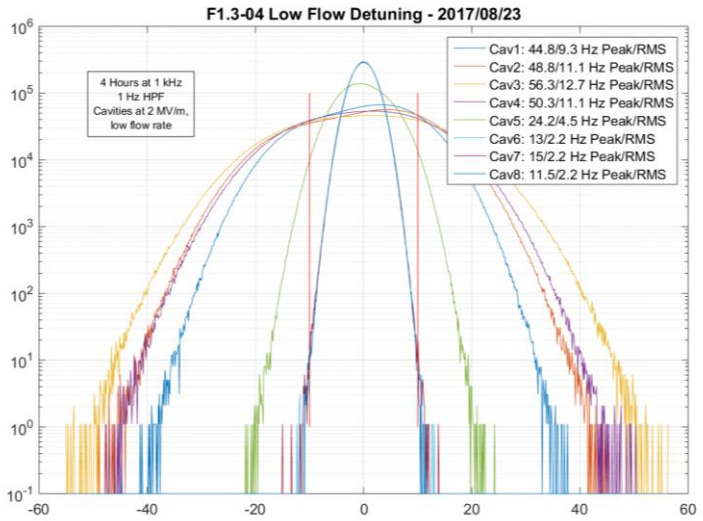


F1.3-03 After Improvements

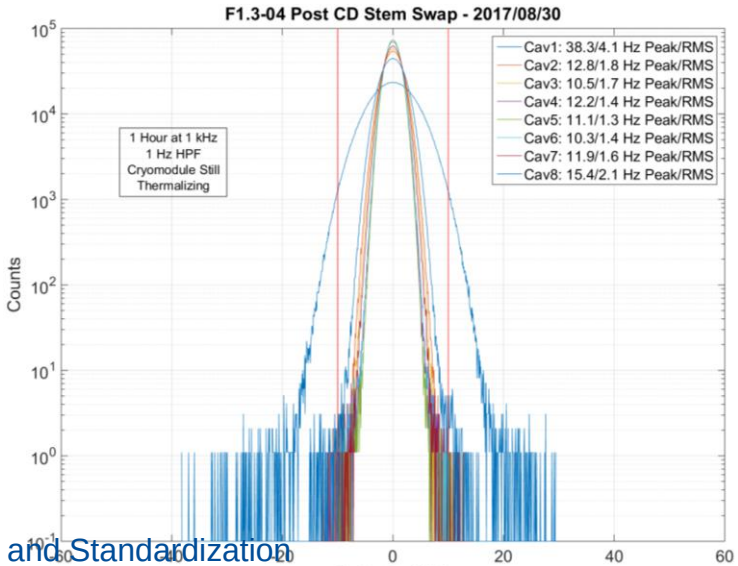
Slide by Jeremiah Holzbauer

Cryogenic Valve Plumbing – Cooldown Valve Leakage

- F1.3-04 presented with higher than expected microphonics, worsening as the cryomodule thermalized
- Noise was narrowband and showed complex spatial and spectral distribution in cryomodule
- Testing showed strong correlation with cooldown circuit, eventually proven to be coherent bubbling due to cooldown valve leakage
- Swapping valve stem returned expected performance, although testing schedule prevented detailed studies
- Tails seen in ‘post-swap’ data are likely due to continued thermalization of cryomodule after cooldown
- Additional QA check step now included to prevent valve leakage in the future



