# LCLS-II Cryomodule Assembly and Design Changes/Issues at Fermilab

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LCLS 2-HE CRYOMODULE PERFORMANCE WORKSHOP

April 25-26, 2019

# Outline

- Introduction
- Cryomodules Assembly
  - Assembly workflow at work stations
  - Issues, non conformances experienced & mitigated
- Summary

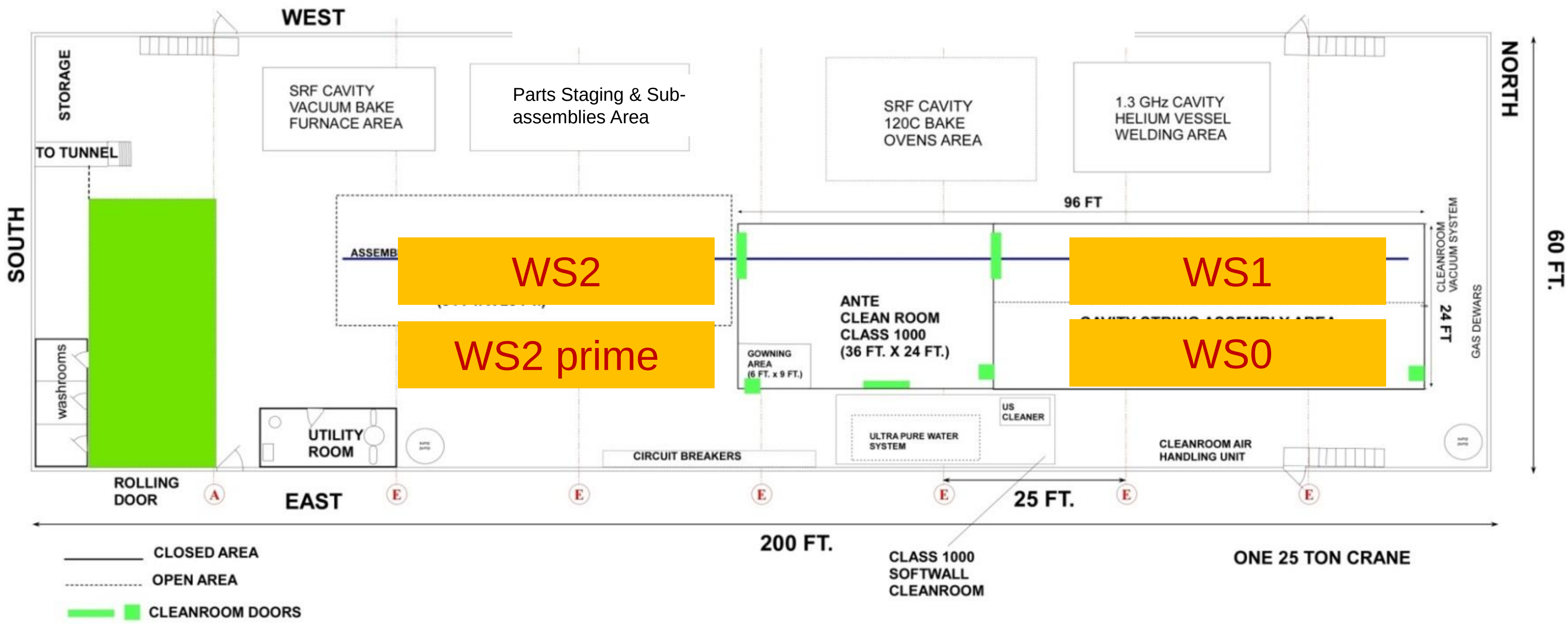
# Introduction

- Fermilab is responsible to assemble, test and ship nineteen 1.3GHz CM and three 3.9GHz CMs for LCLS-II project
  - To date, we have completed the assembly of 16 LCLS-II 1.3GHz CW cryomodules at Fermilab
  - 2 cryomodules require rebuilding
- In order to minimize field emission degradation of the SRF cavities in the beamline; starting from F1.3-7, we have increased scrutiny for cavity string assembly in ISO4 cleanroom with internal assessments then with an external audit. Since then performance of the tested CMs exceed the project specifications.
- Post F1.3-6 failure during transport to SLAC, an audit of the Cold Mass Assembly [outside of the cleanroom] (special focus on warm end coupler assembly) was conducted at Fermilab by DESY team

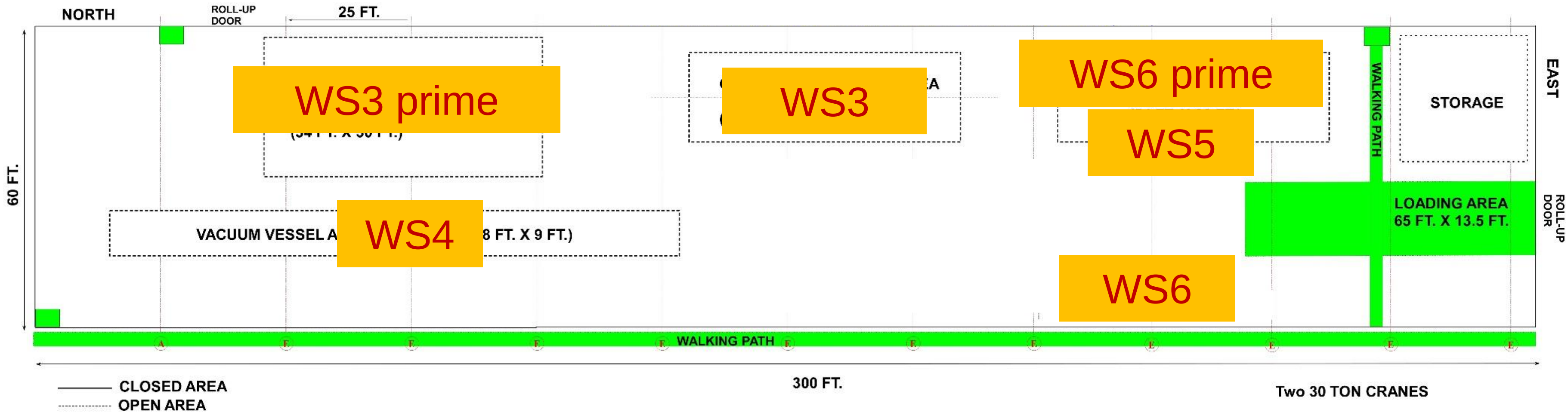
# LCLS-II Production CMs Workflow at Fermilab –work stations

1. Receive dressed, ready to be tested in VTS (vertical test stand) cavities from the vendors (Beamline under vacuum)
2. Incoming Inspection at IB4
3. Test cavities in VTS at IB1
4. Qualified Cavities go to MP9 cleanroom for cold end coupler assembly (WS0). Non qualified cavities are re-processed (HPR, light EP etc.) and re-tested
5. 8 qualified cavities, Magnet Spool Tube, BPM, Gate Valves, Interconnecting Bellows: Cavity String Assembly at MP9 Cleanroom (WS1)
6. Cold Mass Assembly at MP9 (WS2 / WS2 prime)
7. Cold Mass Assembly at ICB (WS3 /WS3 prime & WS4)
8. Final Assembly (WS5) and prep for transport to CMTS (WS6) at ICB
9. Cryomodule Test at CMTS
10. Prep & Ship to SLAC at ICB (WS6 & WS6 prime)

# MP9 during LCLS-II Production



# ICB during LCLS-II Production

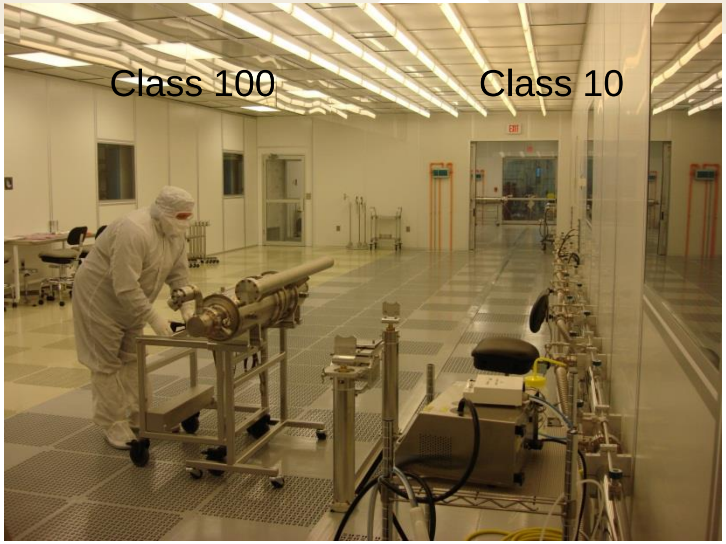


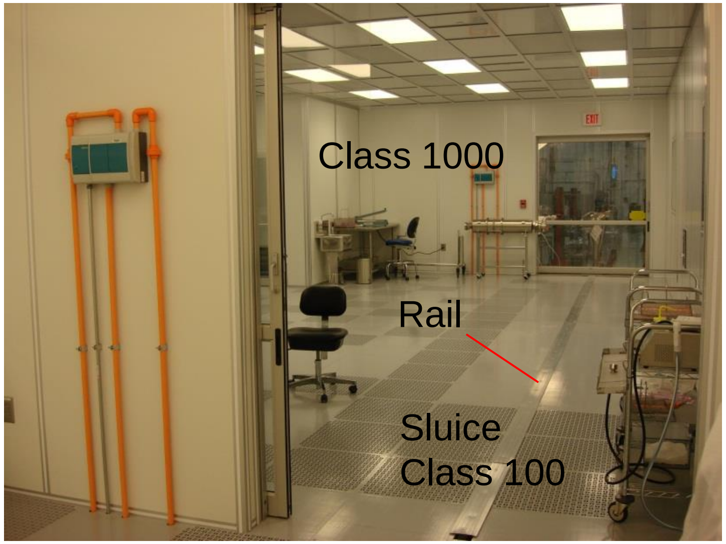
# MP9 Clean Room

Cavity String Assembly Clean Room (WS0 & WS1)

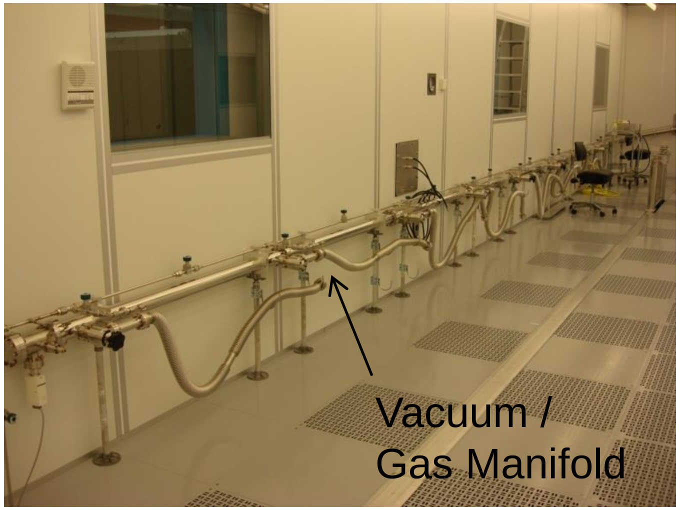
A ~250 square-meter clean room:

- Class 1000 (ISO6) ante cleanroom area
- Class 100 (ISO5) sluice area
- Class 10 (ISO4) assembly area
- Class 100 (ISO5) staging/storage area

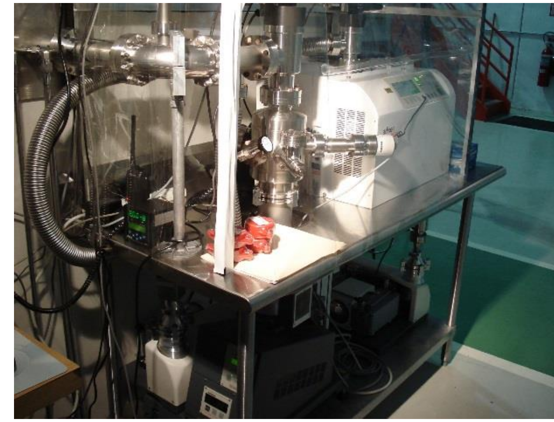


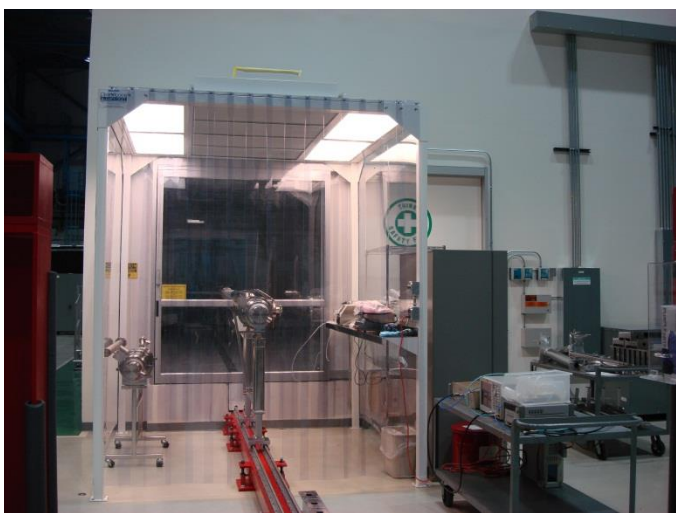
# MP9 Cleanroom Infrastructure




8 stations for pumping, purging and backfilling



Particle Free UHV Pumps System



Class 1000 softwall cleanroom for dry cleaning before entry to ante cleanroom

Cavity Support Fix Rail System


Boiled-off LN2 gas dewars and gas delivery panels

# Parts / Fixtures / Hardware Entrance to Cleanroom Preparation

*Magnetic Hygiene Quality Control for every part, hardware, fixtures, tools that will be used in the cleanroom for assembly prior cleaning*

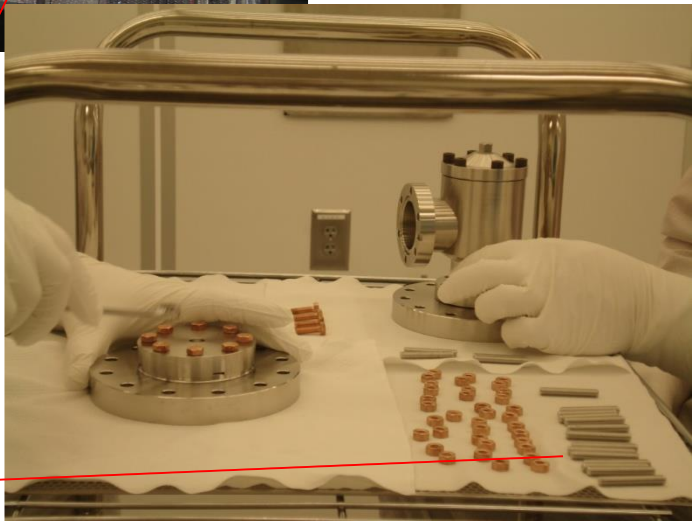
ISO 6 softwall cleanroom

ISO 4 Hood

US cleaners

Assembly hardware:

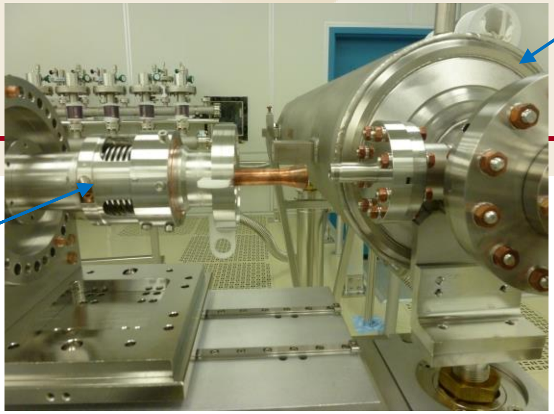
- Wash in the ultrasonic bath
- Dry under ISO 4 hood
- Move into the ISO 6 ante clean room
- Blow clean with ionized nitrogen while monitoring the particle count in the sluice area (ISO 4)
- Transport into the ISO 4 assembly area

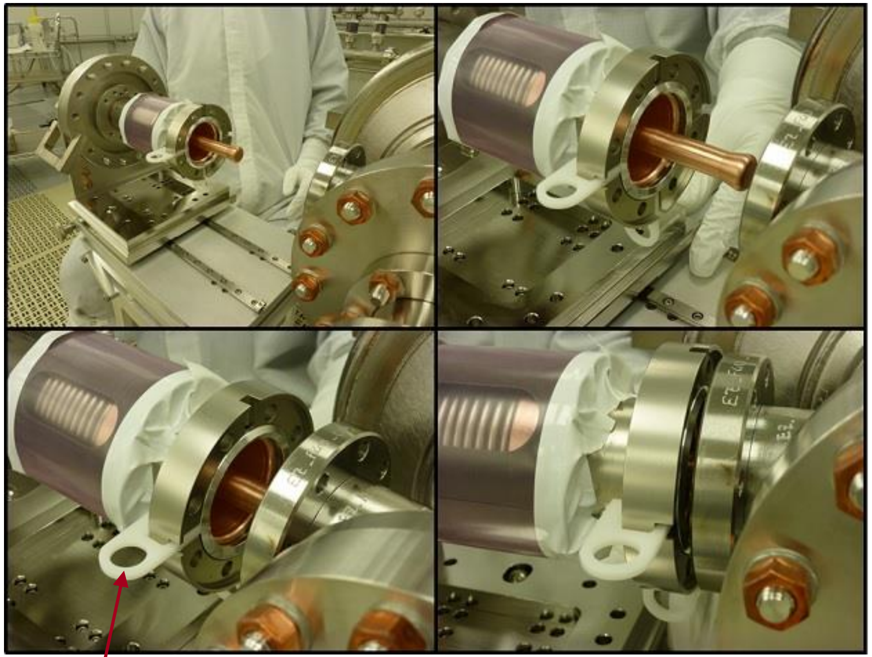


Electro-polished, rolled thread 316L stainless steel studs; silicon bronze nuts

# Cold End Coupler Assembly (at WS0)

1. Verify torque and tighten as needed all the fasteners for the cavity beamline(under vacuum) as received *(starting with F1.3-7)*
2. Assemble & leak check pump/backfill/purge flex hose to the cavity right angle valve
3. Open right angle valve (vacuum on both sides)
4. Record as received vacuum levels
5. Leak check, RGA cavity beamline
6. Backfill (vent) cavity beamline.
7. Remove a cold end coupler from the storage manifold
8. Assemble cold end coupler to the cavity using particle free flange assembly (PFFA) procedures
9. ~~Pump down, leak check, RGA~~ *(Eliminated starting from F1.3-9)*
10. ~~Backfill (vent)~~