Thermalized Detuning

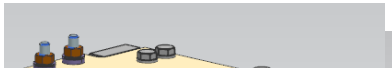


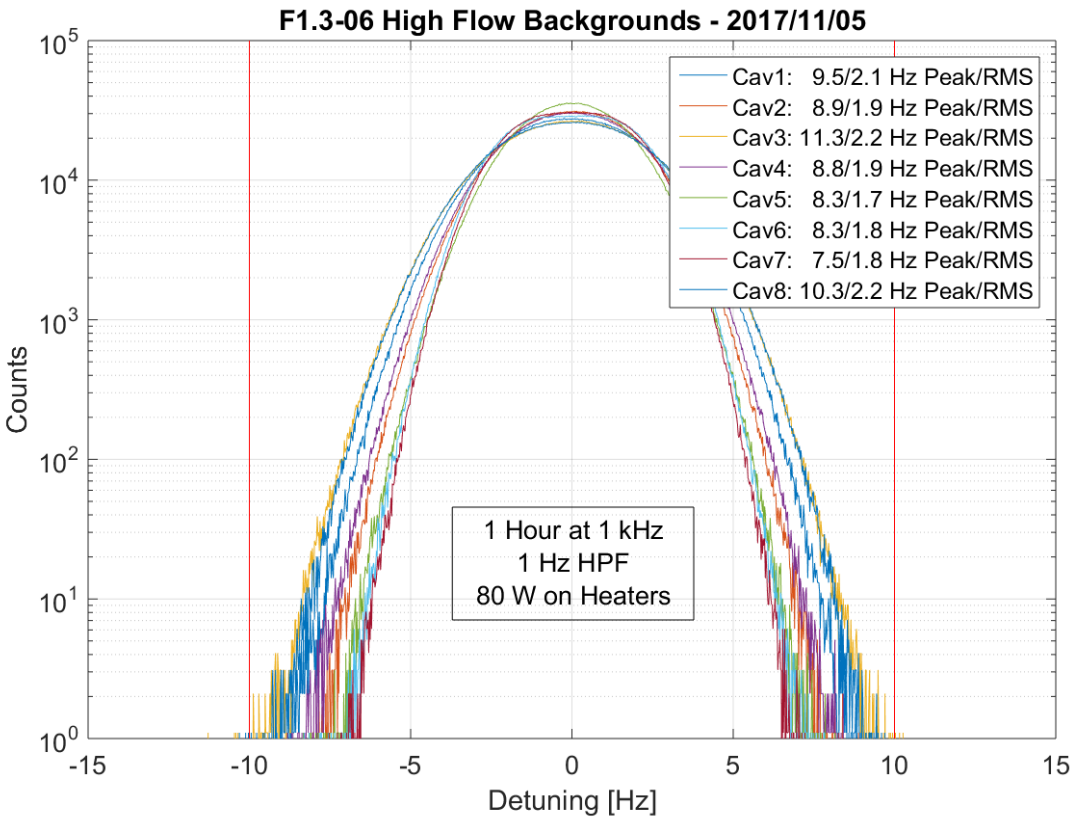
Post CD Stem Swap

Slide by Jeremiah Holzbauer

Cavity 1 Mechanical Connections – Mitigation
Beamline Gate Valve Bellows

- Replacing spool piece between cavity 1 and gate valve with a bellows is non-trivial
- Corrective fix includes extending t arms with fixture to connect to gat
  - When replacing spool piece bellows, fixture fully supports valve
  - Current supports are long ar connected to the 300 mm pi needle bearing for the longitu motion
- With gate valve is supported by frame/helium vessel, the spool pie be replaced with a bellows to sep mass from cavity/tuner system
- First cryomodule with bellows to be tested will be F1.3-06 (on deck at FNAL)





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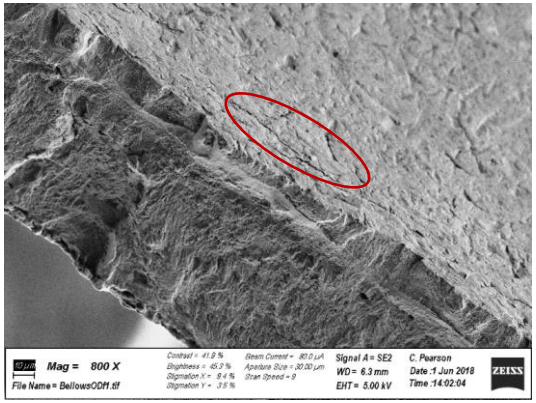
F1.3-05 and F1.3-06 Coupler Bellows Cracked during Transportation

Cavity 4



Cavity 5

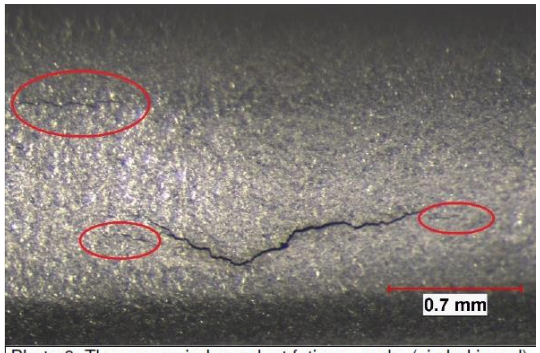


Photo 8: Three more independent fatigue cracks (circled in red) around the secondary fatigue crack.

- Failed bellows examined after sectioning them:
- SLAC (Chris Pearson) Report on Cavity 4 Bellows: "*This is an example of high stress low cycle fatigue. That is, the material at the fracture location experienced multiple bending stress cycles at or above the yield strength, work hardening locally and eventually failing in a brittle manner.*"
- SGS report on Cavity 5 Bellows: *"Fatigue fracture initiated on the outside surface at multiple locations at grain boundaries that were infiltrated with braze metal. Uni-directional bending stresses initiated and propagated the multiple fatigue cracks completely through the bellows."*

Courtesy of C. Adolphsen of SLAC

F1.3-05 and F1.3-06 Lessons Learned

See Tom Peterson’s slides.

Summary

- A few significant cryomodule incidents have occurred during LCLS-II Cryomodule production.
- Incidents have been addressed.
- Lessons learned greatly benefit future projects such as PIP-II.