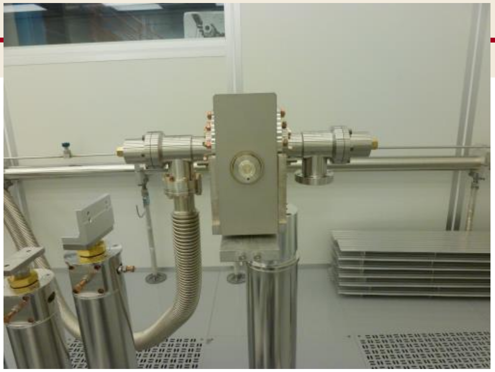


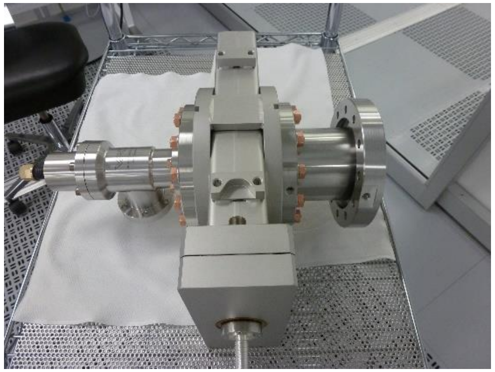
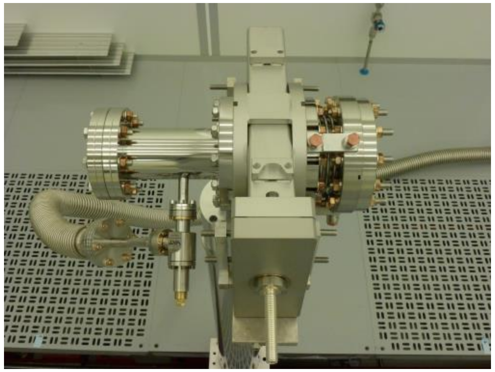
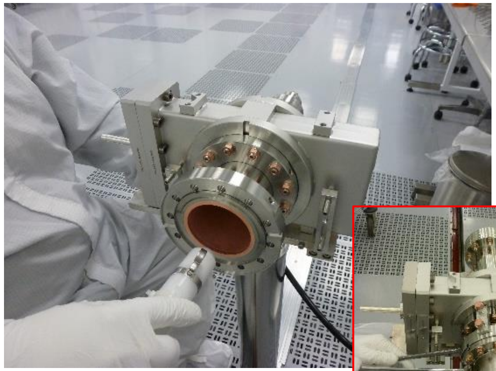
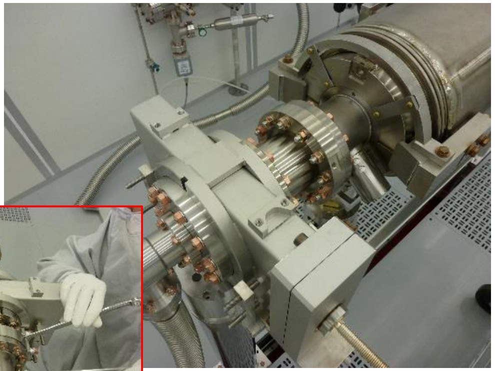
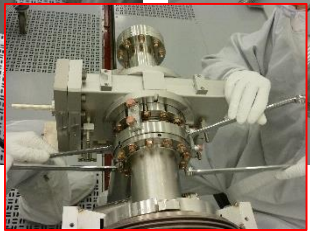



Starting from F1.3-7, we introduced gasket holder (JLab design)

# String Assembly-I (WS1)

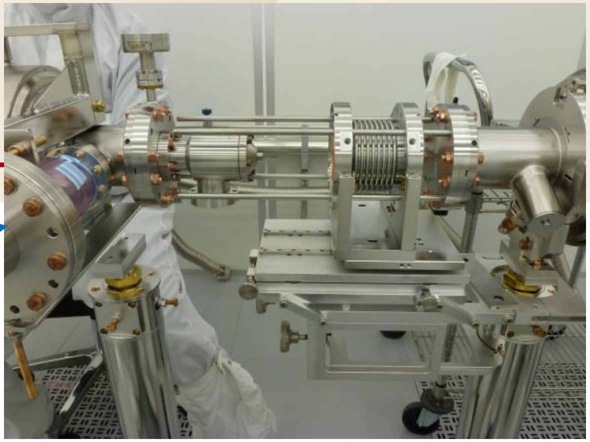
- Leak check gate valves and right angles valves before string assembly [both directions] *(started with F1.3-5)*
- Align 8 cavities for string assembly
- Gate Valve (GV1) to Cavity #1 Assembly:
  - Check the particle free cleanliness of the GV and clean as needed
  - Sub-assembly of the GV peripherals
    - *Short spool for F1.3-1 through F1.3-5*
    - *Short bellows for F1.3-6 and forward*
  - Installation to the cleanroom post and flex hose assembly
  - Alignment to the cavity beam line flange
  - Assemble the gate valve to the cavity

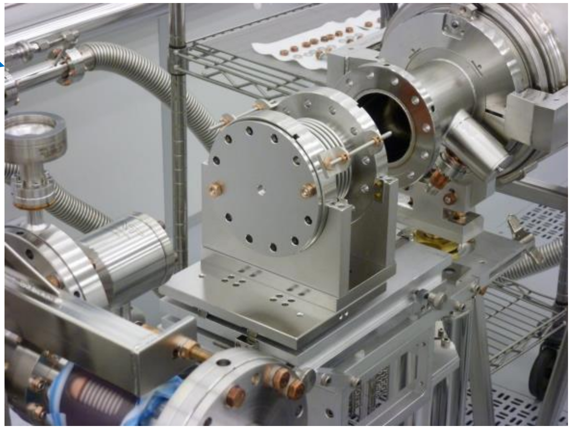


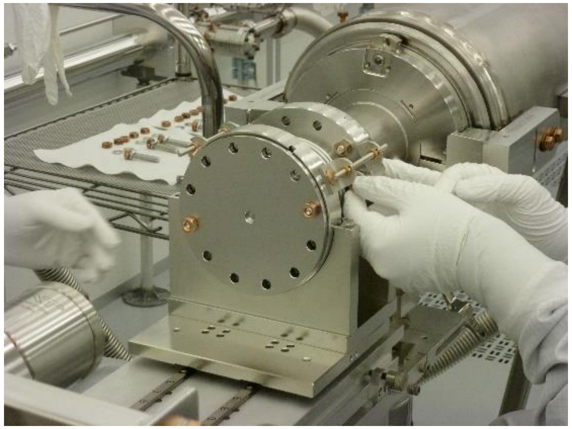






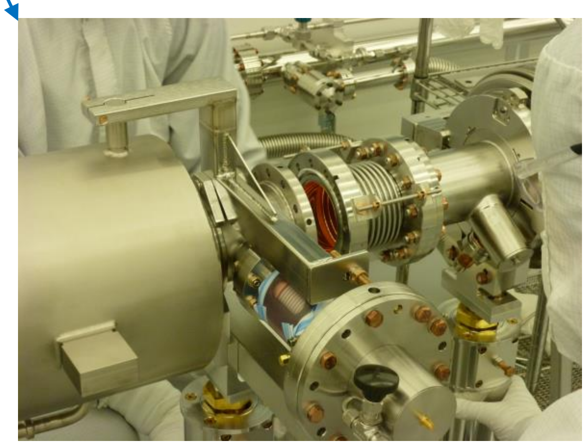
# String Assembly-II (WS1)

- Interconnect bellows assembly between SRF cavities
  1. Align bellows to the cavities
  2. Assemble bellows to Cavity (n+1)
  3. Assemble bellows to Cavity (n)



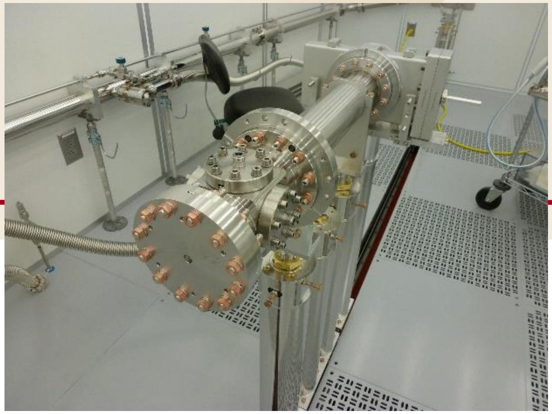






Repeat these steps 7 times to interconnect 8 SRF cavities

# String Assembly-III (WS1)



- BPM sub-assemblies with feedthroughs *(titanium-grade 2 SHCS; increased torque from 12 N-m to 16 N-m starting from F1.3-8, after F1.3-6 beamline loss incident during transport to SLAC and post mortem, fasteners were replaced with titanium grade-5 studs and torqueing sequence is updated)*
- BPM + Magnet Spool Tube + GV2 assembly and leak check
- BPM/Magnet package subassembly to the 8 cavities string
- Pump down the fully assembled cavity string
- Bag and conduct final leak check
- Backfill to atmosphere-vent

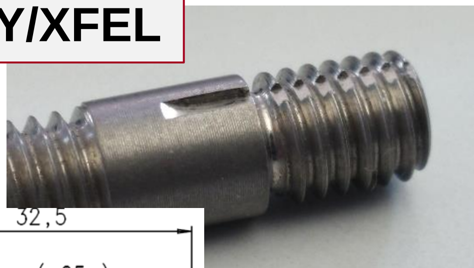
# Post F1.3-6 beamline loss incident, corrective actions are implemented

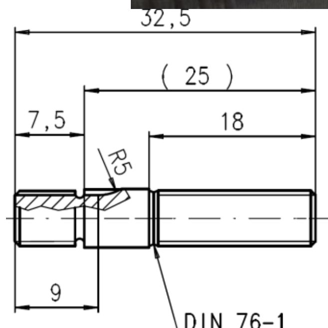
- Replaced grade 2 Titanium socket head cap screws with grade 5 Titanium studs, 316L nuts and washers
  - Materials specifications and certifications are confirmed and verified
- Demonstrated reproducible gasket crush of at least 0.2 mm on BPM subassemblies using torque of 12~14 N*m with the new hardware.
- Thermal cycled new BPM subassemblies to ensure gasket compression does not change after thermal cycles and leaks do not appear.
- Measured new fastener yield and tensile strength and ensured studs are being used in their design range.
- Modified BPM assembly procedure to reflect new hardware and torque sequence and pattern that is consistent with XFEL and what was used to demonstrate leak tight BPM assemblies during bench testing.
- Updated all assembly travelers with the new procedures
- F1.3-1, F1-3-4, F1.3-7, F1.3-9 were partially disassembled. BPM hardware were replaced. Additional procedures are added that every fastener in the CM is tightened and secured against unintentional loosening by at last 2 means of locking I(torque, Loctite, Belleville/lock washers etc.)

C. Ginsburg

# DESY/FNAL/JLab comparison: BPM feedthrough fasteners

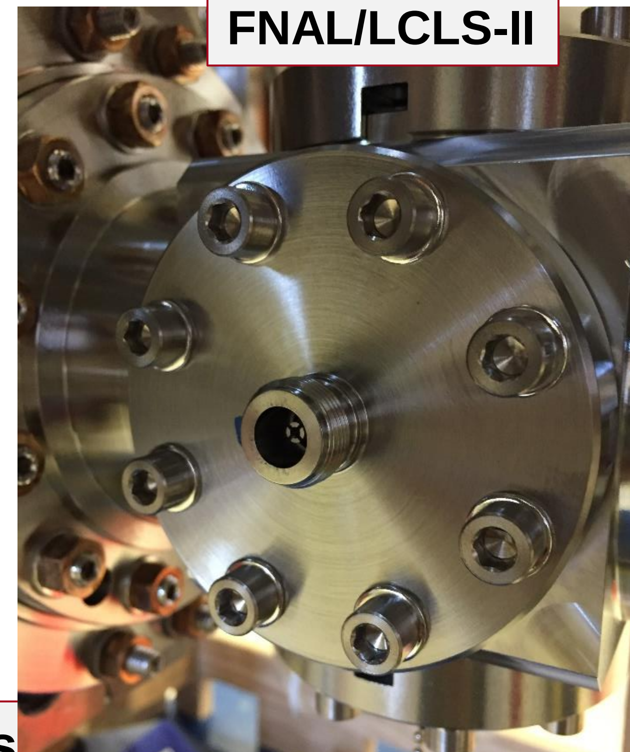
**DESY/XFEL**






**DESY/XFEL**

**FNAL/LCLS-II**



## DESY/XFEL fasteners

Titanium grade 5 studs – specialized design
316L (A4-70) hex nuts
316L (A4-70) washers

## FNAL/LCLS-II fasteners

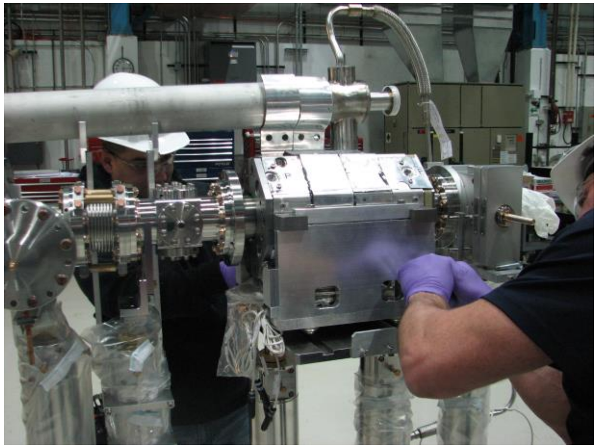
Titanium grade 5 SHCS fasteners intended, not spec'd
Titanium grade 2 SHCS fasteners ordered/received
316L SS washers

Hardware is UHV cleaned, not electropolished
FNAL and JLab use identical HW procured by FNAL, except J1.3-01: SS bolts/washers
F1.3-06 assembly was missing the SS washers – all others checked and ok

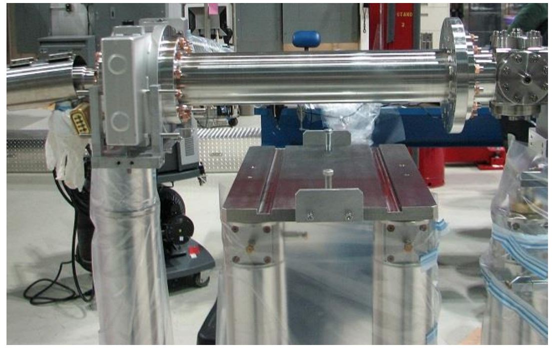
# Cold Mass Assembly at WS2

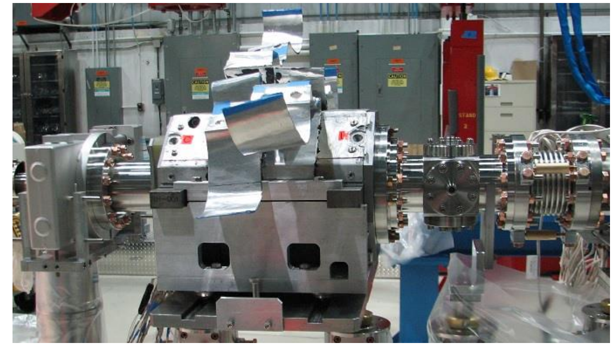
Tasks outside of the clean room before the Cavity string was lifted off the cleanroom posts (lollipops) and married to Upper cold mass assembly:

- Split Magnet installation
- 2-phase circuit pipes-peripherals cutting & welding
- Instrumentation (sensors, heaters etc.) installation to cavity helium vessels
- Cavity magnetic shields installation
- Cavity helium vessel insulation (MLI) installation
- Needle bearings and housings installation
- Marry Upper cold mass to Cavity String
- Upper cold mass to 2-phase pipe welding
- Cool down line to cavity helium vessels welding
- Alignment(X-Y-Z)
- Complete 2-phase pipe invar rods radial clamps welding
- Leak check of the helium circuit
- Electrical checks
- RF checks

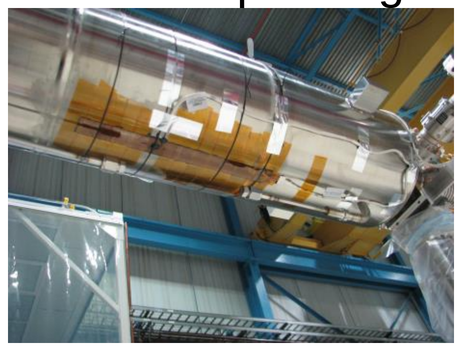


Cavity String on cleanroom assembly tooling rolled to WS2

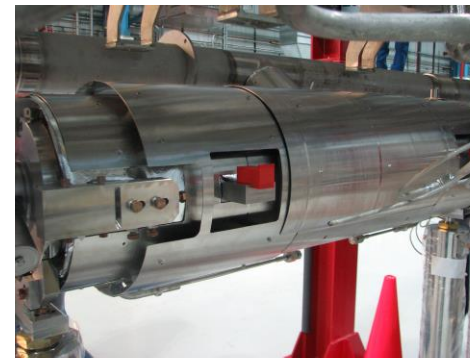




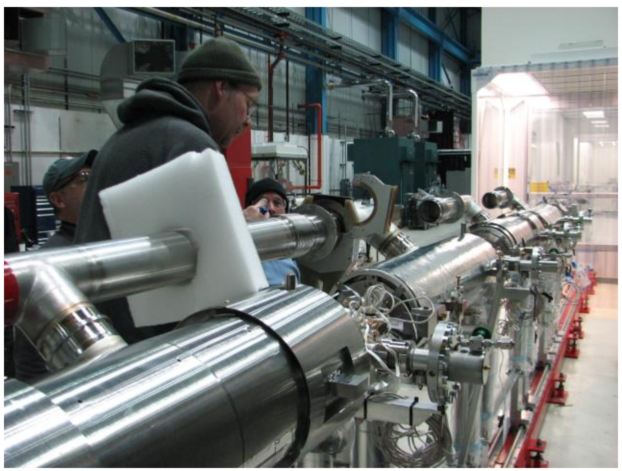
Split Magnet Installation



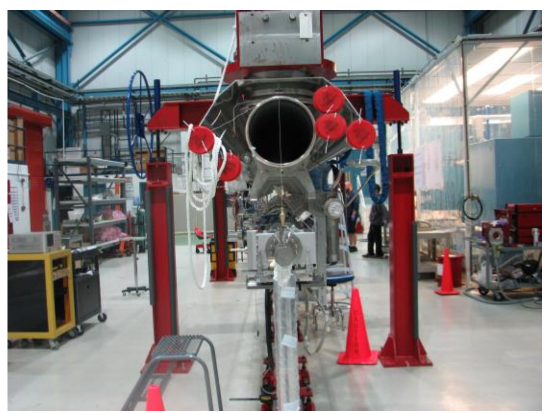
Instrumentation



Magnetic Shielding

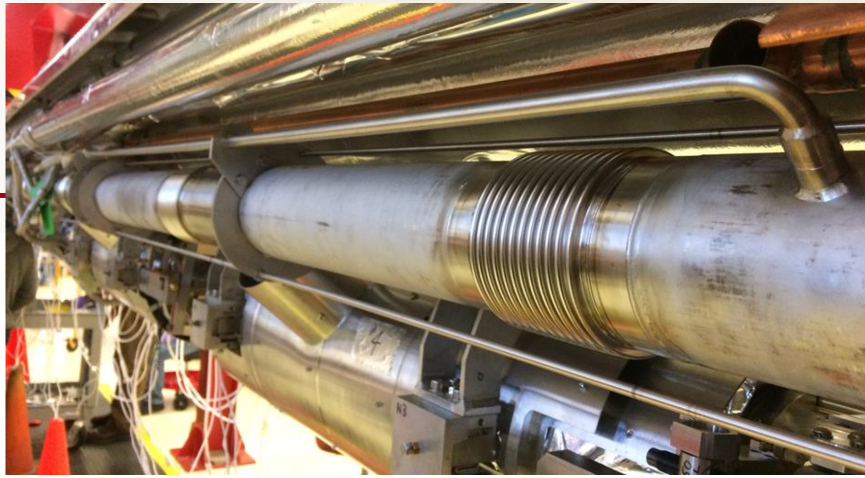


2-phase Pipe Welding



Upper Cold Mass to string alignment

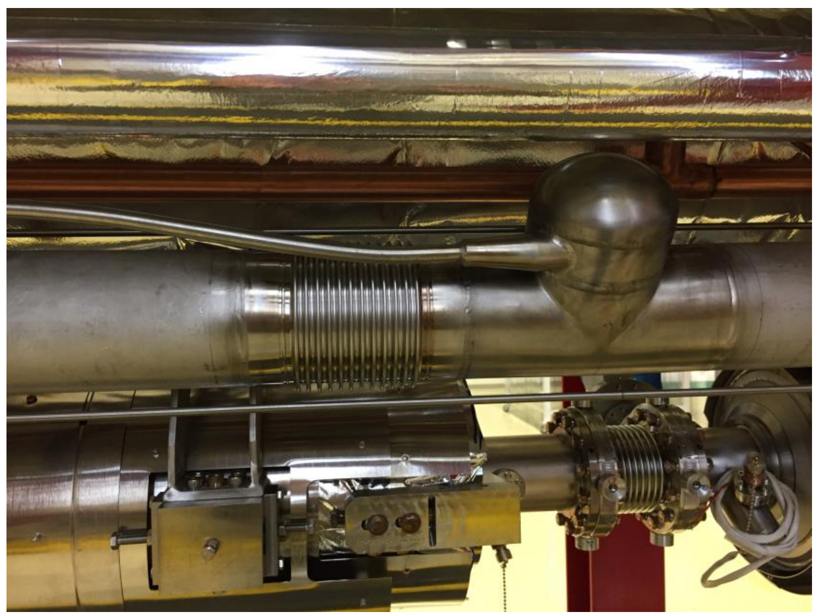
Cold Mass Upper and cavity string coupled



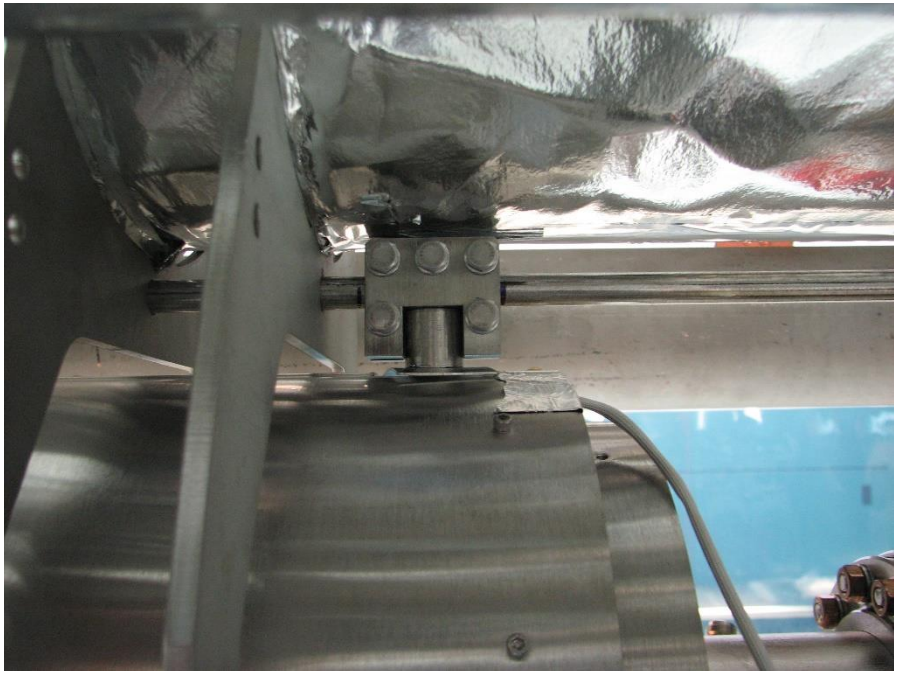
JT injection to 2-phase
pipe for F1.3-1 & F13.2


Baffle added for
F13.2 & Beyond

Optimizations for microphonics & to obtain better liquid management

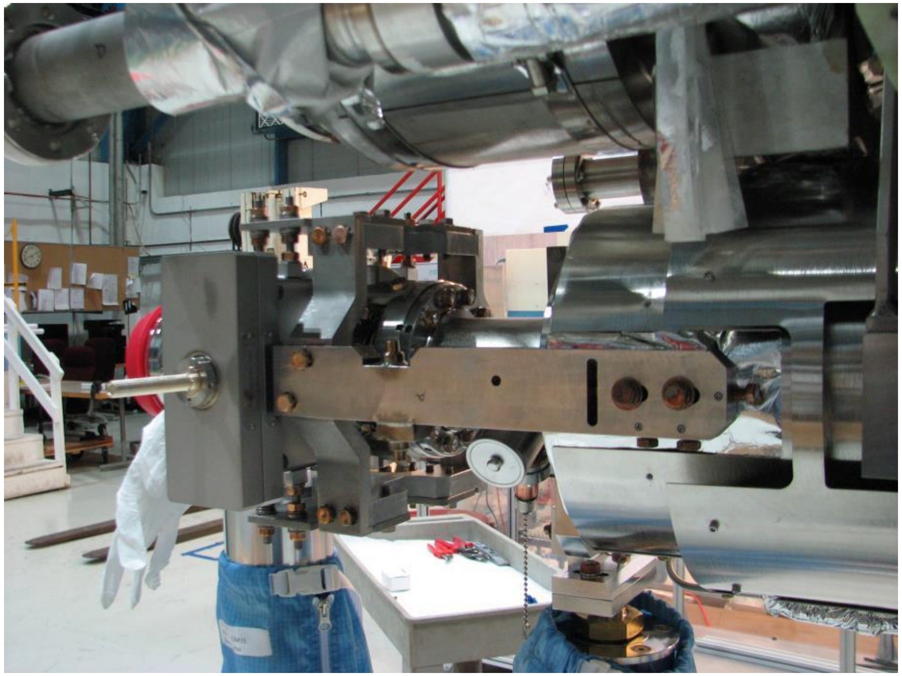


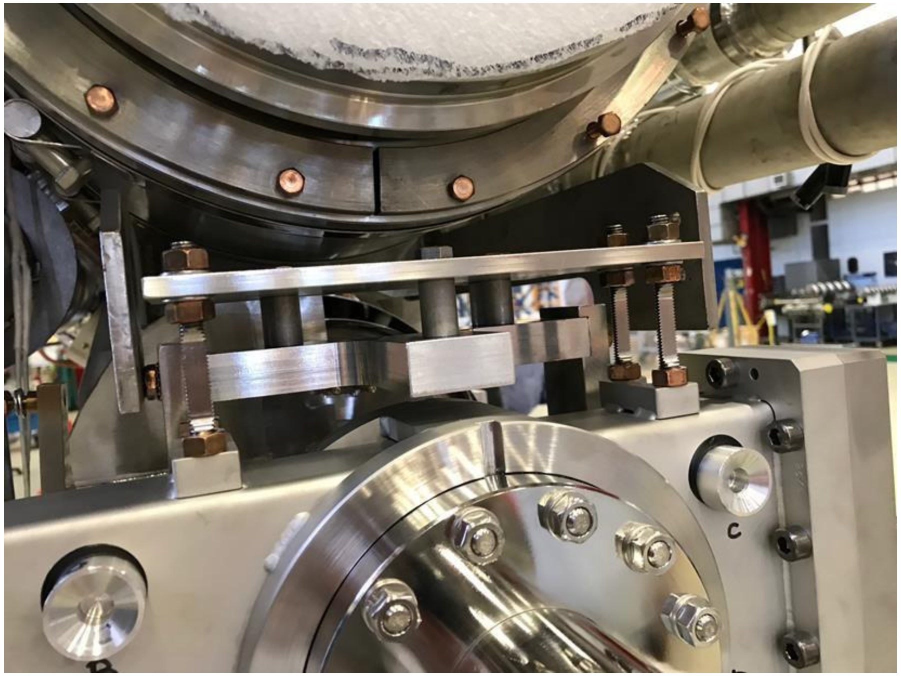
Tangential injection manifold is
added for F13.3 & Beyond



Standard cavity to invar rod clamp for F1.3-1

Reinforced clamp design for Cav#1 and Magnet for F1.3-2 & Beyond (to react vacuum forces)





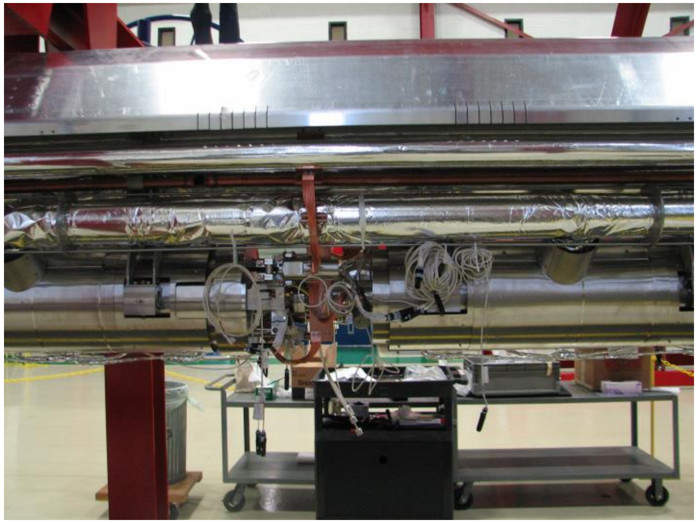
Standard configuration (bellows between Cav#1 and valve) gate valve support frame installed to F1.3-7 at WS2

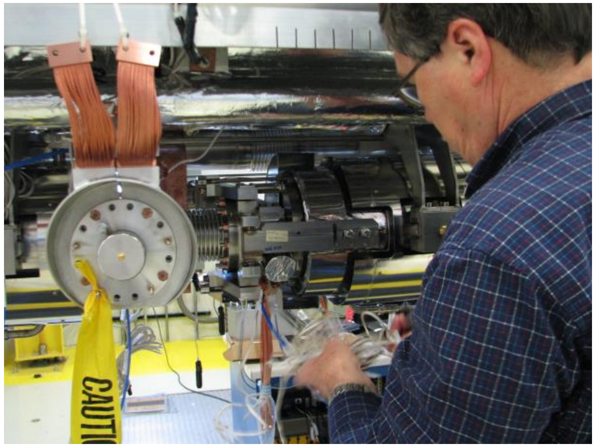
Flex configuration (spool between Cav#1 and valve) gate valve support frame installed on F1.3-4 and F1.3-5 (installed to a completed CM)

*Final decision is not to install the flex gate valve support. Only F1.3-4 has this support*

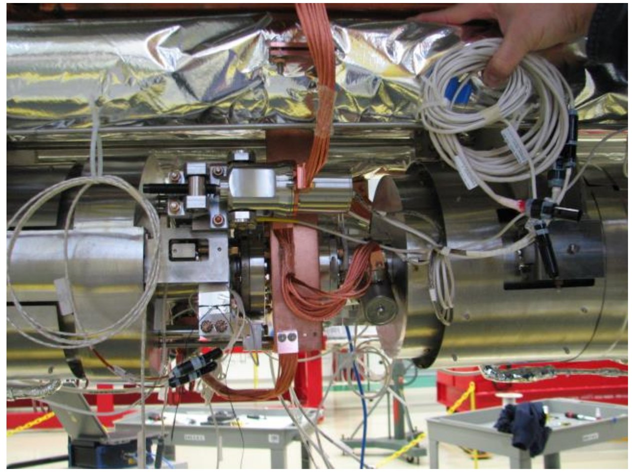
# Cold Mass Assembly at WS3

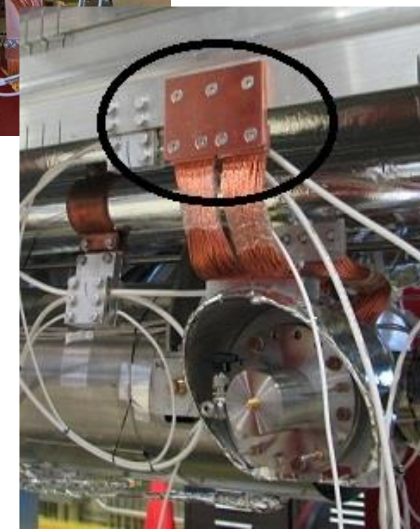
- Magnet current leads thermal intercepts installation
- Remove helium vessel safety brackets & Assemble end lever tuner system
- Complete thermal intercepts assembly (HOM connectors, FPC 5K, tuner motor)
- RF cables installation
- Complete the end caps magnetic shielding assembly
- Complete the harnessing of the instrumentation wires & RF cables
- Thermal intercepts installation for RF cables
- Electrical & RF Checks
- HOM notch frequency tuning
- Install and weld lower 50K aluminum shields



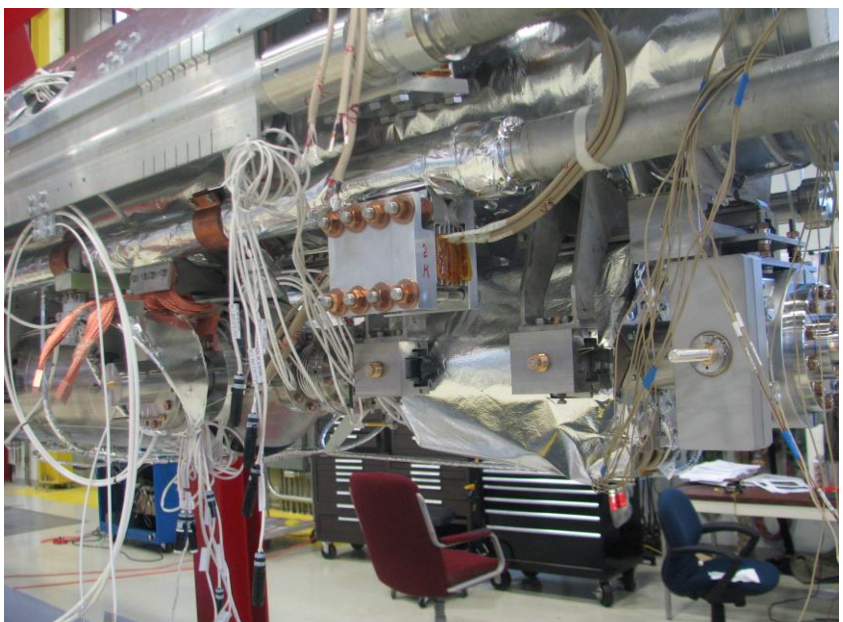


Tuner Assembly





Thermal Intercepts Assembly

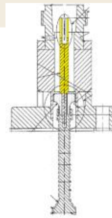


Magnet Current Leads

Lower Heat Shielding Welding

# F1.3-5 Cav#2 HOM connector replacement

- During final HOM notch frequency tuning at WS3, when the RF cable was removed, RF engineer noticed that Cav#2 HOM1 pin is broken
- Local cleanroom tent was built. Nitrogen fogger was used to optimize the location and rotation speed of the fan filter unit
- Procedures are developed, tested on a the bench with a spare cavity
- HOM connector with broken pin was replaced and leak checked successfully
- This is a one time incident. Official root cause analysis is not done
- Mitigation Strategy: ensure that protection caps are installed throughout the cold mass assembly. RF group changed the procedure for HOM notch frequency tuning: Keep the RF cable connected during tuning

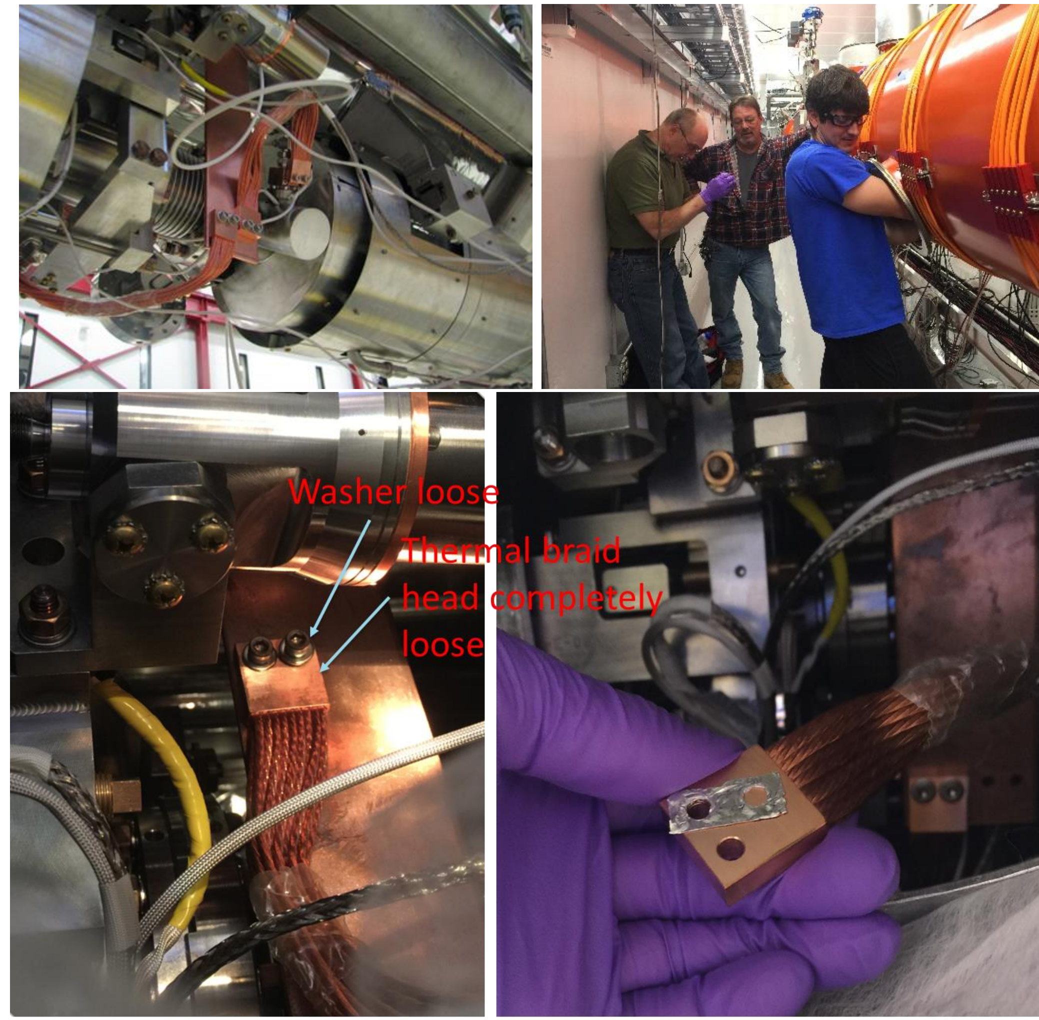







# F1.3-3 Cav#3 coupler side end group heating

- We did an autopsy by accessing from tuner access port
- The root cause of the problem was that the fastener used to bolt the thermal braid to the connector copper clamp had bad thread and jammed to the nut before properly tightening. Jamming caused faulty torque verification quality check result
- To eliminate re-occurrence, we have introduced extra QC steps such as checking the assembled thermal intercepts by wiggling the clamp, sink & more attention to the torqued fasteners by peers, lead techs and responsible engineer




A bad bolt (poor thread) caused false torque satisfaction.

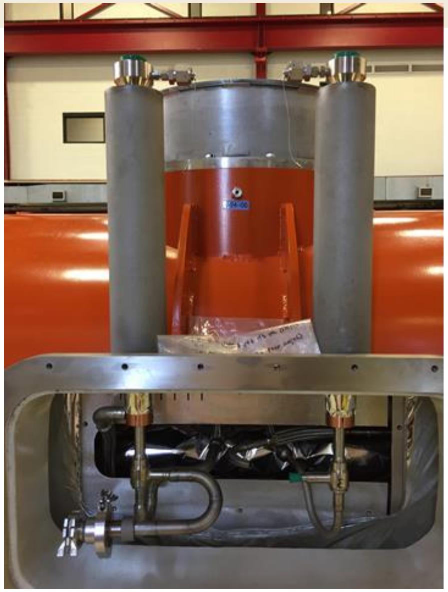
# Vacuum Vessel Assembly at WS4

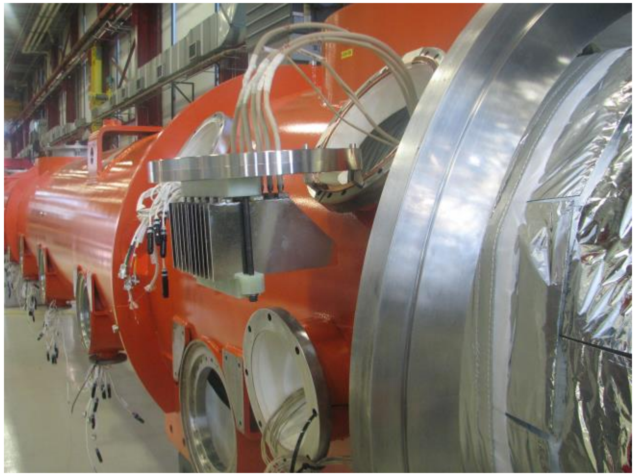
Assembly tasks:

- 30 layers of MLI as pre-made blankets
- Electrical & RF checks
- Slide vacuum vessel onto the cold mass
- Assemble cold mass supports
- Align cold mass to the vacuum vessel and transfer to external fiducials (laser tracker)

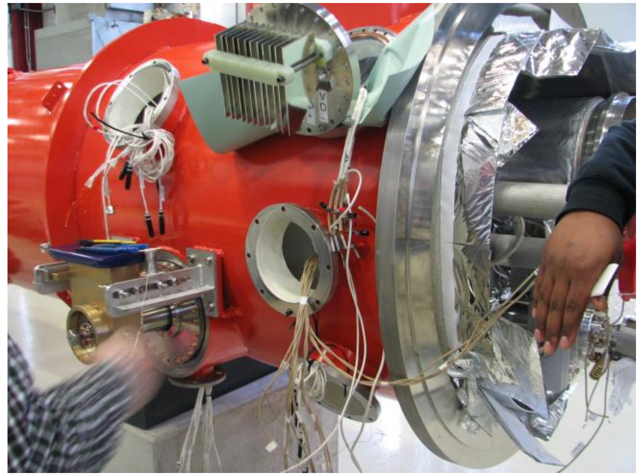
# Final Assembly at WS5

- Weld JT/Cooldown valves
- Leak check
- X-ray
- Pressure tests
- Install warm part of the fundamental power couplers and leak check
- Install FPC waveguides and tuner motors
- Route & terminate instrumentations wires and RF cables to the feedthrough flanges
- Install coupler pumping lines, pumps & leak check, leave under vacuum
- Leak check beamline vacuum, leave under vacuum
- Pump down and leak check insulating vacuum (lots of O-rings, challenging leak check)



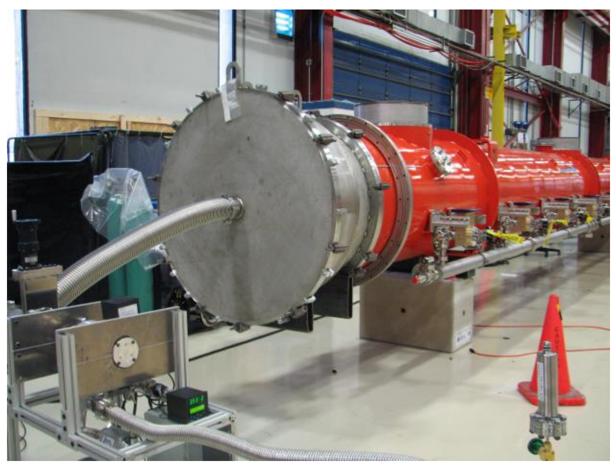


Magnet current leads soldering to the flange




Instrumentation flanges

Warm end coupler Installation

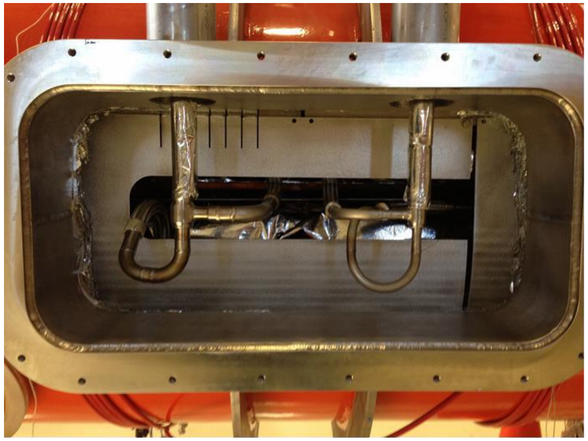


Insulating Vacuum Leak Check

# Optimizations done at WS5

| F1.3-1 | F1.3-2 | F1.3-3 & Beyond |
|---|---|---|
| JT and CD valve stems do not have wiper rings (TAO issue) - retrofit during CMTS tests | JT and CD valve stems have wiper rings | JT and CD valve stems have wiper rings |
| JT and CD valves are welded with standard (as designed configuration) | JT and CD valves are welded with reverse configuration | JT and CD valves are welded with reverse configuration |

Gas guarded DN10 size JT and CD valves with reverse configuration is installed on some tested CMs and will be installed on all CMs before shipping to SLAC.

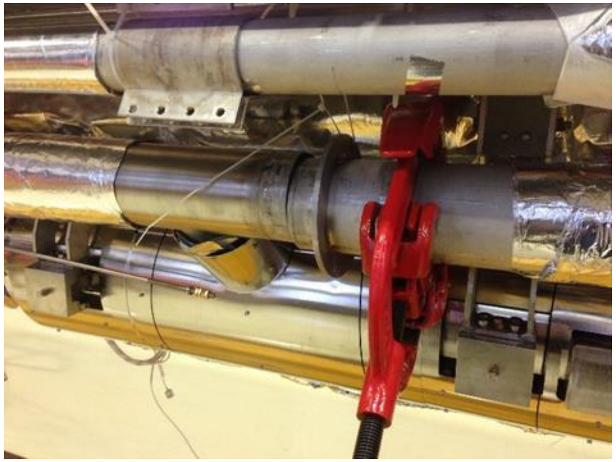


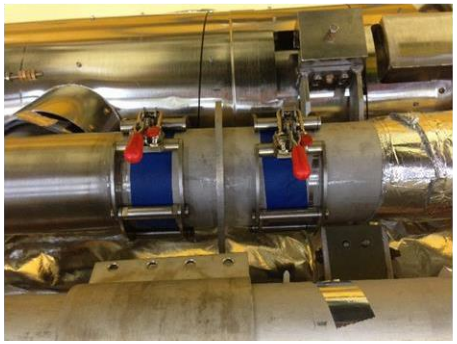
Normal Direction

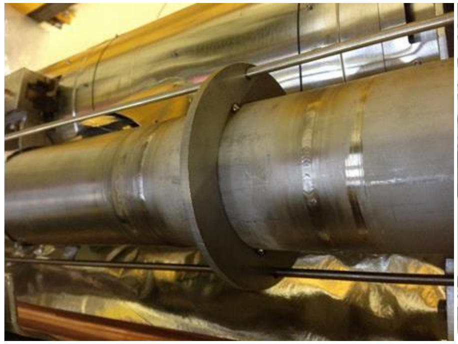
Reverse Direction

# CM08 Line G leak discovered at WS5

- During Line B+G+H leak check at WS5, a leak was found on Line G (2-phase pipe). We tried to repair this leak through a tuner access port without success.
- Four upstream lower shields were removed to expose the 2-phase pipe
- 2-Phase invar rods removed
- Pipe section with leak was cut from 2-phase line
- New pipe section has been welded

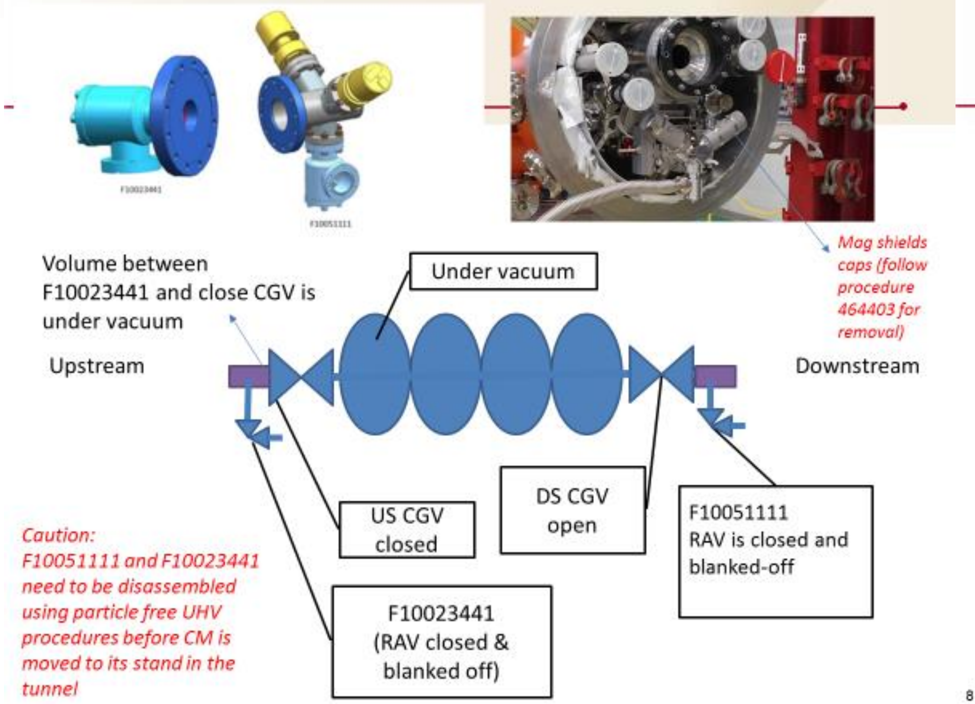




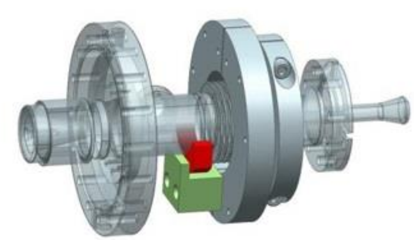


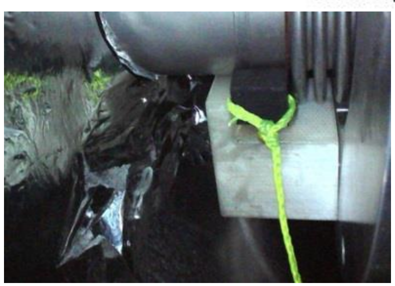
Mitigation: Complete the longitudinal (Z) alignment of cavities at WS2, weld 2-phase pipe disks and install invar rods before Line B+G+H leak check at WS2

# Prep & Ship to SLAC at WS6

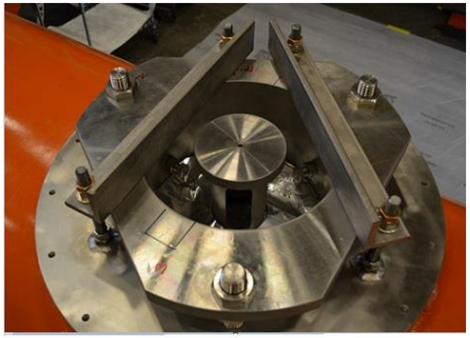



Beamline reconfiguration



M-mounts installed to support the cold end coupler bellows during CM transport (removed at SLAC)



Center Post Clamps (long)

End Post Clamps (short)

Cold Mass Supports Tie-downs

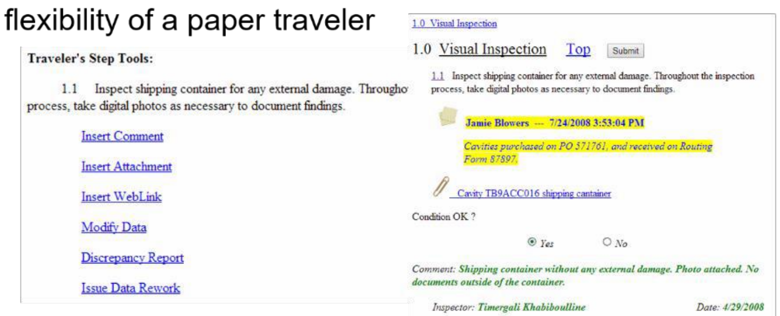
# QA Framework – APS-TD Organization

- In the APS-TD, the quality functions are centralized in one department
- This department covers Design/Drafting, Acquisition, Incoming QC, Process Engineering (travelers), and Inventory/Parts Control, and overall QA

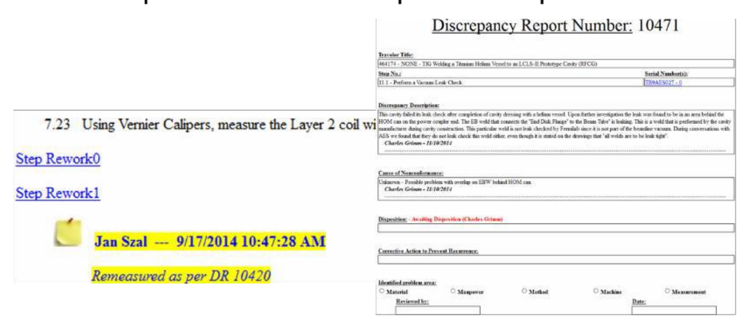
- QA Plan section 4: "*Resources necessary to safely complete the work of the Project [are provided]. These resources include…the necessary infrastructure and work environment to allow the work to be done safely and to meet all quality requirements.*"
- As much as possible material handling is done through the use of tooling and fixturing, so as to protect workers and materials.
- When fixturing is not practical, materials are handled carefully by hand, using appropriate PPE.

- All components go through an incoming inspection
- The inspection varies from verifying appropriate part IDs to full mechanical testing
- All components are logged into a tracking database
  - Each receiving "batch" is assigned a unique "Routing Form" number, which connects the parts back to their Purchase Order and to their inspection results
- Serialized components are inspected according to a traveler; non-serialized parts are inspected as a batch
- "Acceptance Criteria Strategy" documents are maintained per the SLAC LCLS-II QA Plan requirements

- All travelers are fully electronic; http://vector.fnal.gov/
- System is currently read-only to the world, so easy data sharing is in place
- As much as we could, we replicated the functionality and flexibility of a paper traveler




- All non-conformances are recorded using built-in Discrepancy Report System and are resolved by the Lead Engineer before proceeding to next step
- Rework Steps will be issued if process repeat is needed



# Summary

- CM assembly at Fermilab is progressing well. After we complete the assembly of 1.3GHz CMs, we will switch to 3.9GHz CM assembly
- Infrastructure and Production Workflow at Work Stations work well. We continue to make minor improvements to increase productivity and efficiency
- We were able to hire most of the trained contract techs as full-time though turnover (mostly due to getting hired for full time positions at Fermilab for different projects) of the trained contract techs continues to be an issue. Current hands-on workforce is well trained and well experienced.
- CM assembly is heavy touch labor process. QA/QC processes are well established for the CM production. Travelers (step by step assembly procedures, cautions for extra critical steps, sticky notes-comments, DRs) are used. Quality culture is implemented and continues to be improved as we build more CMs